ADVANCED WIREBOND INTERCONNECTION TECHNOLOGY

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by

Shankara K. Prasad
INKROMA
Bangalore, India

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Dedicated to

My primary school teacher K. Gopalachar
High school teachers H.L. Ramachandra Shastri & P.N. Venkatanarayana
College teachers Dr. H.N. & T. Ashwatha Narayana Rao
Post graduate advisors, Dr. E.C. Subba Rao, Prof. Herbert Herman &
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Preface

The market size of the semiconductor device industry is close to 200 billion dollars supporting a trillion dollar global electronics vertical. These semiconductor devices are the back bone of almost every product that supports different activities of our lives today. An estimated 60 billion semiconductor, optoelectronic and MEMS devices are packaged in plastic and hermetic packages every year and more than 90 percent of these packages are connected to the device through wire bonding. A back of the envelop calculation indicates that annually we produce close to 5 trillion wire bond interconnections, and this number will continue to grow as the human race gets to be more and more dependant on electronics and automation.

Those of us who have worked in package technology development and assembly manufacturing areas, and in particular with wire bonding, know that wire bonding is a challenging and fascinating field that has a major effect on product quality and competitiveness. In this book, I have tried to address wire bonding from both manufacturing and reliability perspectives. The book analyses and explores the various factors that one needs to consider in order to achieve six sigma in wire bonding process. The factors include design, materials, processing, equipment, quality testing and reliability engineering and last but not the least: operator training.

Although there are many published books and reports on different aspects of wire bonding, my aim was to consolidate a lot of industrial experience complemented with relevant research work and present it in a way that is comprehensible to a wide audience that work in chip design, package design, wafer fabrication, assembly process engineering, manufacturing engineering, equipment engineering, software engineering, quality engineering, reliability engineering, purchasing, maintenance engineering, industrial engineering, failure analysis and new technology development. Wire bonding being an extremely interdisciplinary domain, the book is also intended to attract readers from other fields who can contribute to the advancement of wire bond interconnection technology.

This book is intended to be a comprehensive source of information and knowledge that enables both a newcomer to the field and a veteran who needs instant information to make a decision on a process problem. The book explains not only how to do things such as: designing a bond pad or a lead finger, how to select a right bond wire, how to design a capillary and how to optimize a bonding process on the factory floor; but the book also explains why to do it that way. Because, my strong belief is that, to achieve six sigma in any process, not only should one know how to do things properly but also why it is done that way.

Every attempt has been made to make this book as technically accurate and up to date as possible, and to present the information in a form understandable to the wide range of engineers. The book covers theory as well as practice, as it builds a strong base of understanding wire bonding technology in the hope that this will help to achieve higher degrees of performance and reliability.

In the earlier days of wire bonding technology development, lot of research and development was done at R&D organizations as well as semiconductor companies. Today, most of the technology development is done by the vendors, and in some cases in collaboration with R&D organizations. The assembly manufacturing companies and the semiconductor companies depend heavily on the information provided by the vendors who supply the materials, equipment and process methodologies. To develop this book, I have relied heavily on information provided by vendors of materials and equipment. The sources of information have been their product catalogs, technical brochures, technical seminars, personal discussions and conference proceedings. I am indebted to all the companies whose information has been used in developing this book. But to my readers I wish to inform that use of any company information in this book is neither a recommendation of their product nor a validation of their technology. The reader is advised to use this information to learn to make better judgement when selecting any bonding material, equipment or process.

A wire bonding engineer in a packaging factory has to develop and depend on his own repository of explicit and tacit knowledge to apply in manufacturing and achieve six sigma in the bonding process. This knowledge must be interdisciplinary and encompass a wide spectrum of information about wire bond design, bonding materials, wafer metallization, passivation, bonding equipment technology, process technology, quality testing and reliability problems. In this book, I have brought in a new system of information and knowledge management in order to address the wire bonding process from the perspective of material, machine, methodology and manpower. Based on my experiences in the industry and the current best practices in the industry, I feel the system that I have used in this book to discuss each topic is the way information is demanded by personnel involved in wire bonding. The macro format of the KM system is described in the following paragraphs.

For example, in identifying a wire bond material for a particular packaging application, one must be aware of the requirements of the material for that application. The requirements will be met by a host of materials from which the engineer can choose from. One must understand how that chosen material is manufactured in order to make sure that bond wire material manufacturing process (upstream process) has no impact on the wire bonding process or the wire bond reliability in the specific application. The wire bond material must be tested based

on standard test methodologies for specified quality both at the supplier and the usage factory. The test methods must be clearly defined and followed.

Similarly, the equipment requirements must be specified for a particular application of bonding. The appropriate wire bonding equipment must be selected based on criteria and options available. The equipment performance must be thoroughly evaluated for the application. The cost of ownership of the process and equipment must be calculated. The equipment calibration and maintenance system must be clearly established and followed.

From the process stand point, the process specification must be clearly established before a device gets bonded. The impact of each and every process variable must be clearly understood. The process optimization methodology must be defined and the process must be optimized before releasing for production. The optimized process must be controlled with statistical process control techniques. The process parameters must be calibrated and monitored using monitoring technologies. The process mechanism must be understood thoroughly to achieve high process reliability and product reliability. The chip and the package have to be designed for manufacturability and the design rules must be established such that it covers every conceivable variant of device design. The process problems and corresponding solutions must be systematically documented.

The quality test methodologies must be described with test methods, test variables, failure modes, interferences, test applications and usability limitations. Both design and manufacturing perfection are essential to reliability. The book addresses the different problems and stresses which impact device reliability and suggest solutions to overcome these reliability problems.

Along with this book a CDROM is attached which contains 2D and 3D animations of many concepts that are discussed in this book. The animations with voice-overs help the reader grasp the ideas faster with visual experience, which I feel leads to better retention. For example, an IC design engineer would have rarely seen a wire bonding machine place a ball bond on a bond pad he has designed. When he sees an animation in the CD and visually experiences how difficult it is to place the ball in the centre of the bond pad accurately, and all the factors that play a role in this precision placement, he may appreciate the challenge and come up with newer ways of pad design.

The reader will notice that the units such as mils and microns are used arbitrarily, and in some instances in the same paragraph. The choice of using both SI units and English units was reluctantly made since most of the American companies and some of the subcontractor companies still use the latter, and engineers do use both the units interchangeably. To describe force, the unit of gm-f is used, and in few instances the unit of milliNewtons is also used. Graphs and figures are reproduced with the same units that the originals were published in. I believe the information

will be more accessible and understandable to professionals who work in the field if the units are the ones that they recognize.

Acknowledgments

This book would not have been possible without the dedication and personal involvement of Ms. Sudha Rao. Her painstaking interest in presenting technically correct yet beautiful images, her attention to detail in preparing the text and her artistic rendition of wire bonding concepts in the multimedia CD- deserve my sincere appreciation and gratitude. Thank you Sudha for making it happen.

I would like to thank my colleagues in our company who have contributed immensely in literature search, graphics development, software development and text preparation. My special thanks to Ambika Rao, Rama Venkatesh, Keshav Prasad, Savitha Jois, Ramesh Chandra, Alok Elhance and Umashankar.

To acknowledge adequately all those who have contributed to the completion of this book would require endless pages for the listing of technical articles. I have read and the discussions I have had with many engineers and managers from semiconductor companies, materials vendors, equipment suppliers, and my students. However, I would like to specifically acknowledge with thanks my interaction with two friends: Mr. Ali Sabui of ST Microelectronics whom I met during a wire bonding project in the early 90's and Dr. Rama Shukla with whom I developed the first packaging course in the mid 80's. Both have been instrumental in inspiring my interest in wire bond interconnection technology.

1

Introduction

Imagine a world without personal computers, space shuttles, aero planes, cars, TVs, mobile phones, digital cameras and DVDs. Imagine what is yet to come! Almost every part of our life has been and will be impacted by electronic products. The technologies behind every one of these life solutions are based on microelectronics, micro-systems, photonics, MEMs and RF/Wireless devices. These devices need to be packaged appropriately depending on the application where the device is being used. For example, if the device is in a disposable telephone card, the appropriate packaging technology may be laminated chip-on-board; on the other hand if the device is used in a long term mission to mars, the appropriate packaging technology may be hermetically sealed multi layer ceramic packaging technology. But in either case, the device has to perform according to its design, and the most critical part that connects the micro world of the device to the macro world of application is the "interconnection" technology. The three major interconnection technologies in the microelectronics domain are wire bonding, flip chip bonding and tape automated bonding (TAB).

Today, we manufacture more than 60 billion devices per annum and the variety includes devices that control air bag systems in a car, devices that bring a video image on to the PDA in your hand and devices that control the missile that bombs an enemy target with a precision of +/- 1 meter. Market demands more functions in smaller, faster, cheaper devices and these devices are getting packaged in varieties of packages such as CSP, BGA, WCSP, TCSP, and Stacked BGA. But large volumes of devices are still being assembled in slightly older packaging technologies such as PLCC, TQFP, SOIC, SOP, PDIP and SSOP. More than 90% of these packages are interconnected with gold and aluminum wire bonding technology.

The predictions of many of the leading packaging analysts in the industry is that as devices shrink and the requirement for thin and small packages increase, flip chip will replace wire bonding and will be the choice interconnect in the near future. Will flip chip completely dominate the interconnect domain? We do not think so!

Considering the billions of packages that are assembled every year and the enormous wire bonding infrastructure that exists across the globe, anyone who has been in the semiconductor assembly industry for more than 2 decades knows that gold ball bonding continues to be the technology of choice. Today, more than 90 percent of the chip interconnect is covered by gold ball bond.

If we recall the decade of the 1980's, tape automated bonding (TAB) technology was supposed to replace wire bonding. TAB was touted as the technology of the future both because it would support high speed microprocessor packaging and because the technology was amenable to mass production (gang bonding process). Needless to say, today, TAB technology has expired and wire bonding technology has progressed to support both high performance device packaging and high through put manufacturing.

Flip chip is a slightly different story. The technology has existed for more than 35 years. Why has it not been widely utilized as an interconnect? Simply, it is because of lack of infrastructure and standards. But recently more companies have been established in the USA, Europe and the Fareast and flip chip has become a manufacturing worthy technology. Once the technology is available globally, and the standards are developed, the industry will accept the technology and the flip chip volume will grow.

While flip chip clearly is going to claim its share of the market due to its performance advantage, the growth in wire bond interconnects will not diminish in the near future. The wire bond technology continues to reinvent itself as the demands of the device require. Wire bond technology will remain the technology of choice because it is ultimately the lowest cost technology. As the silicon wafer fab technology has progressed towards sub-micron line widths, the wire bond technology has kept pace with it. This can be seen in figure 1.1, and is expected to keep abreast till 2008.

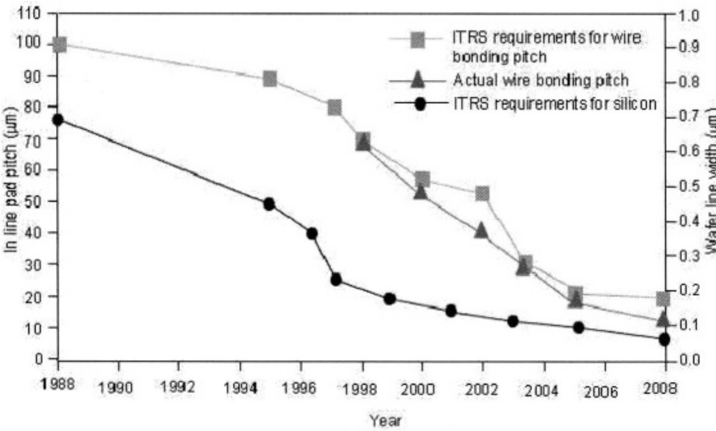


Figure 1.1 The progression of wire-bonding capability has tracked silicon technology [Courtesy: Advance packaging]

Looking at the roadmap in Table 1.1, predicted by the international technology roadmap for semiconductors (ITRS), we can see relationship between silicon feature sizes and pad pitches for both wire bond and flip chip technologies.

Table 1.1 International technology roadmap for semiconductor predicts the trends for wire-bonding and flip chip technologies [Courtesy: Advance packaging]

		2000	2001	2002	2003
Wafer technology node	Line width (µm)	0.18		0.13	
On chip clock performance (MHz)	High performance	1386	1600	1724	1857
	Cost performance	693	800	890	989
Chip-to-board clock performance (MHz)	High performance	693	800	862	929
	Cost performance	166 / 347	166 / 400	200 / 445	200 / 495
Wire bond interconnect (µm)	High performance	50	45	35	30
	Cost performance	45	40	35	30
Flip chip (area array) (µm)	High performance	200	175	175	150
	Cost performance	165	150	130	120
Overall package profile (mm)	High performance	1.2 - 1.7	1.0 - 1.2	1.0 - 1.2	1.0 - 1.2
	Cost performance	1.2	1.0	1.0	1.0

No doubt that wire bonding has enabled significant reduction in pad pitch. This has facilitated IC designers to scale die sizes in relation to their requirements for reductions in silicon device feature sizes.

1.1 Wire Bonding Technologies

The purpose of wire bonding is to create electrical interconnection between the IC chip and the package. In gold ball bonding, for example, the first bond is done on the bond pad on the chip and the second bond is done on the lead finger. The objective of the wire bonding process is to create a perfect interface between the bond wire and the bond pad on the die and the bond wire and the lead finger on the package.

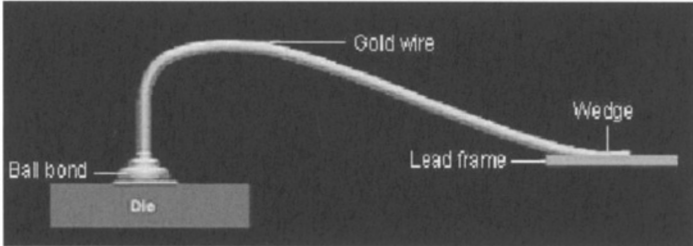


Figure 1.2 Creating a ball bond and a wedge bond

There are three wire bond technologies used in the industry today.

- thermosonic ball bonding
- ultrasonic wedge bonding
- thermocompression ball bonding

1.1.1 Thermosonic Bonding

The process of bonding the wire in which we use ultrasonic energy, high temperature and bond force is called thermosonic bonding, as shown in

Figure 1.3. A simplified process of thermosonic bonding at different stages of bonding process is described in figure 1.4.

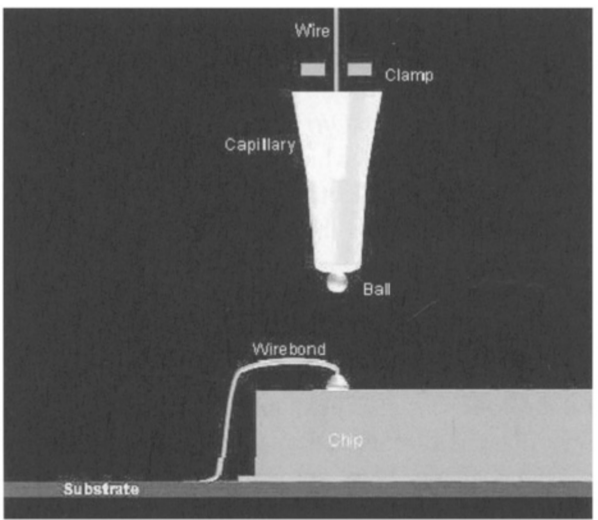


Figure 1.3 Thermosonic Bonding **[VIEW- IN- CDROM]**

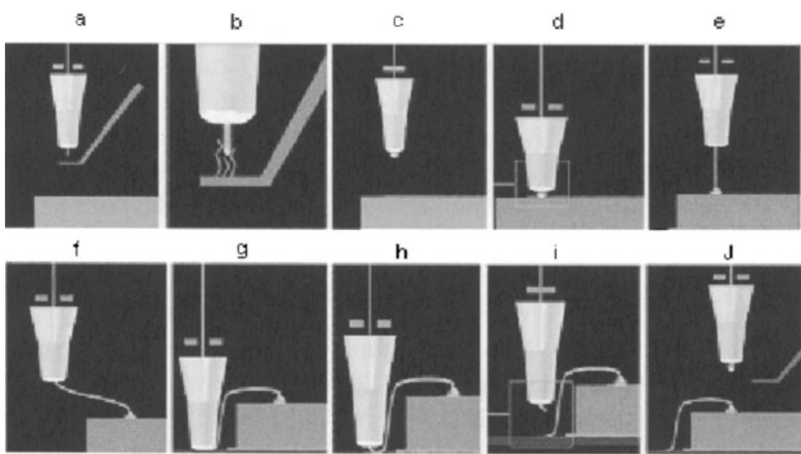


Figure 1.4 Step-by-Step view of thermosonic bonding process

Step by step bonding process is described below.

(a) Wire threading: The wire bonding process cycle begins with the wire threaded through the capillary. The wire is fed through the capillary and a specific length of wire extends below the capillary tip and the wire length below the capillary determines the size of the free air ball.
(b) The EFO (Electronic Flame Off): The EFO electrode discharges a very high voltage and melts the wire which forms the ball. The amount of EFO current, the gap between the electrode and the wire and duration of the spark determines the ball size and the ball shape.
(c) Ball positioning in the capillary: The EFO wand retracts to its initial position. The wire clamps open, and an air tensioner (an air column wire drag system) applies force to seat and center the ball in the conical chamfer of the capillary.
(d) Formation of first bond: The capillary descends to the first bond position. The capillary is first moved by the machine to a position above the target pad in the x-y plane. New automatic machines do this with a PRS which controls the machine. The machine then lowers the capillary. There are two components to this downward motion. An initial high-speed downward motion, and a slower controlled-velocity descent during which the bonder senses contact with the surface. The capillary presses the ball on the bondpad with certain amount of bond force and the ultrasonic energy is applied for certain duration of bond time. During this the interface bond between gold and aluminum is formed. As the ball touches the pad, the creation of the first bond is underway. With force applied by the machine-controlled capillary tip and ultrasonic energy transmitted through the capillary, the ball is squashed and the first bond is formed. Ball bonding on the bond pad occurs through a combination of plastic deformation and interfacial slip of the two materials due to force, temperature, and ultrasonic energy applied.
(e) Raises to loop height: Now the looping of the wire begins. The capillary ascends to the top of the wire loop. During the ascent of the loop, the required calculated wire length is metered out precisely. At the top of the loop, the wire clamps close so that no additional wire can enter the loop.

(f) Loop formation: During the trajectory, precisely controlled motion algorithms, both on the ascent to top of loop and in descent towards second bond, enable the wire bonder to produce some of the special loop shapes required by today's advanced packages. They include 'worked' loop shape, BGA and CSP loops.

(g) Second bond formation: As the capillary descends, wire protruding from the capillary contacts the surface first. As the capillary continues downward, the wire rolls upward, lifting and shaping the loop near second bond. The ultrasonic vibration transmitted through the capillary is delivered by the tip surface to the bond. Two welds are formed during second bond formation. First, the capillary face forms and welds a crescent (fishtailed) shape, attaching the wire to the lead. Second, inner chamfer of the capillary welds the tip of the wire still within the capillary to the substrate (the 'tail bond'), providing the attachment that will allow the proper length of wire to be metered for the next ball.

(h) Determination of tail length: The clamp opens. The capillary rises to a position just enough to make the new Free Air Ball, pulling the wire through the capillary. This height provides a cylindrical volume of wire equal to the volume required for the programmed ball size for the next ball bond. If the second bond is not welded securely, this volume is either incorrect or the EFO wand will fail to fire. The tail must be long enough to prevent a ball from forming in the chamfer and weakening the "neck" area.

(i) Wire tearing: Clamp closes and holds the wire, the bond head ascends towards the EFO fire position, tearing the tail bond from the substrate. The wire tears at its weakest point under the sharp edge of the chamfer, which serves as a stress concentration line. The correct volume of wire for formation of a new free air ball protrudes from the capillary tip. Exaggerated force or impact at the second bond may cut the wire during bond creation, resulting in "no ball" stoppage. Parameters should be set so that only the clamps will tear the wire.

(j) Formation of tail length: With a tail of wire hanging under the capillary hole, the machine is ready to perform the next bond.

1.1.2 Ultrasonic Wedge Bonding

Wedge - Wedge bonding of aluminum wire is done at room temperature with ultrasonic energy applied to the wire. The ultrasonic wire bonding is used mainly in packages, where the package cannot be heated to a high temperature. Aluminum wire bonding is also used for devices which are used in high current applications. A simplified process of ultrasonic wedge bonding is shown step by step, in figure 1.5

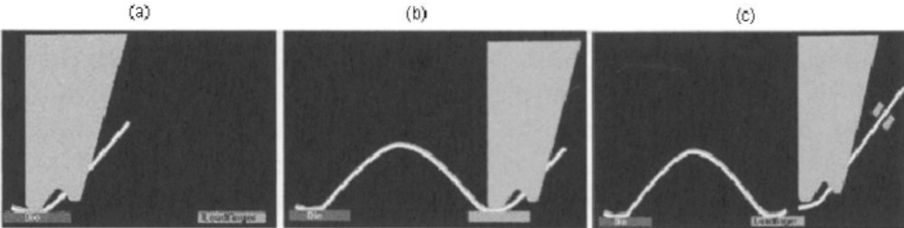


Figure 1.5 Wedge bonding process

In wedge bonding the wedge applies force on the aluminum wire and ultrasonic energy deforms the aluminum wire and also creates the bond on the die. Then the wire is looped and the same process repeated on the lead finger on the package. After the second bond is complete the wire is broken and the bonding process is repeated.

1.2 Advantages of Ball- Wedge Bonding

Ball-Wedge bonding has a number of advantages over Wedge-Wedge bonding, including the following:

- one of the major attractions of the gold wire ball/wedge interconnection technique over that of aluminum wire wedge/wedge bonding is that the

wire can be led off in any direction from the first ball bond. This facilitates automation.

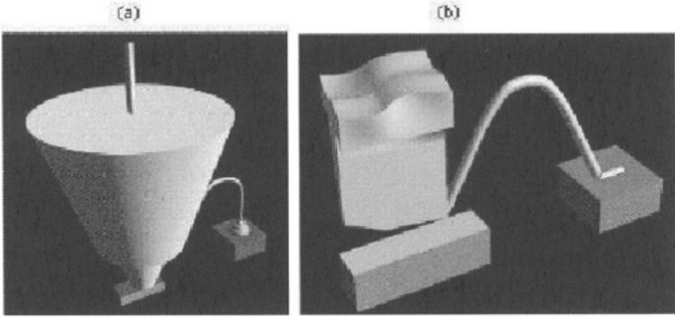


Figure 1.6 (a) Ball bonding has 360° (omni-directional) freedom of movement (b) Wedge bonding is unidirectional

Because of the 360 ° freedom of movement after the first ball bond the second bond can be formed in any direction without damaging the ball neck and this is a fast process. Where as the in case of the Al wedge bonding the wire has to be parallel to the wedge and therefore the device under bonding has to move and this slows down the bonding. The wedge wedge bonding has only one direction to move which means the wire has to travel parallel to the bond foot. Any small deviation from this loop path will create micro crack at the heal and associated reliability problems. This uni-directionality slows down the bonding process.

High temperature thermosonic ball bonding operation is more reliable and less critical than the ultrasonic wedge bonding operation at room temperature.

The wire from a wedge bond comes off at a small angle to the substrate and wires can contact the edge of an active device and short circuit, especially when the second bond is lower than the first bond as shown in figure 1.7. This is less likely to happen in ball bonding as the lead-off is perpendicular to the device.

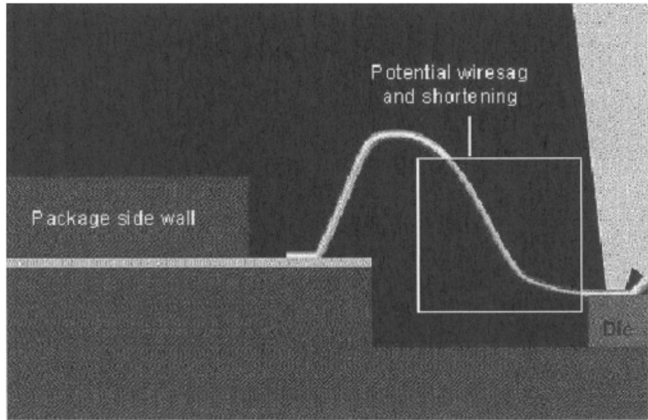


Figure 1.7 Potential short circuits due to edge contact during wedge bonding process **[VIEW-IN-CDROM]**

1.2.1 Disadvantages of Thermosonic Ball-Wedge Bonding

The multi-directionality of gold ball bonding does mean, however, that the second (wedge) bond can be made with vibrations applied to the weld in any direction relative to the wire axis. The weldability of the wire to the lead finger is affected by the direction of vibrations. The bond pull strength is higher for bonds bonded with longitudinal vibrations compared to bonds bonded with transverse vibrations. These issues are discussed in detail in section chapter 4.1.

1.3 Advantages of Aluminum Wedge Bonding

Wedge-wedge bonding with aluminum wire is widely used for ceramic packages. The bonding tool for wedge-wedge bonding has only one bonding direction, contrary to the cylinder-shaped symmetrical tool used for ball wedge bonding. With this configuration of the wedge bonding tool, it is possible to fabricate tools with very small dimensions in the direction

perpendicular to the bond. Wedge-wedge bonding using 25 µm gold wire is capable of bonding on 50 µm die pad pitch. Some of the other advantages of ultrasonic aluminum wedge bonding are:

- no special environments or shielding gases are necessary because it is a room temperature joining process
- relatively simple tooling requirements
- interface temperatures remain well below the melting point of the materials being joined under normal conditions. Contamination by thermal oxidation of the welding interface is therefore, not a problem
- metallurgically sound welds can be obtained between many dissimilar metals
- no major surface preparation is necessary before bonding
- intermetallic phases are seldom formed in the weld zone of dissimilar materials
- there are no electrical discharges to contaminate or damage the device
- fine wires can be joined to thin foils or to thick sections.

1.3.1 Disadvantages of Aluminum Wedge Bonding

The disadvantage of the wedge-wedge method is that it will always be more complex than ball-wedge bonding. The reason is, the need to align tool and bonding direction on the device.

Commercially available wedge bonders are slow, thus hindering gold wedge-wedge bonding from becoming a reasonable alternative to gold ball bonding. Some of the other disadvantages of wedge-wedge bonding are:

- precise alignment of the bonding tool must be maintained
- close control of clamping pressure is essential when welding to thin films in order not to disrupt the film
- one of the joining members must have a certain degree of ductility
- very thick metallizations can not be satisfactorily bonded.

1.4 Thermocompression Bonding

In thermocompression bonding of Au wire, we use only high temperature and bonding force to create the bond between the Au wire and the bondpad. No ultrasonic energy is used during bonding. This has certain advantages and is used in special applications such as bonding of GaAs devices.

1.5 Comparison of the Three Bonding Technologies

In the semiconductor industry, the most widely used wire bonding technology is the thermosonic bonding, followed by ultrasonic bonding and thermocompression bonding technologies. Table 1.2 gives a comparison of these technologies and their relative merits.

Table 1.2 Comparison of the three wire bonding technologies

Bonding Technique	Advantages	Disadvantages
Ultrasonic wedge bond	. Least sensitive to contamination . Al bond at room temperature . Excellent Al-Al bond . Simple parameter set up . Lowest wire loop height . Highest yield, <30ppm	. Auto wedge bonder is more complicated than auto-ball bonder . Pontential cratering problem . Al wire unreliable on Ag . X-Y wire pad orientation required, slow autobonding
Thermosonic bond	. Lower temperature than TC . Complex looping possible . Non-directional ball bonding	. Sensitive to contamination . Some cratering potential . More set up parameters required . Larger bond pad required . Somewhat lower yield than US wedge bond.
Thermocompression bond	. Simple parameter set up . Negligible cratering . Non-directional bond . Excellent Au-Au bond	. High temperature required . Sensitive to surface contamination . Not suitable for small pad . Lower bond yield

1.6 Ultra Fine Pitch Wire Bonding

In this age of smaller electronic gadgets, the use of high density, high I/O, and high frequency chips is becoming more widespread. And as the Silicon real estate continues to increase in value, die shrinks are common place. The easiest place to save space is in the size of the bond pads, and the space between them, referred to as bond pad pitch (BPP). In response to the escalating requirements for increased circuit densities and smaller product form factors, the use of ultra fine pitch wire bonding is becoming increasingly popular, and the current generation of wire bonders can operate at BPPs of 60 microns or less, as depicted in figure 1.7.

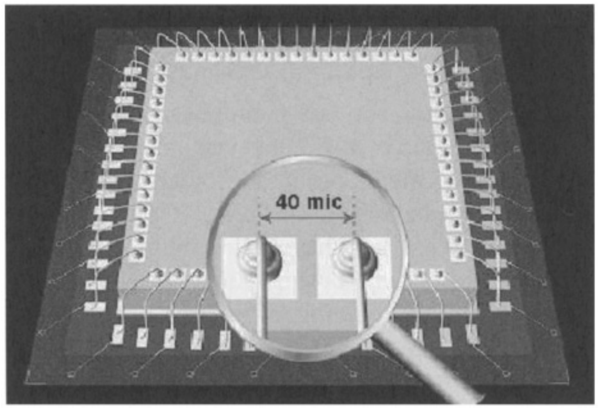


Figure 1.7 Schematic representation of 40 micron Bond pad pitch on a device **[VIEW-IN-CDROM]**

Today high density IC chips with bond pad pitch is as low as 60 microns is already in production in limited volumes. Bonding equipment to meet 60 micron pitch bonding have already been developed and bonding equipment to meet even 45 micron BPP are currently under development. To achieve zero defect bonding process with such ultra fine pitch devices, we need to understand and develop new bonding materials technology, equipment

technology, process technology, new capillary design, newer methods of quality testing and some unexpected reliability issues.

1.6.1 Challenges in UFP Bonding

To achieve six sigma with ultra fine pitch bonding at 60 micron pad pitch, one needs to thoroughly understand various factors related to bond wire materials, bonding equipment, process technology, capillary technology, quality test methods and reliability issues.

In chapter 2 on Materials Technology, we will study what the requirements of the bonding wire are depending on high current application, low loop application, stacked die application or long loop application. Some applications demand high tensile strength and low elongation wires, and some require short HAZ length. We review different materials choices available in the industry and provide guidelines as to how an engineer needs to weigh the pros and cons of different wire products and choose the right wire for an application to meet both high productivity and high reliability. In the section on wire manufacturing, we will give a glimpse of how bond wire is manufactured, and what are the up-stream processes that can have an impact on the actual bonding during package assembly production. The process consistency of wire bonding is highly dependant on the quality and consistency of the bond wire. In the section on wire quality, we specify what quality attributes are crucial for a bonding wire. In the last section on wire quality testing, we explore the many different methods of quality testing that one can use to validate the goodness of the wire for production.

In chapter 3 on bonding equipment we focus on issues such as:

- what are the wirebond equipment capabilities required for fine pitch wirebonding,
- how does one select the right kind of bonding equipment for a particular packaging application
- how does one analyse the cost of ownership of a wire bonder

- how does one evaluate the performance of a wire bonding machine and
- what are the maintenance issues to be addressed

In chapter 4 we explore the innumerable number of factors that affect the yield, quality and reliability of the bonded device and understand the effect of each of these variables and the interaction of these variables with each other. In the section on process variables, we shall address a host of these factors that impact the bonding process. When there are numerous variables interacting and impacting the process consistency, one needs to understand how the bonding process should be optimized for maximum yield. The section on process optimization addresses the different optimization approaches and techniques. Once the process is optimized, it needs to be controlled using statistical process control methodologies and any deviations from the optimum process can be corrected in real time. This topic has been dealt with in the section on process control. The many variables in the wire bonding process such as temperature, ultrasonic energy, bonding force and such need to be measured on a periodic basis and these measurements require special technologies. The section on process monitoring explores many different techniques that are in use today for wire bond process monitoring. The focus of wire bonding is to create a perfect metallurgical interface between the wire and the bond pad metallization. This involves both mechanical interaction between two metals and diffusional reaction at the interface. It is possible to optimize the process and make it perfect only by understanding the impact of each of the process variables and their effect on the metallurgical bond that forms between the wire and the bond pad. The section on process mechanism helps one to gain knowledge of the intricacies of the metallurgical science behind the thermosonic and ultrasonic wire bonding technologies. How to design a bond pad both from the device functionality perspective and from manufacturability perspective is discussed in detail in the section on design for bondability. Topics such as bond pad shape, bond pad size, staggered pad pitch and bond pad positioning are addressed here. The many problems that one encounters during the bonding process and the necessary solutions are discussed in the section on process problems and solutions.

In chapter 5, we discuss in detail established methodologies such as bond pull test, bond shear test and visual inspection. In this chapter we shall also understand the applicability, advantages and limitations of each test.

In chapter 6, we shall discuss some of the major reliability failures such as purple plague, spiking, cratering, wire sweep, corrosion and heel crack. Apart from these we shall also discuss other reliability failures such as die attach pad shift failures, over current failures, grain growth failures, Al bond failures on Ag plated leadframes, aluminum silver corrosion and gold silver problems.

In chapter 7 we will take a look at some of the recent applications, such as opto-electronics and stacked die packaging where wire bonding has been used. By understanding the demands made by these new packaging applications, one can appreciate the criticality of understanding the wire bonding technology and its importance in the "food chain" of micro chip manufacturing and more importantly in the electronics vertical. We will also explore the new copper wire bonding technology that is gaining relevance and importance in the IC assembly industry in the past few years. Issues related to materials, equipment and reliability of copper wire bonds and the current industry trends in each of these domains will be discussed.

2

Materials for Wire Bonding

Bonding wire – An overview

Bonding wire used for microelectronic interconnection bonding is a precision metallurgical product developed for the semiconductor manufacturing industry. During the semiconductor assembly manufacturing operation, the wire bonding process line must operate consistently, and the yields of wire bonding process must approach 100 percent. Semiconductor manufacturers seek to maximize assembly yields by optimizing the bonding wire to their particular chip metallization, package design, package constructions and bonding machine configurations. This demands extremely stringent quality standards on the bonding wire that is used in assembly production. In addition to consistent productivity, today's Ultra Fine Pitch wire bonding applications require that the bond-wire geometry has very low loop, very short loop, and use very thin wire. The bonding wire must meet these critical requirements of fine pitch applications. Many high power IC applications also demand high current carrying capability of the bonding wire and high fatigue resistance. Long term reliability requirements of the IC device demand that the wire must ensure high mechanical strength and corrosion resistance in harsh environments.

Designing such a material with the above requirements and manufacturing high quality bonding wire material are critical to achieve high performance and reliability of the device as well as achieve zero defect wire bonding process. Figure 2.1.1 shows the different parameters that have an impact on the bonding wire selection. Experience in the industry shows that there is no

standard bonding wire that meets all wire bonding applications and the wire selection for any particular application depends on the chip metallization, package design, package construction and bonding machine configuration.

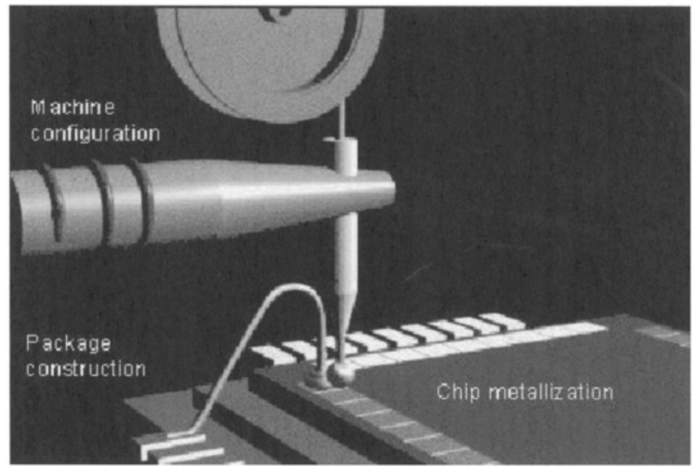


Figure 2.1.1 Selecting the right bonding wire for an application depends on parameters such as bondpad metallization, package design and machine configuration

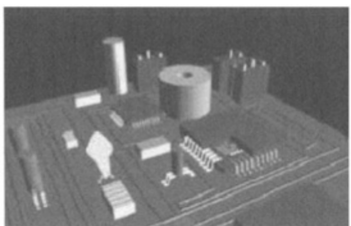
2.1 Bond Wire Material Requirements and Properties

2.1.1 Critical Requirements of Bond Wire

The bond wire is the link between the micro world of the semiconductor chip and the macro world of printed circuit board with the lead frame as the intermediary. We can see from Figure 2.1.2 the wire bonds connecting the micro world and the macro world.

The material requirements of the bond wire connecting the device to the package depends on the device performance as well as the application where the device is being used. For example, if a high current device is used in space applications, then the bond wire required is Al and the package

used must be a ceramic hermetic package. From this example, we can see that the wire must have high current carrying capability, must with- stand power cycling, must with stand temperature cycling, and must have long term corrosion resistance. On the contrary, an inexpensive Chip-on-Board IC device used in a singing Christmas card, needs bond wires that can be bonded at high speed to reduce manufacturing cost but with minimum reliability requirements.



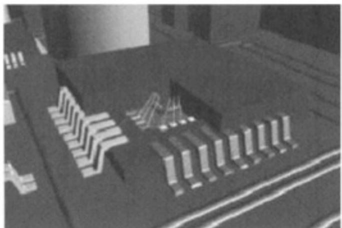


Figure 2.1.2 Schematic of a PCB with passive components and a IC and a zoomed image of an IC showing wirebond interconnection from chip to leadframe

Considering the innumerable number of devices in the industry and the varied applications that the devices are being used, it is but natural that bond wire material must meet many requirements, including high electrical conductivity, high current capability, high tensile strength, controlled elongation, high Young's Modulus, ultrasonic bondability, thermosonic bondability, high productivity, low wire loop, high wire loop, superior loop linearity, short wire length, long wire length, sag resistance, bond pad metallization, high thermal fatigue resistance, high creep resistance, corrosion resistance, high frequency, wire drawability, fine grain size, long shelf life, and slow uniform intermetallic growth to.avoid purple plague.

Let us review and discuss some of the above requirements in detail to help us understand the complexity of the materials technology required for today's wire bonding process.

2.1.2 High Electrical Conductivity

The electrical signal integrity of the device is dependent on the electrical property of the wire. The main purpose of bonding wire is to carry the signal in the form of electrical current, from the chip to the outside world. Therefore the electrical conductivity and the electrical resistivity of the wire are crucial properties. Electrical conductivity is defined as the electrical charge flux per unit voltage. As we can observe from figure 2.1.3, for a one volt potential difference, higher the electron (electrical charge) flux, higher is the electrical conductivity of the material. As shown in figure 2.1.4, in pure Au metal, electrons flow freely without any scattering. This indicates that the electrical conductivity is high. But when Au is alloyed with dopants like Be, the electron flux is reduced due to scattering of electrons. Due to this scattering the electrical conductivity is decreased.

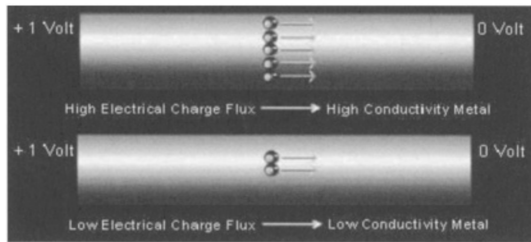


Figure 2.1.3 High electrical conductivity versus Low electrical conductivity

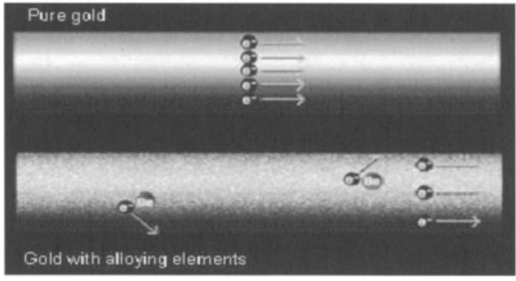


Figure 2.1.4 Impact of Impurity Atoms on Electrical Conductivity
[VIEW-I N-CDROM]

The electrical conductivity of the bond wire depends on the type of material. For example, Ag metal has the highest electrical conductivity followed by Cu, Au and Al, as shown in table 2.1.1.

Table 2.1.1 Physical properties of bond wire materials. **[Adopted from Product catalog: American Fine Wire]**

Properties	Units	Au	Pd	Pt	Ag	Al	Cu
Melting point	°C	1063	1552	1770	961	658	1083
Density	g/cm^3	19.32	12.02	21.45	10.5	2.7	8.92
Lattice constant at 20° C	Angstrom	4.0786	3.8907	3.9231	40.774	4.049	3.6153
Lattice structure		FCC	FCC	FCC	FCC	FCC	FCC
Specific heat at 25 °C	Cal/g.°C	0.0308	0.0584	0.03136	0.056	0.215	0.092
Heat conductivity	Cal/cm.sec.°C	0.744	0.18	0.174	1	0.53	0.941
Coeff. of linear expansion(0-100 °C)	10^{-6}m/m.°C	14.16	11.1	9.1	19.17	23.6	16.5
Specific electrical resistivity	$Ohm.mm^2/m$	0.022	0.11	0.107	0.016	0.027	0.017
Electrical conductivity at 20°C	%IACS*	78	16	18	108	64	101
Hardness	N/mm^2	220	400	400	260	200-500	400-1100
Modulus of elasticity	N/mm^2	79000	123600	173200	82500	70500	123000
Tensile strength	N/mm^2	135	180	130	138	100-200	210-370

Addition of any alloying element to a pure metal reduces the electrical conductivity of the metal. For example, addition of chromium atoms into Au or Al or Cu increases the electrical resistivity of these metals. As atomic percent of dissolved Chromium increases, the electrical resistivity of Cu, Au and Al increases, as shown in figure 2.1.5. But it should be noted that for addition of the same amount of chromium, Al shows higher resistivity compared to Au or Cu. The resistivity of Al changes from 2.6 micro ohms to 4.0 micro ohms with addition of 0.3 at. % of Chromium; where as resistivity of Cu changes from 1.7 to 2.4 micro ohms with 0.3 % addition of chromium. Similarly addition of any impurity atoms to a pure metal increases the resistivity. However, the impact on resistance change depends on the type of alloying element. For example, 99.99% Au with 100 ppm of alloying elements shows a dramatic increase in resistivity. This increase in resistivity occurs when the wire is heated for 100 hrs at 200° C. However, 99% Au with 1% Pd impurity, does not show an increase in resistivity even up to 600 hrs of heating at 200° C.

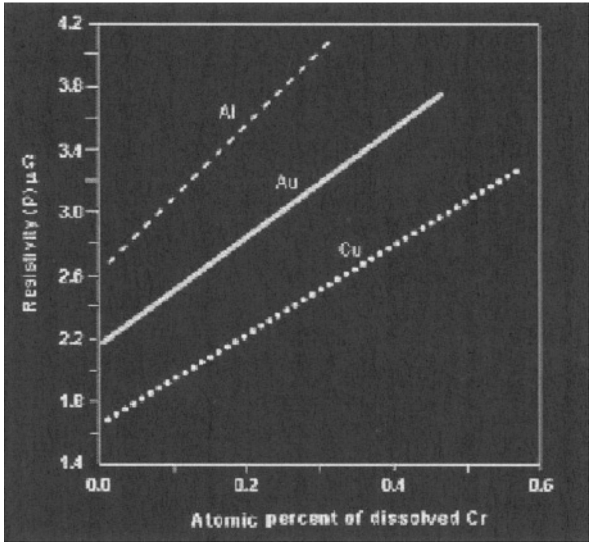


Figure 2.1.5 Impact of chromium impurity atom on resistivity of Al, Au and Cu [M-1]

As shown in figure 2.1.6, the electrical resistance of the Au wire changes when exposed to high temperature. Here we see a conventional "four nine" Au wire with some alloying impurity, the resistance reaches 70 ohms after 100 hours of exposure. Whereas, a different alloying element increases the resistance only to 50 ohms, after 100 hours of exposure. The resistivity of new Au-Pd alloy is not affected even after exposure to more than 500 hours at 200°C. However, addition of alloying elements is necessary for improving the mechanical properties of pure Au or any pure metal. The impact of different alloying elements in Au that enhance the mechanical properties with minimum impact on the electrical conductivity. [M-1]

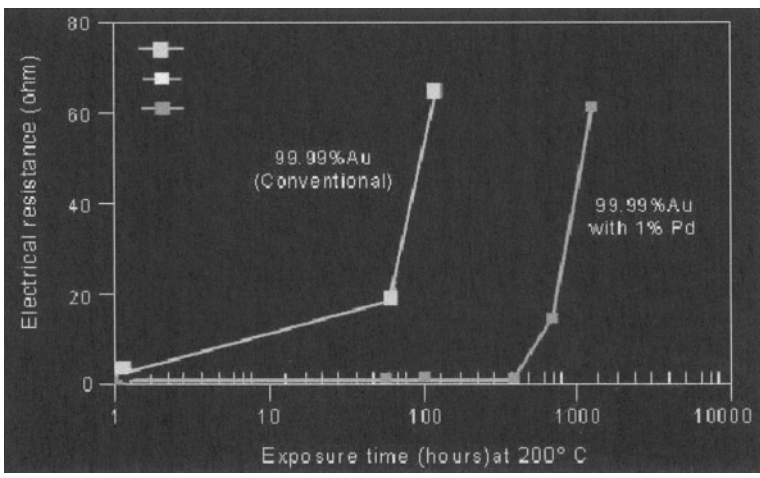


Figure 2.1.6 Variation of electrical resistance at high temperature
[Courtesy: Small Precision Tools Ltd]

2.1.2.1 Electrical Resistivity of Wires

The resistivity of Al or Au wire is dependent on the purity of the wire. The resistivity of 99.999% pure Au is 2.4 micro ohms, resistivity of 99.999 % pure Al is 2.6 micro ohms and 99.99 % pure Al is 2.8 micro ohms. The electrical resistance of 5N wire is much lower than 4N Al wires, as shown in figure 2.1.7. It can also be seen that an increase in wire diameter results in decrease in wire resistance of Al wire. We can calculate the resistance of any wire by using the electrical resistivity value. A demo of calculation of wire resistance can be viewed in the CD. Majority of IC applications require 25 to 38 micron diameter wire and this is adequate for signal and power connections. The choice of wire size or wire diameter is based on the device requirements as well as bond pad size. Usually, one mil (25 microns) Au wire is used in most BGA-CSP device packaging. However, high current requirements of power devices need the current-carrying capability of 125 to 200 micron wires.

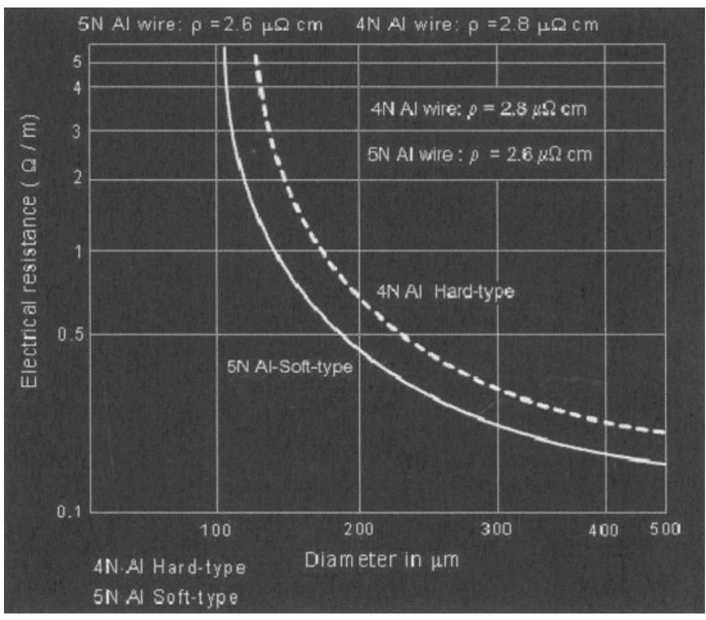


Figure 2.1.7 Electrical resistance vs. wire diameter **[Adopted from product catalog: Tanaka Electronics]**

2.1.3 High Current Carrying Capability

Thinner wires have smaller current carrying capacity than thicker wires, resulting in higher probability for wire fusing under high power conditions. The current carrying capacity is generally measured as the maximum current the wire can carry before it fuses or burns off. Current carrying capability of Au Wire as a function of diameter is shown in the figure 2.1.8. As the Au wire diameter increases, the current carrying capability of the wire also increases. For a particular wire diameter, the fusing current of wire depends on the wire length. We can observe from figure 2.1.9, for a particular bond wire diameter, as the length of the wire increases the current carrying capability decreases.

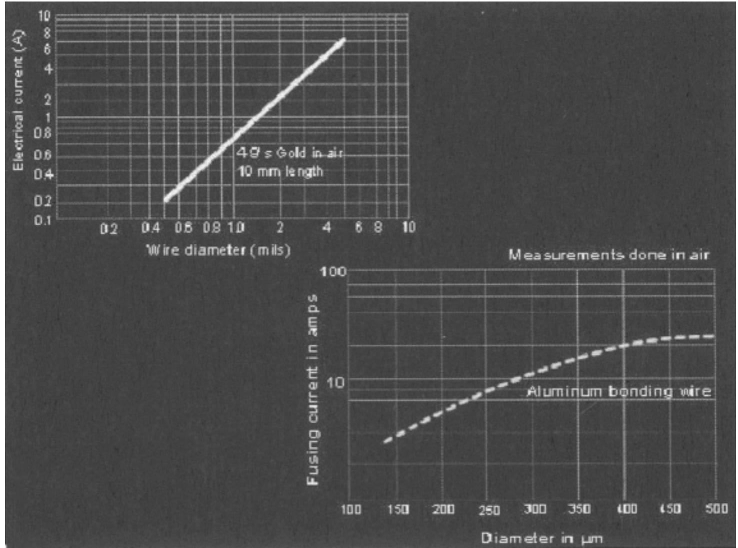


Figure 2.1.8 Current carrying capability of Au bonding wire and Al bonding wire [Adopted from product catalog: Williams Advanced Materials]

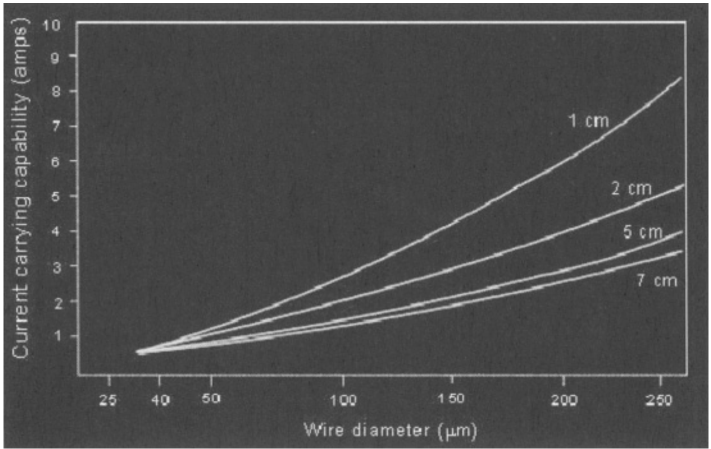


Figure 2.1.9 Current carrying capability at melting point of Al-Si wire
[Courtesy: Heraeus Oriental Hi Tec Company Ltd]

Different diameter wires with different lengths have different current carrying capability (i.e. the fusing current varies). For example, as can be seen in figure 2.1.10, a 25 micron wire of 5 mm length fuses at 0.6 amps where as 30 micron wire of 5 mm length fuses at 0.85 amps. The values shown here are for fusing current measured in air. If the wire is encapsulated in epoxy molding compound or Silicone gel coating, then the fusing current will be usually higher than that in the air, qualitatively shown in figure 2.1.11.

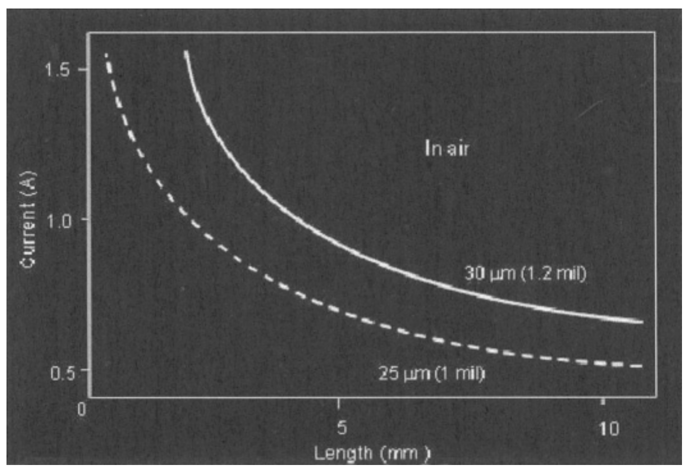


Figure 2.1.10 Current carrying capability of 25μm and 30 μm Au wire measured at room temperature in air [Courtesy : Tanaka Electronics]

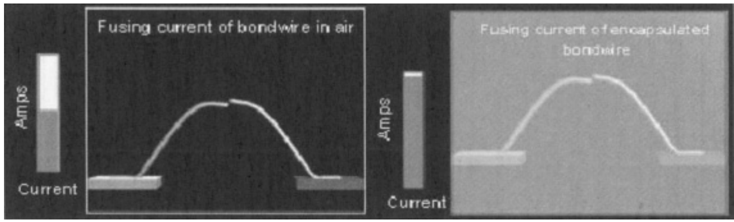


Figure 2.1.11 Fusing current of bond wire in air is lower compared to fusing current of encapsulated bond wire

One can calculate the maximum current that a particular wire can carry using the software module given in the demo CD. **[VIEW-IN-CDROM]**

2.1.3.1 Transient Current Capacities of Bonding Wire

In certain applications, a device draws very high current for a very short period of time. For example, there is a sudden surge in current when a monitor is turned on or when an automobile ignition is turned on. This sudden surge of current, for a short duration is called transient current. A bond wire which may operate perfectly under normal operating conditions, may fail when it is subjected to high current transients. The transient current carrying capability is dependent on many factors such as specific heat of the material, thermal conductivity of the wire material, electrical resistance of wire and electrical pulse duration.

The transient current carrying capability may be calculated using the equation:

$$\theta = \frac{\pi^2 D^4 \rho c}{16 i^2 \alpha \rho_{eo}} \ln(\alpha t^* + 1)$$

θ : Time
D : Wire diameter
ρ : Density
c : Specific heat
i : Electrical current
α : Thermal coefficient of electrical resistivity
ρ_{eo} : Electrical resistivity at reference temperature
t* : Relative temperature

Calculation of transient current using this "empirical" equation, (equation based on experimental curve fitting) gives us an approximate value of transient current carrying capability of any wire. To obtain the actual transient current carrying capability of a wire one has to do experimental evaluation [M-2]. In the industry, usually devices with low current requirement use thin Au or Al wire whereas devices with high current

requirement use only heavy Al wire. Figure 2.1.12 schematically shows bond wires of high current and low current devices.

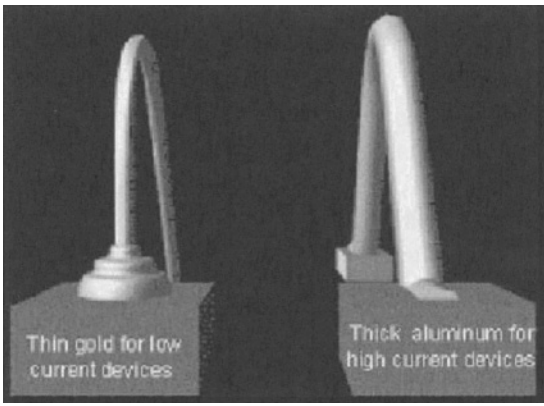


Figure 2.1.12 Bond wires for low current and high current devices

2.1.4 High Tensile Strength and Controlled Elongation

The bond wire goes through many phases of mechanical deformation during the bonding operation, during molding operation, during reliability tests and during the device operation in the field. For example, during bonding the capillary deforms the wire to form the bond and pulls the wire along a trajectory to form the loop. During the molding operation a high temperature, extremely viscous molten molding compound pushes the wire which must with stand the viscous force. During the device operation, the wire is subjected to extremes of thermal and power cycling and this demands excellent fatigue resistance of the wire. For fine pitch packaging applications, low wire loops that do not sag and long wire spans that do not sway are required for tight and compact packages. All the above requirements demand that the bond wire must have very reliable and consistent mechanical properties, including:

- a high tensile strength , controlled elongation and high modulus of elasticity
- stability of tensile strength and elongation through temperature variations of 25-200° C
- a high modulus of elasticity to minimize the wire sweep during the molding process, where the looped wire is exposed to viscous forces of the flowing molding compound.

The mechanical properties of the bond wire, namely, the breaking Load (ultimate tensile strength in technical terms), elongation and young's modulus determine the consistent manufacturability of the device as well as the final reliability of the wire bonded package. Depending on the application, one has to choose the right tensile properties, i.e. breaking load, young's modulus and elongation.

2.1.5 Stress Strain Curve

The relationship between the stress and strain that a material displays is known as a Stress-Strain curve. It is unique for each material and it is obtained by recording the amount of deformation (strain) at distinct intervals of tensile or compressive loading. The stress-strain curve of a wire obtained using tensile testing gives the values of breaking load and elongation. The mechanical properties of bond wire are defined by a stress-strain curve. Figure 2.1.13 shows the critical parameters of the curve, which are the yield strength, the breaking strength and the elongation. The area under the stress strain curve determines the toughness of the wire.

The stress axis represents the applied force, while the strain axis, represents the wire's response to the pulling stress which appears as the wire elongation. Higher the yield strength and the breaking strength, higher is the material strength.

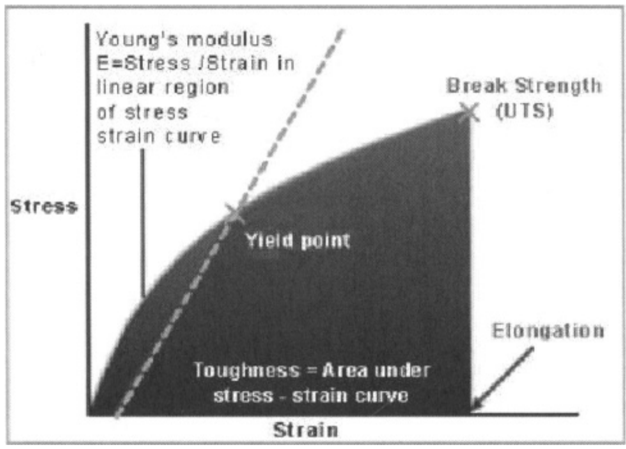


Figure 2.1.13 Stress strain curve **[VIEW-I N-CDROM]**

2.1.6 Breaking Load

Breaking load is the amount of stress a wire can sustain before the breaking point. High tensile strength of the wire is necessary for loop height control and wire length stability. Relatively hard wire is needed for small diameter wires (less than 2 mil diameter) with tensile strength ranging from 13-18 grams for 1 mil and 19-21 grams for 1.25 mil wire. However, higher tensile strength wires exhibit greater hardness of the wire. This may lead to fracture of Si under the bond pad during the bonding process. Harder wire may also result in non-stick problems during the formation of second bond on the lead frame. Wires with lower tensile strength have a tendency to be softer, and this reduces the range of bonding schedules and may also result in wire sagging.

2.1.7 Controlled Elongation

Elongation is defined as the amount of strain at a particular stress level. We can observe from figure 2.1.14, high elongation at low stress level indicates softer (weaker) wire, where as low elongation at high stress

indicates hard (strong) wire. Elongation pertains directly to the elasticity of a particular wire in a certain state of hardness. Generally, higher the elongation of a wire, lower is the wire hardness. Elongation is also an indicator of how much a wire can stretch under various stress-strain conditions before plastic deformation occurs. Higher elongation wire stretches more easily compared to a lower elongation wire.

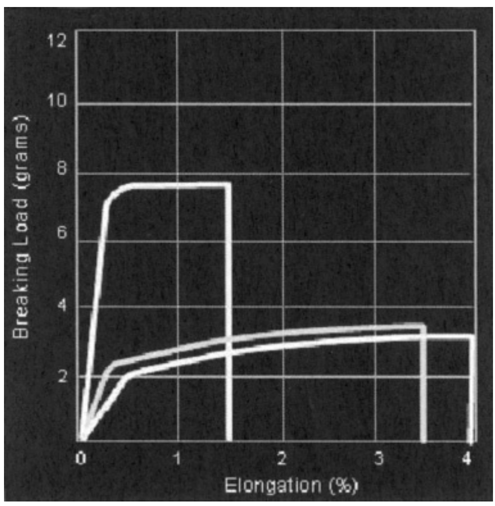


Figure 2.1.14 Bond wires with different elongations
[Adopted from product catalog: Tanaka Electronics]

Let us see how elongation has an impact during wire bonding process. High elongation of the wire has the advantage of smooth looping and no wire break during bonding process, but may lead to wire sagging and excessive tail residue after second bond formation as shown in figure 2.1.15.

On the other hand, low elongation of the wire has the advantage of minimum wire sagging, but may lead to wire breaking during high speed bonding or short tail length after second bond formation as shown in figure 2.1.16.

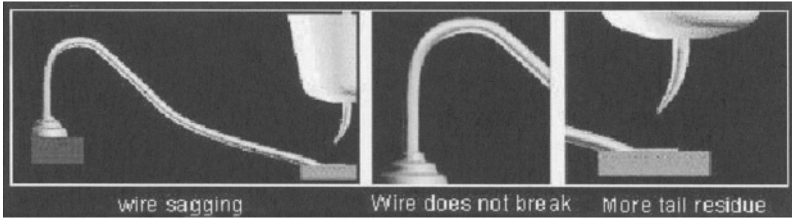


Figure 2.1.15 Effect of high elongation

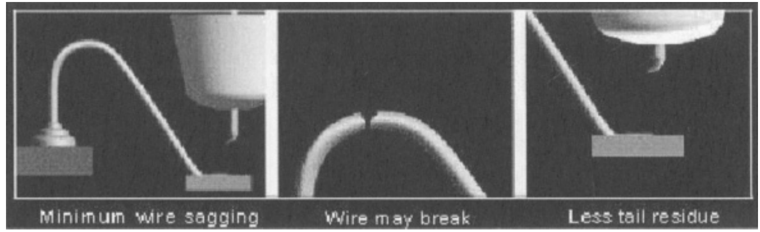


Figure 2.1.16 Effect of low elongation

In ultra fine pitch applications, as the wire becomes thinner the second bond strength on the lead finger becomes lower. In order to increase the second bond strength and to minimize second bond failures, one has to use softer bond wires. Generally it has been observed that as the elongation value increases the bond wire softness increases. Softer bond wires result in better second bond formation. This leads to lower non stick bond failures. This has been shown in figure 2.1.17, where, as the elongation value of the bond wire increases, the percentage of second bond failure decreases.

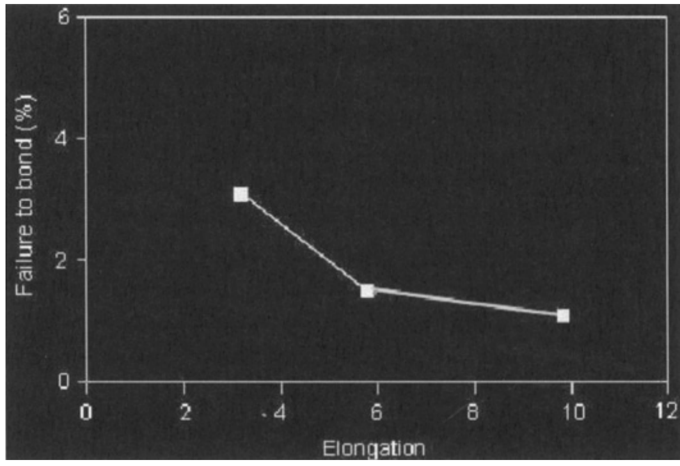


Figure 2.1.17 Heel failures vs. wire elongation [Courtesy: Sumitomo Metal Mining]

Some examples of different types of wires with variable elongation and breaking strength properties are shown in table 2.1.2.

Table 2.1.2 Mechanical properties of Au wire with different diameters [Courtesy: Small Precision Tools]

Diameter (inches)	E.L (%)	B.S (gms) Minimum	E.L (%)	B.S (gms) Minimum	E.L (%)	B.S (gms) Minimum
High speed automatic bonding (HBX)						
0.0007	0.5-2	6	2-5	4	5-8	3.5
0.0008	0.5-2	8	2-5	5.5	5-8	5
0.0009	0.5-2	12	2-5	6.5	5-8	6
0.0010	0.5-2	15	2-5	9	5-8	8
0.00125	0.5-2	22	2-5	14	5-8	10
0.0015	0.5-3	32	3-7	19	7-11	16
0.002	0.5-3	42	3-7	37	7-11	33

We can see that in case of a 1-mil wire, for an elongation value of 0.5 to 2% the breaking strength is 15 grams. As the elongation increases to 5 %, the breaking strength reduces to 9 grams and when the elongation is between 5 and 8 % the breaking strength is 8 grams. As we can understand from the

previous discussions, higher elongation wire is preferred for good weld bondability. However, as the elongation increases the breaking strength of the wire decreases and as the breaking strength decreases wire sagging and wire sweep becomes a serious problem. Therefore, choosing the optimum elongation of a bond wire is an engineering challenge and is critical for a particular package application.

2.1.7.1 Choosing Elongation and Breaking load of 25 μ Gold Wire

Wires with different elongation, tensile strength and toughness value are manufactured to suit different applications. For example, we can see in figure in 2.1.18 that, though the wire diameter used is the same, three different types of wires M-type, L-type and H-type are used for high speed - standard loop bonding, high speed-low loop bonding and low loop bonding and high speed - high temperature bonding respectively.

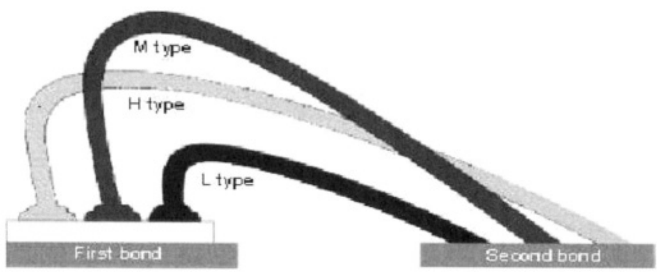


Figure 2.1.18 Wire type for different loop height and loop length
[Adopted from product catalog: Mikyeongsa]

Bond wires with high tensile strength and optimum elongation need to be chosen depending on the loop shape and loop length. In figure 2.1.19, three different types of wires are shown which are used for low, medium and high loop applications. They are H- type, L- type and M- type respectively. We can observe that depending on the type of wire, the breaking load, elongation, and toughness are different. Let us compare each wire type.

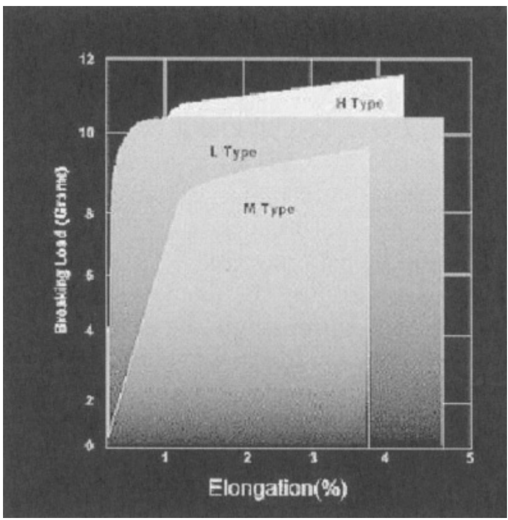


Figure 2.1.19 Elongation and breaking load [Adopted from product catalog: Mikyeongsa]

The M-type wire has a breaking load of 9.5 grams at an elongation value of 3.8 where as the L-type wire has a breaking load of 10.5 grams at an elongation of 4.7. If we calculate the area under the L-type curve, it is much greater than the area under the M-type curve. This indicates that the toughness of L-type wire is much higher than M-type wire, and this facilitates high speed low loop bonding. The H-type wire has been developed with much higher tensile strength and slightly lower elongation value for sustaining high temperatures during high speed automatic wire bonding process.

We can produce Au and Al bonding wires with different breaking loads and elongation values by adding different alloying elements and subjecting the wire to different heat treatments. The heat treatment of the wires during wire fabrication also impacts the grain size of the alloy which in turn affects the mechanical properties of the wire. Let us review and discuss in detail the impact of alloying elements and heat treatments in designing the right bond wire for the right packaging application.

2.1.8 Alloying Elements and its Impact on Mechanical Properties

Mechanical properties of Au wire are controlled by alloying the Au with other elements, such as Be, Ca or Pd and a host of other impurity atoms. The mechanical properties of Au wire, namely tensile strength and elongation depend on the atomic radius of the dopant atom. The atomic radius of the dopant atom in turn depends on the atomic number and the position of the element in the periodic table.

In designing the Au wire for ultra fine pitch bonding applications, we can select alloying elements with different atomic numbers and different atomic radii.

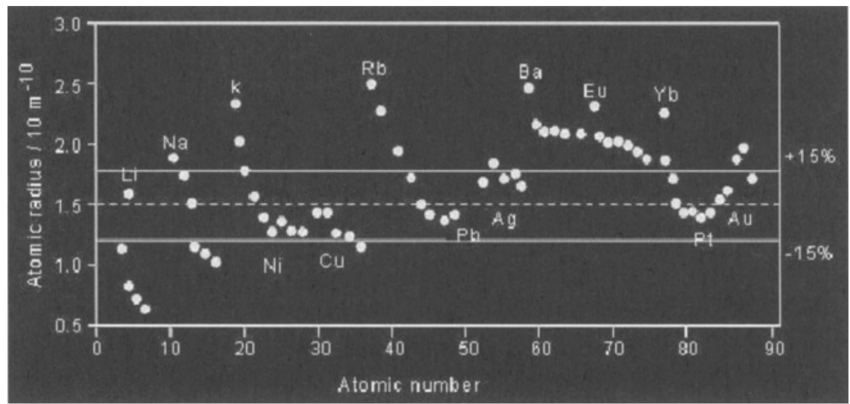


Figure 2.1.20 Atomic radii of elements [Courtesy: Sumitomo Metal Mining]

In figure 2.1.20, we can observe, Ni has an atomic number of twenty-eight and an atomic radius of 1.25, whereas Barium (Ba) has an atomic number of 56 with an atomic radius of 2.5. When either of these elements are added to Au, with an atomic number of 79 and a radius of 1.5 the resulting alloy will be dramatically different.

2.1.8.1 Interstitial Dopants

An interstitial dopant such as Be, sits in the interstitial positions of the Au crystal structure. The tight fitting of Be atom at the interstitial site creates a

small localized stress area. Figure 2.1.21 shows, localized strain field created in the Au crystal structure. This localized strain will hinder smooth dislocation motion and therefore resulting in increased mechanical strength of the Au alloy.

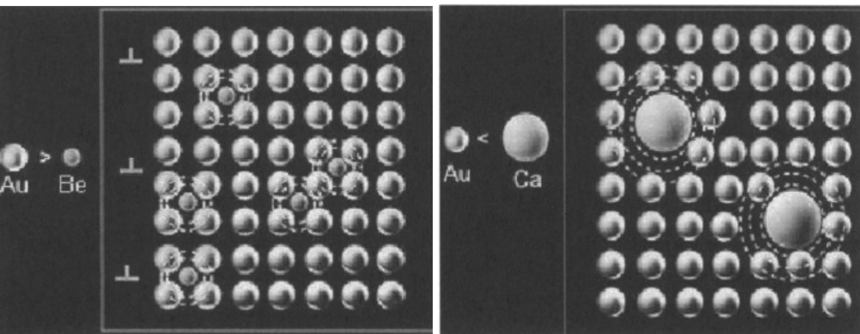


Figure 2.1.21 Interstitial type dopant

Figure 2.1.22 Substitutional type dopant

2.1.8.2 Substitutional Dopants

Instead of an interstitial dopant such as Be, one can introduce substitutional dopants like Ca. The dopant atom occupies the position of a Au atom in the crystal structure thereby creating a very large stress field as shown in figure 2.1.22. This stress field affects dislocation motion resulting in higher strength of Au alloy. As we have discussed previously, it is important to recognize that, generally, whenever an alloying element is added to a pure Au there is a significant decrease in electrical conductivity of Au.

2.1.8.3 Palladium Substitutional

Recently, however, research has shown that Pd substitution in Au, not only enhances the mechanical properties, but also has negligible reduction in the electrical conductivity of the Au alloy. When we add Pd into a Au matrix, the Pd atom replaces a Au atom in the crystal structure as shown in figure

2.1.23. This creates a small stress field around the Pd atom. This stress field enhances the tensile strength of Au.

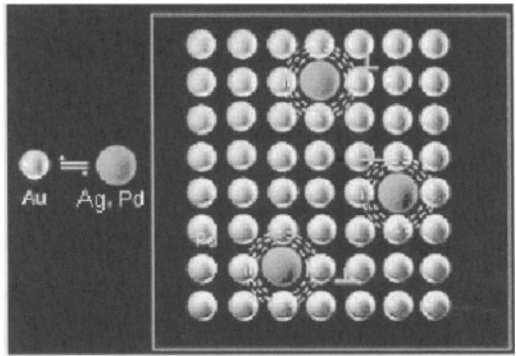


Figure 2.1.23 Substitutional type dopant – palladium

2.1.8.4 Design of Gold Wire

With the advantage of modern metallurgical manufacturing technologies, now it is possible to design the Au wire with the right quantities of interstitial and substitutional dopants, and thus control both the mechanical and electrical properties of the wire. To obtain a Au wire designed specifically for a particular wire bond application, it is important to control the dopant concentration in the Au alloy. Figure 2.1.24 shows an example of a design of Au wire having both interstitial impurities and a substitutional impurity.

To design the Au wire for an application such as, a low loop CSP, or a long loop BGA or for a stacked chip package with staggered bond pads, understanding the mechanical and electrical effects of interstitial impurities like Be or substitutional impurities like Ca, or a noble metal like Pd, is crucial.

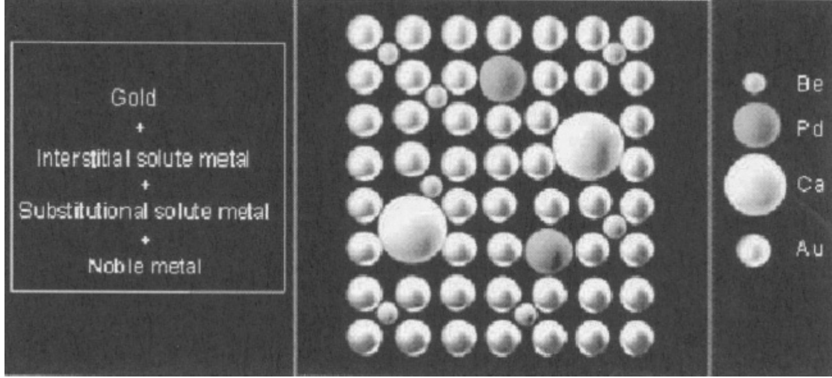


Figure 2.1.24 Design of gold wire **[VIEW-I N-CDROM]**

2.1.9 Grain Sizes of Wires

Gold and gold alloys are polycrystalline in nature, and each crystal in the polycrystalline structure is also known as a "grain". The grain size of bonding wire depends on the alloying element added to pure Au, the rate of wire drawing during wire manufacturing and the heat treatment that the wire is subjected to after the drawing process. The resultant grain size of the Au wire impacts the mechanical properties of the wire such as strength, ductility and deformability, and generally it is observed that:

- small grain size gives hard wire
- medium grain size gives medium hard wire
- large grain size gives soft wire

Figure 2.1.25 shows the micro-section of wire with small, medium and large grain structures. Just like we could design the wire for a specific mechanical property by controlling the alloying elements, it is possible to design the wire with controlled grain size for a specific mechanical property. This is achieved by optimized heat treatment of the wires during manufacturing.

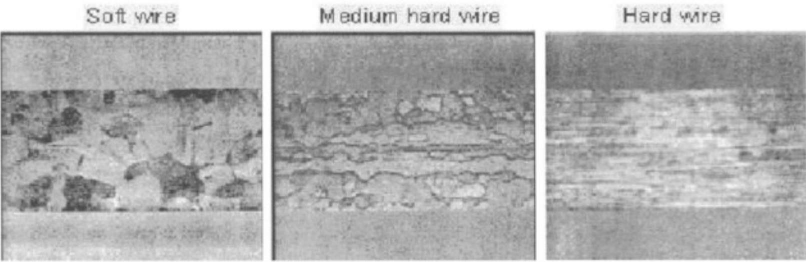


Figure 2.1.25 Micro section of wire [Courtesy : Heraeus Oriental Hi Tec Company Ltd]

2.1.9.1 Importance of Grain Size of the Gold Bond Wire

The grain size of the Au ball bond has major effect on the Heat Affected Zone (HAZ) length and the ball deformation. Let us review these below.

When the Au bond wire is melted to form a ball, it affects the grain structure of the ball as well as the grain structure of the wire just above the molten ball. This heat affected region above the ball is known as the HAZ.

When the Au wire is melted to form a ball during the bonding operation, if the grain size of the Au bond wire is large and equiaxed, it results in long HAZ. If the grain size is small and columnar, the HAZ length will be shorter. This is shown in figure 2.1.26. We will discuss the impact of HAZ on looping in greater detail in section 2.2.

After the Au wire is melted to form a ball, force is applied on the ball to deform it into a ball bond. This amount of deformation depends on the grain size of the molten ball. If the molten ball has equiaxed large grain structure, the deformation is large and can also have slight eccentricity. This is shown in Figure 2.1.26. A molten Au ball with small grain structure and columnar grains has a tendency to deform less and thus result in more uniform circular bond.

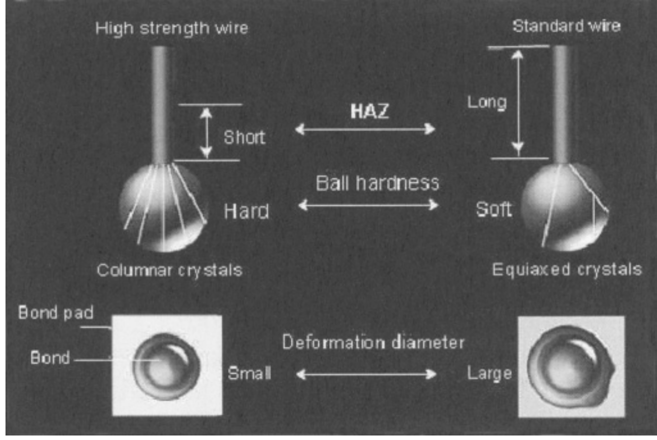


Figure 2.1.26 Ball formation of high strength wire [Courtesy: Sumitomo Metal Mining]

2.1.10 Coefficient of Thermal Expansion Compatibility

In plastic encapsulated packaging applications where there is a need to use Al bonding wire, it is important to have thermal expansion compatibility between the wire and the encapsulant material. If the Al wire is stiff (elongation range of 1 to 2), the wire may fail due to thermal expansion mismatch between the wire and the encapsulant. In such case, Al bonding wires may be preconditioned prior to encapsulation, thereby allowing them to attain up to seven percent elongation. This would provide a bonding wire that is extremely forgiving in applications where the coefficient of thermal expansion mismatch between the wire and encapsulant is severe.

2.1.11 Productivity of Wire Bonding Process

As we have discussed in chapter 1, one of the major differences between ball bonding and wedge bonding is the speed of bonding. Ball bonding inherently is a faster process. If the packaging application requires high

speed through put of the device during bonding operation, the choice is always ball bonding. This requirement forces one to choose a wire that can form a ball which limits the choice to Au and Cu.

2.1.12 Bond Wires for Hermetic Packaging

Hermetic packaging technology consists of ceramic packaging, CERDIP packaging and metal packaging technologies. These packaging technologies use high temperature process (greater than 400° C) for encapsulating the device. This process is termed hermetic package sealing. If one uses Au bond wire in hermetic applications, during the hermetic sealing process, the Au bond on Al bond pad is exposed to temperatures above 300 C for more than few minutes. This high temperature exposure degrades the reliability of the bond drastically. This is called Kirkendall voiding and is discussed in greater detail in Chapter 6.1 Therefore, for hermetic package applications, it is usually recommended to use only Al wire bonding.

2.1.13 Corrosion Resistance

Plastic packaged devices are exposed to harsh environments during field operation and under such conditions diffusion of moisture, contamination molecules and ionic impurities can occur through the porous polymeric structure of the plastic encapsulant. During the device operation, the bond wire is carrying electrical current and if such bond wire is exposed to moisture and contamination, the wire is very vulnerable to corrosion. Therefore it is important, for non hermetic applications, to choose a bond wire material that can withstand corrosive environments. Generally noble metal wires are used in non hermetic applications.

2.1.14 Device Bondpad Size

As the device integration increases, the number of device I/O's increases and there is a corresponding increase in the number of bond pads on the

chip. The increased number of bond pads results in bond pads occupying more area on the chip.

The areas where the bond pads are located on the chip can not allow device circuitry and thus expensive "chip real estate" is taken up by the bond pad. Figure 2.1.27 shows that the silicon area required increases as a function of bond pad size and as a function of I/O and thus increasing cost per chip. In IC design industry today, in order to reduce the chip size, and to maximize device yield per wafer the designers are demanding that the bond pads be as small as possible.

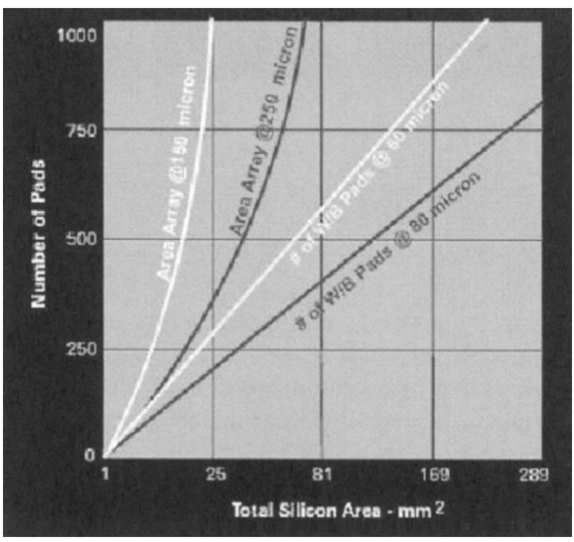


Figure 2.1.27 Increase in silicon area as a function of number of pads and pad size

Requirements of smaller bond pads on the chip, as small as 50 microns today, as shown in figure 2.1.28, as well as reduced spacing between the bond pads demand very thin wires, These thin wires must be capable of supporting the electrical requirements of the device, withstand high speed automated bonding process as well as be able to endure operational stresses. Special alloying techniques are needed to develop stable, thin wire technology.

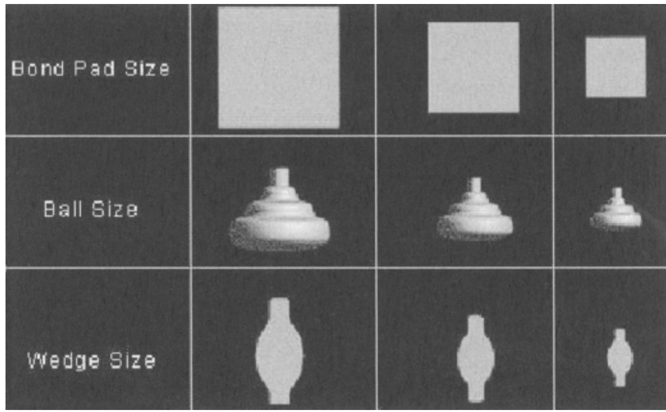


Figure 2.1.28 As the bondpad size decreases the ball size and wedge size decrease

2.2 Choice of Bond Wire Material

As we discussed in the previous section the requirements of the bond wire material is very specific depending on the application, and therefore the bond wire properties have to be engineered to suit the requirements. In this section we are going to discuss different materials options available in the industry and examine how to select bond wires for different device and packaging applications.

2.2.1 Bonding Wire Materials Choice

Bonding wire is typically specified by its material type, diameter and mechanical properties, such as the breaking strength, elongation and the length of the heat affected zone (HAZ). Let us review and discuss in detail two of the common bond wire materials namely Au alloys and Al alloys. These two metals are the most prominently used for wire bond application in the IC industry. We will also briefly discuss other wire materials such as Cu and Pd.

2.2.1.1 GOLD: A Strategic Choice!

The majority of the electronics industry uses Au wire ball bonding. Gold is popular because of its good electrical and mechanical properties, and it can be alloyed easily with other elements to control the mechanical properties according to the requirement of the packaging. It's non-corrosive, and it doesn't migrate to other materials surrounding it. These qualities allow it to maintain a reliable interconnect throughout the life of the product. Gold's alternatives are not as robust and many lack overall reliability.

2.2.2 Alloying of Gold to Improve Mechanical Properties

Pure Au is very soft. It is difficult to draw it into fine wires that can be used for high speed wire bonding process. Relatively small concentrations of impurity atoms, however, increase the mechanical strength and improve the metallurgical stability, and render the alloyed Au metal workable. Any number of foreign atomic species may be added to pure Au to toughen the metal. Some of the alloying additives are Be, Ca, Cu, Ag and Pd.

2.2.2.1 How Alloying Improves Mechanical Strength of Gold?

The strength of a material is determined by dislocations movement in the material when stress is applied. Dislocations move through pure metals without any obstructions. This results in soft malleable metal. When impurity atoms are present, the dislocation motion is hindered resulting in higher stress required for plastic deformation of the metal. This results in higher tensile strength and hardness. The dislocation motion is shown in figure 2.2.1. If the impurities are not uniformly distributed then the dislocation motion is not uniform, resulting in inconsistent mechanical properties of the metal.

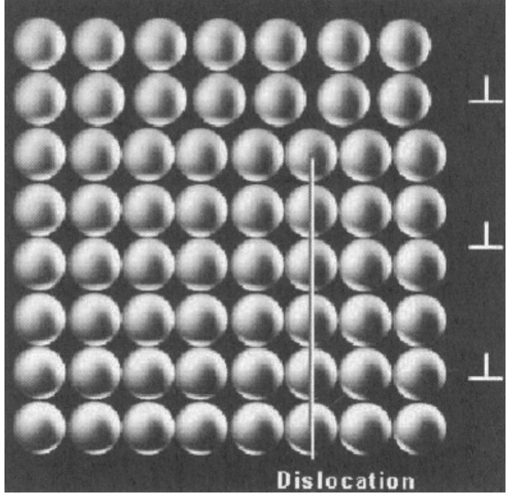


Figure 2.2.1 Dislocation in pure metal

2.2.2.2 Alloying Elements and their Effects on Gold Wire

Each alloying element has certain advantages, for example: Beryllium: Helps in refining the grains and thus increase the tensile strength of Au. Lanthanum: increases the Young's Modulus of Au, while elongation is not affected. Calcium: lowers the modulus, while improving elongation. Indium: results in moderate increase in both the modulus and elongation [M-3]. Doping is necessary in order to maintain uniform physical properties in the bonding wire. Since the type and amount of doping material added has a substantial effect on the resulting properties of the Au bonding wire, wire manufacturer must take utmost care to make sure that foreign elements are not picked up during the various processing steps. The typical concentrations of the alloying elements are in the parts per million (ppm) range. Copper doped Au wire generally contains 30 to 100 ppm Cu by weight; Be-doped material has typically 5 to 10 ppm Be by weight. After refining Au to 99.999% purity, it is doped to manufacture stabilized (smaller grain size) Au bonding wire. For manual bonding, Cu doped wire

is satisfactory. But higher strength Be doped Au is often preferred for automated applications.

Beryllium-doped wire, sometimes referred to as Be-stabilized, is about 10% stronger than Cu-doped ("Cu-stabilized") wire. Beryllium-doped material retains a 10% to 20% higher break strength compared to Cu-doped wire after the customary annealing operation. Since modern thermosonic bonding process involves high-speed capillary movements that generate greater wire stresses than in slow manual bonders, increased strength of Be-doped wire is advantageous. It is recognized that Be-doped Au wire is less susceptible to wire sagging than Cu-doped material. Different types of Au wire, with different alloying elements and heat treatments, are used for different applications. We can observe from figure 2.2.2, one wire supplier suggests for an SOJ type package with high loop height but a short loop span, the SAG type of wire, whereas, for ultra fine pitch high pin count BGA type packages with a loop height of 150 microns and loop span of 5 millimeters, NL series of wire is recommended.

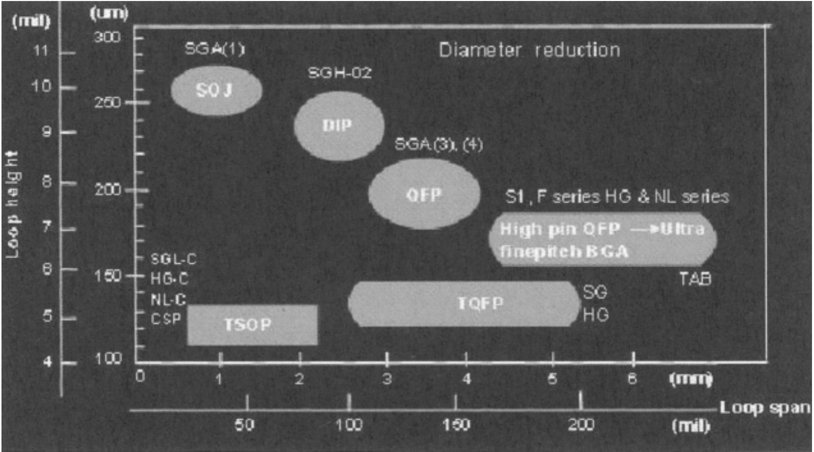
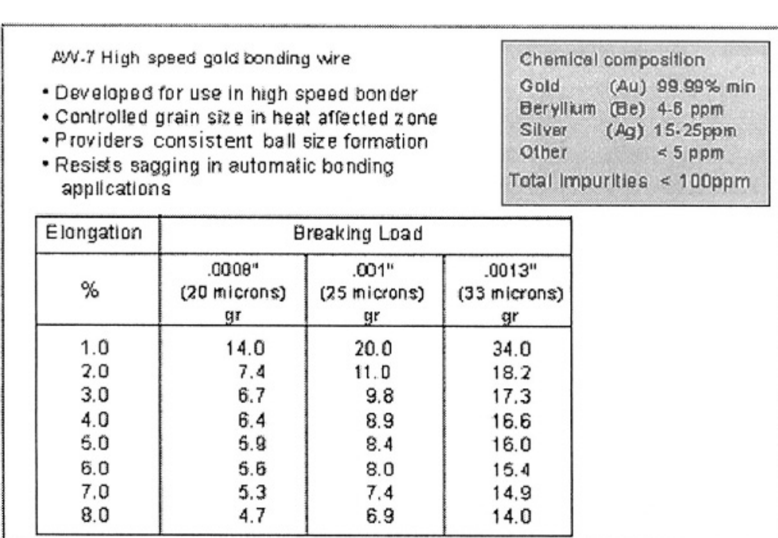


Figure 2.2.2 Bond wire recommendation for different packaging application
[Courtesy : Sumitomo Metal Mining]

Another bond wire supplier recommends, to minimize sagging in automatic bonding applications, a Au wire with Be concentration of 4 to 6 PPM and Ag concentration of 15 to 25 PPM for use in high speed bonders. This is shown in table 2.2.1.

Table 2.2.1 High speed Au wire properties [Adopted from product catalog: American Fine Wire Corporation]



AW-7 High speed gold bonding wire

- Developed for use in high speed bonder
- Controlled grain size in heat affected zone
- Providers consistent ball size formation
- Resists sagging in automatic bonding applications

Chemical composition		
Gold	(Au)	99.99% min
Beryllium	(Be)	4-6 ppm
Silver	(Ag)	15-25ppm
Other		< 5 ppm
Total Impurities		< 100ppm

Elongation	Breaking Load		
%	.0008" (20 microns) gr	.001" (25 microns) gr	.0013" (33 microns) gr
1.0	14.0	20.0	34.0
2.0	7.4	11.0	18.2
3.0	6.7	9.8	17.3
4.0	6.4	8.9	16.6
5.0	5.9	8.4	16.0
6.0	5.6	8.0	15.4
7.0	5.3	7.4	14.9
8.0	4.7	6.9	14.0

After completion of the wire bond, the superiority of Be-doped Au wire over Cu-doped Au wire may be less distinct. Beryllium-doped and Cu-doped Au wires show essentially identical bond pull strengths. There is only a minor difference between Cu-doped and Be-doped wire which is resistance to the creep rupture failure mode in plastic integrated circuit (IC) packages.

2.2.2.3 Atomic PPM versus Weight PPM

The mechanical properties of the Au wire are affected by the number of dopant atoms present. The concentration of the dopant atoms is generally

described either in weight percent or atomic percent. One should be careful in specifying the requirements of dopant concentration in an alloy. Let us understand the differences between atomic and weight percent. Copper-doped Au wire generally contains 30-100 ppm Cu by weight. Beryllium-doped Au wire has typically 5 to 10 ppm Be by weight. It should be appreciated that while "weight ppm" is an operationally convenient measure of impurity content, metallurgical properties are mediated proportionately to the number of dopant atoms present. Converting weight ppm to atomic ppm, using the atomic weight ratios of Au, Be and Cu as appropriate, one observes that 65 ppm (weight) Cu in Au is approximately equivalent to 200 ppm (atomic). On an atomic basis, Cu-doped Au wire has about the same added solute level as Be-doped Au wire. "Atomic ppm" is a better measure of dopant concentration from a physical point of view.

2.2.3 Gold Wire for Thin and Fine Pitch Applications

Today, for BGA, CSP and other ultra-thin packaging applications using automatic high-speed bonding, problems such as ball neck damage, heel crack, wire sagging and others cannot be permitted. The wire suppliers design wires with different dopants and heat treatments depending on the application requirement. In table 2.2.2 wires are compared from different suppliers.

2.2.4 Selection of Wire for Low Loop Applications

There are two ways to control the loop height of a wire in thin plastic packages. One way is by controlling the loop profile using machine software to control the trajectory of the capillary, as discussed in section 4.1.7. The other method is to control the property of the wire such that the wire has a short Heat Affected Zone (HAZ).

2.2.4.1 What is HAZ?

When the wire melts to form a ball the immediate neighbouring region above the ball also reaches high temperature and creates a re-crystallized

zone. This is the heat affected zone and is shown in figure 2.2.3. The grain size of the HAZ and the length of the HAZ depend on the alloying elements used in the Au wire.

Table 2.2.2 Cross reference (25μm) [Courtesy: Sumitomo Metal Mining]

Features type	Loop height μm (mil)	Room temp. strength/ gf	Strength at 250C/gf	Features	AFW type	Tanaka type	Matsuda type	Mitsubishi type
SGR	220 (8.7)	7.0	3.5	For manual bonding Less damage to bonding pad	Aw1	Y	M1	
SGS	190 (7.5)	10.5	8.5	Standard type Suitable for high speed bonding	(AW6)	FA	F2	MGH1.2
SGH	250 (9.8)	9.5	5.0	High loop type Easy to control looping	AW2	C	H1	MGS1.3
SGA (1)	230 (9.1)	10.5	8.0	Higher loop type Stronger than conventional SGH type	AW7 AW8	M2	K3	MGM 4
SGA (3)	215 (8.5)	11.5	9.0	Suitable for high speed bonding with smaller diameter than SGS type	AW28	M3	K5	MGM 5
SGA (4)	200 (7.9)	12.0	10.0	Suitable for high pin count and long loop bonding with middle loop height			K4	MGM6
SGL(1)	150 (5.9)	11.5	9.0	Low loop type Suitable for TSOP and TQFP	AW10	GLD	L4 L5	MGHL1
SGL (2)	140 (5.5)	12.5	11.0	Extra low loop type suitable for TSOP and TQFP	Aw 14	GL2	L3	MGHL1
SGH -02	220 (9.1)	10.5	6.0	High loop type Neck part is stronger than SGH	Aw 23	GHA		MGM 3
FO	180 (7.0)	12.5	11.5	Less wire sweep Suitable for reducing diameter of F1			T2	
F1	195 (7.7)	12.0	10.0	Less wire sweep Suitable for long loop span bonding			T1	MGM7
F3	210 (8.3)	12.0	10.0	Less wire break by vibration Suitable for reducing diamter of SGH		GMB - 2		
S1	235 (9.3)	11.5	9.0	Better straightness Suitable for high-pin QFP			K1	
S2	215 (8.5)	11.5	9.0	Less chip damage Suitable for brittle chip and BGA				
NL3	160 (6.3)	13.5	12.5	Stronger among the 4N pure gold wire Suitable for fine pitch, long loop bonding			T3	
HG-2	130 (5.1)	13.5	12.5	Stronger, high reliability 2N gold wire Suitable for fine pitch bond, diameter reduction		GPG		

The HAZ region has large grain structure and thus lower strength. Therefore, the wire deforms at lower stress levels than the base wire. When the capillary moves to form the loop, the bend radius will form within the

HAZ. The size of this radius is completely dependent on the length of the HAZ. shorter the HAZ, shorter is the loop height.

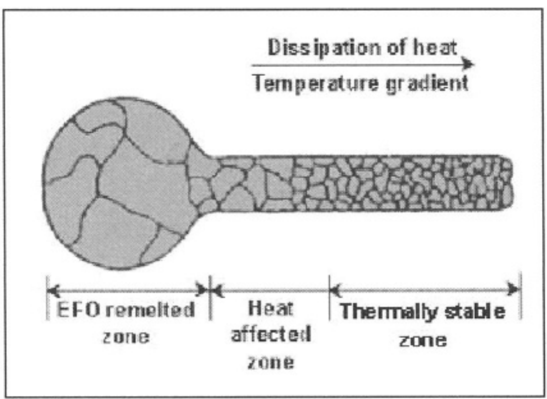


Figure 2.2.3 Heat Affected zone **[Adopted from product catalog: American Fine Wire Corporation]**

2.2.4.2 HAZ and Dependence on Recrystallization Temperature

When the free air ball is formed, a certain length of wire above the ball gets affected by the high temperature and forms the HAZ. We can observe from the figure 2.2.4, if the wire is designed with a recrystallization temperature of 300° C it exhibits a longer HAZ length after free air ball formation. This wire can be used for high loop height applications only. On the other hand, if we design a wire with a recrystallization temperature of 480° C, the HAZ length will be short and the wire can be used in low loop applications.

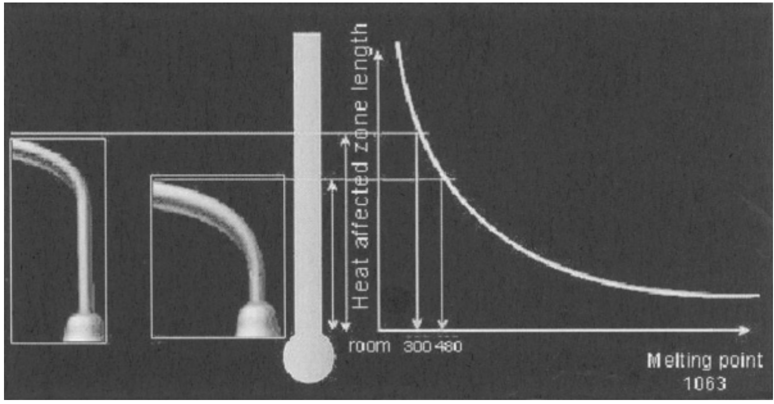


Figure 2.2.4 Temperature distribution during free air ball formation [Courtesy: Sumitomo Metal Mining]

The recrystallization temperature of a Au alloy is modified by controlling the alloying elements in the wire. Gold wire used in for loop heights greater than 10 to 12 mils, is doped with Be, as discussed before. Today, many different elements such as Ca, La, Ag, Pd, Mg, Ni, Ge, Cu, Ga, In and Ti are used to modify the recrystallization temperature of Au wire which in turn allows loop height control. Table 2.2.3 shows the dopant effects on recrystallization temperatures.

Table 2.2.3 Dependence on dopant species for recrystallization temperature of Au [M-5]

Purity of gold	99.999%	99.995%			
Dopant Species		AG, Pd, Pt	Mg, Ni, Si	Co, Cu, Fe, Ga, Ge, In	Al, Be, Ca, Pb, Sn, Tl
Recrystallization temperature in deg C*	150	150	150 to 200	200 to 300	Over 300

* Degree of cold work is fixed at 99% temperature quoted are those measured for continuous annealing through a ring type furnace.

For example, when Ag, Pd and Pt are used as alloying elements, the re-crystallization temperature remains at 150°C, whereas when cobalt with germanium is used as an alloying element, the re-crystallization temperature ranges between 200 - 300°C.

2.2.4.3 Some Adverse Effects of Specially Alloyed Wires

Most of the Au alloy wires designed with special dopants have high levels of dopants and sometimes exceed 100 ppm limit. The addition of increased amounts of dopants may lead to some reliability concerns. For example, addition of alloying elements may cause shrinkage defects during ball cooling. The presence of large shrinkage pores and hollow balls has been found [M-4] when using low-loop bonding wire. Alloying elements such as La or Ca may induce surface oxidation on the molten ball, resulting in weldment problems. One disadvantage of low loop bond wire is that, the assembly production facilities cannot merely replace their existing wire type with a low loop variety for all applications on the manufacturing floor.

2.2.4.4 Comparison of Wire Mechanical Properties at Different Temperatures

During high speed bonding, the capillary reaches temperatures greater than 250° C and the wire also reaches high temperature because of its contact with the capillary. This results in degradation of the wire mechanical properties which may affect process consistency. Therefore, the mechanical properties of the Au bonding wire for high pin count low loop applications are tested both at room temperature and at high temperature. This is necessary to understand the behaviour of the wire during high speed bonding, particularly from the point of view of loop profile optimization. The mechanical property of Au wire is shown in table 2.2.4. Here we can observe the variation in the value of elongation and breaking load at room temperature as well as high temperature.

Table 2.2.4 Mechanical Properties of Au wires at room temperature and at 250° C
[Adopted from product catalog: American Fine Wire Corporation]

Mechanical properties									
Diameter Microns	15	18	20	23	25	28	30	32	33
Mils	0.6	0.7	0.8	0.9	1.0	1.1	1.2	1.25	1.3
Recommended spec									
Elongation (%)	2-5	2-6	2-6	2-6	2-6	2-7	2-7	2-7	2-7
Breaking load (g)	3-7	5-9	7-12	10-15	13-18	16-21	18-23	20-26	22-28
Room temperature @ 4% EL									
Breaking load (g)	5.4	7.5	9.6	12.7	15.4	18.5	21.8	23.6	25.1
High temperature @ 250°C/20 sec									
Breaking load (g)	4.9	7.0	9.0	11.7	14.5	17.2	20.2	22.1	23.6

Wires with higher tensile strength are preferred for low loop and long wire application. Figure 2.2.5 shows the variation in elongation and tensile strength for a particular type of wire. The recrystallization temperature of the wire is about 480°Centigrade and even at such high temperature the wire maintains a high strength of 20 grams. For low loop and long wire type of applications one would recommend a wire with these elongation and high temperature strength characteristics.

Wire suppliers are producing wires that still keep good tensile properties even at high temperatures. In figure 2.2.6, we see that FO type wire, with a high temperature tensile strength of about 11 grams is used for low loop applications, whereas, a SGH type wire with a low tensile strength of 5 grams at high temperature is used for high loop application. In order to optimize the process of wire selection for high speed low loop application, one must understand the behaviour of the mechanical properties of the wire at room temperature and at 250° C. Figure 2.2.7 gives a comparison of 3 types of wires and their change in mechanical properties from room temperature to 250° C. From the data shown below, for high temperature and high speed bonding, FA -type wire is recommended over Y-SR type or C-type.

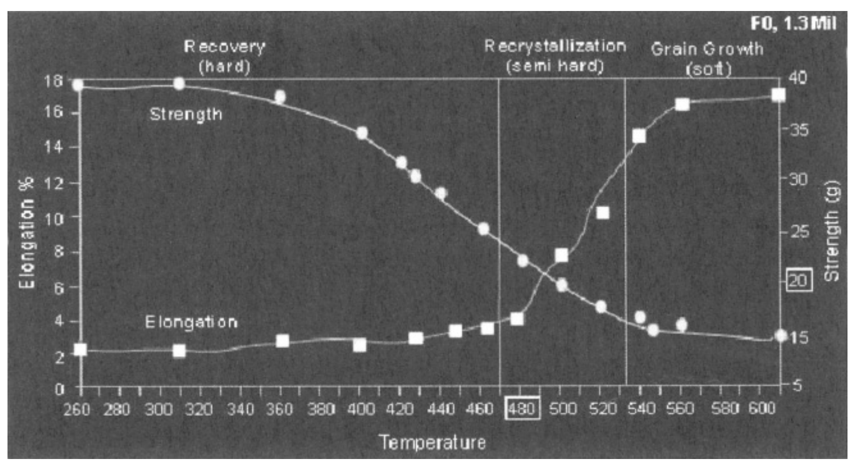


Figure 2.2.5 Shows the variation in elongation and tensile strength as a function of temperature. The wire shows strength of 20grams even at recrystallization temperature of 480° C [Courtesy: Sumitomo Metal Mining]

We can observe in figure 2.2.7 the FA type wire having high elongation and high breaking load at room temperature.

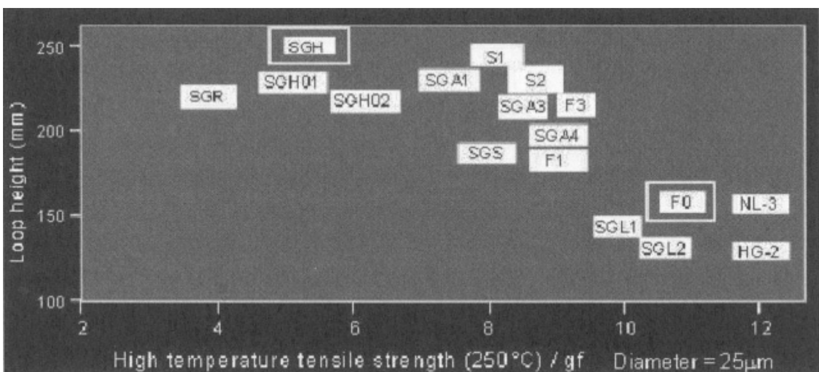


Figure 2.2.6 Wires that exhibit high tensile strength at 250° C are used for low loop height applications [Courtesy: Sumitomo Metal Mining]

The FA type wire maintains moderately high tensile strength even at high temperature. In comparison to FA type wire, the tensile strength of C type and Y type wire decreases significantly.

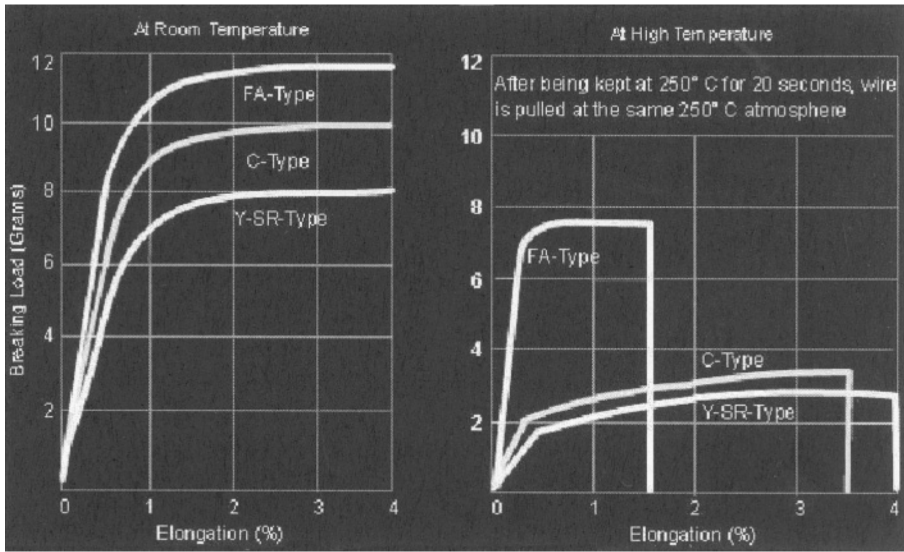


Figure 2.2.7 Comparison of mechanical properties at different temperature [Adopted from product catalog: Tanaka Electronics]

Varieties of wires from many suppliers are available in the market. Suppliers design their wires to meet specific requirements of the IC manufacturer.

We can observe in the table 2.2.5 that for short loop distance, the C and FA type wires are suitable, whereas for long loop distance the Y-SR and Y-Soft wires are more appropriate

Some of the suppliers of wire suggest a wire selection guide depending on the requirements of bonding such as loop shape, tail residue and bonding strength. The wire selection criteria are shown in table 2.2.6.

Table 2.2.5 Suggested bond wires for specific requirement
[Adopted from product catalog: Tanaka Electronics]

Type/Conditions	Y-Hard	Y-SR	Y-Soft	C	FA
For short loop distance				■	■
For long loop distance		■	■		
To avoid loop drop				■	■
To achieve smallest quantity of tail residue					■
To avoid wire breaking					■
To make bonding strength higher					■
To attain higher loop altitude				■	
For manual bonder	■	■	■	■	
For automatic bonder		■	■	■	■

Table 2.2.6 Wire selection criteria [Adopted from product catalog: Tanaka Electronics]

Bonding Requirement	Characteristics of FA - Type
Loop shape	After the first bonding, the wire is shaped in a straight upward position. The altitude of the loop is lower than that of the Y-type wire, but the occurrence of drop is much less.
Breaking of wire	The FA-type wire, even if the bonding speed increases and the load for the wire becomes heavier, as much more strenght than the Y-type wire
Tail residue	Wire cutting for the FA-type is easier, because crystallization of material does not occur in full scale until the second bonding, which results in a small quantity of tail residue.
Bonding strength	The pulling strength for the FA-type wire is 2 grams higher than that for the Y-type wire.

2.2.5 Aluminum and Aluminum Alloys as Bonding Wire Material

Aluminum-alloy wire was developed in the late 1950s as a means of avoiding the "Purple Plague" problem associated with Au bonding (for more detail about purple plague refer section 6.1) Pure Al wires are used for high current applications. High current applications which require bond wires greater than 5 mils in diameter use as drawn Al wires. In the smaller wire sizes (less than .003" diameter); pure Al wire does not suffice. It does not have enough mechanical strength to support high speed bonding. For small diameter applications, Al-1% Si and Al-0.5% Mg are preferred because of the greater ease in drawing, and higher pull strengths that are obtainable after bonding. Furthermore, compared to pure Al the addition of either Si or Mg to Al results in a wire with physical values which can be much more closely controlled.

2.2.6 Aluminum with 1% Silicon

Very pure Al is too soft to be easily drawn to a fine-diameter wire. In order to toughen the metal, alloying of the metal is required. Alloying Al with Si *is* preferred to prevent the cause of Al spiking (more details about spiking are discussed in section 6.2). The nominal composition of Al + 1% Si has emerged as the standard alloy for ultrasonic bonding wire.

In Al-1% Si material, Si tends to agglomerate into larger and fewer Si particle at higher temperatures resulting in generally lower elongation accompanied by hard and brittle spots. When some types of Al-1% Si material are held at temperatures of the order of 200° C for as short a time as 30 seconds, agglomeration of Si can occur with resultant drop in elongation.

2.2.7 Aluminum-Magnesium Wire

The advantage of Mg over Si as a solute in Al wire alloys is that the equilibrium solid solubility of Mg in Al is about 2% by weight. This compares, as noted previously with about 0.02% Si equilibrium solid

solubility in Al at 20° C. At 0.5 to 1.0% Mg concentration there is no tendency toward second-phase segregation as is the case with Al + 1% Si.

Aluminum alloyed with 0.5% to 1% Mg can be drawn into fine wire. The finished product exhibits breaking strength and elongation similar to that obtained in Al- 1% Si. Aluminum-Magnesium alloy, wire bonds satisfactorily and has superior resistance to fatigue failure at first-bond heel compared to Al + 1% Si alloy.

Some users prefer the Al-0.5% Mg material since it is stronger for any given elongation than an equivalent size of Al-1% Si wire. It is less affected by temperature than is the Al-1% Si material when the wire is subjected to thermal cycling. The Al-0.5% Mg material is, unlike the Al-1% Si material, thermodynamically stable and hence does not show a drop in elongation as the annealing proceeds. From the point of view of wire bond processing, studies have shown that:

- 1% Si-Al and 1% Mg-Al one mil wire are equivalent in their behaviour with respect to bonding parameters.
- 1% Si-Al and 1% Mg-Al have equivalent effect on the electrical properties of devices bonded with the two types of wire.

2.2.7.1 Comparison of Micro-structural Behaviours of Al-Si and Al-Mg Wires

In general, Al wire drawing is performed at low deformation rates near room temperature. Small additions of Mg or Si will cause the wire to undergo three stages of micro-structural change which are listed below.

- the formation of a dislocation cell structure
- cell boundary sharpening and refinement
- dynamic recrystallization

The room temperature solubility limit of Mg is approximately 1.7 in Al. The mechanism of strengthening of Al with Mg impurity is by solution hardening. The tensile strength of solid solution strengthened Al-Mg wires is dependent upon Mg concentration. As Mg concentration increases, cell deformation and dynamic recrystallization are retarded while dislocation density tends to increase thereby impeding cross slip at low to moderate tensile strains. Where as in case of Al-Si alloy, the solubility of Si in Al, at

room temperature is zero weight percent. The strengthening of Al wire is by dispersion hardening due to Si particles (precipitates) in the Al matrix. The tensile properties of dispersion strengthened Al-1% Si wires are sensitive to Si particle size and Si particle distribution.

Solution hardened Al-Mg alloys has two obvious advantages over the dispersion hardened Al-l % Si alloy. The first advantage is that the mechanical properties of solid solution Al-Mg alloys are far more predictable in the process temperature range. The other advantage is that unlike Al-l % Si bonding wire, Al-l %Mg and Al - 0.5% Mg wires become more ductile as the processing temperature approaches 200° C. [M-6]

2.2.8 Gold-Wire Substitutes

The fluctuation in the price of Au during certain times for example in the early 80's periodically causes increased attention to the development of Au-replacement materials for T/C and T/S bonding. Another reason for substituting Au wire is the need to find a stronger wire material that would allow the use of finer wire diameter, thereby allowing potentially finer bond spacing. Adequate substitutes for Au have been developed for a few particular applications, but generally suitable material is not yet available.

2.2.8.1 Silver Wire

Silver wire, for example, may be drawn to finer diameter, balls nicely on T/C and T/S bonders, has excellent thermal and electrical conductivity and is thermocompression bondable to conventional semiconductor metallization. However, susceptibility to corrosion may be a problem.

2.2.8.2 Aluminum Wire Ball Bonding

The possibility of ball bonding of Al wire has been studied extensively considerable success has been shown with ball bonding of Al using special processes, equipment and tooling to form the ball. However, successful implementation of the technology has not been made due to the complexity of the Al ball bond process in normal ambient conditions.

2.2.8.3 Palladium

Compared to Au wire, Pd wire has greater strength, greater hardness and higher electrical resistivity. As shown previously in table 2.1.1, Pd has very high tensile strength and modulus of elasticity compared to Au. But its electrical conductivity is 16 compared to that of Au which is 78. The mechanical properties of Pd wire are compatible with normal wire bond requirements. We can observe in figure 2.2.8 the breaking load of Pd which changes dramatically between elongation values of 0.5 and 2%.

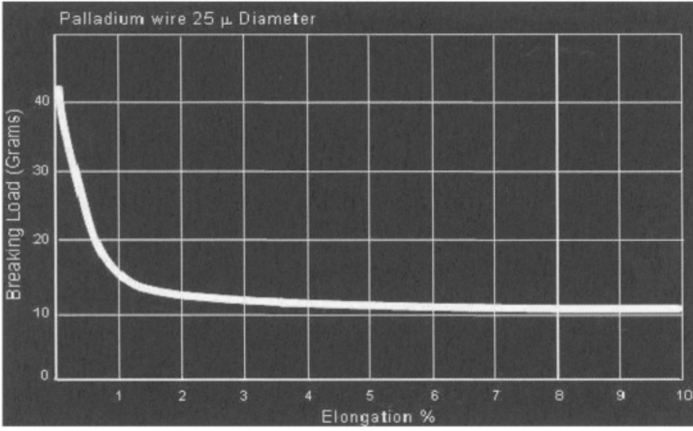


Figure 2.2.8 Breaking load vs elongation of palladium wire **[Adopted from product catalog: American Fine Wire Corporation]**

Palladium wire presents a cost effective alternative to Au bonding. Palladium wire has high strength both at room temperature and high temperature. The variation of breaking load with temperature is not as drastic as that of Au. Figure 2.2.9 shows the breaking load of Pd wire which does not change much even when the wire is heated at 350°C. But one must be aware that the higher hardness of Pd may cause cratering under the bondpad during bonding.

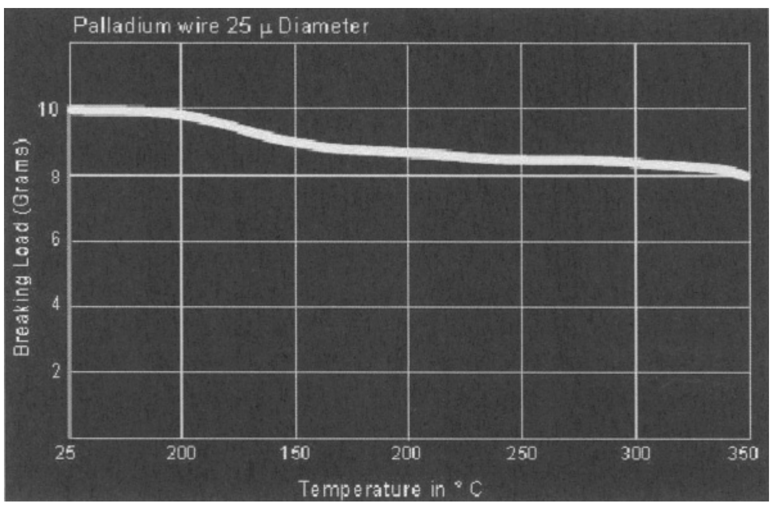


Figure 2.2.9 Breaking load vs testing temperature [Adopted from product catalog: American Fine Wire Corporation]

2.2.9 *Copper*

Copper is the new buzz word in the semiconductor industry. Chip makers are considering replacing Al metallization on the die with Cu to increase performance and lower the cost of their devices. On the assembly side, traditional Au wire is going to be replaced with Cu wire for fine pitch applications. However, cost would not be the driving factor for this conversion from standard Au wire processes (wire diameter 0.8 – 1.3 mil) to Cu wire, and it may even require superior technology and initial process effort in production. Rather, the motivation to use. Cu wire instead of Au wire is determined by the physical metallurgy. Apart from the well-known advantages of higher mechanical strength, lower electrical resistance and greater stiffness as compared to Au wire, Cu wire bonded on Cu pads will provide a highly reliable, monometallic contact system – a far superior candidate for connecting future smaller, denser, higher frequency ICs. Copper wires have been used since early 1970's in discrete and high power

devices. New studies have shown that Cu wire can also serve as a viable, cost saving alternative to Au in many high-end, ball and wedge bonding applications. Copper's excellent mechanical and electrical characteristics, combined with its slower intermetallic penetration, have yielded Cu bonds with strength and reliability that are at least as good as, if not superior to comparable Au bonds.

By nature, tempered and annealed Cu wire, at room temperatures, exhibits tensile strength and elongation characteristics that are comparable to, Au wire. Copper wire is approximately 25% more conductive than Au wire, accounting for better heat dissipation and increased power ratings. This feature is a contributing factor to the development of high-power, high-performance, fine-pitch devices using thinner diameter Cu wire. However, substituting Au wire with Cu is not without its disadvantages. Studies have shown that there are a few challenges to overcome in order to obtain a robust and reliable Cu fine pitch production process. The formation of relatively oxide-free initial balls requires the appropriate electrode design and the correct inert gas flow rate. The Cu pads on the die will also require adequate gas shielding to prevent oxidation. Copper has much less tolerance for environmental contaminants compared to Au, and as such translates into greater emphasis on clean room air quality. Process windows are also expected to be smaller, thereby increasing the need for machine capability to be enhanced (higher resolution, better control. In some high power and low cost packaging applications, bonding wires made of Cu are a technically efficient and economic alternative of Au. In addition to low material cost and very good conductivity. The advantages of Cu wire are:

- high thermal stability
- high pull-test values
- good loop stability
- intermetallic phases are avoided

A detailed discussion of copper ball bonding is presented in chapter 7

2.3 Wire Manufacturing

2.3.1 Manufacturing of Gold and Aluminum Bonding Wires

Bond wire manufacturing is done in a class 1000 or class 100 clean room to achieve very high quality and consistency of material properties. Wire manufacturing involves several manufacturing steps before it is ready for the customers. The production process flow involves in obtaining ultra high purity Au or Al (99.999% purity) by zone refining or electrolytic refining. After refining the metal it is melted and cast into ingots. The cylindrical ingot is drawn into wire and annealed to relieve stresses. The wire is washed and re-annealed before winding on spools of appropriate size. Quality inspection is done at the end of the process to check for mechanical, physical and chemical consistency. Figure 2.3.1 shows the flow of bond wire manufacturing.

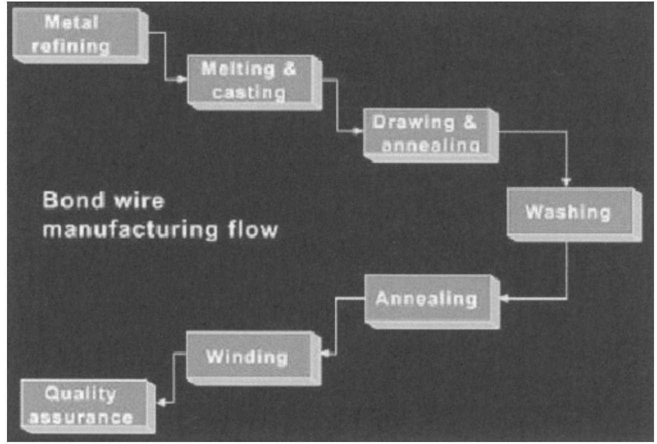


Figure 2.3.1 Bond Wire Manufacturing Flow **[VIEW-IN-CDROM]**

Let us review each of the processes in the wire manufacturing flow in detail.

2.3.2 Metal Refining

The process of bond wire manufacturing involves production of the starting material, namely Au alloy or Al alloy. These metals are refined to a very high purity by either zone refining or electro-refining. The purity achieved is 99.999%. This is also called 5N pure metal. It is necessary to get such high purity metal, because impurities even in small quantities cause significant changes in mechanical properties of Au and Al.

2.3.3 Melting and Casting

The Au is melted and small additions of alloying elements are added to the parent metal to modify its properties. The dopants levels are generally in PPM (parts per million) concentration levels. Therefore, it is critical that the doping be homogeneous and there is an adequate composition control. No impurities other than the intended dopants must be allowed in the melt.

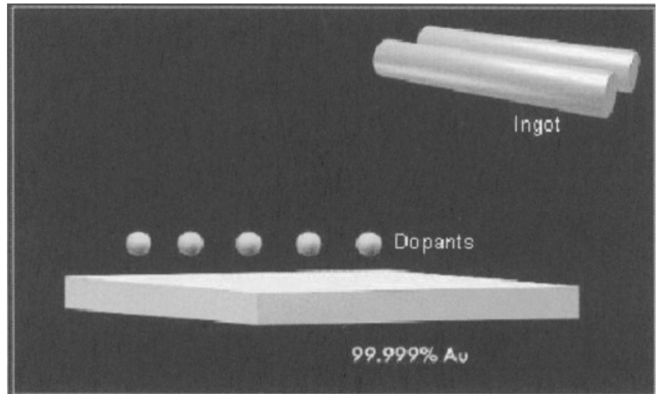


Figure 2.3.2 Melting and casting of Au alloy ingots

As shown in figure 2.3.2, dopant element is added in pure Au to create the required alloy and this alloy is cast to obtain Au alloy ingots. State-of-the-art melting and casting demand digitally controlled temperature measuring

devices for consistency and high reliability of every melt produced. High vacuum melting equipment is used for doping the molten metals. Cast Au ingot is microscopically examined prior to drawing process to assure surface cleanliness and integrity.

2.3.4 Wire Drawing

Wire drawing is carried out in equipment specifically designed to facilitate the production of wire with specified physical properties as well as surfaces that are free of contamination. Particular attention must be given to:

- the amount of reduction per pass
- drawing lubricant concentration
- drawing lubricant temperature
- die design in order to achieve the highest quality wire

2.3.4.1 Dies of different diameters

The wire is extruded through progressive dies which have reduced diameter. Dies of different inner diameter are schematically shown in figure 2.3.3.

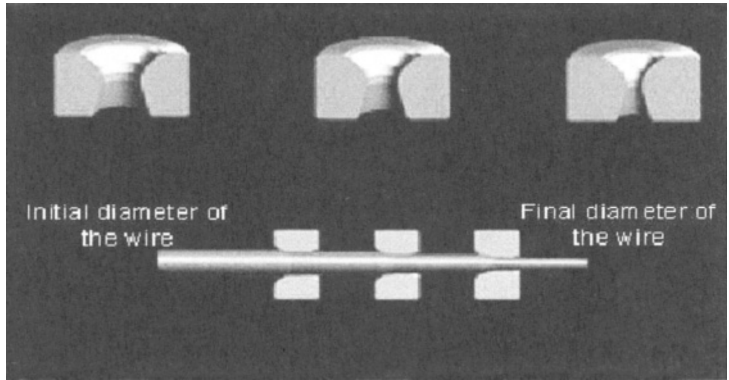


Figure 2.3.3 Dies of different inner diameter

The initial Au or Al rod in cast form is about half inch in diameter. The rod is passed through a series of dies (more than 20) with decreasing inner diameters to draw the wire to the required thinness. The final diameter of the wire is typically 0.001 inch. Alloy rods must be reduced in diameter approximately 400 times to reach 20μm diameter wire. Exceptional drawability is essential in Au bonding wire. Each meter of processed alloy creates over 160km of 20μm wire. Controlling the diameter accurately is of critical importance.

Multi-die drawing reduces material to typically 25μm diameter, but also as small as 15μm diameter. Precise dimensional tolerances and controlled reductions are necessary for producing high quality wire. Machine design and machine set-ups need to be optimized specifically for Au wire drawing and for each drawing stage. Lubricants and die need to be monitored daily and changed regularly to maintain the close tolerances required for fine pitch wire bonding.

2.3.4.2 Surface Cleanliness of Bond Wire

Clean wire will minimize or eliminate the problems associated with clogged capillaries. If the extruded wire is coated with lubricant residue or micro metal burrs or dust particles, this could accumulate at the tip of the capillary during the wire bonding process as shown in figure 2.3.4. The clogged capillary hinders smooth wire movement through the capillary hole and this leads to process inconsistency. In addition, the residue may harden due to heat and create bonding problems.

Today's wire manufacturers have recognized the importance of bond wires with clean surfaces and have developed unique lubricants, that not only provide excellent lubrication, but they are so constituted that no component of the lubricant bonds to the wire, thus assuring very clean, smooth wire that will not clog capillaries.

Wire manufacturing companies must also take care to process different materials through specially designated equipment which are used only for particular material so as not to cross-contaminate the various metals. Separate sets of critical items such as dies and rolls should be maintained for each material. Today, modern processing equipment used in wire drawing provides clean, smooth wire that will yield high quality wires.

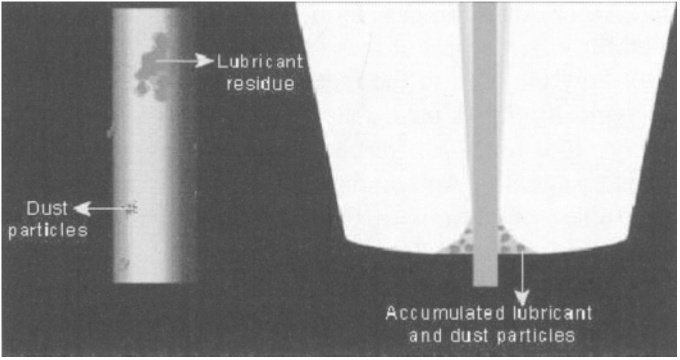


Figure 2.3.4 Capillary clogging due to lubricant residue, burrs and dust particles

2.3.4.3 Cleaning the Drawn Wire

Cleaning of the drawn wire is a very critical step. It involves removal of surface contamination without damaging the surface. It is also necessary that no residue of the cleaning solvent must be left on the surface. The drawn wire is cleaned thoroughly to remove the lubricants and oils accumulated on the surface of wire during the drawing process.

2.3.5 Hydrostatic Extrusion

Some companies use hydrostatic extrusion instead of wire drawing through a series of dies. With hydrostatic extrusion, die friction is extremely low. Only four diamond dies are required to reduce a 0.25" diameter Au rod or billet to 0.001" diameter. Fewer passes also assure cleanliness from the very start of reduction. Other advantages of the hydrostatic extrusion process include:

- tiny fractures are healed by the extreme pressures, which encase the metal, as it passes through the die. The drawing process tends to open up any submicron-size fractures or inclusions
- wide die angles assure better mixing and greater homogeneity of the extruded wire [M-7].

2.3.6 Annealing

As the wire goes through the different stages of wire drawing through a series of dies, the wire is subjected to a tremendous amount of stress. This leads to excessive generation of dislocations, internal stress and small grains which increases wire hardness as well as non uniform mechanical properties. Therefore the drawn wire is subjected to controlled high temperature annealing and heat treatment to obtain uniform properties and grain size control as well as to remove any internal residual stresses. Annealing parameters that are critical in determining the physical properties of wirebond materials include: annealing temperature, the duration at annealing temperatures and atmosphere employed during annealing.

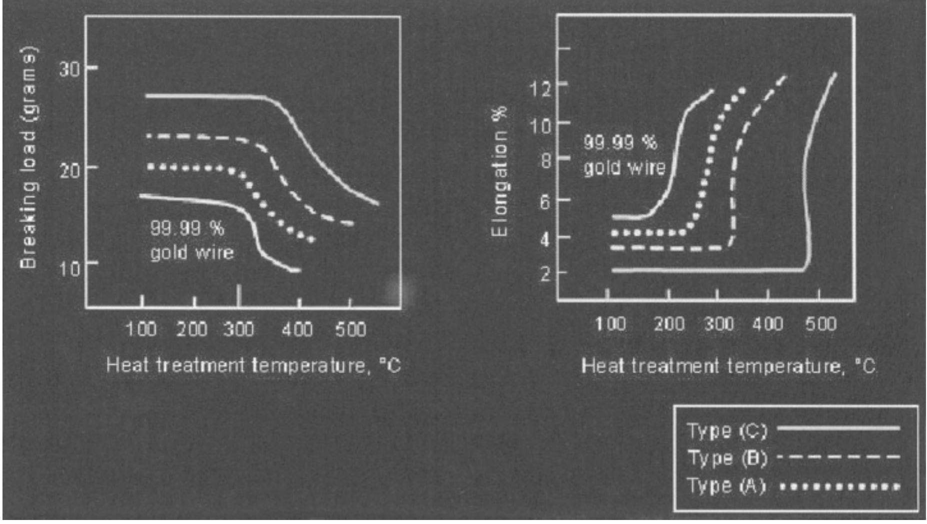


Figure 2.3.5 Effect of heat treatment temperature on breaking load and elongation [M-8]

All Au bonding wires must be "strain-annealed" at the final diameter to provide the most robust bondability. As the annealing temperature increases, the elongation increases and the break load decreases. A typical Au bonding wire application at 25μm diameter specifies 3% to 6% elongation. Figure

2.3.5 shows the effect of heat temperature on breaking load and elongation. We can observe that, the breaking load of pure Au decreases dramatically at about 290°C whereas the breaking load of type 'c' alloyed Au wire starts to decrease only at about 400°C. To maintain constant elongation even at high temperature, pure Au is alloyed with different elements.

2.3.7 Winding and Spooling

After annealing, the wire is respooled to customer specified lengths, spool size, colors and termination tapes. Respooling is performed with a programmable winding machine, and a typical spool length is 1 to 2km.

2.3.7.1 Spooling for Manual Bonders Application

In earlier times, when manual wire bonding was predominantly used in semiconductor assembly, Au wire for thermocompression and thermosonic bonding was customarily coiled on anodized Al spools which have a barrel approximately 1.0-1.1 inch wide and nominally 1 to 2 inch diameter. Two common styles of spools were the single-flange and the double-flange type. Gold bonding wire was generally coiled on spools in a single layer. About 300-350 ft of 0.001 to 0.00125 inch diameter wire could be coiled single-layer on a 2 inch spool. Smaller spools hold about 90 ft of 0.001 inch diameter wire if the coiling is single layered, whereas the same spool holds about 200 to 400 ft of .001inch diameter wire, if coiling is multilayered. One of the major concerns with multilayer coiling was that the multilayer coiling of soft annealed Au wire might induce wire kinking during despooling. This is because, when very clean Au wires comes in contact with one another for even relatively brief periods of time at ordinary room temperatures, the Au wires "cold weld" together. Cold welding strand-to-strand would make the despooling of multilayer-coiled Au bonding wire very difficult.

2.3.8 *Spooling for High Speed Automated Wire Bonders*

The spools that were originally designed for manual wire bonders and the spool capacities of 400 to 1000 ft were sufficient for several shifts of operation between spool changes. With the new high speed automated bonders, more spool capacity is needed to reduce spool change down time. This assists in long term cost savings. Now the requirement is for spools with wire lengths of 5000 meters or approximately 15,000 ft of wire on a single spool. Table 2.3.1 shows, that the winding per spool can vary anywhere between 2000 meters to 6000 meters. Longer length of wire per spool provides better utilization through minimum spool changes. However, to achieve longer lengths of wire per spool one has to change the technology from a standard multi pitch to zebra multi pitch and number of steps from 6 to 24.

Table 2.3.1 Winding capability [Courtesy: Malaysian Electronics Materials SDN. BHD]

Length	2km	3km	5km	6km
Spool Type	AL-4	AL-4	AL-4	Al-4
Winding Condition	Standard / Multi-pitch	Multi-pitch	Zebra/ Multi-pitch	Zebra/ Multi-pitch
Step	6	12	24	24
Step Tension	2-step	3-step	4-step	5-step

Fine wires with diameters of 0.7 mils through 2 mils are very difficult to spool in large lengths. Companies have developed precision spooling technologies to supply bonding wire without kinks and surface damage.

Generally, wires are wound on a spool with lengths of 1000 and 5000 meters. The winding method used, today, for multi layer spools are:

- step tension cross winding
- step tension multipitch

- zebra winding

The winding capability of the supplier plays a critical role in bonding process stability and consistency. As we move towards high speed automated wire bonding process, the amount of wire required on the spool increases. The winding technology has dramatically changed between 1970 and 2000. In the 70's parallel winding was used and the maximum length of wire was about 100 meters per spool, whereas in 90's step tension cross winding could accommodate about 2000 meters of wire per spool. Today companies use step tension multi-pitch and zebra winding to accommodate as much as 6000 meters of wire on a single spool. Figure 2.3.6 shows the different types of wire winding techniques.

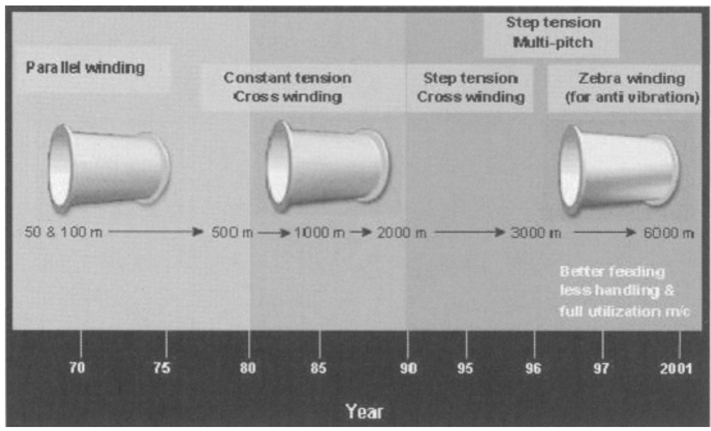


Figure 2.3.6 Chorological improvement in winding technologies
[Courtesy: Sumitomo Metal Mining]

Today, the new winding technologies provide better feeding and less handling of the wires and facilitate full utilization of the machine. Bond wire manufacturing companies have developed micro-processor controlled winding systems. This process results in effective and consistent despooling characteristics and significant cost saving through the use of multi-layer wound wire up to 6,000 meters. Different colored spools are used to

identify wires of different diameter and type for different applications. This minimizes confusion on the manufacturing floor, particularly when different products are being processed on the same line. This is a fool proof operator friendly method.

Table 2.3.2 shows the color classification of spools ending type and case label to identify the wire diameter. Each spool is taped with color tapes to indicate the start and the end of spooled wire. Typically, the START tape is green and the END tape is white. But this can be changed according to the customer requirements. One can also specify if the winding should be clockwise or anti-clockwise.

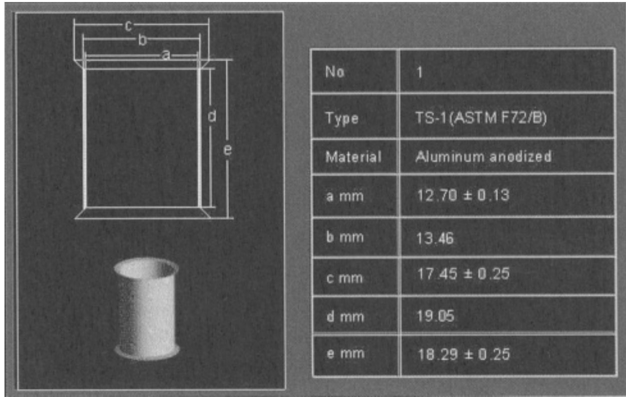
Table 2.3.2 The color Classification of the Wire diameter
[Courtesy: Tanaka Electronics] **[VIEW-IN-CDROM]**

Diameter		Spool	Ending tape	Case label
µØ	mil	Color	Color	Color
18	0.7	Blue	Green-white	Black
20	0.8	Blue	Green-white	Red
23	0.9	Orange	Green-yellow	Orange
25	1.0	Blue	Green-blue	Blue
28	1.1	Blue	Green-white	Green
30	1.2	Black	Green-red	Black
32	1.25	Brown	Green-white	Brown
35	1.4	Blue	Green-white	Red
38	1.5	Purple	Green-white	Purple
40	1.6	Blue	Green-white	Yellow
50	2.0	Blue	Green-yellow	Red
Others			Green-white	Pink

2.3.8.1 Types of Spools

There are two major kinds of spools. The single flange spool and the double flange spool. Different types of spools are used depending on the wire diameter, wire or ribbon type, type of application, and the type of bonder used. Present day spools are generally made of anodized Al. Type of

spools and spool dimension are shown in figure 2.3.7. (To view more varieties of spools with their information please access the CD)



No	1
Type	TS-1 (ASTM F72/B)
Material	Aluminum anodized
a mm	12.70 ± 0.13
b mm	13.46
c mm	17.45 ± 0.25
d mm	19.05
e mm	18.29 ± 0.25

Figure 2.3.7 Anodized Al spool and its dimensions **[VIEW-IN-CDROM]**

Many companies still send back the empty spools to the bond wire vendor. But, one should be aware that small scratches and nicks may occur due to mishandling of spools, during assembly manufacturing. If new wire is spooled on re-used spools, it may affect the spooling and despooling operations.

2.3.9 Quality Assurance of Bond Wire

Quality assurance of the bond wire involves: tensile test, rewinding test, Compositional analysis, bonding test and visual inspection. Let us review and discuss each one in detail.

2.3.9.1 Tensile Test

Tensile test is performed to check for breaking load and elongation of the wire. The quality of the wire is determined by the consistency of the breaking load and elongation. The mechanical properties of the wire,

namely breaking load and elongation are tested using Instron testers. As discussed in the previous section, the mechanical properties of the wire, tensile strength and elongation are highly dependent on factors such as:

- distribution of alloying elements in the alloy
- rate of wire drawing
- heat treatment conditions
- reduction ratio from higher diameter to lower diameter

The elongation values of the wire which depend on speed of wire drawing as well as annealing conditions have been found to show large variations. Therefore, real time statistical process control (SPC) during wire manufacturing is absolutely necessary for assuring final quality and consistency of the bonding wire.

2.3.9.2 Elongation Consistency

If the process parameters are not controlled using SPC, then the elongation is not consistent. We can observe from figure 2.3.8 (a), before implementation of statistical process control the elongation value ranges between 1.2 and 2.8. After SPC implementation during wire manufacturing, the elongation value has a much tighter distribution.

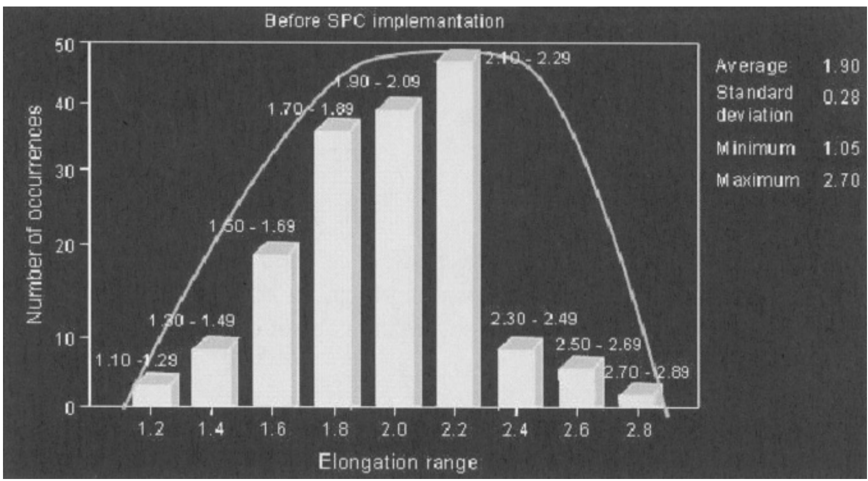


Figure 2.3.8 (a) Elongation consistency before SPC

We can observe in figure 2.3.8 (b) the elongation value has a tighter distribution of 1.5 to 2.6 with a standard deviation of 0.18. Elongation consistency is crucial for wire bond process reliability. An example of process problem is that if the elongation of the bond wire is not consistent, it may result in swaying of wire during high speed bonding.

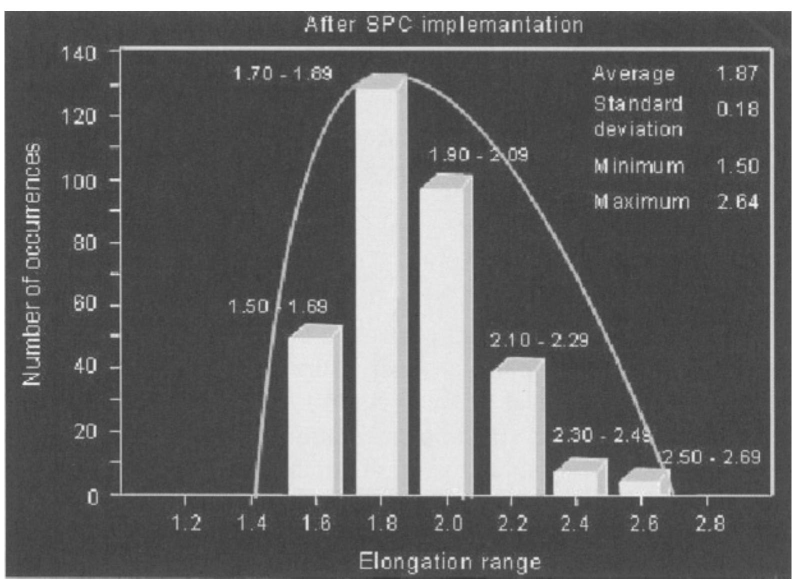


Figure 2.3.8 (b) Elongation consistency after SPC

2.3.9.3 Control Charts for Elongation

Wire manufacturers must implement SPC in their process and maintain control charts for elongation and breaking load, on a lot by lot basis as well as on an hourly basis. Figure 2.3.9 shows the control charts for elongation.

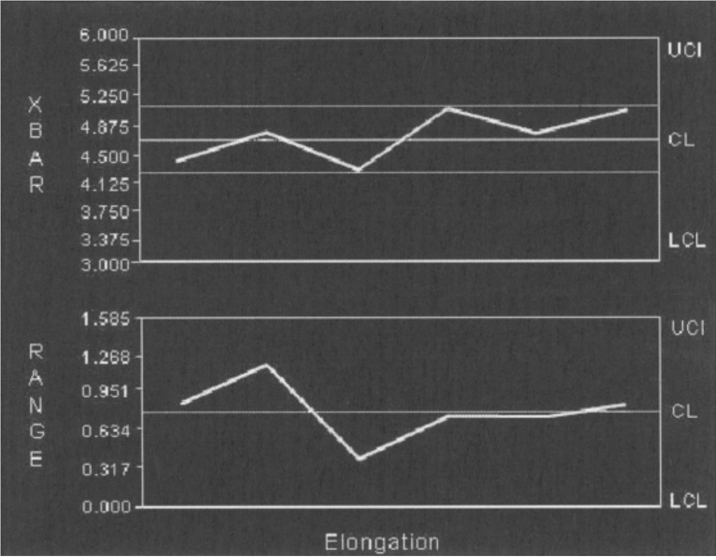


Figure 2.3.9 Control charts for elongation

2.3.9.4 Breaking Load Consistency

Similar to consistency in elongation one has to look for tight distribution of breaking load. If the breaking load is not consistent, it will result in wire breaking during bonding and wire stretching. The breaking load consistency is shown in figure 2.3.10. The breaking strength distribution must have a tight distribution with low 3σ values. The breaking strength is also monitored using control chart techniques and the values for any specific wire must fall within a specified range. Larger the range, greater the inconsistency during wire bond processing. Wire material closer to the upper control limit (UCL) tends to be hard and result in non-stick and wire break. Whereas, wire material closer to the lower control limit (LCL) tend to be soft and result in wire sagging.

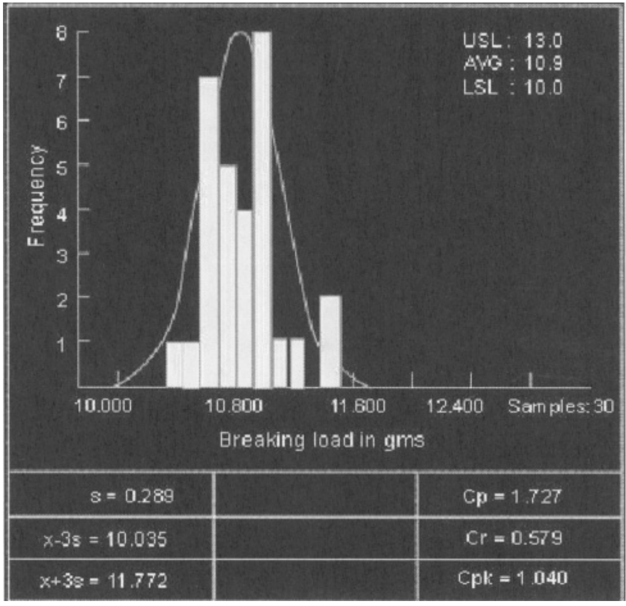


Figure 2.3.10 Breaking load consistency

2.3.9.5 Composition Analysis

In order to achieve highest purity of Au for use in bond wire manufacturing, companies refine the Au in two stages, primary stage is by electrolytic refining process, and secondary stage is by zone refining process. Maximum allowed element contamination is shown in table 2.3.3. The breaking strength distribution must have a tight distribution with low 3σ values. The breaking strength is also monitored using control chart techniques and the values for any specific wire must fall within a specified range. Larger the range, greater the inconsistency during wire bond processing. Wire material closer to the upper control limit (UCL) tends to be hard and result in non-stick and wire break. Whereas, wire material closer to the lower control limit (LCL) tend to be soft and result in wire sagging.

Table 2.3.3 Standard specification for element content [Adopted from product catalog: Mikyeongsa]

Elements	Au	Ag	Cu	Fe	Mg	Pb	Si	Pt	Others
Contents	99.99% min	5 PPM max	5 PPM max	5 PPM max	5 PPM max	5 PPM max	5 PPM max	5 PPM max	5 PPM max

Since the impurity level is so critical, spectrographic analysis are routinely made on the melts and recorded by melt number. For the major wire manufacturers, this melt number identifies a given lot of material as it is processed through the plant, thus enabling to keep process manufacturing records on each lot throughout all subsequent manufacturing steps in order to adequately identify the finished products. Bond wire manufacturing involves addition of alloying elements into pure Au or Al. If the alloy preparation is done properly, the alloying elements are distributed uniformly in the alloy. Chemical analysis of the wire and close control of alloying element composition and identification of any contaminants is essential for consistent bondability of the wire. To achieve consistent wire properties, tight control of dopants is very essential. The dopant elements in Au and Al wire are in very low concentrations, mostly in ppm range. Even small variations in dopant concentration will affect the final mechanical properties of the wire. Therefore, very careful compositional analysis of wire is carried out using sophisticated methods such as inductively coupled plasma. Figure 2.3.11 shows the process of composition analysis using inductively coupled plasma. Companies use inductively coupled plasma spectroanalyzer (ICP) for full in-house chemical analysis of dopants, alloying and impurity elements. This state-of-the-art analytical capability allows one to have full control of the chemistry of Au, Al and other metals from the refining stages through casting and cold working. This provides a finished bonding wire with more stringent chemical composition.

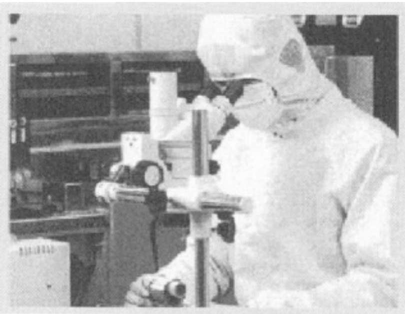


Figure 2.3.11 Composition analysis using inductively coupled plasma [Adopted from product catalog: L G Metals]

2.3.9.6 Bonding Test

Although, the mechanical and chemical properties of the manufactured wire are close to specification, that is not an assurance of good bondability of the wire during IC assembly manufacturing. Therefore, wire manufacturers perform a "Bondability test" on every lot of wire material produced and assure that no contamination or residue affect the bondability.

2.3.9.7 Visual Inspection

Visual inspection under an optical microscope is performed on wound spools to inspect for surface defects, dust particles and non-uniformity of wire winding. The wire surface is inspected for defects and contaminations after spooling.

Figure 2.3.12 Scanning electron microscopy analysis [Adopted from product catalog: Mikyeongsa]

Higher magnification scanning electron microscopy (SEM) inspection is performed on a sample basis to inspect defects like scratches and burrs. Figure 2.3.12 shows an operator performing inspection using an SEM.

2.3.10 Storage of Wire

As discussed earlier, the wire properties change over a period of time and this is impacted by the temperature of storage, storage atmosphere and most importantly storage position. Importance must be given to how bond wire is stored before use in IC assembly manufacturing.

Bonding wires should be stored in a dust-free environment between 60° to 72° F. For extended storage of Al and Al alloy wires, refrigeration or freezing is recommended. The proper way to store spools of wire on the shelf is by keeping the axis of the spool horizontal to the shelf as shown in figure 2.3.13. This removes the possibility of gravity acting on the wire and causing the wire to shift down on the spools. One should not store wire in such a way that the flange is standing flat on the shelf.

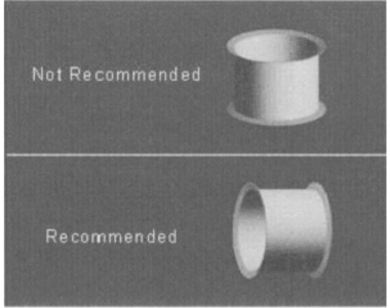


Figure 2.3.13 Recommended storage position for bond wire spool

2.3.11 Shelf Life

Breaking strength and elongation of wire held in storage may change with the passage of time. This aging is caused by the relaxation of cold working stresses induced during wire drawing. The changes in breaking strength and elongation over time will affect the consistency of the wire bonding process on the manufacturing floor. Testing has shown that hard as drawn wire begins to weaken within six weeks of manufacture. Specifically, the breaking strength of certain alloys decreased by between 5 and 15 percent in that period, and then decreased more slowly for the balance of the two-year period of that particular test. It is observed that the breaking strength decreases with increased time of storage perhaps as much as several grams in hard temper 0.001 inch diameter Al-1% Si wire. Figure 2.3.14 shows the change in tensile strength decrease in pure as drawn Al wire as a function of

time. Longer the wire is stored, lower is the tensile strength. This is attributed to room temperature recrystallization of the drawn wire and relief of internal or residual stresses in the wire.

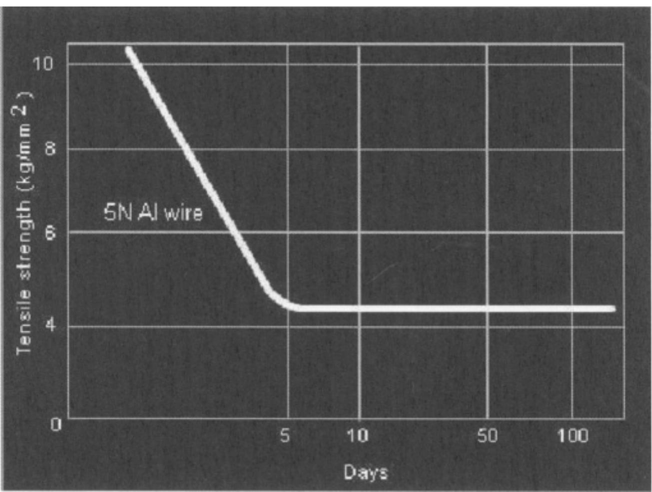


Figure 2.3.14 Change in mechanical properties of high purity Al with lapse of time [Adopted from product catalog: Tanaka Electronics]

2.3.11.1 Residual Stresses

When a thick wire is drawn through dies to reduce to a smaller diameter, it goes through strain hardening and the grain size becomes small. Because of this the drawn wire material has very high residual stresses. During long term storage at room temperature, there is slow grain growth and relaxation of residual stresses, resulting in reduction in tensile strength and increase in elongation. This is also called wire aging. Very strong, heavily cold worked material suffers the greatest degradation, whereas annealed wire is affected to a lesser extent. Though, residual stress relieving would be expected to increase elongation, in some cases the elongation is reduced. This is attributed to non-uniform metal relaxation. It must also be noted wire aging

is more pronounced in some ranges of breaking strength and elongation than in others.

Stress relaxation during storage may change the bonding characteristics of a wire lot. To minimize uncertainty, it is generally recommended that wire inventory be stored at temperature not exceeding 70°F and in nitrogen ambient in controlled humidity chambers. Some companies adopt a discretionary policy of discarding bonding wire after three or six months. The principle here is that they would rather toss out good wire than risk a change in metallurgical properties that could affect the yield for a given machine setup.

2.4 Quality of Bondwire

The quality of wire depends on the wire manufacturing process and process control during wire manufacturing. The mechanical parameters namely breaking strength and elongation are important, but adequate control over these properties is more easily achieved with pure Au than with the more complex alloy systems like Au-Be or Au-Pd or Al + 1% Si.

The statistical process control system at the wire manufacturer should be based on the elongation of the wire. SPC wire elongation data is obtained from Instron machine tensile tests. The data thus obtained is compiled at two stages of the wire manufacturing process. The first stage is at a large diameter for intermediate processing control and the second stage is at finished size.

All master spools of intermediate-sized wire must be tested. A master spool yields approximately 75,000 feet of finished wire. The SPC in the manufacturing line should be performed on the master spool material as well as on the smaller (slave) spools on a sample basis. The master spool and the slave spools are shown in Figure 2.4.1.

On each master spool a series of consecutive tensile fracture tests are performed. The elongation data from each master spool are averaged. Then from the maximum and minimum values of the obtained elongation data, the elongation range is computed. The average and range values are then plotted on a SPC chart.

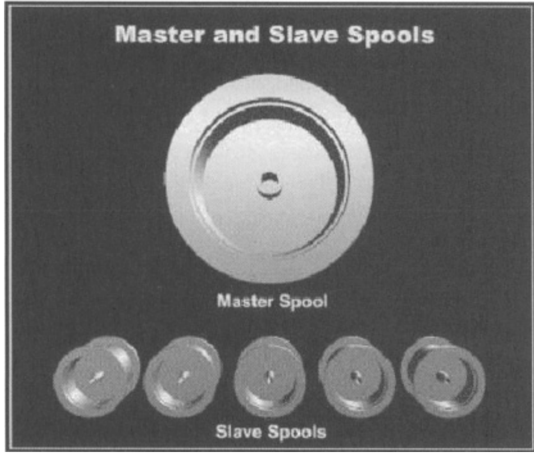


Figure 2.4.1 Schematic representation of master spool and slave spools

2.4.1 Surface *Cleanliness and Chemical Analysis of Drawn Wire*

It is vitally important that the bond wire should be free of surface contamination. A serious potential contamination problem is insufficient removal of the lubricating material used in drawing the wire. These lubricants are essentially transparent film residues, a few hundredths of a micrometer thick on the wire and are difficult to detect by optical or other means. In addition to the possibility of interfering with making the bond, their presence can lead to problems such as corrosion of Al metallization or later device degradation due to the water or contaminants that may be included with the lubricant. Therefore, the surface characteristics of bonding wire, i.e., the physical and chemical nature of the surface, should be given equal importance with the bulk physical properties. However, the surface properties are more often assumed than measured. There are two basic reasons for this: First, pertinent surface properties are not easily specified, other than in very general terms. Second, these properties are not easily measurable. The net result is a tendency on the part of the user to

assume that the vendor has supplied a wire with 'optimum surface properties'.

The inadequacy of such a specification is seen upon considering the interaction of prospective contaminants with surface topography and sub-surface or near-surface defects. During fabrication the wire undergoes 99% percent of deformation, and unless the greatest care is exercised in maintaining correct reduction ratios and a clean circular die aperture at every stage of fabrication, laps, seams or folds may develop in the wire. These features trap lubricant, so that in the finished wire 'reservoirs' of potential contaminants may exist concealed in surface or sub-surface defects. They can become a problem when the wire is heated (e.g., during Au bonding) and the entrapped contaminants expand and seep out. Structural defects of this nature are not easily detected, even with the aid of SEM.

The surface topography of the finish-drawn wire must be such that it does not trap residual contaminants and hinder cleaning. The importance of efficient cleaning with regard to bondability has been demonstrated by the bond strength distributions. These results obtained from two spools of wire with identical physical properties. The first spool was inadequately cleaned, the second was cleaned thoroughly. The inadequately cleaned wire bonds failed in a 'lift-off' mode [M-9].

The internal chemical composition of the Au or Al alloys as well as the surface chemical composition of the drawn wires significantly impacts the wire bonding process. For example, hydrocarbon contamination on Au wire can affect the Free Air Ball formation during ball bonding. Therefore, wire manufacturers conduct a detailed chemical analysis on wires after the manufacturing process is complete and the report is usually attached with the shipped lot. The chemical analysis includes ion chromatography and chemical titration methods. More recently, some manufacturers, in addition to the capabilities for chemical analysis, use scanning electron microscope (SEM) with full X-ray energy dispersive spectroscopy for characterization of surface and internal integrity of the bond wire. SEM equipped with light element analyzer is used for identification of elements such as chlorine, carbon, oxygen, nitrogen, sulphur and boron. In addition, the microscopes are equipped with a back scattering device for detailed image delineation and non-metallic element detection.

The vacuum chamber in the SEM is equipped with despooling device to allow direct observation of the wire surface, under a scanning electron beam, during despooling. In producing Au bonding wire, the control of surface finish and surface cleanliness are given highest priority. These precautions are required to prevent bonding capillary clogging.

2.4.2 Control of Silicon Dispersion in Aluminum alloys

Control of Si dispersion in Al-Si alloy is a principal concern of wire manufacturers. With properly used metallurgical techniques, however, it is possible to manipulate the Si distribution purposefully in order to adjust the wire's mechanical parameters over a relatively large range. Special techniques such as field ion microscopy are used to check for the uniformity of Si dispersion in the Al alloy. One should appreciate that uncontrolled Si-rich second phase is only one of the several particulate species which may degrade the bonding wire alloy. The manufacturer must, in addition to maintaining uniform Si dispersion, prevent oxide inclusions from dross and pickup from melting crucibles and billet molds [M-10].

2.4.2.1 Fatigue Failure of Aluminum due to Silicon Precipitate

Failure of bonding wire occurs due to metal fatigue during thermal cycling as well as power cycling. This is due to thermal expansion and contraction of the wire due to heat. Usually, failure occurs at the heel of the bond because that is the weakest point in the bonded wire (refer 6.6.1 figure in chapter 6.6) If the heel area of the Al wedge bond contains non uniform distribution of Si precipitates, then the fatigue failure is accelerated due to the brittleness of the Si particle. If Si precipitate is present near the heel, the fatigue failure occurs much more easily. This is a significant problem in Al -Si wire, if used in higher power applications. Figure 2.4.2 shows the failure near the heel due to Si precipitate.

It has been shown that fracture characteristics are chiefly controlled by the nature of the Si particle in the material. If the Si particle distribution is not uniform, variations in bonding performance and line yield from wire lots with 'identical' specification will also occur. In the worst case, Si particles concentrated in localized regions may cause large variations in the hardness of the wire.

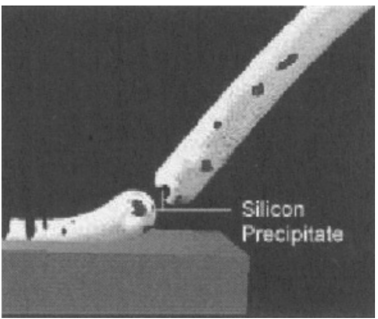


Figure 2.4.2 Failure due to Si precipitate

Problem arising from this include:

- fracture or cracking in the wire during bonding
- lift-off of the wire due to improper set-down
- damage to the Si chip under the bond
- wire breakage in the bonding equipment

It is necessary to specify the consistency of tensile elongation properties in each spool and thus, the Si is present in controlled form, as fine particles, uniformly dispersed throughout the aluminum matrix. While the need for consistency in the properties of Al-Si wire is to a large extent self-evident, the parameters involved in ensuring process consistency are less so. Thus, if reproducible results are to be obtained, a well-tuned ultrasonic bonder requires wire of consistent properties, which implies that the compressive yield strength, ductility and fracture characteristics of the wire be consistent.

2.5 Testing Methods and Specifications

We have reviewed the importance of the mechanical properties such as tensile strength, elongation and Young's modulus and the importance of chemical and metallurgical uniformity of alloys used in bond wire manufacturing. These characteristics of the wire have to be measured using established techniques and the measurement methods must be standardized,

so that the results are interpreted uniformly globally. In this section, we will discuss the test methods, methodologies and specifications used in the industry today, including mechanical properties testing, composition analysis and visual inspection.

2.5.1 Mechanical Properties Testing

It is necessary to specify the mechanical properties of bonding wire by setting acceptable ranges for the break strength and elongation for a specific wire diameter. The breaking strength is the tensile stress applied at failure and the elongation is the percentage extension at failure of a wire specimen subjected to a tensile test at room temperature. The specifications and methodology of mechanical testing have been specified by ASTM standards. For example, the ASTM standard method of test F 219 (ASTM standard) specifies that the tensile testing of any bond wire be done with following test conditions. The test conditions are:

- wire length of test specimen = 10.00 inches
- extension rate during testing = 1.0 inch per minute
- temperature during testing = 25° C or room temperature

ASTM Specifications F 72, F 487 and F 638 prescribe breaking strength, elongation values and tolerances appropriate to various types, sizes and temperatures of bonding wire. But we should keep in mind, that these specifications are only a starting point in writing initial purchase specifications. Wire bonding engineers must select bond wires to maximize bond yields by adjusting wire properties to suit the specific application for which the wire is used. A wire bond engineer must develop the wire specification by testing a variety of wires which exhibit a range of breaking strengths and elongation values. Then the material which performs best must be selected.

This is a sound approach in principle, but in practice, it sometimes yields disappointing results. The difficulty is due to the working conditions on a high production bonding line which may be considerably different from those existing in the laboratory during the wire qualification tests. Considering the difficulty of performing meaningful wire qualification studies in a laboratory, running the tests on an operating production line is highly recommended. In most companies, bond wire specifications are

continuously adjusted as production line experience accumulates. Starting from some arbitrary breaking strength and elongation values, specifications slowly evolve and bond yields typically improve over a period of years. This approach is satisfactory for mature packaging operations, which assemble large volumes of one type of package, say, DRAMs. But with current trend of wide range of packaging options, variety of chip metallizations, small lot sizes and non-dedicated machines, it is highly inefficient to depend on one type of wire. When sudden changes are introduced into the system, e.g., a new wire vendor's product appears on a line or changes are made in lead frame or chip metallization, it is imperative that proper qualification procedures are followed to meet the demands of zero defect manufacturing.

Therefore, it is important to recognize, that the objective of mechanical testing should not be the attainment of the strongest wire. The wire material in addition to having the highest mechanical properties, must meet manufacturability criteria, such as:

- bondable over a range of bonding parameter variables
- bondable over a period of time, say few weeks

2.5.1.1 Test Fixtures and Test Conditions for Tensile Testing

The bond wire tensile properties are tested by holding the wire with special grips and application of tensile stress along the wire. To reduce the variation occasioned by the tensile test procedure careful attention should be paid to design of the tensile grips and the gripping surface. It is very important that there should be no air drafts during testing. Figure 2.5.1 is a schematic representation of tensile testing method.

As described in the previous sections, the elongation consistency is the best single definition of wire metallurgical quality. Therefore, wire quality inspection and process control program should be based on the elongation of the wire. However, it is also important to note that any specification calling for a relatively narrow elongation range of each spool must consider that even the most carefully executed procedure will extend the range. Thus a specified range of 1.0% is unrealistically severe and a 1.5% range under normal quality control testing conditions is more realistic.

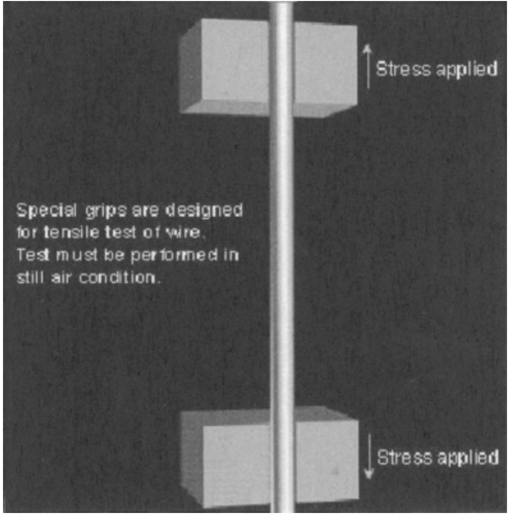


Figure 2.5.1 Schematic representation of tensile testing of bond wire

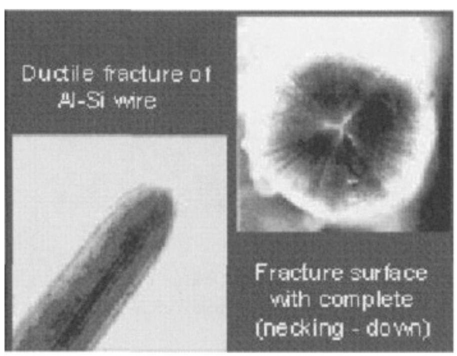
2.5.2 SEM as a Diagnostic Tool of Fracture Mode Analysis

Scanning electron microscopy can be used for fracture mode analysis of a wire after it has been subjected to tensile testing. SEM has been used to examine the morphology of tensile fracture surfaces resulting from Instron wire pull tests. After the tensile test, two types of wire breaks are generally observed. The first type is ductile fracture in which the mating ends are bullet-shaped. The second type exhibit deep cavities, indicating microporosity. Let us review each of these failure modes and what it means from the perspective of wire bond process.

2.5.2.1 Ductile Fracture of Wire

The bond wire, when tested on an Instron tensile tester, breaks when the breaking load is reached. Usually a pure metal wire breaks in the "Ductile Fracture Mode", by the formation of a uniform bullet shaped tip. This is also the failure mode of an alloy that has uniformly distributed impurity

precipitates such as Al-Si alloy. Figure 2.5.2 (a) shows the SEM photograph of the ductile fracture of Al-Si wire. When we perform tensile testing, the metal undergoes plastic deformation and results in a thin neck formation and finally fails by ductile fracture.



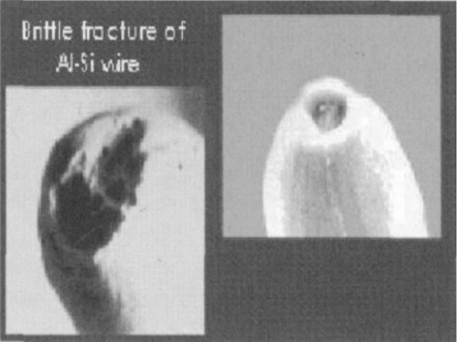


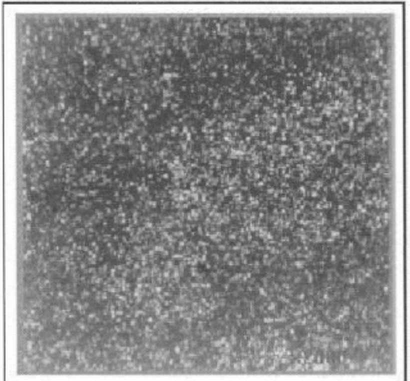
Figure 2.5.2 (a) Ductile fracture of Al-Si wire Figure 2.5.2 (b) Brittle fracture of Al-Si w ire

2.5.2.2 Brittle Fracture of Al-Si Wire

If the alloying is not uniform and large precipitates exist in the alloy, during tensile pull test, the wire will break at the neck in a brittle fracture mode, due to the presence of Si precipitates. Figure 2.5.2(b) shows an SEM photograph of formation of brittle fracture in Al-Si wire. The brittle fracture of wire during tensile testing indicates inconsistent wire properties. This failure mode is an early indication of process problems such as wire breakage or non-sticking of bonds.

2.5.2.3 Silicon X-ray Image of Fractured Surface

The fractured surfaces after tensile testing were analyzed using X-ray imaging techniques. Figure 2.5.3 (a) shows an X-ray image of ductile fracture surface which indicates uniform distribution of very fine Si particles. Figure 2.5.3 (b) shows an X-ray image of the brittle fractured surface which clearly indicates large Si precipitates.



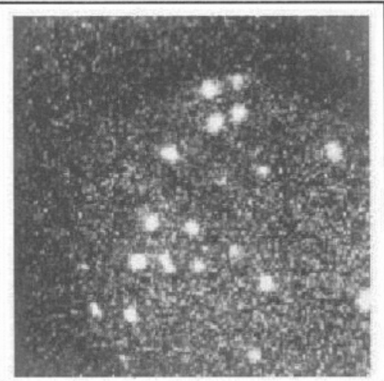


Figure 2.5.3 (a) X-Ray image of ductile fracture surface. (b) Image of brittle fracture surface [Adopted from product catalog: Plessey Materials Corporation]

These X-ray images clearly show that when the Si impurity in Al is uniformly distributed, the Al metal goes through a slow and uniform plastic deformation finally resulting in a bullet shaped point contact ductile failure. However, when large Si precipitates exist in the alloy, initially the Al undergoes plastic deformation, but when the stress is closer to breaking strength, the large Si precipitates acts as a fracture site and the wire results in brittle fracture.

2.5.3 Visual Inspection

Visual inspection is of the utmost importance in all wire fabricating operations. Most wire manufacturers inspect the wire under a microscope for surface defects, surface contamination and poor winding to make sure that only the highest quality material is shipped to the customer. To accurately inspect finished wire visually, one should use an incandescent light source, such as that supplied by most microscope manufacturers. It is suggested that the incident light is at about a 45° angle to the axis of the spool. A magnification of 30× is recommended. In fine pitch applications, the wire surface morphology needs to be analyzed at high magnification to

look for minute burrs, nicks and scratches. High magnification inspection is done to identify these micro defects using a scanning electron microscope.

2.5.4 Wire Diameter Measurement

Measurement of wire diameter is occasionally a source of contention between suppliers and users of fine bonding wire. Wire manufacturers, with few exceptions, prefer indirect weighing for diameter determination. This method is documented in ASTM Standard F 205. In the standard procedure, a measured length of wire is weighed on a microbalance and the diameter is calculated using the room temperature density of the wire metal. For Al, Al-1% Si and Al-1% Mg wires the ASTM standards cite the metal density as 2.70 g/cm^3 (F 487, F 638), the density of Au is 19.34 g/cm3 (F 72). For example, a 0.2 meter specimen of 0.001 diameter Au wire weighs 1.90 mg; a 2.00 meter length of 0.001 in diameter Al-1% Si wire weighs 2.74 mg. The validity of the weighing method for diameter measurement depends upon the wire cross sections being round. In practice, it is generally safe to assume that these conditions are met.

It is also feasible to determine wire diameter directly using a sensitive mechanical micrometer apparatus. This method is always suspected because of the danger of deforming the soft wire between the micrometer jaws, thus producing erroneous measurements.

In comparative tests of micrometer method and the weighing method, it has been found that direct micrometer diameter determinations for a variety of fine wires agreed closely with those inferred from weighing. But suitable precautions need to be taken to make direct diameter measurements valid. Optical measurements of wire diameter are generally unsatisfactory. In order to obtain sufficient magnification to make the image size large enough for adequate viewing, the depth of field becomes too shallow for accurate edge definition. A shadow-projection technique might be the devised, but few commercially available instruments are provided with enough magnification to assure the required resolution. A SEM could be calibrated to perform accurate diameter determinations.

3

Bonding Equipment

Introduction

The driving force behind today's wirebonder advancements are productivity and ultra fine-pitch bonding capabilities. Wire Bonding equipment choices and configurations have a considerable effect on the productivity, yield and reliability of the wire bonding operations. The capital expenses associated with bonding equipment are large and in any major assembly operations the capital expenses are multiplied several times over by the number of bonders installed at a time. However the equipment cost is small compared to the yield losses associated with poor bonding yields and low productivity over the life time of the bonding equipment. This is particularly relevant today when more sophisticated, high pin count and expensive devices are being wire bonded. This chapter on bonding equipment focuses on issues such as:

- what are the wire bond equipment capabilities required for fine pitch wire bonding
- how does one select the right kind of bonding equipment for a particular packaging application
- how does one analyse the cost of ownership of a wire bonder
- how does one evaluate the performance of a wire bonding machine and
- what are the maintenance issues to be addressed

3.1 Equipment Capability Requirement

As we move towards higher pin count devices, finer pitch bond pads and fine pitch lead frames, the wire bond interconnection technology demands bonding equipment to satisfy major requirements such as:

- increased bond placement accuracy
- improved ball formation
- accurate touch down detection, impact control and deformation control
- precise looping control
- capability to handle varieties of material handling systems
- extensive process control
- bond program portability / transfer of recipe
- high process yields
- high speed bonding
- consistent process quality
- minimum machine down time
- improved operation ease (man machine interface)
- fine wire handling capability
- large bonding area
- variety of loop formats
- low loop heights
- fast conversion times
- small equipment foot prints
- off line Programming

Let us review and discuss some of the above requirements in detail to help us understand the complexity of the equipment technology that is required for today's wire bonding process.

3.1.1 Bond Placement Accuracy and Repeatability

Bond placement accuracy and bond placement repeatability are two crucial requirements that an ultra fine pitch wire bonder must satisfy. Bond

placement accuracy is defined as the ability to place the wire bond in the exact location on the bond pad taught during programming of the bonder for a particular bond pad configuration. The accuracy of bond placement is crucial both on the bond pad and on the leadfinger. Figure 3.1.1 shows an example of a misplaced ball bond and the amount of displacement from the actual taught location.

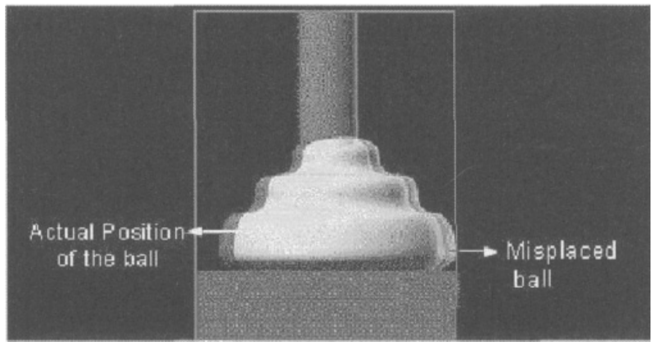


Figure 3.1.1 Accuracy of Ball Positioning

Numerically, the accuracy of ball placement is defined as : The average distance between actual bond location and Bond Teach Position of "n" wires bonded on "n" devices.

Bond placement repeatability (Ball Placement Standard Deviation) is defined as the ability to place a bond in the same location over "n" devices. Numerically Bond placement repeatability is defined as the Variation of the Distance between Actual Bond Location and Bond Teach Position.

3.1.1.1 Ball Placement on Bond Pads

Because of the close proximity of bonds on high lead count devices, an automatic wire bonder must be extremely accurate with consistent bond placement. It must be able to reliably bond as close as 50 micron center-to-centre distances.

From the point of view of process reliability, high speed fine pitch wire bonding machines, must be able to place the ball bonds with great

consistency and stability, over a long production time. In figure 3.1.2 we see that even after placing 400,000 ball bonds, the variability of ball placement accuracy is +/- 2 microns both in X direction and in Y direction. This kind of consistency and stability is expected of every machine, for every device, for every loop shape and in every factory.

In addition to the causes mentioned above, the other causes of inaccurate positioning of the ball is, inconsistent free air ball. If the free air ball size is not controlled precisely then the ball deformation will be non uniform which will result in off centred bond and inconsistency in bond placement

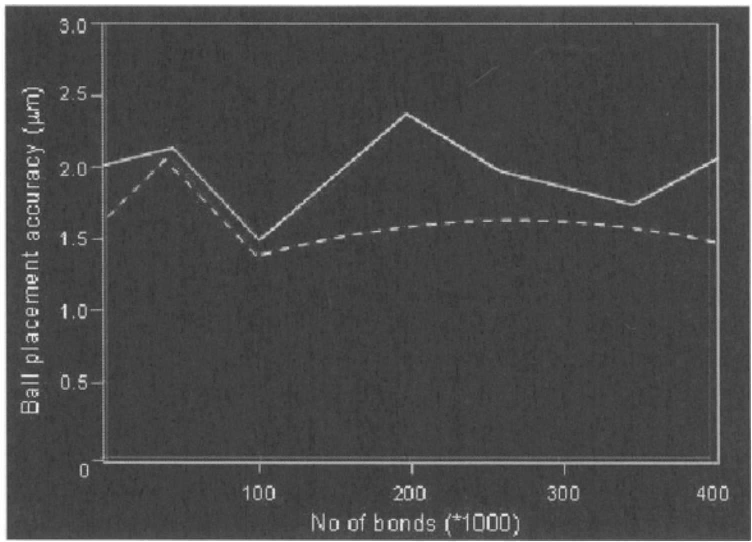


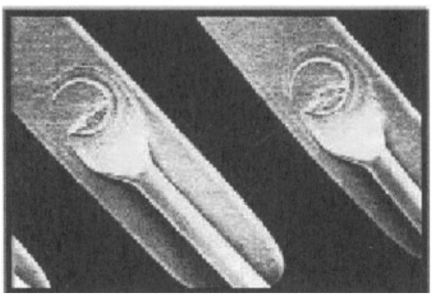
Figure 3.1.2 Ball placement accuracy [E-1]

3.1.1.2 Bond Placement on Lead finger

The lead fingers on high-lead-count lead frame or on a BGA substrate are thin, narrow and are very fragile. The reduced width of the lead finger combined with variances in lead positions due to lead finger fragility, poses great difficulty in locating second bond pad locations. In today's wire bonding machines, a high-resolution Pattern Recognition System (PRS) can resolve this problem by optically finding each lead and correcting the

programmed bond location. In addition developments in X-Y table positioning accuracy have enabled today's machines to attain fine pitch bonding capability.

When the angle of approach of the bond wire to the lead finger is zero, or in other words, when the wire is parallel to the lead finger, the second bond can be centred on the lead finger. This is shown in figure 3.1.3. However the accuracy of the second bond placement depends on machine stability, as well as the accuracy of the PRS system. We can see in fig 3.1.2 that machine instability and improper PRS or video lead locator may result in off centre second bond positioning.



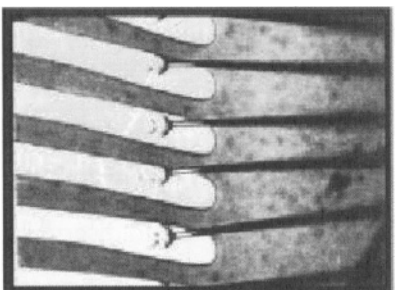


Figure 3.1.3 (a) Weld centring (b) Off-centre, out of specification weld

3.1.1.3 Pattern Recognition System

The pattern recognition system (PRS), together with the indexer and the bondhead, determines the accuracy and throughput of a wire bonder. Today's demands for speed, accuracy and reliability are fulfilled with a combination of modern CCD cameras, specialized optics, illumination techniques, modern Digital Signal Processors (DSP) and intelligent algorithms.

Pattern recognition furnishes the ability to perform automatic alignment of components. Compared to the time-consuming, fatiguing and error-prone process of manual alignment, pattern recognition represents a significant technological step forward in automating wire bonding process and inspection.

The PRS is not only important for the alignment of a device, but is used increasingly to support the operator during time consuming teaching

procedures. The PRS defines an accurate ball position (centred) on the bondpad. The PRS also specifies a centred wedge position with an operator specified tip distance on the lead finger.

The main challenge in the new generation of PR systems is to reduce execution time while improving the robustness of the system. A common approach is to use Artificial Intelligence based algorithms for the PR systems during teaching. This will reduce the amount of data required for the references which in turn reduces the execution time.

3.1.1.4 Types of Pattern Recognition Systems

Among the types of pattern recognition systems available today are:

- edge detectors
- moments technique systems and
- correlation algorithm systems

The most accurate and discriminating pattern recognition system available today for IC assembly is that based on a correlation algorithm. In the correlation algorithm system, camera video is successively divided into bi-level video by the electronics of the pattern recognition unit. As this bi-level video is stored in the form of pixels, a matrix of these pixels is formed, each either white or black corresponding to the analog image on the monitor.

Using advanced computer platforms with Digital Signal Processors, ASICs and Multi Processors, companies have developed very powerful algorithms for grey scale correlation, artificial intelligence (AI), parallel processing and neural networks. The new algorithms together with high resolution cameras have been able to achieve very high accuracy as well as high bonding speed.

When 'teaching' the bonding machines a pattern, the pattern recognition unit stores an area of pixel information in its memory. Usually, the size of this area is a grid of 128 x 128 pixels and is called the reference area. A threshold value is automatically selected when the reference is stored. Any part of the video above this threshold value becomes white and any part below, black.

During the execution of the actual program during wire bonding, real-time video information in pixel form is compared with the stored reference information as the pattern recognition unit searches an area 240 x 240 pixels

to find the reference area. Video pixels from the current pattern are matched with reference pixels from the stored pattern as the two patterns are correlated. The location found with the highest correlation is selected as the best point. Through this process, the pattern recognition unit searches and finds the updated position of the real time reference and transmits X-Y co-ordinate data to the system computer. The search procedure takes approximately 100 to 150 msec.

3.1.1.5 Reference Systems

During wire bonding, we need to teach the wire bonder specific reference patterns in order to perform wire bonding consistently and accurately on every device. The structures on the chip have exceptional repetition accuracy with respect to shape and size and therefore, we use these for defining the reference system.

The Pattern recognition System recognizes two reference points for example, R1 and R2 on a chip and all bonds on the chip are specified relative to this reference system as shown in figure 3.1.4.

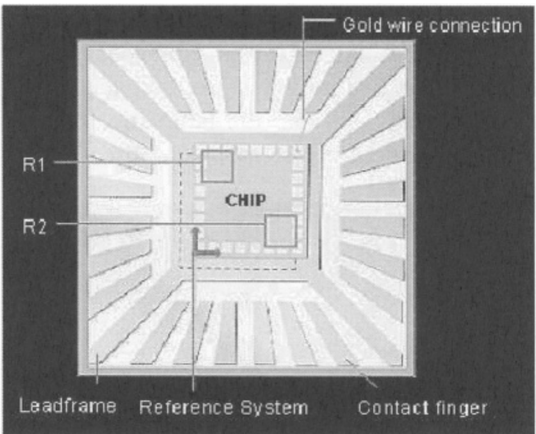


Figure 3.1.4 Chip reference patterns during teaching [Courtesy : ESEC]

However, during production, as a result of the die bonding and the mechanical positioning accuracy of the wire bonder indexer, the chip and its contact point locations are no longer in exactly the same place as they were during teaching. The PRS searches for the position of the two reference patterns taught redetermine the position and rotation of the reference system and then accurately calculates the positions of the contact points. For every single leadframe contact point (lead finger), the position is determined in exactly the same way. Once all contact positions have been determined, the wire bonder starts the bonding operation.

3.1.1.6 Illumination

The consistency and reliability of the Pattern Recognition System is very dependent on the uniformity of illumination which in turn is dependent on the light source. Some of the advanced bonders have LED illumination technology along with software-controlled lighting, both oblique and direct, to ensure optimum illumination for all device types. LED illumination source provides more even illumination, reduces light intensity to the operator and increases system reliability. The light source is capable of 256 different illumination levels which are unaffected by changes in line voltage regulation. The 256 illumination levels enhances the bonder's ability to recognize alignment points and provides precise package alignment. Another advantage of the LED lamp, is that the lamp life is usually about 4 years compared with 1 month for conventional light sources.

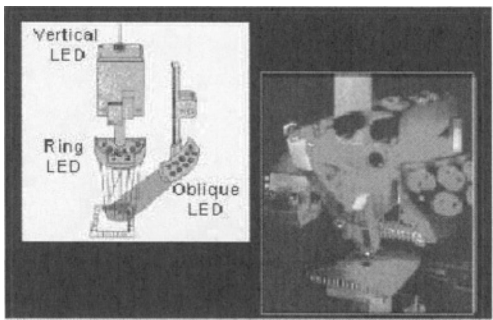


Figure 3.1.5 Three source of programmable LED illusion
[Courtesy : Kulicke & Soffa]

For a pattern recognition system to operate efficiently and consistently, illumination of the bonded unit must be uniform. One of the techniques to achieve uniform illumination is to use LED lighting in three formats, vertical, ring and oblique lighting, as shown in figure 3.1.5. This configuration is found to be more stable. This also reduces reflection, glare and blooming. Elimination of glare also enhances contrast and PRS efficiency.

3.1.1.7 Bond Head Technology

The bondhead is one of the most important modules of a wire bonder. It must meet the toughest specifications for the increasing demands for high precision in fine pitch bonding, excellent motion control for low looping, high speed for the required UPH and low maintenance to minimize machine downtime. Some of the modern automatic wire bonders make use of flying bond head technology or direct drive technology in the bonding head. This allows precise software controlled touch down dynamics and bond force control. The combination of bondhead technology and improved EFO control allows the bonder to make the small consistent bonds required for fine pitch bondpads. There are three major types of bond heads based on three different concepts.

1. Spindle concept

Bond head table movement can be controlled by different mechanisms and one popular concept is the spindle concept. Spindle concept is originated from the machine tool industry and this conventional approach from the machine tool industry has been steadily improved to meet the demands of wire bonding.

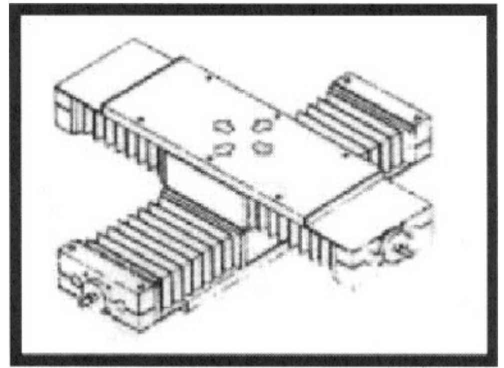


Figure 3.1.6 The spindle concept [E-2]

This conventional approach has been used for a long time in wirebond machine development, but as we go to higher precision in fine pitch bonding, the spindle concept has limitations.

One of the major limitations is that the spindle preload which is necessary to increase the accuracy causes additional friction in the spindle system which retards the drive acceleration, leads to system wear out and influences the behaviour of the control system. It has been found that system control algorithms require non-linear modelling due to non-linear behaviour of friction and because of this, it is difficult to get optimum accuracy for the positioning and optimum tracking of the loop trajectory.

2. Pantograph concept

The drawbacks of the spindle drives started the search for other types of drives, and the Pantograph concept was initiated. Studies have shown that this drive system also has certain drawbacks due to friction and non linear control algorithms.

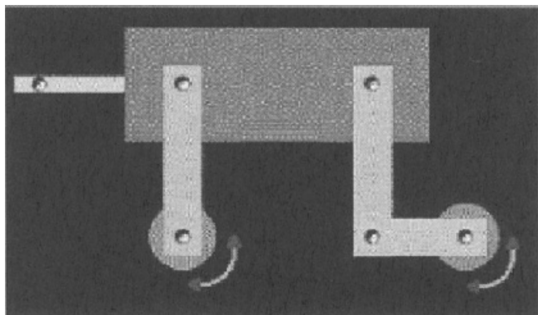


Figure 3.1.7 Pantograph drive [E-2]

3. The flying bondhead

The flying bondhead technology is one of the most recent technologies. This system is based on an air bearing technology. The air bearing technology is a frictionless technology which means no friction during bond head motion. This technology seems to exhibit better placement accuracy

and loop control. But we must recognize that the mechanical controlling mechanism for a flying bond head is very difficult and controlling such a system needs a sophisticated technology.

The concept of the flying bondhead provides a linear, frictionless bondhead table and with this approach, the kinematics of the bondhead is determined by warless and play less air bearings. As the bondhead has no physical contact with its environment, friction is completely eliminated. Flying bondhead is a system developed by ESEC company.

The advantage of air bearing system is a friction free movement of the bond head in X as well as Y direction. With this technology, it is possible to keep the bondhead within a tolerance of 1 μm over the entire loop trajectory and this is a big advantage for the position accuracy. The flying bondhead design comprises only three moving parts. This enables the mass and the inertia of the bondhead to be reduced to a minimum. Some of the other advantages of the flying bondhead technology include high reproducibility, accurate loop tracking, high positioning accuracy, high acceleration and low maintenance.

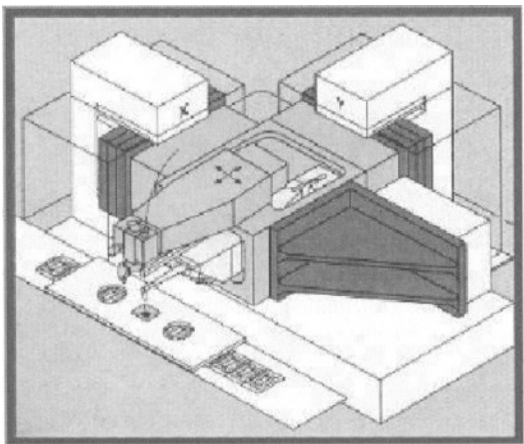


Figure 3.1.8 A schematic of a flying bondhead [E-3]

Placement accuracy of a ball bond is very critical in fine pitch wire bond technology. The misplacement of the bond can be due to PRS, thermal

expansion, bearing Y, bearing X, control algorithm and resolution. Figure 3.1.9 shows an example comparison of bond misplacement by a conventional bond head versus a flying bond head. The flying bond head configuration displays a very tight distribution. The misplacement is minimum with a flying bondhead and the six sigma value is below 20 microns, whereas, with conventional technology, the six sigma is more than 50 microns.

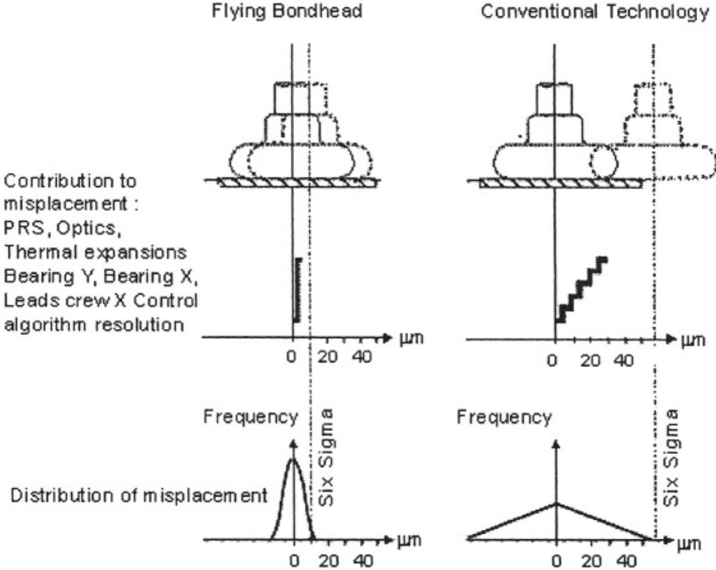


Figure 3.1.9 Distribution of bond misplacement with flying bondhead and conventional bondhead [E-3]

The three types of bond heads are compared for their characteristic features and advantages in table 3.1.1. The three major bondhead table systems are spindle drive, pantograph drive and flying bondhead. This table presents characteristic features of each of these systems and we see here for example, the friction of the bondhead table is large for spindle drive, medium for pantograph drive, and no friction at all for flying bondhead because the flying bondhead operates on air cushion.

Table 3.1.1 Comparison of characteristic features of three types of bond heads [E-2]

Concepts	Spindle Drive	Pantograph Drive	Flying Bondhead
Kinematics	Linear Coupled Spindle Motion	Rotational, Coupled Motion	Linear, Not coupled
Dynamics: -Mass -Friction -Preload	Large Large On spindle	Medium Medium On drive	Small No friction On air cushion
Drive	Coupled with Spindle Motion	Direct	Direct
Position Measurement	Indirect	Indirect	Direct
Control Algorithm	Complex Modeling	Complex Modeling	Linear (LOG)

A direct drive, linear bond head , yet another technology used in wirebond equipment allows precise motion control throughout the wire bonding process. This design ensures that there is minimal error between the motor and the tip of the bonding tool. Accurate control coupled with low mass of the bond head, results in lower die impact forces and looping control.

3.1.2 Ball Control

As the number of leads per device has increased, bondpad sizes have decreased to allow more pads per device. Over the past five years, pad sizes have decreased from 4 mils to less than 2.5 mils. Bonding on these smaller pads requires consistent formation of smaller balls and precise control of the bonding process.

If the free air ball size is not controlled precisely then the ball deformation will be non uniform.. This will result in off centred bond and inconsistency in bond placement. An example of perfect and imperfect ball shape is shown in the figure 3.1.10. Smaller ball sizes require greater

control over the negative EFO (Electronic Flame-Off). EFO developments have enabled production equipment with precise parameter control to form free air balls that are less than 2 wire diameters across (using 1 mil wire).

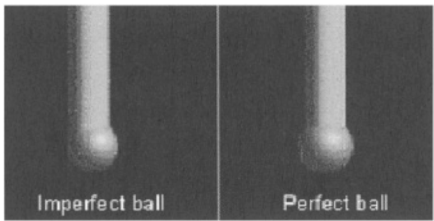


Figure : 3.1.10 Precision of ball control

The precision of the ball shape and size depends significantly on type of EFO as well as on EFO parameters such as current and time and many other factors as shown in figure 3.1.11

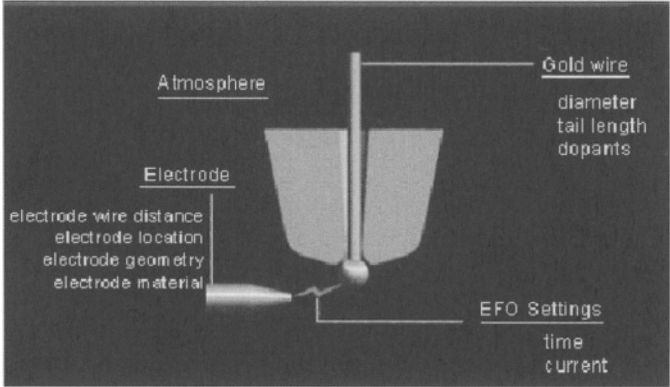


Figure 3.1.11 Ball formation influencing factors

3.1.2.1 EFO Technology

Negative EFO torches are most widely used in today's wire bond equipment. Used with ball bonders, the EFO torch acts as the cathode of a

negative EFO system. Discharges ranging from 1500 to 6000 volts are used with precise time control to form the required free air ball size. Today's equipments must incorporate closed loop current feedback , voltage feedback, and automatic time control system to provide precise and consistent ball size control as well as minimize carbon build up as shown in figure 3.1.12

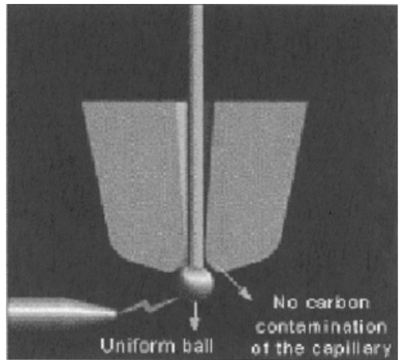


Figure 3.1.12 Negative EFO

Smaller discharge voltage and longer EFO time can result in carbon build up at the tip of the capillary. This carbon build up on the tool increases the deterioration rate of the EFO torch which in turn leads to inconsistent ball formation. However it is possible to control carbon build up on the torch by automatic time control. Some of the wire bonding companies uses proprietary materials to prolong EFO torch life.

The other benefits of a negative EFO unit are:

- reduction of cratering
- better grain formation and
- longer capillary life

3.1.2.2 Bond Force Control

Coupled with the bond head motion is the bond force control. With thinner packages, smaller pad size and therefore, smaller initial ball size, the impact and force control take an increased importance in the wire bonding process.

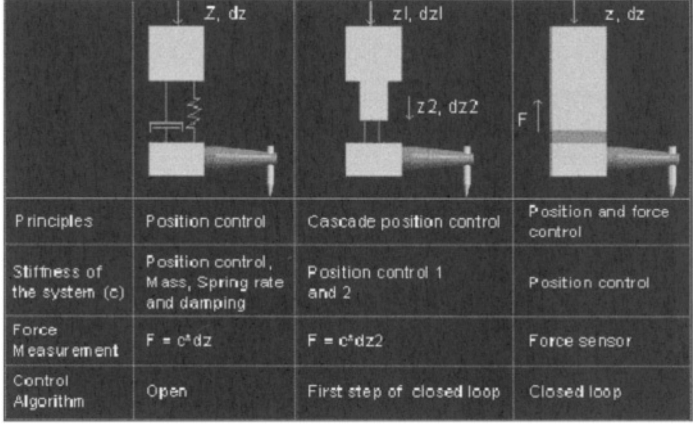
The conventional concept for bond force control was a spring/damper system where the bond force was linearly dependent on the spring ratio and the over travel distance of the bond head. The function of the damping is to reduce capillary motion when the bond head is not in contact with the surface. The weakness of this concept is that damping and spring coefficients are very dependent on external conditions such as operator influence, temperature during calibration, production and wear of the

damping element. After calibration, the system is not in a closed control loop and can drift away from the initial settings.

The spring/damper system has been replaced with a cascade system by using where the height of the capillary is controlled with two separate drives. The first drive is responsible for the large height movements of the whole bond head while, the second drive controls the tip of the bond head which includes sonotrode and capillary. The dependency on external conditions has been reduced as the critical elements (spring and damping) are not used any more.

3.1.2.3 Position and Force Measurement

Force control during bonding is a very critical issue. There are three major systems of force control that are based on three different principles, namely, position control, cascade position control, and position and force control as shown in figure 3.1.13. In the position control system, one uses a spring damper system. In position and force control system, one uses a position control system as well as a force sensor with a closed loop control algorithm. This facilitates online real time force control.



	Z, dz	zl, dzl / z2, dz2	z, dz / F
Principles	Position control	Cascade position control	Position and force control
Stiffness of the system (c)	Position control, Mass, Spring rate and damping	Position control 1 and 2	Position control
Force Measurement	F = c*dz	F = c*dz2	Force sensor
Control Algorithm	Open	First step of closed loop	Closed loop

Figure 3.1.13 Three major systems of bond force control [E-2]

The best possible results for a controlled force transmission are achieved when using force measurement. When the capillary touches the surface, the control loop is switched from position control to force control. The force control loop is capable of reacting on every change in the bond area, such as chip height deviations or deformation of the ball. Closed loop bond force measurement along with position control leads to a controlled and reproducible force transmission.

3.1.3 Looping Control

High density packages require looping to be consistent in height and straightness to avoid interference with adjacent wires, and to minimize the effects of wire sweep during encapsulation. Increased lead counts also increase demand for longer loop lengths without sagging or S shaped wires. Additionally, as packages become increasingly thinner, lower loops are required. As we can see in figure 3.1.14, in case of devices with double row bondpads, wire looping and loop height need to be controlled precisely, otherwise, the curved wire may short and create reliability problems.

With precision control of wire looping and with selection of proper equipment and bond wire material, it is possible to avoid curved wires and thus avoid shorting as can be seen in figure 3.1.15

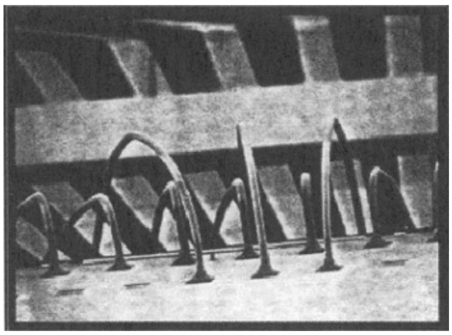


Figure 3.1.14 Curved wires on chip with double row bondpads

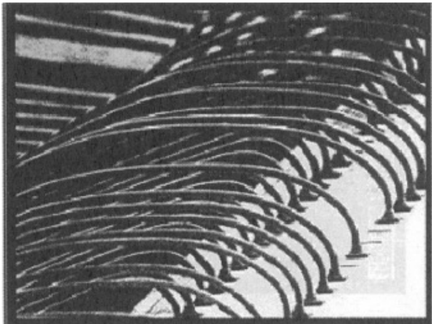


Figure 3.1.15 No curved wires

High density packages require looping to be consistent in height and straightness to avoid interference with adjacent wires, and to minimize the effects of wire sweep during encapsulation. Increased lead counts also increase demand for longer loop lengths without sagging or S shaped wires. Additionally, as packages become increasingly thinner, lower loops are required. With increasing trend towards thin packaging technologies loop height requirements of less than 4 mils high are becoming more common.

As we can see in figure 3.1.16 to obtain a particular loop profile two major parameters need to be optimized. One is Kink height, and the other, the reverse loop distance.

When we consider a standard loop profile, the two variables, kink height and loop factor, both have a significant affect. As we can see in figure 3.1.17 when the kink height changes from 20 to 60 the loop height changes significantly indicating that kink height has a course tuning effect. Where as, when the loop factor changes from 325 to 375 we observe significant change in loop height for a kink height value of 20 but negligible change in loop height for a kink height value of 60.Loop factor seems to have a fine tuning effect on loop profile.

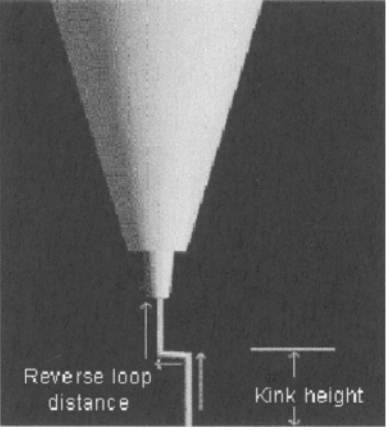


Figure 3.1.16 Kink height and reverse loop parameters
[Courtesy : Kulicke & Soffa]

Meeting the looping requirements of high lead count and fine pitch devices, therefore, has forced equipment companies to develop software algorithms to ensure stringent control over capillary motion during looping trajectories. Most of the bonders today allow the process engineer to make selections from a library of looping motions.

This offers additional flexibility and control over looping depending on the needs of the particular device being bonded. Some of the latest ball bonders allow looping options such as BGA loop, CSP loop, CSP long loop, Spider loop, RF loop, J wire loop, and the standard loop. Along with this looping option the bonders have looping capability with maximum wire length of 7.5 mm and a loop height of 100 microns. In addition the wire sway during bonding is less than 1 wire diameter for a wire length of approximately 3mm.

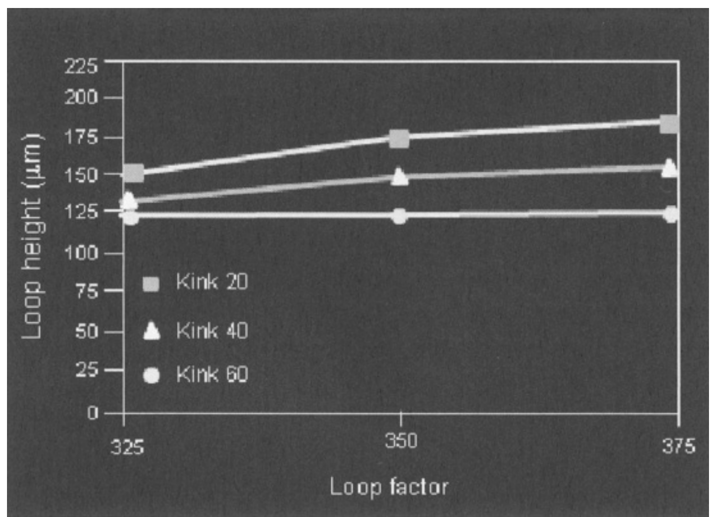


Figure 3.1.17 Effect of kink height and loop factor on loop heights [E-4]

3.1.3.1 Wire Clamp

The wire clamping mechanism provides precise control and helps in determining the wire trajectory during bonding. The gap between the wire

and the clamp, as well as the force the clamp exerts on the wire have an impact on the wire loop trajectory, as is shown in figure 3.1.18.

3.1.3.2 Open Loop

Most of the conventional wire clamps use a spring as force generator and a solenoid or voice coil drive to open the clamp. To achieve reasonable open and closing times and defined force on the wire, the clamp system is manually adjusted with a set of calibration screws to define the spring preload and the limit stops. The disadvantages of this concept are the operator dependent calibration of the spring force and the long-term drift of the spring behaviour.

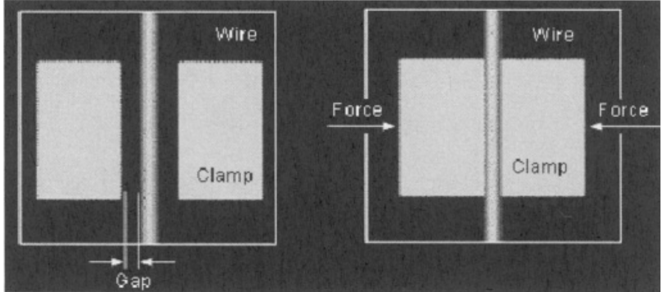


Figure 3.1.18 Controlling clamp gap and clamp force

3.1.3.3 Closed Loop

To overcome the inconsistency and drift problems of the open loop clamp technology, modern wire bonders use a closed loop control system. This system is based on two assumptions: 1. If the size of the clamp gap is known, the wire clamp can be better controlled. 2. If the force on the wire is known the clamp force can be better controlled. If we know both the clamp gap and the clamp force on the wire, then it is possible to program both and thus enabling system calibration to be done automatically.

Faster clamp open and close times enhance productivity and reduces overall wire cycle. Coupled with this, the clamp status information is used in

synchronization with the bond head motion and the EFO. The combination of these technological inputs results in high reproducibility, controlled timing, operator independence and simple maintenance.

3.1.4 Material Handling Systems

Material handling systems (feed systems) are key elements of an automated manufacturing line, especially, when unit volumes are high. But these handling systems must be designed such that: the design is flexible, does not need excessive maintenance and causes minimum down time.

The task is to design a programmable feed system to accommodate as wide a variation in package types as possible while, at the same time, keeping the mechanism simple.

3.1.4.1 Quick Change Material Handling Systems

Material handling systems in previous generation bonders had long conversion times due to the large number of parts being changed and the associated set-up times. Today, high pin count devices are assembled in small lot sizes. This demands reduced setup time when converting the bonder from one device type to another. This is to assure the overall machine utilization and reduce factory floor downtime.

The material handling systems are designed with a modular approach to speed up conversion times. With the current generation of modular material handling systems, only the heater block and clamping mechanism of the work holder is typically replaced as a single module which is designed and calibrated for a particular device type. The conversion of the work holder takes less than 10 minutes.

3.1.4.2 Flexibility through Work Holder Modularity

The new bonding machines have the flexibility and adaptability to support work holder options for different package types. The flexibility is achieved through work holder modularity. For example, today in many wire bonders, the leadframe work holder is capable of accommodating packages such as SOIC, QFP, BGA, TQFP, TSSOP, LOC, TSOP, PQFP and POWER QUAD.

The other types of handling systems are flat boat, tape BGA and J boat work holders. Usually boat work holders are used for packages such as: CERQUAD, PGA, CERAMIC – BGA and MCM.

Manual pedestal work holders are available for all bonders and these are configurable for all devices. Different varieties of work holders that can be used in large areas automatic wedge bonders are shown in figure 3.1.19. These are particularly useful in chip-on-board and multi-chip-module applications.

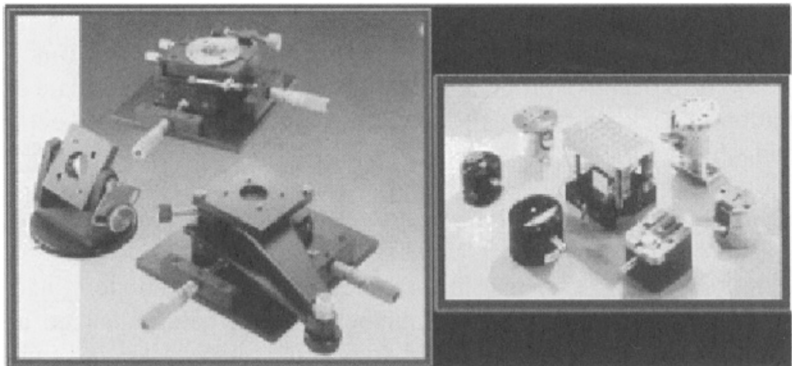


Figure 3.1.19 Examples of manual pedestal work holders [Adopted from product catalog: Dage Corporation]

3.1.5 Recipe Transfer or Portability of Programs

Manufacturing tolerances among machine components as well as day to day wear of machine parts can cause each machine to perform slightly differently. All machines on the production floor must be producing bonded product that is identical and consistent.

Another critical requirement for quick conversion between high lead count device types is the ability to transfer large bond programs from one bonder to another bonder. This requires "true bond program portability". True bond program portability occurs when a set of bond parameters programmed on one machine can be downloaded into other machines on the factory floor and

bonding can continue without the operator having to perform any fine adjustments.

As devices become more complex, the importance of consistencies among all bonders on the factory floor becomes crucial. In fine pitch ball bonding, consistent production of small free air ball is an absolute necessity. The EFO setup parameter on the machine must be consistent, so that, the effective free air ball diameter is actually equal to input free air ball diameter. In figure 3.1.20 we see that the variation in FAB diameter is + or – 3 microns on five different machines for different input FAB diameters.

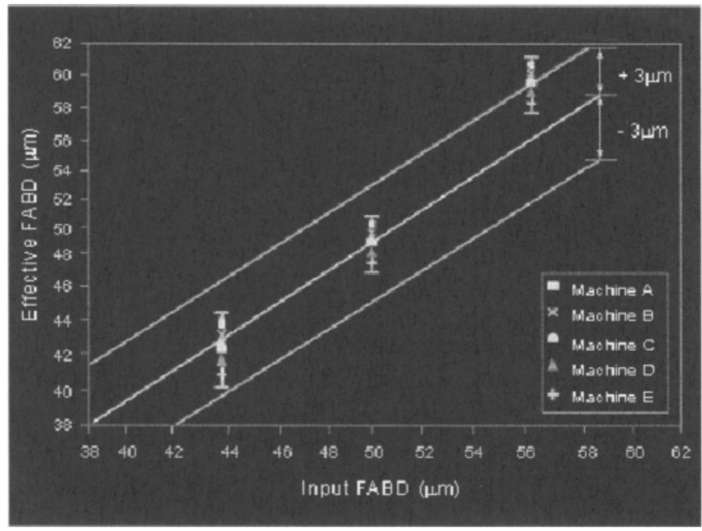


Figure 3.1.20 Portability of EFO functions on five different machines [E-1] **[VIEW-IN-CDROM]**

3.1.6 Yield

Wire bonding yield is of critical importance on high lead count devices. Per wire bonding yield must be significantly higher to achieve acceptable package yield. Yields above 99.99 percent are the standard for many

advanced automatic wire bonders. Some of the features contributing to high yields are:

- a wire bond monitoring system, which can detect missing or broken wires
- sub-pixelling, a software enhancement to the PRS which reduces pixels (picture elements) into sub-segments for more accurate bond placement

3.1.6.1 Calculation of Yield

The device yield can be calculated based on the lead count of the package and the per wire yield. Suppose the yield rate of a wire bonder is in the range of 99.7%. For a 100-lead device, this means statistically, one wire out of every four devices will be bad, so that package will have to be reworked. With the high average selling price of many devices even scoring in the 99th percentile may not be enough. For more detail on device yield calculation as a function of wire bond process yield, please see the software demo of device yield calculation, in the accompanying CD **[VIEW-IN-CDROM].**

3.1.7 Bond Throughput

Higher the speed of bonder operation, higher is the throughput per hour. The throughput of a bonder is dependent on few factors such as: bonding time (wire cycle time), pattern recognition time, indexing time, machine up time, and lead count of the package. Please see the software demo for UPH of a bonder **[VIEW-IN-CDROM]**

From analysing the above equation, we can see that the wire bond equipment developer must pay attention to increasing the speed of bonding, speed of PRS, and speed of indexing. With increased integration of the IC, the number of bondpads on a chip increase, and therefore, the bonding speed must increase in order for wire bonding to be an economical interconnection technology.

Here, in figure 3.1.21, we see the trend of bonding speed for a two millimetre wire. In 1990, the bonding speed was 160 milli seconds per wire which reached 75 milliseconds per wire by year 2000. The bonding speed trend is toward 50 milliseconds (greater than 20 bonds per second) by 2005.

The total bonding time (wire cycle time) depends on loop length, loop height, first bond time and second bond time. The latest bonders today claim the wire cycle time of 50 milliseconds based on 2.5 mm loop length 250 micron loop height 8 millisecond first bond time and 9 milliseconds second bond time.

To achieve high machine throughput, the equipment manufacturer must guarantee maximum machine up time. This makes it imperative that the machines must have high values of MTBA (Mean Time Between Assist) and MTBF (Mean Time Between Failure) and low values of MTTA (Mean Time To Assist) and MTTR (Mean Time To Repair).

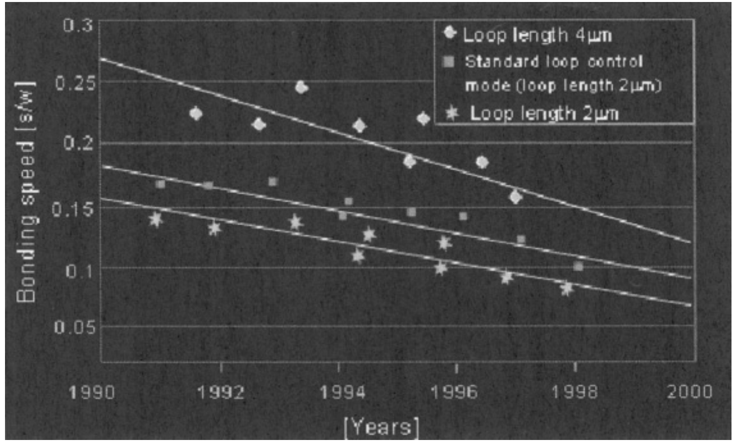


Figure 3.1.21 Trend of bonding speed **[Courtesy: Kulicke & Soffa]**

3.1.7.1 Advantages of Bonding Equipment Automation

One method to improve quality of the bonding process is through the replacement of manual and semi automated wire bonders with high throughput systems. One "operator" monitoring bank of four automated systems can produce more bonds over an eight-hour shift than nearly eight operators hunched over eight manual bonding systems. Quality of the bonds are much better with the automated equipment, since the operator is rarely called upon to make any decisions that will affect the quality of the

throughput other than closing down the line because something major has gone away.

Today's fragile fine pitch assembly processes rely on consistency. It is difficult to reproduce a process identically using human intervention. Human handling of products reduces yields. To enable higher yields and greater consistency, factories are turning to automation and communication packages to reduce or eliminate the human factor.

An operator is no longer required to target each bond or to determine individual loop heights. The little reverse looping motions that humans formerly used in manual wire bonding for controlling loop configuration and height are now programmed into the automatic bonders. With automation, the wire bonders have increased productivity dramatically. The bond quality and consistency have also scored major gains, chiefly through the elimination of the operator's involvement in the wire bonding cycle. However, the human factor cannot be totally eliminated, because the high speed automatic bonder cannot monitor itself beyond recognizing when a wire has broken. Human factors obviously play a large part in controlling the quality of wire bonds.

Because materials vary greatly, problems still occur during the bonding cycle. These problems are close to being overcome by wire bonding equipment vendors, but for now, human involvement is still necessary. Operators take the place of electronic monitors and stop the machines when they see a problem happening, thus preventing the machines from producing a large number of bad parts.

3.1.8 Transducer Technology

Today's assembly process engineer has to deal with a number of wire bonding equipments that are incorporated on the assembly floor. The use of so many different types of bonding equipment can exacerbate any engineer particularly, when dealing with a multiplicity of products that involve so many different bonding parameters. Regardless of how complex the bonding machine is, the process parameters are all common; i.e. bonding force, impact velocity, temperature, time and ultrasonic energy. Very good control and characterization can be achieved with most of these parameters

except the ultrasonic energy. To really understand the impact of ultrasonic energy on the bonding process we must understand the issues surrounding the Ultrasonic energy. The ultrasonic energy is the result of electrical energy being converted into mechanical motion by a Piezo-ceramic transducer. This transducer is fabricated from various elements designed to transfer Ultrasonic energy to the bond interface with maximum efficiency. If the transducer design or manufacturing is not optimum, this will impact the performance of the transducer during the wire bonding operation.

To analyze the performance of a transducer, we need to examine two specific types of variables: variables intrinsic to the transducer and variables extrinsic to the transducer.

3.1.8.1 Intrinsic Variables

Intrinsic variables are those defined by the properties and behaviour of the materials used in the transducer fabrication process. The transducer is made of a stack of crystals of Piezo-ceramic material, such as Lead Titanate, Lead Zirconate, Barium Titanate or any other blend. Low impedance (10 to 30 ohms at 0.2 watts) transducers are made of stacks of these ceramic crystals. Research has shown that low impedance transducers produce the highest quality bonds in the shortest time. The value of the impedance directly relates to the scrubbing force divided by scrubbing motion. These transducers combine high motional tip velocities with low vibrational force.

Because of its chemical composition, the transducer becomes sensitive to temperature variations which can result in changes in transducer performance.

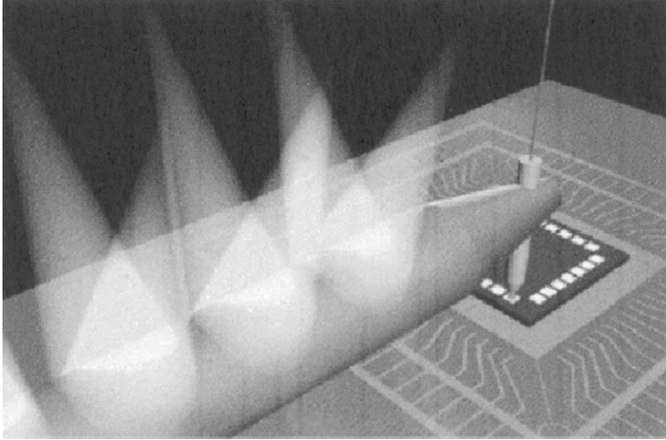


Figure 3.1.22 Property changes of the transducer **[VIEW-IN-CDROM]**

As can be seen in Figure 3.1.22, even lighting system in a bonder can change the temperature of the transducer by few degrees centigrade which will affect the resonance characteristics of the transducer. This in turn will affect the stability of ultrasonic coupling and energy transfer on to the bonding interface. Therefore, in designing bonding equipment, one must accommodate for constant low temperature of the transducer.

Similarly, the materials used in the fabrication of the transducer body, (Stainless Steel, Aluminum, Titanium, etc.) each have unique mechanical and materials properties that need accurate modelling to achieve efficient coupling and energy transfer as well as a lasting performance. Temperature variation, machine stresses and end user environment must be considered in the selection of the material.

3.1.8.2 Extrinsic Variables

Extrinsic variables are those that are induced by the control system, the manufacturer or the end user. These can either be originated during the fabrication of the transducer or during set up by the end user or the type of Ultrasonic generator. The manufacturing's of transducers demand special attention to details and strict quality control procedures that are key to

achieving repeatability, maximum performance and higher yields. Some of the issues of critical importance are:

- transducer design that guarantees minimum energy losses, when assembled into the machine
- transducer design that guarantees maximum energy transfer to the interface of the weld
- transducer that is repeatable in terms of dimensions and weight

Modern automatic bonding equipment demands higher repeatability of the location of the centre of gravity and the centre of mass of the transducer in order to achieve the level of precision and control required by the Z axis mechanism (bond head).

In addition to the transducer design, the other parameters that contribute for optimum ultrasonic coupling between the bonding tool and transducer are, the torque on the tool, and the length of the bonding tool below the transducer as shown in figure 3.1.23. The variation of bonding tool dimensions (length) must be considered in the initial design to insure best coupling between the bonding tool and the transducer.

The set up of the transducer in the bonding machine has to consider the effect of torque on the bonding tool, the length of the bonding tool below the transducer, the torque required to mount the transducer to the bonding head assembly and the operating temperature of the process chosen.

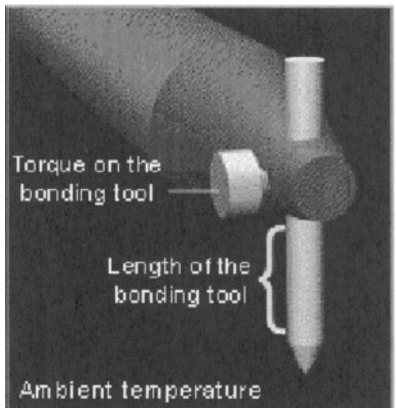


Figure 3.1.23 Effect of bonding tool length and torque on tool resonance

As we can see in figure 3.1.24 the transducer impedance is significantly affected by two parameters namely temperature and the torque applied to the bonding tool. As the torque increases, the impedance decreases whereas, the

temperature increases, the impedance increases. So, it is important to establish adequate procedures to characterize the level of variability induced by a given brand of transducer, its intrinsic variables and the extrinsic set up parameters.

The transducer, because of its electrical performance, can be considered a capacitive, inductive and resistive circuit that is very sensitive to changes which affect the current and the voltage applied to it. This circuit is considered optimum, when the current and the voltage applied at the determined frequency are in phase and in resonance with the reactive reactance or impedance. The current and voltage are applied with an ultrasonic generator.

3.1.8.3 The Ultrasonic Generator

The ultrasonic generator is used to produce Ultra sonic energy that gets transmitted through the transducer on to the bonding tool and consequently to the ball – bondpad interface. The Ultrasonic generator is composed of a power supply that drives a transducer which is coupled to the welding tool by an impedance-matching mechanical system known as the "horn" (Acoustic resonator). The complete mechanical system exhibits a sharp vibration resonance which is preferentially excited by the driving system.

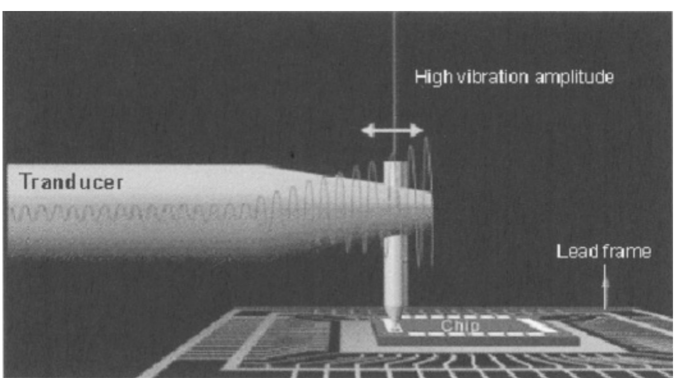


Figure 3.1.24 Transmittance of ultrasonic vibration to capillary

The choice of operating frequency for ultrasonic bonding of metals is largely governed by the thickness of the material to be welded by the machine. Usually lower frequencies (i.e. 10-40 kHz) are used for materials of 0.5mm thick and above. All machines designed for wire bonding applications (wire interconnections to integrated circuits) operate in the region of 60kHz to 140 kHz. Wire bonders are designed to operate at a single frequency only. Most machines incorporate self-correcting systems to alter the electrical excitation frequency to compensate for the changes in the resonant frequency occurring during the welding cycle or resulting from external changes.

3.1.8.4 Ultrasonic Generator Technology

Resonance is defined as that frequency at which the relative phase of the exciting voltage and current are equal and the impedance is minimum. The ultrasonic generator is as important as the transducer because, it must be capable of controlling the intrinsic variables as well as the extrinsic variable and must be capable of maintaining stable resonance over a long period of production operation.

Selecting the generator that will perform desirably is also a very critical task and the two main features to look for are phase lock circuit and operating mode of the generator.

3.1.8.5 Phase Lock Circuit

The purpose of this circuit is to locate and maintain resonance in the transducer with minimum drift between current and voltage. Ideally, zero phase shift is desired, but a shift no greater than 12 degrees is acceptable. The same is true for the stability of the circuit, where phase jitters must be minimized (<0.5 degree). The locking range should be between 2500 and 4000 Hz from the resonant frequency.

3.1.8.6 Operating Mode

The ultrasonic generator can be designed to operate under three different modes; namely, constant current, constant voltage and constant power. constant current, theoretically provides constant motion of the bonding tool

as the load changes causing impedance changes. This is true, when measured in free air but during actual bonding, no satisfactory correlation has yet been demonstrated. Constant voltage is preferred because it allows the use of the current signal as an analytical tool to determine the relative quality of the weld formed. Unfortunately, the data obtained do not represent a real time measurement of the mechanical or chemical weld taking place during bonding. Many ultrasonic generators promise some kind of signal analysis, but they are not yet capable of providing real time feedback.

Constant power should theoretically and practically be the control technique of choice. When bonding takes place, changes in impedance due to external loads, surface contamination, tool wear, wire hardness, etc. cause changes in resonance which in turn cause variation in the energy output; but if a system is capable of measuring those changes as they occur and then increase or decrease voltage and current to maintain constant power, then the energy output is the same. If the energy is same, then repeatability between bond is possible, no matter how many bonds the package has or whether the energy is used to enhance chemical reactivity or the mechanical interlocking of the metals bonded. If in addition, automatic constant power control is available to measure and correct on demand the various variables induced by the transducer, then parameter portability and repeatability from machine to machine is possible.

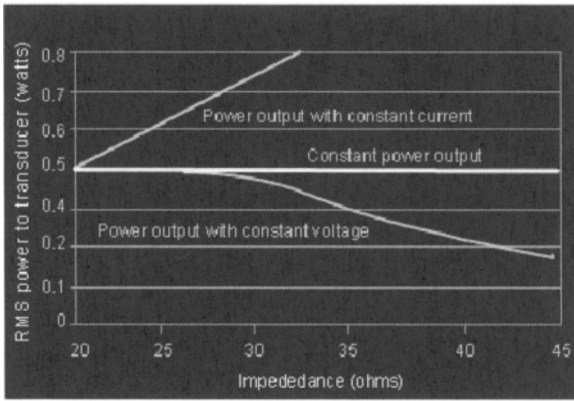


Figure 3.1.25 Impact of impedance on ultrasonic energy output
[Adopted from product catalog: Verity Instruments]

It is shown in figure 3.1.25 that as we increase the impedance, the RMS power to transducer varies. If it is a constant current source, the power output increases, whereas, under constant voltage conditions, the power output decreases with impedance. With use of real time ultrasonic power controller, it is possible to have constant power output to the transducer.

The table 3.1.2 gives examples specifications of ultrasonic generator with constant power controller that is used in the industry. This table describes the specification of an automated ultrasonic power supply. This ultrasonic generator has a frequency range of 20 to 200 kHz, and is usable for bonding both gold and aluminium wire.

Table 3.1.2 Ultrasonic generator specifications **[Adopted from product catalog : Verity Instruments]**

Output power	*3.4 watt into a 25 ohm load*
Auto adjustment increment	1.7 watt into a 50 ohm load
Auto power control	1% of maximum preset power
Accuracy	+/-5% of maximum preset power
Frequency range	*20 to 200 kHz*
Auto cal, Freq. Range	+/-7% of center frequency
PPL lock range	+/-7% of transducer resonant frequency
Maximum phase error	12 degree
Maximum phase jitter	<0.5 degree
Interface	*Parallel opto isolated digital port*
Requirements	3m Amps mimimum switching current
Wire size range	0.5 to 2.0 mil, gold and aluminum
Minumum bond time	1 msec per channel
Power requirements	85 to 265 VAC, 47 to 440 Hz, 20 Watts
Dimensions	71/2 in W.x 3 3/4 in. H x 10 in. deep

3.1.9 *Off Line Programming (OLP)*

When we need to wire bond high I/O devices or high lead count packages such as PQFP, BGA or stacked die packages, programming these packages on the wire bonder is quite difficult. These are fine pitch long loop packages and are technically complex to program the wire layouts. A typical wire

bond lay out programming of a 352 BGA package ranges from 2 hours to a maximum of 6 hours, depending on the expertise level of a wire bond engineer and the level of difficulty of wire bond requirements. Manual programming of high lead count devices not only is time consuming but also leads to wire bond defects. Typical defects obtained from manual processing are wrong wire lay-out, missing wire and excess wire.

Use of Off Line Programming (OLP) not only dramatically reduces programming time, it also reduces number of defects due to manual programming limitations.

3.1.9.1 Comparison of OLP with Manual Programming

A conventional way of manually handling wire bond layout programming provides a lot of 'teach and trial' errors which contributes delay on wire bonding process. Off-line programming which is commonly known as OLP has been developed to make use of CAD capability to determine the exact X and Y position of wire bond points through the use of BMCT (Bond Map CAD Toolkit) software from a file-based bonding diagram. BMCT output program provides a text file which is used to create the binary file using OLP software. This binary file when loaded to a wire bond machine will automatically create the wire bond programming layout file.[E-5]

In many factories, implementation of OLP in high ball count BGAs wire layout programming had led to a significant reduction of wire layout programming time. Results show that OLP will provide zero defect on wire layout programming, since the bond points were generated based on endpoints of the lines of wires in CAD.

Off-line programming is exactly the same as the conventional wire lay-out programming in terms of application. It only differs on the methods of application. In a conventional wire lay-out programming, we use the teach and trial on wire bond machine in defining the actual bond position of each of the bond points whether it is a ball bond or stitch. Whereas on Off-Line Programming, we use CAD - Computer aided design software to provide the exact bond positions of all ball bond and stitch simultaneously. A specially customized interface program which is termed BMCT - Bond Map Tool Kit Software will enable a CAD drawing of any bond diagram to be converted to a text file consisting of X and Y position of all its ball bond and stitch. This

text file is then converted to binary file for automatic generation of wire layouts using OLP compiler.

In off-line programming, the bonding program is developed by a packaging engineer in association with the chip designer for a particular package. The CAD data is then converted to a format that the wire bonder can recognize. The bond program is directly loaded on to the bonder without any intervention by the operator. This technique has been found to save more than 80% of conversion time when a bonder is used for more than one device. A typical OLP flow is shown in figure 3.1.26.

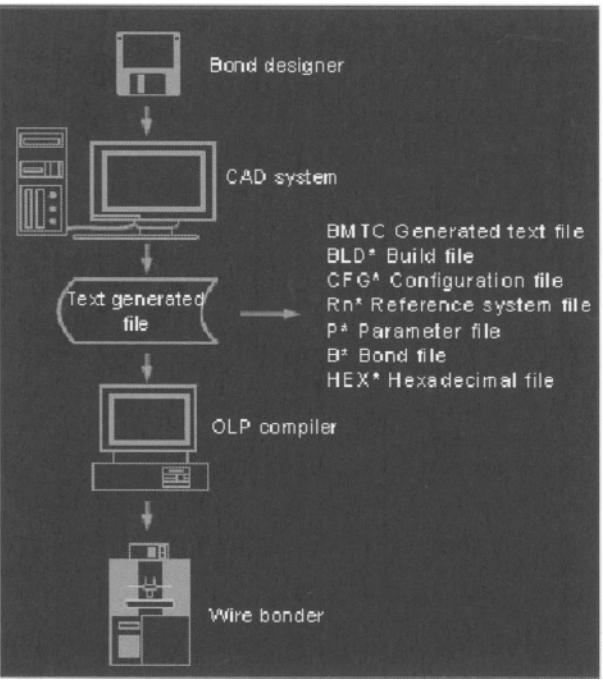


Figure 3.1.26 Schematic of bonding diagram transfer through off-line programming [E-5]

Successful Implementation of OLP depends on CAD file bonding diagram and should be as follows:

- bond diagram drawing must be in the Auto CAD-DXF or DWG format
- all wires must exist in the drawing and be drawn as lines
- wires should be drawn on layers separate from other device components. Different tiers of wires should also be on separate layers.
- the device feature that will be used as the XY zero on the wire bonder must be known and visible on the drawing
- pin #1 should appear in the upper left-hand corner
- bond diagram must be drawn to scale
- drawing must contain latest design revision level. In case of die shrink design, new drawing shall be created reflecting changes in die dimension
- the device feature used for operator and eye points should be known and visible on the drawing

3.2 Equipment Selection and Procurement

Selection and procurement of the right wire bonder demands that purchasing engineer must do the following:

- define the requirements
- perform a market search
- write the procurement spec
- run performance tests
- write the justification
- place the purchase order and
- perform the acceptance test

3.2.1 Defining the Requirements

In order to clearly define the requirements for the bonder to be purchased, requires a thorough understanding of the expectations of the production

engineers, and how the bonder fits into current and future production, process and business plans.

It is recommended that one begins by compiling a list of criteria for review by key personnel who will use and/or be affected by the bonder installation; namely production engineers, maintenance, quality engineer, reliability and purchasing. Procuring as much basic information as possible is critical, focusing on such issues as quality, throughput, productivity, labour reduction, and increased capacity. The final list of the criteria must be circulated so that all stake holders share the same expectations.

This also is a good time to create a project file or binder to hold collected information such as test data, and communications with in-plant personnel and vendors. At the conclusion of the project, the file will serve as a record of the project, allowing others to retrace the steps of any reason.

3.2.2 Performing Market Search

To find qualified vendors, a review of trade/technical journals and conference proceedings, computerized literature searches, and attending trade shows generally are effective approaches. Impressions can then be combined in a brief overview of the market toward an informed narrowing of the field of vendors to three to five candidates capable of meeting the requirements.

3.2.2.1 Evaluating Vendors

Detailed bonder specifications for review must be requested. By talking with technical representatives from each vendor, points not covered in the specifications may be clarified. A user reference list from each vendor is also helpful. Ideally, a minimum of four customers using the model/configuration under investigation should be identified for obtaining unbiased evaluations. So that all the data collected so far may be effectively applied, a “Prioritization Matrix Analysis” (PMA) can now be developed. Each criterion is given a “weighting” based on importance to the project, and each vendor is rated on how well specific criteria are met. Use of PMA is discussed in later chapter 3.3.

3.2.3 Writing the Procurement Spec

The purpose of the Procurement Spec is to protect the buyer from investing in a bonder that fails to perform as claimed. It specifically defines, in writing, expectations of bonder and vendor performance so that "assumptions" are eliminated. The procurement spec should contain the following key elements:

Payment terms: spells out how much will be paid with initial purchase order, how much upon delivery and installation, and what will be held until the bonder is tested, accepted, and released.

Delivery terms : states date of delivery after order, and who is responsible for shipping and damage in transit.

Warranty and service: discloses how long the bonder will be under warranty, response time for service calls, and the penalty if this time exceeded (Does repair include parts and labour?)

Training and documentation: lists what documents will be provided and number of copies of each (operation, maintenance, schematics, etc.), what training will be provided (operation, preventive maintenance, troubleshooting) and at which venue (buyer's or vendor's).

Utility requirements: describes power and other requirements (air, gas, water, etc.) and who is responsible for hook-up.

Performance Criteria: establishes expected throughput, time for job changes, defect levels, downtime, etc.

System evaluation: describes testing and data collection to be performed during the acceptance period, testing duration, and next steps if the bonder fails the evaluation.

Other: resolves design changes occurring after the order is placed, compatibility with existing bonder, compatibility with factory management system and user friendliness.

As the vendor list is narrowed, procurement terms should already be discussed with the vendors under consideration. Acceptance of the buyer's terms (and vice versa) may be an important consideration during the evaluation process.

3.2.4 *Running Performance Tests*

By now, the vendor list should show one or two top candidates. A performance test and/or a plant visit to see the bonder in production is required. For a custom-designed bonder, it is generally helpful to watch a similar bonder, designed and built by the same vendor, operating in a production setting. However, for an "off-the-shelf" bonder, it may be of greater benefit to run various controlled performance tests. During such tests, it is important that the parameters are clearly defined:

- how will the test (s) be run?
- how will the data be collected and analyzed?
- what materials, parts, measuring devices, and especially, what trained personnel will be needed?

Ideally, these tests should duplicate those outlined in the procurement spec. The goal is to concentrate the testing on critical elements of the bonder to be purchased. Additionally, the vendor should demonstrate set-up procedures, job changing, preventive maintenance, etc. During a plant visit, it is important to meet with key engineers and technicians to discuss bonder installation, operation, and maintenance.

- does it operate as advertised?
- are the operators constantly adjusting the bonder to keep it on-line?
- how does it look (check oil dripping from seals, worn/loose parts, etc.)?
- if evident, are such problems due to bonder design or lack of preventive maintenance?
- how difficult is bonder set-up?
- is the proper documentation provided for operation, maintenance, and troubleshooting?
- is the bonder "user friendly"?

3.2.5 *Writing the Justification to Purchase the Bonder*

Justification of Purchase is a means of organizing and summarizing the collected information into a concise package. All that remains is to

summarize the important points for presentation to management. Its key points should emphasize primary benefits; reduced labour, increased capacity, improved quality etc. The following questions should be addressed:

- why have a particular vendor and model been selected?
- does the bonder meet the criteria?
- what benefits can be expected?
- when will payback occur?

The justification also must consider all related costs such as shipping charges installation, spare parts inventory, added support staff, etc. Once approved, the justification should be kept in the project binder as a permanent record of all factors considered in the decision to purchase.

3.2.6 How to Write an Equipment Requirement Specification?

Here we give an example of how to write and what to include in a Wire bonder requirement specification for high pin count fine pitch applications.

The purpose of this specification is to define the necessary performances which are necessary for wire bonder to be capable to meet all the quality, reliability and the productivity requirements in order to wire bond any fine pitch high pin count packages on production lines. A wire bonder must provide all the following performances plus what is mentioned in 3rd optical specifications.

Here is an example of the requirements list of a wire bonder

- multichip function with possibility of going from one chip to another in an easy way. The parameter of each system must be used also in manual mode
- double row pad bonding. Maximum loop variation from one row to another must be one wire diameter
- finger finder with possibility of identifying the not found leads and possibility of correction from the lead sides and the lead tip
- separate ball and lead positioning
- wire group possibility

- menu lock and password option at different levels with possibility of entering the spec range values
- automatic or high magnification monitor for bond positioning
- variable polarity, safe voltage non stick detector for ball and weld
- possibility of monitoring the bond force and bond power during the actual bonding time
- wire length capability from 0.5 to 7 mm
- loop height capability from 100 to 400 µm. This range must be guaranteed up to 5 mm. For each wire, the vertical part of the loop must be at least half the total height
- possibility of using from 15 to 50 µm wire diameter
- bond force capability from 0 to 300 grams programmable for each wire. No bond force variation is allowed during bonding
- bond time from 1 to 100 ms programmable for each wire
- possibility of using the frame thickness of 100 to 300 µm
- possibility of using the frame length of 120 to 300 mm
- possibility of using the frame width of 12 to 100 mm
- short change over time for new frame and new product. (10 minutes max.)
- decomposed bond sequence movements (with pause) for process understanding
- trouble shooting
- grey level PRS with mini range of 0.2 mm in X-Y direction and ± 2 degrees in rotation
- with programmable search range and PRS delay
- maximum PRS accuracy of 1 µm
- overall machine precision of 2 µm
- productivity of minimum 125 devices/hour for BGA - 208 leads with maximum wire length of 5 mm
- maximum down time 2% for all device type
- MTBF = 200 hours minimum
- MTBA = 200 minutes minimum
- minimum yield 99.9% for 208 leads reference device.
- inspection possibility on the machine of the bonded devices without stopping the machine

- built in options for SPC measurements with high accuracy. (Ex: loop height, wire deflection, ball size etc.)
- ball size variation of maximum ± µm. This variation will be measured on the bonded balls
- frame indexing precision of ± 10 µm max
- pull test, minimum 5 gram for any wire at any loop height or wire length
- ball shear, minimum 35 grams for any ball size. No cratering is allowed
- ball size- From 1.5 to 3.5 times the wire diameter. This measurement will be done on the bonded balls
- ball centring - 100% of the ball must be located on the pad
- weld size - From 2 to 4 times the wire diameter in width and length
- weld centring - 100% of the weld must be located on the lead
- wire deflection -Maximum ± 50 µm for any types of wire, wire length, or loop height
- a friendly use debugging system
- fast service (spare parts, assistance and updating)
- other requirements as needed for your application

3.2.6.1 Build the Bonder

For off-the-shelf bonder, this phase is generally a waiting period. However, custom bonder requires working closely with the vendor, especially if the buyer is concurrently designing the part or product the bonder will produce.

3.2.6.2 Installing the Bonder

As the installation date approaches, the maintenance department (or contractors) must prepare the workplace for the new addition. This may include marking off bonder(s) location and installing additional necessary bonder, e.g., transformers, pumps, compressors, storage tanks. Other preinstllation requirements may include air, gas, and electrical supply lines, and procurement of special bonder or tools. The installation date and its preparations should be closely co-ordinated with the schedule agreed to with the vendor to keep the project on line.

3.2.6.3 Performing the Acceptance Test

During the acceptance period, the bonder must be proven capable of meeting the expectations defined in the Procurement Spec. Typically two to eight weeks, the period provides a transition time in which the bonder is available to production but is under engineering's control.

3.2.6.4 Releasing the Bonder to Production

The bonder may be released when the following conditions are met:

- all supplemental documentation is written and approved
- a lead operator(s) is trained and certified
- a lead maintenance technician (s) is trained
- any ongoing data tracking (SPC, down-time etc.) is in place

Finally, a release report documenting the results of the acceptance period should be published. It should include summaries of data from tests, downtime tracking, etc. A copy, which serves as closure for the project, is placed in the project binder with the other documentation. Once the bonder is released, the final payment can be made.

3.2.7 Prioritization Matrix Analysis for Equipment Selection.

Wirebond equipment from different vendors have different features and what is useful for your particular manufacturing facility depends on the product portfolio, volume of product, location of plant, level of operators, capability of maintenance personnel, cost of bonder and a host of other critical criteria. For example:

- for production personnel, high machine UPH is important
- for maintenance personnel, low MTBF and MTBA is important
- for quality personnel, consistency and accuracy of bond parameters is important
- for purchasing, cost of bonder is important

In other words, some one has to decide what is important to the organization at that time and then apply PRIORITY consideration to the OPTION under discussion.

Prioritization matrices are designed to rationally narrow down the focus of any team before detailed implementation planning can happen. The Prioritization matrices should be used when the criteria for a wire bonding equipment are agreed upon by all stake holders, but there is disagreement over the relative importance of these criteria. The reader is referred to other books for detailed discussion of PMA methodology [E-6].

Full analytical criteria method is used for Ranking/ prioritizing the criteria for selection of a wire bond equipment. Once the key bonder criteria have been identified, the options (the type of bonder and supplier) need to be narrowed down. There are three basic phases in the PMA process:

1. Prioritize and assign weights to the list of criteria for bonder selection.
2. Prioritize the list of options (bonders from different suppliers)
3. Prioritize and select the best options across all criteria

3.2.8 How to use the Prioritization matrix Analysis

Make a list of all CRITERIA. Compare the importance of each criterion to every other criterion using the following scale :

- equally important
- significantly more important
- extremely more important
- significantly less important
- extremely less important

After relative importance of each of the criteria has been established (PRIORITIZED), each option (Bonders from different suppliers) must be judged based on how completely it meets each of the chosen criteria. Compare all of the bonder options being considered to the criteria being applied. The scale of comparison is as follows:

For a particular criteria, bonder 1 is :

- equally preferred to bonder 2
- significantly more preferred to bonder 2
- extremely more preferred to bonder 2
- significantly less preferred to bonder 2
- extremely less preferred to bonder 2

The prioritization matrix analysis software will rank the bonders and present the final ranking in a graphical format. The reader is directed to try the PMA demo in the accompanying CD, **[VIEW-IN-CDROM]** in order to understand usefulness of this methodology in selecting and procuring the appropriate bonder for an application.

3.3 Cost of Ownership

Cost-of-ownership analysis technique was developed in the semiconductor industry and today the technique has become an important tool for industry managers. CoO assists management in the intelligent selection and purchasing of semiconductor equipment and materials.

Modern cost-of-ownership modelling in the semiconductor industry traces its origin to Intel Corp., where, in the mid-1980s, an intense examination began of the total cost of acquiring, maintaining, and operating purchased equipment. Intel's objective was explicit; develop a purchasing methodology that establishes a sound, quantitative, business-like basis for equipment acquisition.

3.3.1 Cost Efficient Wire Bonding Equipment Selection Criteria

In real life, we always face a question "what is the correct methodology to buy a wire bonding equipment?" and "how to buy a wire bonder that gives value for money?". In the early 1970's the bonding equipment selection was done based on performance and price. In the 1980's the equipment, selection was based on performance, price and support from the supplier, and in the 1990's the equipment, selection was based on performance, price, support and cost of ownership. Today the CoO has the largest contribution in selecting a wire bonding equipment, more than the performance and price.

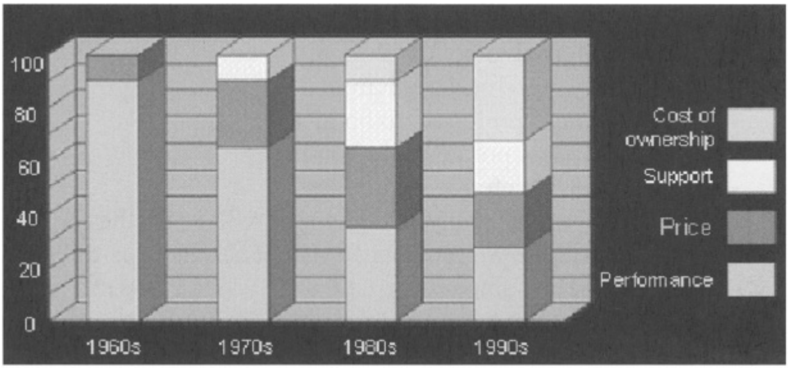


Figure 3.3.1 Cost efficient bonding equipment selection criteria trends [E-7]

The three key performance metrics used to purchase cost effective bonding equipment are: Overall Equipment Effectiveness (OEE), Life Cycle Cost (LCC), and Cost of Ownership (CoO). Out of the three performance metrics, though LCC is one of the most widely used high level metrics, it has the following shortcomings. It does not include:

- effect of the production volume
- product scrap loss due to poor quality output
- consumable cost
- waste disposal cost
- taxes, insurance and interest expense

To overcome the above, SEMATECH has developed a Cost of Ownership (CoO) model which includes the true cost of ownership per good unit produced in a given time period, usually a calendar year.

3.3.2 What is Cost of Ownership?

The CoO depends upon the production throughput rate, equipment acquisition cost, equipment reliability, throughput yield and equipment utilization.

A CoO metric can be expressed quantitatively as the time-period-cost associated with an equipment divided by number of product units manufactured by that equipment in that time-period, i.e.,

$$CoO = \frac{[Fc + Oc + Ylc]}{[T \times P \times Yt \times U]}$$

Where:

Fc Fixed costs
Oc Operating costs
YIc Yield loss costs
T Throughput rate
P Time period
Yt Throughput yield and
U Utilization

Fixed costs: The fixed costs are typically determined from a variety of items such as purchase price, taxes and duties, transportation costs, installation cost, start-up cost and training cost. The allocation to the time period under consideration is a function of allowable depreciation schedule and length of the time period.

Operating costs: The operating costs for a piece of equipment are consumable and material, maintenance, parts, waste disposal and operators.

Yield loss costs: The yield loss costs are those associated with lost production units that are directly attributable to equipment performance.

Throughput rate: Through put rate is the production rate of the equipment, usually expressed in parts per hour.

Throughput yield: Throughput yield is the fraction of good units produced. It is determined by (Total units produced - Defective units produced) / Total units produced.

Utilization: Utilization is the fraction of the total time that a tool is available for production. It is given by:

$$U = \frac{(TT - USMT - SMT - SBT - ET)}{TT}$$

Where :
TT : total time
USMT : unscheduled maintenance time
SMT : scheduled maintenance time
SBT : standby time
ET : engineering time (Including requalification)

3.3.3 Parameters of CoO Calculation

The cost of ownership analysis can be applied to wire bonding operation. The three factors that affect cost of ownership are, fixed costs, variable costs, and yield costs, as shown in figure 3.3.2 and each of them in turn is dependent on wirebond operation, equipment performance, material specification, and capacity of the factory.

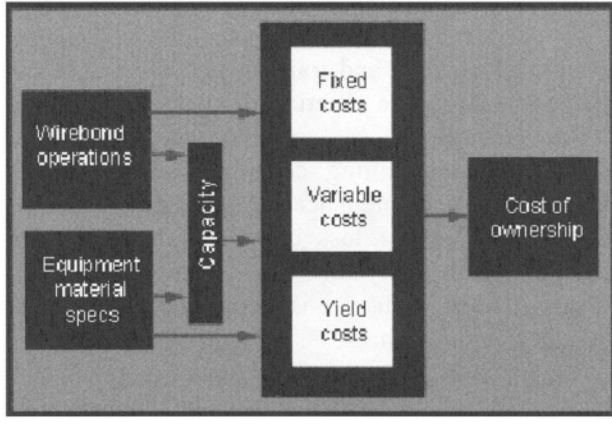


Figure 3.3.2 Cost of Ownership **[Courtesy: Solid State Technology]**

For cost efficient wire bonding, we need to reduce total operating cost and total yield cost over life time. The factors that influence total operating cost include:

- number of shifts per day
- number of operators per shift

- labour rates of operators
- cost of operators
- number of technicians per shift
- labour rates of technicians.
- cost of technicians
- maintenance (excluding. personnel)
- consumables

The factors that influence yield cost over life time include:

- quantity produced over life time
- handling related yield (%)
- tool related yield (%)
- overall yield
- sellable product over life time
- lost product over life time
- cost per position (chip, lead frame)

When we need to perform Cost of Ownership comparison between two wire bonding equipments, we need to consider the following factors:

- work hours per week
- scheduled maintenance
- unscheduled maintenance
- total conversion time
- total assist time
- total stand by time
- overall utilization (%)
- work hours per year
- throughput (units per hour)
- quantity produced over lifetime
- overall yield
- sellable product over life time

3.3.4 Cost of ownership Software

We have included in the accompanying CD a CoO demo software that will give you hands on experience of CoO analysis and understanding the usefulness of a CoO calculation. This demo software is not an elaborate software taking into consideration all parameters, but it does consider some of the major parameters necessary for CoO analysis. We recommended readers to try the demo software model and understand the usefulness of this methodology.**[VIEW-IN-CDROM]** For those of you who would like to perform a detailed CoO analysis we suggest you to procure the complete software. [E-8]

3.3.5 Usefulness of CoO Analysis

As with any simulation tool, the value of the information output is only as good as the data available for input. All the data input, that goes into Cost of Ownership calculation, such as, work hours per week, MTBA, MTBF, MTTA, MTBR, UPH, overall yield, and sellable product over life time, must be realistic and accurate. Assembly manufacturers are therefore moving forward with plans to automatically collect and distribute performance attribute data for equipment and materials. The reader is warned that the assumptions of a cost-of-ownership analysis are by no means without their deficiencies. Presently, some of the problematic issues relate to inadequate consideration of factory flow issues such as bottlenecks, cycle times, and work in progress.

3.4 Equipment Performance

3.4.1 Performance Evaluation of Bonders

Though all bonding equipment vendors claim their product is the best and it only meets all the requirements of our assembly and packaging, we need to be careful in deciding which bonder really meets our requirements. The goal of wire bonder performance evaluation is to really test the bonders for actual

performance to meet our design, production, quality and reliability requirements.

For example, if we need a bonder with high precision bond placement and precise loop control, we must evaluate the bonder for these in reference to other bonders. Similarly there can be a host of critical requirements that need to be evaluated before deciding on the right bonder for our application.

In this chapter we discuss the methodology of wire bonder performance evaluation. This includes:

- evaluation team
- bonder evaluation plan
- decision making list for wire bonder
- performance rating list
- measuring data
- special test survey
- running data comparison
- cost of ownership comparison
- survey of supplier potential / service
- comments from all levels of factory personnel

3.4.2 Bonder Evaluation Team

Since wire bonder is the most critical equipment in assembly process flow, it is imperative that large scale purchase of wire bonders for advanced assembly manufacturing must involve decision makers from different levels in a company. It is recommended that the team must consist of different levels of personnel from the factory, from operator to the manufacturing V.P.

3.4.3 Bonder Evaluation Plan

The bonder evaluation plan must consist of Standard test plan for existing packages, Special test plan for future packages and Quality test plan for new bonder evaluation.

The standard test plan consists of testing devices that are currently in production. For example as we see in table 3.4.1 that the existing packages in production are 40 lead TSOP, 56 lead TQFP and 28 lead SO. The bond pad pitch and the die sizes of the chips that go into these packages are also listed in this table. The test plan contains the type of gold wire, the capillary, and the quality check points. But when we buy a bonder it must be capable of meeting the bonding requirements of not only the existing packages in production but also future packages that are planed to be introduced into production.

Table 3.4.1 Standard test plan for existing package

	Die	Gold Wire	Capillary	Check Point
TSOP - 40 Pad size 5.84 x 5.84 mm	Die size: 4.92 x 4.66 Bond Pad : 115 x 115 mm	Tanaka Type - c ida 32 µm	Gaiser 20D, 1513 N-18M-437gm	Evaluation Format
TQFP - 56 Pad size 4.8 x 6.0 mm	Die size: 307 x 4.12 Bond Pad : 100 x 100 mm	Tanaka Type - c ida 32 µm	Gaiser 20D, 1513 N-18M-437gm	Low Loop Bondability
SO- 28 Pad size 6.2x5.4 mm	Die size: 2.6 x 5.48 Bond Pad : 90 x 90 mm	Tanaka Type - c ida 32 µm	Gaiser 20D, 1513 N-18M-437gm	Evaluation Format

As shown in table 3.4.2 the performance of the bonder must also be tested for long wire (4 to 6 millimetres), low loop and fine pitch BGA packages. Therefore the performance evaluation of the wire bonder must consist of both standard test plan as well as special test plan.

The performance evaluation must be done with a quality test plan which consists of a preproduction test plan and production test plan as shown in table 3.4.3.

Table 3.4.2 Special test plan for future package

Test items	L/F	Device	Gold wire	Capillary
Long wire 4-6 mm	TSOP -40 Pad size : 5.84x5.84 Bond on one side only for longer wire	Die size Bond pad 90x90 µm	Type-GL2-Dia 25 µm	Gaiser
Lowloop height <150 µm	TSOP 84 Pad size : 5.84x5.84	XYZ101 Die size: 64.92x4.66 Bond pad 90x90 µm	Tanaka Type-GL2-Dia 25 µm	Gaiser
Fine Pitch 115 µm	BGA144 Pad size: 4.8x6.0	High Pin Count Fine Pitch Test Die	Tanaka Type-G-Dia 25 µm	Gaiser

Table: 3.4.3 Quality test for new wire bonder evaluation

Quality test items	Sample size of quality test per type (m*n)	
	Test item A	Test item B
Wire pull force	3*10	3/2PCS/HR
Ball shear force	3*10	3/2PCS/HR
Loop height	3*10	3/2PCS/HR
Position accuracy	3*10	N/A
Ball size	3*10	N/A
Wire bent (%)	3*10	N/A
SME (ball,stitch,loop)	1*1 (3x)	1*1 (3x)
Preseal visual insp	all * 20	G2, AQL 0.25

Test Item A : quality test for trial run (inked die)
Test Item B : quality test on volume production products
m*n : n strips taken and m pieces / wires / per strip

3.4.4 Performance Rating of a Wire Bonder

The performance of a bonder is rated in terms of:

- process capability (standard existing packages)
- process capability (special packages for future)
- machine capability
- machine function
- supplier potential/service
- cost of ownership
- comments from all levels of factory personnel

Let us discuss each of the above issues in detail.

3.4.5 Process Capability for Existing Packages

In order to understand the process capability of a new bonder for standard existing package application, we compare different bonder performances for some of the basic requirements of a bonder, such as ball location accuracy, ball deformation size, wire sweep measure, wire pull strength, ball shear force and loop height. Based on the data collected from each test the process capability of bonders A, B, C and D are rated. The process capability is measured by evaluating issues such as ball location accuracy, wire sweep, wire pull strength, and loop height consistency. For each bonder, the process capability score obtained is multiplied with the weightage to get the weighted score, and in table 3.4.4 we see based on evaluation that company A has a score of 75.6, company B = 81.3, company C = 71.8, and company D = 81.3 respectively.

Table 3.4.4 Performance rating of wire bond equipment [E-8]

No	Item description	Wt 1-5	Company A		Company B		Company C		Company D	
			Score (0-5)	Wtd Score	Score (0-5)	Wtd Score	Score (0-5)	Wtd Score	Score (0-5)	Wtd Score
1.	Ball location accuracy	5	3	15	3	15	2	10	4	20
2.	Ball deformation size	4	3	12	4	16	3	12	3	12
3.	Wire sweep measure	4	3	12	3	12	3	12	4	16
4.	Wire pull strength	5	5	25	5	25	5	25	5	25
5.	Ball shear force	5	4	20	5	25	5	25	5	25
6.	Loop height	4	3	12	3	12	4	16	3	12
7.	SEM	5	5	25	5	25	3	15	4	20
	Total	32		121		130		115		130
	Index (Ttl weighted score by Ttl weight x 5) %			75.6		81.3		71.8		81.3

Index (ttl weighted score by ttl weight x5) %

3.4.6 Process Capability for Future Packages

Similar to the evaluation done for existing packages, process capability study must also be done for future packages. In this evaluation we compare different bonder performances for some special requirements of a bonder required for future packages, such as long wire capability, low loop capability, low bonding temperature, fine pitch and small bond pad capability. Based on the data collected from each test the process capability of bonders A, B, C and D are rated. As shown in table 3.4.5 analysis of process capability with special criteria such as long wire, low loop, low bonding temperature, very fine pitch capability, and small bond pad applicability shows scores of 80, 76.7, 72.2, and 77.4 for bonders A,B,C and D respectively.

Table 3.4.5 Performance rating of wirebond equipment for future requirements [E-8]

No	Item description	Wt 1-5	Company A		Company B		Company C		Company D	
			Score (0-5)	Wtd Score	Score (0-5)	Wtd Score	Score (0-5)	Wtd Score	Score (0-5)	Wtd Score
1.	Long wire	4	4	16	3	12	4	16	3	12
2.	Low loop	4	4	16	3	12	4	16	2	8
3.	Low bonding temp	3	4	12	5	15	5	15	5	15
4.	Fine pitch	5	5	25	5	25	3	15	5	25
5.	Small bond pad 80 x80 (32 um)	5	4	20	4	20	4	20	5	25
6.	Small bond pad 80 x80 (25 um)	5	4	20	4	20	3	15	4	20
7.	Small bond pad 70 x70 (23 um)	5	3	15	3	15	3	15	3	15
	Total	31		124		119		112		120
	Index (Ttl weighted score by Ttl weight x 5) %			80.0		76.7		72.2		77.4

3.4.7 Machine Capability

The machine capability of each bonder under evaluation is tested by analysing many factors such as actual UPH, machine down time, PPM defect rate, package change time, tool change time, spool change time and a host of other parameters.

In table 3.4.6 we see that the machine Capability analysis for parameters such as actual units per hour, yield, downtime, package change time, spool change time, pad recognition time, PRS accuracy, touch down detection and many other criteria gives a total score of 73.7 for company A, 74.3 for company B, 61.4 for Company C, and 73.1 for company D respectively.

Table 3.4.6 Machine capability analysis of wire bond equipment [E-8]

No	Item description	Wt 1-5	Company A		Company B		Company C		Company D	
			Score (0-5)	Wtd Score	Score (0-5)	Wtd Score	Score (0-5)	Wtd Score	Score (0-5)	Wtd Score
1.	Actual UPH	5	4	20	5	25	1	5	4	20
2.	Yield	5	4	20	4	20	4	20	4	20
3.	PPM	5	3	15	4	20	5	25	3	15
4.	Down time	5	5	15	5	25	2	10	4	20
5.	MTBS	5	4	20	3	15	3	15	1	5
6.	Type change time	5	4	20	4	20	3	15	5	25
7.	Package change time	5	5	25	1	5	2	10	4	20
8.	Tool change time	1	2	2	2	2	2	2	3	3
9.	Spool change time	1	3	3	3	3	3	3	3	3
10.	Wire capacity per device	2	4	8	4	8	4	8	4	8
11.	Bond speed per device (N) (LC)	1	3	3	4	4	5	2	5	5
12.	Wire (UM)	4	4	16	4	16	4	8	4	16
13.	Bond area	4	3	12	4	16	3	12	3	12
14.	Rail width setting	3	4	12	3	9	4	9	4	12
15.	Feed pitch stroke	2	4	8	4	8	4	8	4	8
16.	Feed speed	1	3	3	3	3	3	3	3	3
17.	Applicable (Elevator) magazine	3	4	12	4	12	4	12	4	12
18.	Applicable lead frame	3	4	12	3	9	3	9	4	12

continue

No	Item description	Wt 1-5	Company A		Company B		Company C		Company D	
			Score (0-5)	Wtd Score	Score (0-5)	Wtd Score	Score (0-5)	Wtd Score	Score (0-5)	Wtd Score
19.	PRS search range	2	4	8	3	6	3	6	2	4
20.	Heater block temp. control	4	4	16	4	16	4	16	4	16
21.	L.R. speed	2	4	8	3	6	3	4	2	4
22.	Bond force range	3	4	12	4	12	4	12	4	12
23.	Pad recognition time	2	4	8	4	8	2	4	2	4
24.	Loop mode	2	4	8	4	8	4	8	4	8
25.	PRS accuracy	2	3	6	4	8	3	6	5	10
26.	U.S. energy range	3	3	9	3	9	3	9	3	9
27.	Dwell time, US time	1	2	2	2	2	2	2	2	2
28.	Touch down detection	4	3	12	5	20	5	20	5	20
29.	Resolution	2	3	6	4	8	2	4	5	10
	Total	87		321		323		267		318
	Index $\frac{\text{Total weighted score}}{\text{Ttl weight x 5}}$ %			73.7		74.3		61.4		73.1

3.4.8 Machine Function

The consistency, accuracy and repeatability of machine functions is evaluated for different bonders based on factors such as accuracy, loop control, clamp, bonding head control, die height search, wire feeder, and a host other factors.

Table 3.4.7 Machine function [E-8]

No	Item description	Wt 1-5	Company A		Company B		Company C		Company D	
			Score (0-5)	Wtd Score	Score (0-5)	Wtd Score	Score (0-5)	Wtd Score	Score (0-5)	Wtd Score
1.	Wire feeder	3	4	12	3	9	3	9	5	15
2.	Index/loading/unloading operation	4	5	20	3	12	3	12	3	12
3.	Loading/unloading operation	3	4	12	4	12	4	12	4	12
4.	Spark	4	4	16	4	16	4	16	5	20
5.	Bonding method	2	3	6	3	6	3	6	3	6
6.	L/UL magazine	3	4	12	3	9	3	9	5	15
7.	P.R. accuracy	4	3	12	3	12	2	8	3	12
8.	Workholder	5	5	25	3	15	5	25	3	15
9.	Die height search	2	4	8	4	8	4	8	5	10
10.	Lead recognition	4	5	20	5	20	3	12	5	20
11.	Loop control	4	5	20	5	20	5	20	5	20
12.	Bonding head control	5	3	15	5	25	3	15	5	25
13.	XY table	4	3	12	4	16	3	12	5	20
14.	Clamp	5	5	25	3	15	5	25	5	25
15.	Product control	5	4	20	5	25	5	25	4	20
16.	Error control	3	4	12	4	12	4	12	5	15
17.	Data input	4	4	16	5	20	4	16	5	20
18.	External interface	3	4	12	4	12	4	12	4	12

Continue

No	Item description	Wt 1-5	Company A		Company B		Company C		Company D	
			Score (0-5)	Wtd Score	Score (0-5)	Wtd Score	Score (0-5)	Wtd Score	Score (0-5)	Wtd Score
19.	CPU	3	4	12	4	12	4	12	5	15
20.	Wire program stroge	1	3	3	3	3	3	3	3	3
21.	Matrix	5	4	20	4	20	5	25	4	20
22.	Signal	3	3	9	4	12	5	15	4	12
23.	Self diagnosis	4	4	16	4	16	4	16	4	16
24.	Modular design	3	4	12	5	15	4	12	5	15
25.	SPC feasibility	3	4	12	4	12	4	12	4	12
26.	Missing ball dectector	4	5	20	5	20	3	12	3	12
27.	Auto US feed back	3	4	12	4	12	4	12	4	12
28.	EFO feed back	3	4	12	4	12	4	12	4	12
29.	Standard working height	2	4	8	4	8	4	8	4	8
30.	Dimensions (W.D.H)	5	3	15	3	15	5	25	4	20
	Total	106		426		421		418		451
	Index (Ttl weighted score by Ttl weight x 5) %			80.4		79.4		78.8		85.0

3.4.9 Supplier Potential and Services

When we select any bonder for production, even the best bonder may have a breakdown and it needs technical support from the supplier. Therefore supplier service and his potential for upgrading the technology for future products is an important determinant. Some of the factors to consider are company profitability, development and Upgrade capability, willingness to share technology and experience, machine and Spare parts delivery, service, supplier's attitude and innovation rate. As shown in table 3.4.8 the supplier potential and service capability scores are 95.2 for company A, 84.1 for company B, 78.6 for company C, and 81.4 for company D respectively.

Though this is a qualitative analysis, it must be included in the overall performance evaluation of the bonders.

Table 3.4.8 Supplier potential [E-8]

No	Item description	Wt 1-5	Company A		Company B		Company C		Company D	
			Score (0-5)	Wtd Score	Score (0-5)	Wtd Score	Score (0-5)	Wtd Score	Score (0-5)	Wtd Score
1.	Development/upgrade capability	5	5	25	5	25	5	25	5	25
2.	Company profitability	3	5	15	4	12	5	15	4	12
3.	Willingness of sharing bond technology & experience	5	5	25	4	20	3	15	4	20
4.	M/Cspare parts delivery	4	5	20	5	20	4	16	4	16
5.	Service	4	4	16	4	16	4	16	4	16
6.	Supplier's willingness /attitude	5	5	25	4	20	3	15	4	20
7.	Innovation rate	3	4	12	3	9	4	12	3	9
	Total	29		138		122		114		118
	Index $\left(\frac{\text{Total weighted score}}{\text{Total weight x 5}}\right)$ %			95.2		84.1		78.6		81.4

3.4.10 Comments from all levels in the Factory

Any equipment output is very much dependant on the personnel that handle the equipment. So it is with bonders. Unless the operator feels comfortable using it, unless the maintenance technician feels the equipment is easy to maintain and the process engineer feels that product quality and yield can be high with the bonder, the maximum utility of the machine is never achieved. Therefore, it is important to give some weightage to the comments from personnel that will be working with the bonders.

In table 3.4.9 we see, the score for company A is 76.7, company B 78.3, company C 75, and company D 80, based on comments from operators, maintenance personnel, and engineers.

Table 3.4.9 Comments from all levels of manufacturing personnel [E-8]

No	Working people	Wt 1-5	Company A		Company B		Company C		Company D	
			Score (0-5)	Wtd Score	Score (0-5)	Wtd Score	Score (0-5)	Wtd Score	Score (0-5)	Wtd Score
1.	Operator	5	5	25	3	15	4	20	4	20
2.	Repair & Maint. people	4	3	12	5	20	4	16	4	16
3.	Engineer	3	3	9	4	12	3	9	4	12
	Total	12		46		47		45		48
	Index (Ttl weighted score by Ttl weight x 5) %			76.7		78.3		75		80

3.4.11 Survey of Score

The score from different analyses are tabulated and the process and machine capabilities are calculated.

Table 3.4.10 Survey of score [E-8]

Evaluation item	Supplier	Company A	Company B	Company C	Company D
Part I	1. Process capability / product quality (standard test)	75.6	81.3	71.8	81.3
	2. Process capability / product quality (special test)	80.0	76.7	72.2	77.4
	Average	77.8	79.0	72.0	79.3
Part II	1. Machine capability	73.7	74.3	61.4	73.1
	2. Machine function	80.4	79.4	78.8	85.0
	Average	77.1	76.9	70.1	79.0
Part III	1. Supplier potential/service	95.2	84.1	78.6	81.4
Part IV	1. Processing cost index	100.0	93.3	53.3	80.0
Part V	1. Comments of all level	76.7	78.3	75.0	80.0

Table 3.4.10 shows the overall score of different companies A, B, C and D for different evaluation items, such as process capability with standard test, process capability special test, machine capability, supplier potential, processing cost, and comments from manufacturing.personnel.

3.4.12 Decision Making

The final decision on the best performing bonder is made by taking all the scores and assigning certain weightage to each item. A sum of the weighted score will decide the best performing bonder.

The performance rating of a wire bonder is based on seven main factors, process capability, product quality, processing cost, machine capability, supplier potential and service, and qualitative comments from all levels of factory personnel, from operator to manufacturing vice president.

Table 3.4.11 Decision making list [E-8]

No	Item Description	Wt %	Company A		Company B		Company C		Company D	
			Score	Wtd Score	Score	Wtd Score	Score	Wtd Score	Score	Wtd Score
1	Process capability/product quality	30	77.8	23.34	79.0	23.70	72.0	21.60	79.3	23.79
2	Processing cost	30	100	30.00	93.3	27.99	53.3	15.99	80.0	24.00
3	Machine capability/function	20	77.1	15.42	76.9	15.38	70.1	14.02	79.0	15.80
4	Supplier potential/service	10	95.2	9.52	84.1	8.41	78.6	7.86	81.4	8.14
5	Comments	10	7.67	7.67	78.3	7.83	75.0	7.50	80.0	8.00
	Total			85.95		83.31		66.97		79.73
	Ranking			1		2		4		3

Wt = Weight   Wtd. score = Weighted score

Each of these parameters has a weightage. The calculated score from each parameter is multiplied by the weightage to get the weighted score, and the

weighted scores are added for each bonder and then ranked. Based on analysis of all the above parameters, we see in table 3.4.11 that the company A has the highest ranking with a total score of 85.95, and company C has the lowest ranking with a total score of 66.97.

3.5 Equipment Maintenance

Maintenance of bonding equipment is extremely important in maintaining device quality and integrity. If maintenance is not performed to the equipment manufacturer's specifications, degradation of the product is likely. This is particularly true when we are trying to bond 8 to 12 wires/sec. on a high speed automatic wire bonder.

During high speed bonding with an automatic wire bonder, a great deal of motion is involved for the bonding head, the x-y table, the wire clamp and many other systems; if those parts are not well maintained, difficulties will follow. Usually manual machines don't require quite the same type of maintenance as an automatic bonder.

3.5.1 Establishing a Maintenance Program

The maintenance program and maintenance schedule for production floor bonders depends on the type of machine failures that one encounters during production. Machine failure can be due to machine, materials, operator and process parameters.

The maintenance program for a bonder or a set of bonders on the production floor can be developed based on the machine down time distribution. The amount of maintenance, both scheduled and unscheduled, depends on the total down time of a machine. Let us understand the total down time and the contributing factors to total down time.

Here is an analysis of total down time for 26 machines on a manufacturing line monitored over a period of one month. Out of a total usable time of 10,970 hours, about 4380 hours was the down time. This is approximately 40%. The overall downtime of the machine which includes scheduled, unscheduled and standby downtimes is a total of 4380 hours. One needs to

analyze the causes of these downtimes and to implement corrective action to minimize machine downtime. Reducing downtime increases productivity which in turn minimizes cost of ownership of wirebond equipment.

As shown in figure 3.5.1 the major causes for 4380 hours of machine down time are short stop, pattern recognition stop, No bond program, no ball, indexing problems, no unit on the bonder, no operator at the bonder and others.

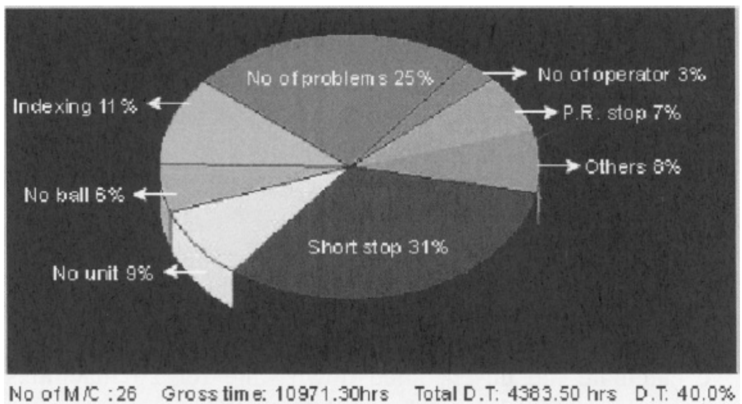


Figure 3.5.1 Example of major causes of machine down time in a particular factory

3.5.2 Stand by down time

Out of this 4380 hours of down time, more than 29% of the down time (3,230 hours) was attributable to "Stand By" down time. That means for 26 machines, out of 10,970 hours of useful time, 3,230 hours was downtime due to standby mode. The causes for this stand by mode down time are short stop, no unit on the machine, no problem with the machine, no operator at the machine, pattern recognition stops, and others. As we can see in graph 3.5.2 the machine stoppage in this case is not due to any technical reason and no maintenance program can be incorporated as corrective action.

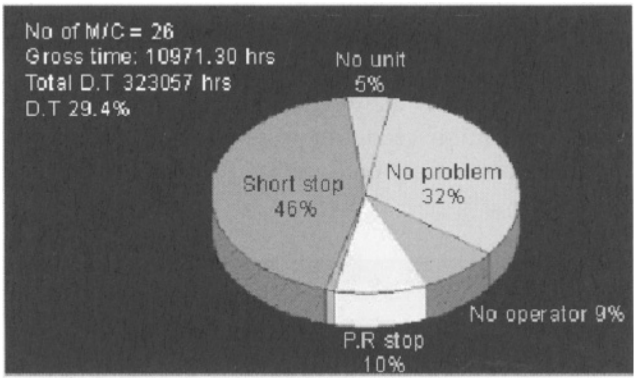


Figure 3.5.2 Break down of causes for stand by down time

3.5.3 Unscheduled Down Time

The productivity of a wirebonder is determined by how often it breaks down, how often it needs assistance and the time it takes to setup the bonder. When we calculate the unscheduled down time for 26 machines, it was found that out of 10,970 hours of usable time, 960 hours was unscheduled down time(8.8% of the total down time).

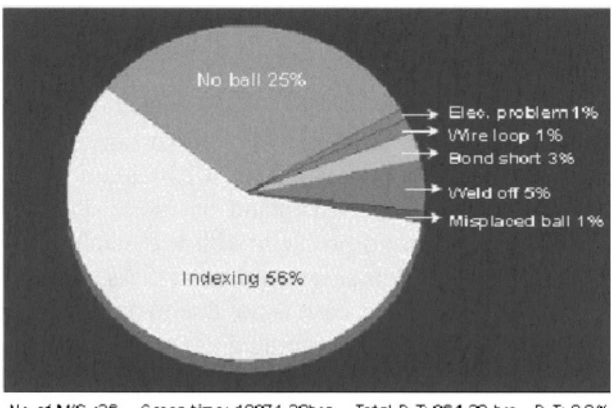


Figure 3.5.3 Break down of causes for unscheduled down time

The causes of unscheduled down time are, indexing, no ball on pad, electrical problem, wire loop problem, bond-short problem, weld-off, and misplaced bond problem as shown in graph 3.5.3.

3.5.4 Scheduled Maintenance

Every wirebond equipment requires scheduled downtime for capillary changing, conversion from one device to the other, preventive maintenance and servicing, and occasional materials problems. As shown in graph 3.5.4 , out of 10,970 hours, the scheduled downtime was only about 190 hours, which consisted of: conversion from one device to another, capillary change, material problems, and system fault. From this analysis we see that the total time spent on preventive maintenance was about 20 hours per month for 26 machines. This is about one hour per machine per month. And this has contributed, possibly, for the significant amount of unscheduled down time.

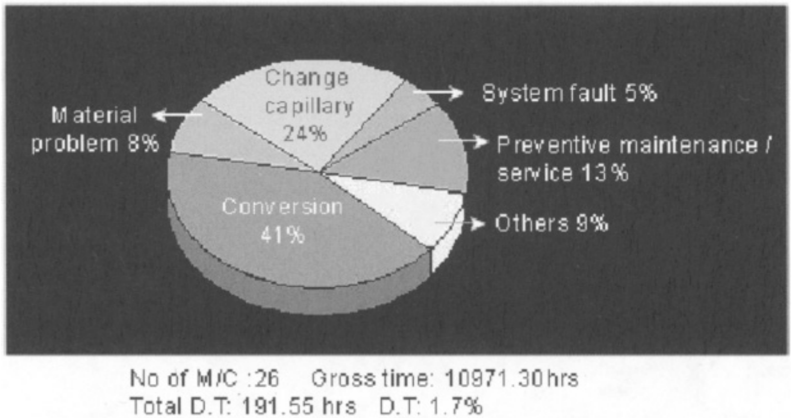


Figure 3.5.4 Break down of causes for scheduled down time

3.6 Preventive Maintenance program

Modern wirebond machines are designed to minimize conversion time, capillary change time, as well as with very short time required for preventive

4

Process Technology

Wire bonding process is the most crucial process in the semiconductor assembly manufacturing flow. The wire bond process effectiveness depends on the choice of materials, choice of equipment and how well the operators have been trained to perform the operation. The process capability is determined by the yield, the quality of the wire bond and the reliability of the wire bond interconnection. There are innumerable number of factors that affect the yield, quality and reliability of the bonded device and one needs to understand the effect of each of these variables and the interaction of these variables with each other. In the section on process variables, we shall address a host of these factors that impact the bonding process. When there are numerous variables interacting and impacting the process consistency, one needs to understand how the bonding process should be optimized for maximum yield. The section on process optimization addresses the different optimization approaches and techniques.

Once the process is optimized, it needs to be controlled using statistical process control methodologies and any deviations from the optimum process can be corrected in real time. This topic has been dealt with in the section on process control. The many variables in the wire bonding process such as temperature, ultrasonic energy, bonding force and such need to be measured on a periodic basis and these measurements require special technologies. The section on process monitoring explores many different techniques that are in use today for wire bond process monitoring. The focus of wire bonding is to create a perfect metallurgical interface between the wire and the bond pad metallization. This involves both mechanical interaction between two metals

and diffusional reaction at the interface. It is possible to optimize the process and make it perfect only by understanding the impact of each of the process variables and their effect on the metallurgical bond that forms between the wire and the bond pad. The section on process mechanism helps one to gain knowledge of the intricacies of the metallurgical science behind the thermosonic and ultrasonic wire bonding technologies.

It is now well known that what is designed well manufactures well and works well. How to design a bond pad both from the device functionality perspective and from manufacturability perspective is discussed in detail in the section on 4.6. Topics such as bond pad shape, bond pad size, staggered pad pitch and bond pad positioning are addressed here. Finally, as we well know, any process as diverse, as complicated and as crucial as wire bonding is associated with process problems leading to low yield or poor quality and risk of reliability. The many problems that one encounters during the bonding process and the necessary solutions are discussed in the section on process problems and solutions.

4.1 Process Variables

A number of variables play significant role that impacts the bonding process. Wire bonding process consistency and process reliability are dependent on major variables including:

- wire bonding parameters
- bond pad metallization on the chip
- metallization on the lead frame
- bonding wire
- bonding tool
- operator skills

Figure 4.1.1 shows the different variables that impact the bonding process. Other variables such as package design, PRS, EFO, Wire feed consistency, synchronization, missing bond detector, heater block, lead frame clamp, tool resonance and software related bugs can also impact the bonding process stability and consistency.

Now let us study in detail some of the important process variables that contribute in creating a perfect bond and review the complexity of each of these variables and understand their impact on wire bond process yield and product reliability.

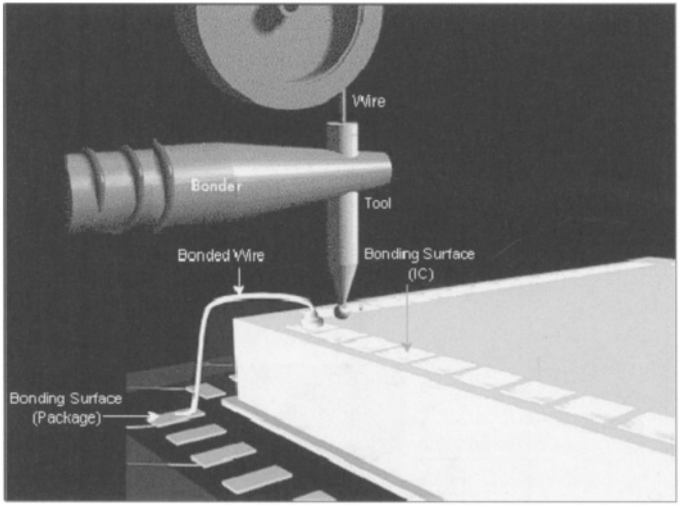


Figure 4.1.1 Bonding variables **[VIEW-IN-CDROM]**

4.1.1 Bonding *Parameters*

The bonding parameters are the settings that an engineer makes of the wire bonding machine. These machine settings are different for each type of device and package combinations. These machine parameters need to be optimized for each device and the bonding machine must be tuned to only that particular set of parameters for bonding a particular device-package combination. The use of correct bonding parameters assures a perfect bonded interface and the long term reliability of the bond. Some of the major bonding parameters that control the bonding process are listed below:

- bonding force

- bonding time
- ultrasonic energy
- bonding temperature
- loop control

As shown in figure 4.1.2, the control factors such as force, power, time and temperature give rise to response factors in the form of ball shear strength and wire pull strength. The quality and goodness of the wire bond is determined by high ball shear strength and high wire pull strength value. The optimum combinations of these control factors are normally determined on a trial basis for any particular application, with the ultrasonic power being the primary control factor.

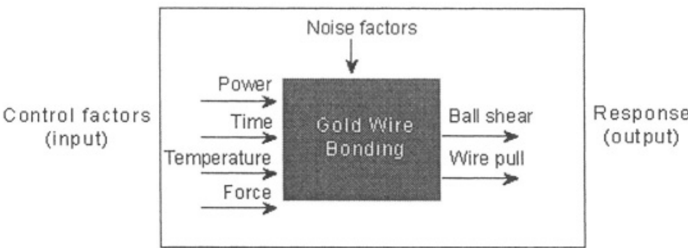


Figure 4.1.2 The gold wire bonding process [P-1]

The main variables that control the goodness of the gold wire bonding process are ultrasonic power, bonding time, bonding temperature and bond force.

All these bonding parameters are interdependent and the parameter values depend on many factors such as the bond pad metallization hardness, the wire hardness, the thickness of the materials being welded in contact with the bonding tool tip and the bonding tool itself. The bonding tool is a critical component because of the requirement to transmit energy to the interface without excessive dissipation.

4.1.2 Bonding Force

The bonding force applied during bonding must be sufficient to maintain tool/wire contact without slippage, and must be sufficient to effect maximum ultrasonic coupling at the wire-pad interface but not so excessive that it causes severe deformation or damage to the wire or the bond pad.

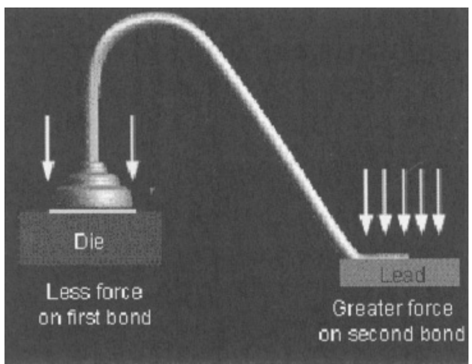


Figure 4.1.3 Force sufficient to maintain wire contact without slippage

As shown in the figure 4.1.3, the force required to create a Au ball bond on the Al bondpad is less than the force required to bond the Au wedge bond on the lead finger. This is because the ball bond forms an interface between the gold and aluminum when Au ball is at a very high temperature and the interface bond created is a metallurgical bond. The wedge bond is more of a mechanical bonding between the Au wire and lead frame metallization without any metallurgical reaction and therefore requires greater force for the second bond interface formation.

In case of ball bonding if the force is low during first bond, the interfacial contact is not good enough for metallurgical reaction. If the force is too high the ball may get squashed. Similarly if the force on the second bond is low, the bond may not stick. Higher force, on the other hand, is a concern, because this induces micro-cracks at the heel of the second bond.

In thermosonic bonding the force required for wedge bond in the longitudinal direction is lower than the force required in the transverse direction, and this is schematically shown in Fig. 4.1.4. During wedge bonding on the lead frame, the capillary applies force on the wire and clamps the wire on to the lead frame, and the ultrasonic power is transmitted on to the wire. When the capillary vibrational movement is longitudinal (parallel) to the loop orientation, the amount of force required to bond the second bond is lower than the bond force required when the capillary movement is transverse (perpendicular) to the loop orientation. This is attributed to the surface area of contact between the capillary face and the wire. Modern bonding equipment have software capability that allows the second bond force to be programmed such that the bonding force can be set separately for individual bond fingers.

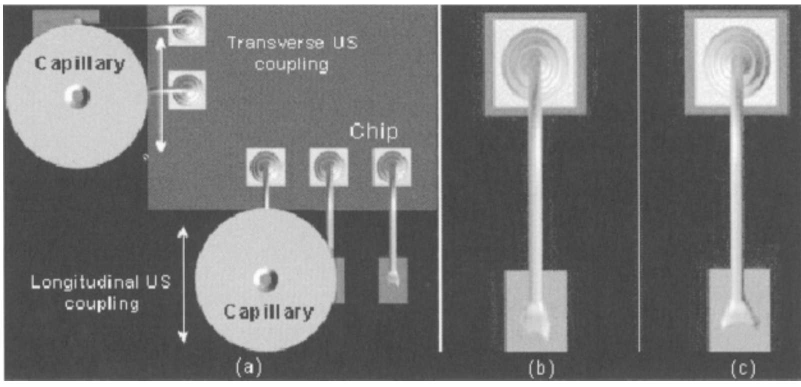


Figure 4.1.4 (a) Schematic representation of longitudinal movement of capillary and transverse movement of capillary. (b) Second bond formation with longitudinal ultrasonic coupling (c) Second bond formation with transverse ultrasonic coupling

4.1.2.1 Bond Force in Ultrasonic Wedge Bonding

In ultrasonic aluminum wedge bonding, the force required for first bond on bond pad as well as second bond on the lead finger are much higher than what is required for thermosonic ball bonding. This is because the ultrasonic

wedge bonding is done at room temperature and there is no “metallurgical reaction” at the interface between the wire and the bond pad metallization.

In ultrasonic wedge bonding the force required to hold the Al wire during bonding depends on the bond pad metallization and its hardness. During wedge bonding if the bonding force is high the aluminum metal tends to squeeze out and in some cases it may result in electrical shorting, particularly when bond pads are close to each other. This effect is more predominantly encountered in case of power devices which have thick Al metallization.

It has been found that both in gold ball bonding and in Al wedge bonding technologies, higher bond force gives rise to greater cratering propensity under the bond pad [P-2]. And in certain situations, even lower bond force has been shown to be the cause of cratering. According to general industry notion, cratering at low bond force values has been attributed to “ploughing effect” of the wedge or the capillary, where the capillary exhibits a jumping and hammering effect on the bond pad. However, this phenomenon has not been observed universally. This topic is discussed in greater detail in Chapter 6.3.

4.1.3 Ultrasonic Energy during Bonding

During bonding process ultrasonic energy is applied to the bond wire through the capillary. The ultrasonically vibrated ball or the wedge “scrubs” against the bond pad metal and thus the interfacial bond is formed. In case of Au ball bonding the ultrasonic vibration creates a metallurgical intermetallic interface and in the case of aluminium wire bond, the ultrasonic vibration creates a mechanical interlocking bond at the interface, as is shown in figure 4.1.5.

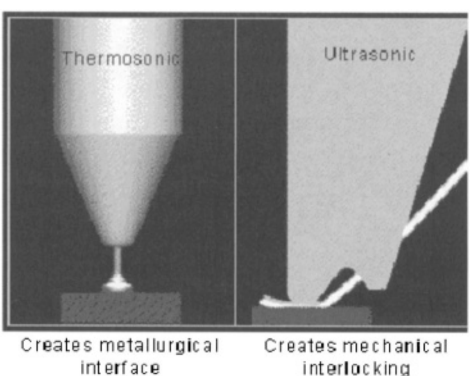


Figure 4.1.5 Effect of ultrasonic energy on Au ball bonding and Al wedge bonding

The amplitude of vibration impacts the bond deformation. The amount of deformation is directly proportional to the amplitude of vibration.

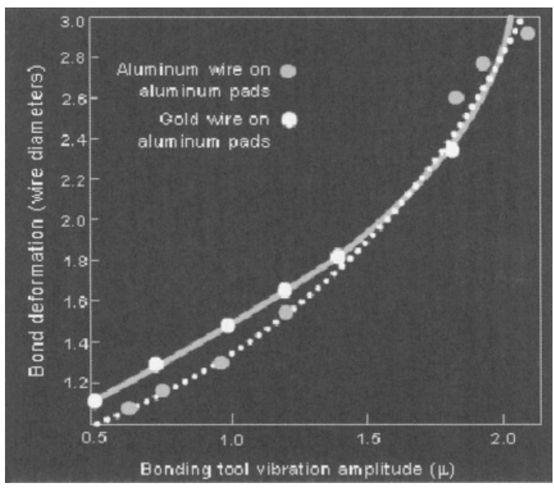


Figure 4.1.6 Bond deformation vs. tool vibration amplitude [P-3]

the bonding deformation in terms of wire diameter as a function of the vibration amplitude of a bonding tool. For example, for gold wire on aluminum, vibration amplitude of 1 micron produces bond deformation 1.5 times the diameter, whereas vibration amplitude of 2 microns produces a bond deformation of 2.8 times the wire diameter. For the ultrasonic vibration frequency, if the amplitude is excessively high, there is a possibility of fracture of already bonded contact areas before the termination of the welding period.

4.1.3.1 Ultrasonic Coupling in Longitudinal and Transverse Directions

In case of aluminum wedge bonding the transducer applies the ultrasonic energy always in the longitudinal direction (parallel to the loop orientation) and therefore the ultrasonic coupling is uniform for all bonds. Gold ball bonding is omni-directional. This omni-directionality means that the second bond can be made with ultrasonic vibration applied to the weld in any

direction relative to the wire axis. In case of thermosonic gold bonding the ultrasonic energy applied is both in longitudinal and transverse directions. The ultrasonic coupling is, therefore, different in different directions.

It is observed that in Au bonding that when ultrasonic energy is applied longitudinally or parallel to the wire, the bonded weld area is comparatively greater than the bonded weld area when the ultrasonic energy is applied in the transverse or perpendicular direction to the bond wire. We can see here, the weld shape and weld area is quite different in longitudinal, compared to transverse bonding. The second bonds have slightly different shapes in longitudinal and transverse directions as shown in Figure 4.1.4.

In the figure 4.1.7, we can observe that, the pull strength for wires bonded with longitudinal vibrations have higher bond pull strength compared to wires bonded with ultrasonic vibrations in transverse directions. We can also see that wires with zero strength are more when the welds are formed with transverse vibrations.

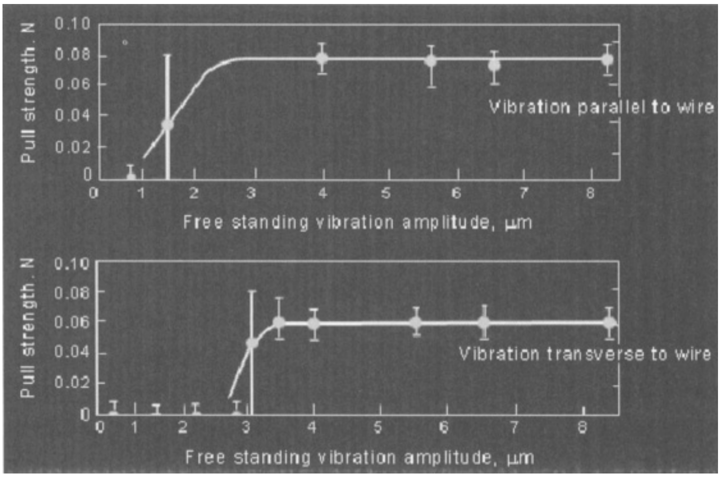


Figure 4.1.7 Weld pull strength vs tool amplitude [P-4]

From the above discussions, we see that the force and ultrasonic energy requirement for bond wires which are parallel to the bondhead is different from the force and the ultrasonic energy required to bond the wires which are

perpendicular to the bond head. Therefore, today's wirebonding equipments have the facility to program the force and the ultrasonic energy that varies continuously from Y-axis to X-axis.

4.1.3.2 Ultrasonic Power Requirement for Different Metallizations

Though no systematic study has been done on different metallizations and their bondability, it is generally observed by experienced engineers in the industry that the ultrasonic power requirement depends on the type of metallization, the alloying element in aluminum bondpad, type of metallization on lead finger, the metallization structure, its hardness, and the temperature of bonding. For example we observe in figure 4.1.8 that the formation of ball bond interface on gold metallization is significantly different from formation of the bond interface on an aluminum metallization. We see that gold ball bonding on aluminum metallization shows greater variation in ball shear strength and the shear strength increases dramatically with ultrasonic power. However, in case of gold metallization, the ball shear strength is quite high, even at low ultrasonic power and increase in ball shear strength is marginal as we increase the ultrasonic power setting.

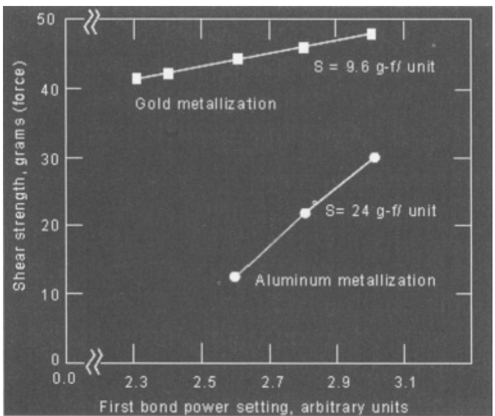


Figure 4.1.8 Ball bond shear strength as a function ultrasonic energy on Au and Al metallization [P-5]

4.1.3.3 High Frequency Ultrasonic Energy

Today's high pin count BGA-CSP packages use polymeric substrates manufactured with FR4 glass epoxy or similar materials, and these materials do not withstand conventional bonding temperatures of greater than 200° C. These advanced fine pitch BGA and CSP substrates are susceptible to deformation and damage at these high temperatures and therefore necessitate low temperature bonding for devices bonded on organic substrates. In addition to low temperature requirement, the high I/O count of these packages demand high speed bonding.

Studies have shown that when high ultrasonic energy is used, not only can the temperature of bonding be reduced, but also the time required for forming the bonded interface is also significantly reduced. At high frequency the temperature of bonding can be as low as 100° C and bond time can be as low as 10msec.

4.1.3.4 High Frequency versus Low Frequency Bonding

From the table 4.1.1, we can observe, that when the ultrasonic frequency is 120 kHz and the bonding temperature is 125°C, the bonding time required for first bond formation and second bond formation is 10 milli seconds and the bonding force required is 20 gms for the first bond and 90 gms for the second bond. With these bond parameter settings the ball bond shear force of 36 grams is obtained. When the bond is formed with 60 kHz ultrasonic energy at 125°C, to achieve the same shear strength, we need longer bonding time of 20 ms for first bond and 30 ms for second bond at a higher bonding force of 40 gms on first and 120 gms for second bond.

This reduced temperature and time requirement at 120 KHz has been attributed to increased mechanical scrub between the ball and bond pad interface. In addition to decreasing the temperature during bonding, the use of high-frequency ultrasonic power will also lead to changes in the plastic deformation behaviour of the ball and pad material due to the fundamental change in mass transport behaviour within the bond. The mechanism of high frequency bonding is discussed in greater detail in chapter 4.5.

Table 4.1.1 Comparison of 120 and 60Khz low temperature bonding for PBGA packages [Courtesy: Kulicke & Soffa]

Frequency (kHz)	Temp (°C)	Squashed ball size (mils)	Ball size Std. dev (mils)	Time (millisec)	Force (grams)	Ball shear (grams)	Shear/ area (grams/mil)	Ball shear Std. dev (grams/mil)
120	125	2.8	0.05	10/10	20/90	36	6.17	1.49
60	60	2.8	0.04	20/30	40/120	34	5.52	2.43
60	125	2.8	0.06	20/30	40/120	34	5.52	2.43
60	180	2.8	0.05	20/30	40/120	34	5.58	2.31
60	200	2.8	0.05	20/25	30/80	34	5.52	2.07

Note: Each data point represents 200 measurements

Comparison of 120 vs. 60 kHz BGA bonding shows several advantages such as:

- increased throughput - reduction in bond time in the overall bonding cycle leads to a throughput increase of approximately 10%
- pressure forces on the pad required for the first and second bond is reduced by 50% and 25% respectively
- a shear area at the bond interface that is equivalent to that of a typical bonding process for BGA devices at 180 ° C even though temperature has been reduced to 125° C.

4.1.3.5 Shear Strength at Higher Frequencies

The shear value per contact area or shear strength of a ball bond, depends on the ultrasonic frequency as well as the free air vibration amplitude of the bonding tool.

As we can see in figure 4.1.9, the shear strength of the ball bond increases as the frequency of the ultrasonic energy increases from 50 to 140 to 240 KHz. We must also recognize that at each frequency as we increase the amplitude the shear strength value increases. This can be explained by the basic formula for energy in a vibrating system [P-6].

$$E=2m\,(pi)^2\,.A^2.\,v^2$$

where :
E :is the energy of the oscillating body,
m :is its mass,
A :is its amplitude
v :is the frequency.

But the shear strength peaks at a particular amplitude for each frequency and then decreases dramatically. The cause of this observed behaviour has not been clearly understood today.

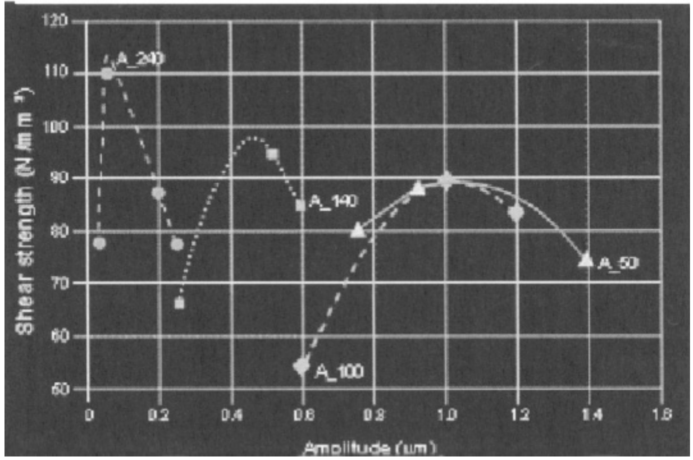


Figure 4.1.9. Variation in shear strength as a function of amplitude **[Courtesy: Small Precision Tools]**

4.1.3.6 Effect of High Frequency on Bonding Time

When we use high frequency ultrasonics it has also been observed, that the time required for bonding is much less compared to low frequency bonding. In figure 4.1.10 we can observe, that as the frequency is increased, the shear strength peaks at an optimum time value. For example, at 240 kHz frequency, the shear strength increases when we increase the time from approximately 2 seconds to 5ms. After that any increase in time, decreases the shear strength and similar phenomena is seen at 140 kHz and

100kHz. Figure 4.1.11 schematically shows the amount of intermetallic formed at the bonded interface at low-temperature bonding (50°C). We can see here that at 60kHz, the interface is about 60 percent covered, at 140kHz the surface is 75 percent covered, and at 240kHz, the surface is more than 90 percent covered.

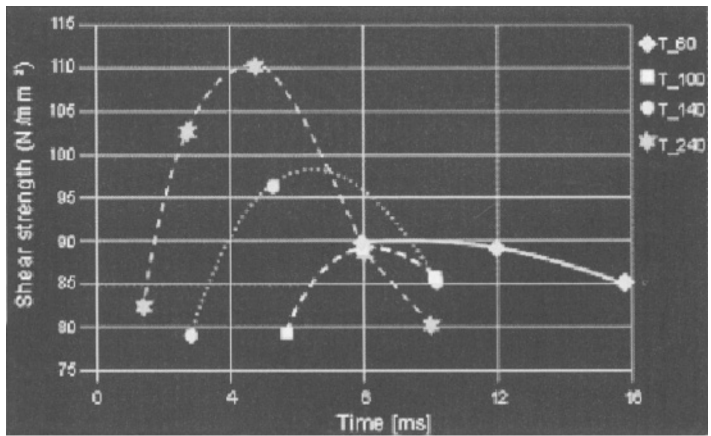


Figure 4.1.10 Shear strength as a function of time [Courtesy: Small Precision Tools]

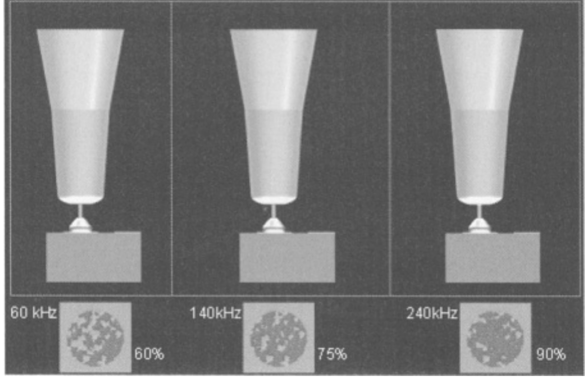


Figure 4.1.11. Intermetallic formation at different frequencies
[VIEW-IN-CDROM]

4.1.3.7 Impact of High Frequency on Bond Pull Strength

In ultra fine pitch bonding application, when we use high frequency ultrasonic energy, the type of capillary used determines the ultrasonic coupling during the bonding operation and this has an impact on the pull strength of the second bond in the longitudinal and transverse directions. From the figure 4.1.12, we can see that when a standard capillary is used, the bond pull strengths of the second bond in the transverse and the longitudinal directions are quite different where as, when a capillary designed for high frequency application is used, the bond-pull strength remains close in both transverse and longitudinal direction.

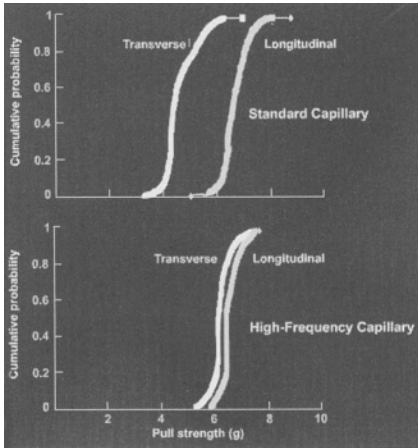
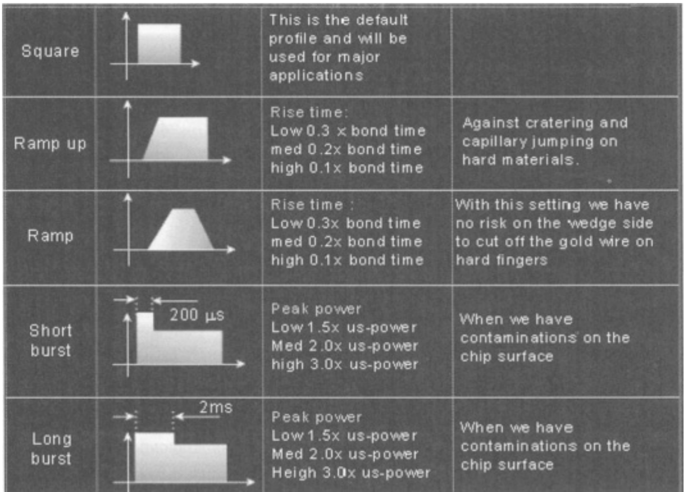


Figure 4.1.12. Variation in pull strength for different capillaries
[Courtesy: Solid State Technology]

4.1.3.8 Ultrasonic Profile

Modern wire bonding machines allow one to program the application profile of the ultrasonic energy during the bonding process. Ultrasonic energy can be applied to the bond wire with different profiles, such as square, ramp up, ramp, short burst, and long burst, as shown in figure 4.1.13. Each of these profiles have a specific effect. For example a ramp-up

profile is used to minimize cratering, whereas, a short burst profile is used when there is contamination on the bondpad. Depending on the conditions of the bond pad metallization, the substrate material contamination and the hardness of the lead finger metallization, the ultrasonic energy can be applied with different profiles.



Square		This is the default profile and will be used for major applications	
Ramp up		Rise time: Low 0.3 x bond time med 0.2x bond time high 0.1x bond time	Against cratering and capillary jumping on hard materials.
Ramp		Rise time : Low 0.3x bond time med 0.2x bond time high 0.1x bond time	With this setting we have no risk on the wedge side to cut off the gold wire on hard fingers
Short burst	200 µs	Peak power Low 1.5x us-power Med 2.0x us-power high 3.0x us-power	When we have contaminations on the chip surface
Long burst	2ms	Peak power Low 1.5x us-power Med 2.0x us-power Heigh 3.0x us-power	When we have contaminations on the chip surface

Figure 4.1.13 Different ultrasonic profiles [P-7]

4.1.3.9 *Effect of Transducer Impedance*

Transducer is the most critical component in a wirebonding machine. The ultrasonic energy applied on the bonding area is generated at the ultrasonic source and transmitted through the transducer, which in turn transmits the energy to the capillary. The characteristics of the transducer, in particular, the impedance of the transducer critically impacts the bonding process. Higher the transducer impedance weaker is the ultrasonic coupling. The impedance of the transducer determines how much ultrasonic energy is transmitted to the bond wire during the bonding process. The transducer impedance can be significantly affected by variables such as the torque on

the screw that holds the bonding tool, the temperature of the transducer and bonding tool drop below the transducer.

In the figure 4.1.14 we can see, as the torque value increases from 4 to 32, the impedance decreases. On the other hand, as the temperature increases from 25 degrees to 90 degrees, the impedance increases. The bonding tool drop below the transducer has only a small impact on the transducer impedance value.

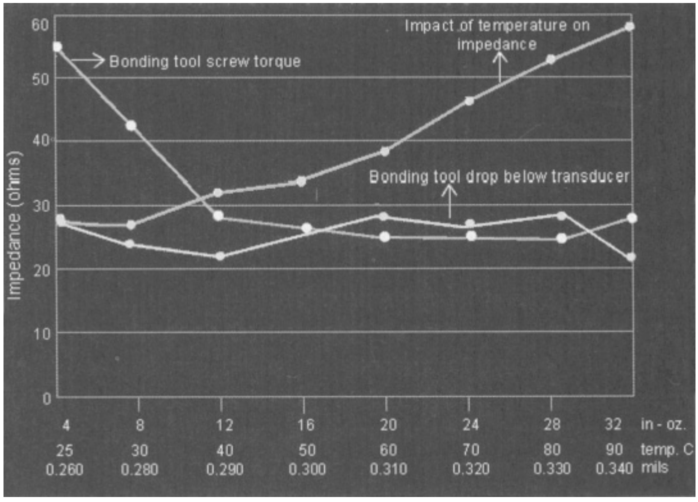


Figure 4.1.14 Impact of process variables on transducer impedance [Adopted from product catalog: Verity Instruments]

4.1.3.10 High Frequency of Bonding on Contaminated Surface

When high frequency ultrasonic is used for bonding, it has been observed that the bonding between the gold ball and the aluminum is much better, even though there is contamination on the bonding surface. For example, it has been observed that during pull test, the number of peel off failures are much higher when 60 kHz bonding is done, whereas, the number of peel off failure is dramatically less when 120 kHz bonding is performed on the same contaminated bond pads. From the figure 4.1.15 we can observe that when

wire bonding is done with 120 KHz and if the bond pad is contaminated with a thin layer of Silicone, initially, there is high bond peel off, but as we increase the deformation width, the peel off rate drops dramatically to almost less than 5%. However, with the same silicone contamination, if bonding is done with 60 KHz ultrasonic energy, the wedge peel off rate continues to be high. Even when the deformation is very high, the peel off rate failure is more than 25%. This indicates that the higher frequency ultrasonic energy does have greater reaction and therefore, better interface strength.

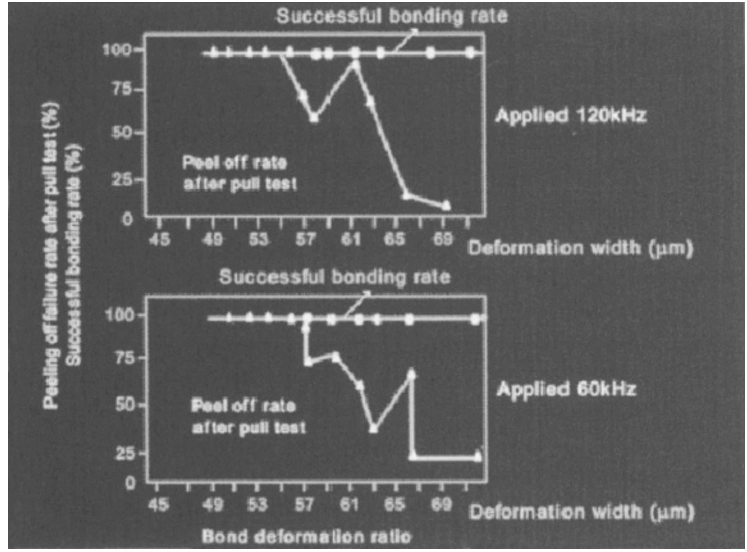


Figure 4.1.15 Variation in bondability as a function of frequency [P-8]

4.1.3.11 Advantages and Limitations of High Frequency Bonding

'High frequency' is a generic term applied to ultrasonic transducers resonating above 65 kHz. During high frequency bonding, the tool velocity is much lower than conventional frequency bonding and the amplitude of movement is much smaller resulting in a shorter bond time. High frequency

bonding also provides the advantage of bonding soft substrates, in terms of achieving good intermetallics with smaller footprint. Significant lowering of bonding temperature benefits kapton based or chip on board type packages. The other advantages of high frequency wirebonding include:

- less critical lead clamping
- larger contact area nailhead / bondpad
- easier bonding on different surfaces
- maximized bond strength
- improved ball shape / uniformity

However, it is important to recognize that high frequency transducers deliver highly variable energies depending upon conditions of loading, pad-ball shear behaviour and transducer modal response. As the frequency of the transducer increases, the bond parameter window decreases, which effectively reduces the number of applications the bonder can accommodate. High frequency system also demands a tightly controlled process with bond pad material and wire composition becoming more critical as the frequency increases. At low frequencies, the variation in shear strength is not significant even with large variation in amplitude. However, at high frequencies the shear strength dramatically varies even with very small variation in amplitude. This makes it imperative that the parameter control must be very tight in order to achieve consistent and reliable bonding process.

Although the higher ultrasonic frequency results in increased shear strengths at room temperature, they also suffer a tighter process window. Even little variation of ultrasonic power at the time of bonding will result in completely deformed nailheads or nonsticking balls. Therefore, the equipment for high-frequency applications requires the capability of advanced bond parameter control. At higher frequencies, the transducer is also subject to large number of parasitic resonances which demands a more sophisticated ultrasonic generator.

4.1.4 Bonding Temperature

Temperature at the bond site plays an important role in the strength of bond formation. Temperature has a more significant impact than ultrasonic energy. Higher the temperature lower is the ultrasonic energy required to form the bond. The extra energy to the bond site, by the addition of heat, generally causes the process to be more robust and allows for a larger working window of the wire bonding parameters. During thermosonic bonding, temperature plays a crucial role. The bonding temperature affects the interface formation between the gold ball and the aluminum metallization during bonding. For reliable thermosonic gold bonding, the wirebonding process requires a minimum temperature. Increased bonding temperature produces stronger thermosonic bonds. Thermosonic bonding to aluminum metallization (with gold wire) shows a wider variation with a greater dependence on ultrasonic energy. From the figure 4.1.16, we see, if the substrate temperature is 60°C, the ultrasonic power required is about 1.5 watts, and still the maximum bond pull strength value is not reached. However, if the substrate temperature is 165°C, maximum bond pull strength is reached even when the ultrasonic power is only 0.9 watts.

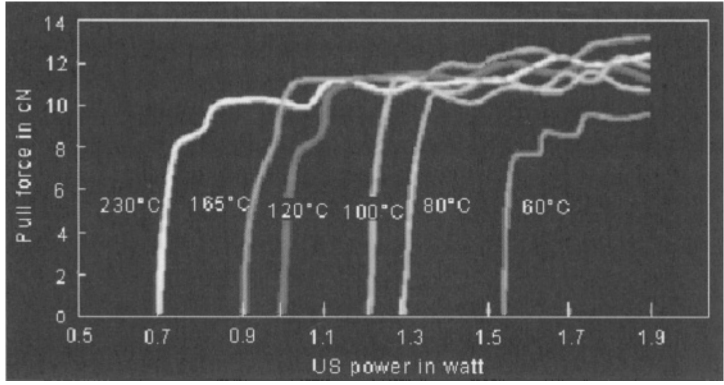


Figure 4.1.16 Influence of substrate heating on the bonding window [P-9]

It is generally observed that, higher the temperature greater is the reaction rate and shorter is the time required for thermosonic bonding. However, very

high bonding temperature, say greater than 250° C, cannot be used for lead frames because the copper lead frame may get oxidized, which may lead to molding compound adhesion problems. Higher bonding temperatures may also lead to gasification and void formation in the die attach adhesives resulting in reliability problems. Packages based on organic substrate technologies, such as BGA, CSP, COB and MCM demand bonding temperatures below the glass transition temperatures of the substrates. It can be observed from figure 4.1.17, for special packages like COB and BGA the maximum bonding temperature allowed is limited to about 150° C or by the Tg (glass transition temperature) of the substrate.

In ultra fine pitch bonding, the second bond strength on the lead finger is more critical compared to the first bond on the bond pad. This is because the wedge formed on the slim lead finger is more prone to stresses during molding and during trim and form operation, and may fail prematurely. To avoid this, strength of the second bond must be maximized during bonding operation. Enhanced second bond strength is obtained when the lead fingers are coated with gold metallization and a higher bonding temperature during bonding increases the second bond strength.

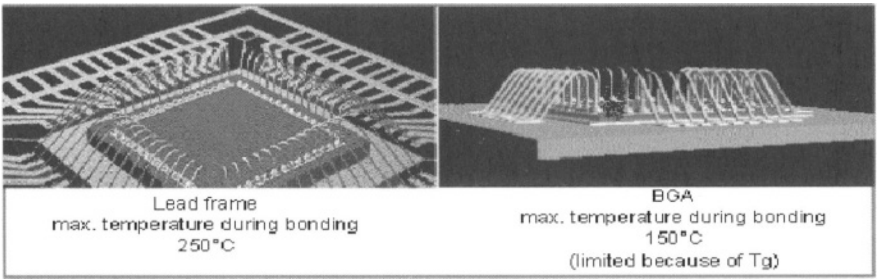


Figure 4.1.17 Maximum temperature during bonding for BGA packages

In figure 4.1.18, we see the effect of temperature on the pull strength of the second bond (stitch bond). When the bond is formed at 100°C, the pull force is about 2 grams increasing to almost 10 grams when the bond is formed at 250°C.

Similarly, in a QFP (Quad Flat Pack) application, the specified temperature for bonding is between 200-250°C. A test was performed to determine the

degradation of first and second bond strength with decreasing temperature for QFP devices. It was determined that the first bond did not suffer a serious degradation; even for a bonding temperature of 100°C the shear per unit area was above 5.75 grams/mil² (a reasonable value). However, the second bond pull strength formed on Ag plated lead fingers, was dramatically reduced when the temperature was reduced from 250°C to 100° C.

For BGA (Ball Grid Array) packages, which require lower temperatures due to their plastic substrates, typical bonding temperatures are in the range of 125°-175°C. For these devices, acceptable second bond strength is obtained due to the gold coating of the leads which enhances the strength of these bonds. As discussed earlier, one of the key technologies that can assist wire bonding at low temperatures is high frequency bonding.

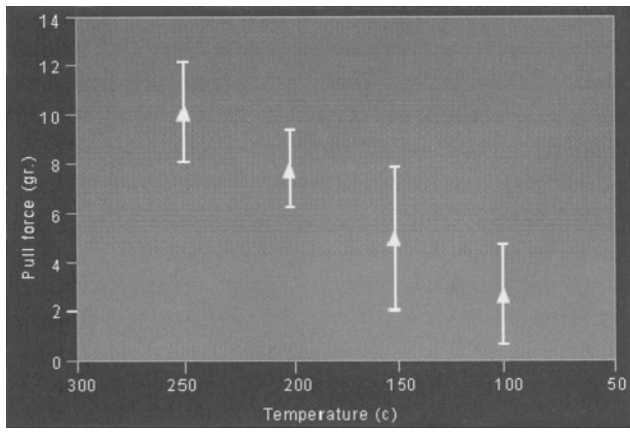


Figure 4.1.18 Stitch pull for BGA devices at different temperatures
[Courtesy: Kulicke & Soffa]

4.1.5 Bonding Time

Bonding time is the length of time the bonding tool is applying the ultrasonic energy to the wire. The longer the time greater is the amount of interfacial reaction. Usually the bond time is longer for ultrasonic Al bonding than for thermosonic Au ball bonding. In thermosonic Au ball bonding, the interfacial reaction is diffusion controlled. That means when the ball and the

Al metallization on bond pad are in contact for longer time, greater diffusion will take place and uniform alloying will occur at the interface.

From the figure 4.1.19, we see the bond time required for thermosonic ball bonding is about 20 milli seconds whereas the ultrasonic bonding with aluminum wire on the same bondpad requires longer bonding time. This is because the ultrasonic bonding is done at room temperature and it takes more time to form a reliable mechanically bonded interface between aluminum wire and the pad. The drawback of "longer bond time' is loss of productivity. Therefore usually on the manufacturing line, many engineers / technicians/operators use higher bonding temperature and keep the bond time short.

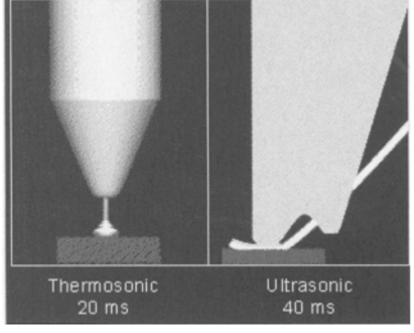


Figure 4.1.19 Bonding time

As discussed in the previous section, keeping the temperature high has a serious disadvantage, particularly in case of high lead count devices. Let us take an example of 208 lead PQFP package. After the first bond is formed, till the 208th bond is completed, the earlier bonds are exposed to high temperature. That means the first bond is exposed to high temperature for at least 25 to 30 seconds depending on the bond time during which time the interfacial reaction will continue and lead to the formation of intermetallic on the first ball bond. In order to prevent the intermetallic formation due to high temperature, it is necessary to keep the bonding time as short as possible. Similarly, longer exposure of BGA packages to high temperature may lead to warpage of the substrate.

Usually it has been observed that compared to bond force, bonding temperature and ultrasonic power, the bonding time is of lesser significance during the wire bond process optimization. The only exception being that, if high ultrasonic energy is employed, then very short bond time periods may be required.

4.1.6 Looping Parameters

One of the most important factors affecting wire bond yield has been the formation of the wire loop, that is, the profile of the wire loop between ball and the stitch bond. In fine pitch bonding technology, the thin and long wires have a greater tendency to form improper loop shapes, to sway, and to sag. Controlling looping parameters and optimizing the loop shapes for consistency for a particular device is a bonding engineer's challenge.

The problem of looping control is actually a very complex one on a typical circuit, because the length of each wire on a device is constantly changing. The loop profile depends on the Kink height, the reverse loop, as well as the trajectory of the bond head. For every loop profile, there is a safe loop trajectory. Below this safe trajectory, the wire has a tendency to buckle. Above this safe trajectory, the wire has a tendency to break, as shown in figure 4.1.20. On a manual bonder a skilled manual bonder operator is necessary for optimal looping control, and the operator is able to respond to the constantly changing conditions for loop formation. In the absence of human intervention, the new bonders have incorporated special wire looping algorithm where the wire loop is dynamically altered as the die height and wire length changes, thus maintaining a relatively constant loop height and shape regardless of wire to wire variations.

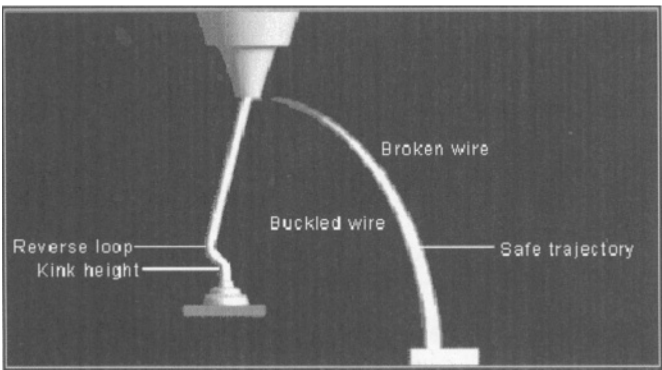


Figure 4.1.20 Kink height, reverse loop and bondhead trajectory effect on loop formation [Courtesy: Kulicke & Soffa]

If the loop is too high it may result in wire sagging, wire sweep, steep angle of approach to second bond and contact with the lid in a ceramic package. If the loop height is low, it may result in ball neck damage, taut (stretched) wire which may fail during thermal cycling, wires touching the die edge and wire touching the lead frame edge. Therefore control of loop height is necessary to improve wire bond yield as well as the reliability of the package.

Whenever a departure from the normal loop height or loop shape is desired, today's bonding equipment software allows tailoring of loops on an overall part basis, on an individual chip basis or on an individual wire basis. Depending on the packaging requirements, different loop profiles are used. As shown in figure 4.1.21, when the bond pads are close to the edge of the die, and the wire loops are long, a standard loop profile is used. However, when the bond pads are not close to the die edge, and the loop lengths are small, the loop profile is a worked loop profile.

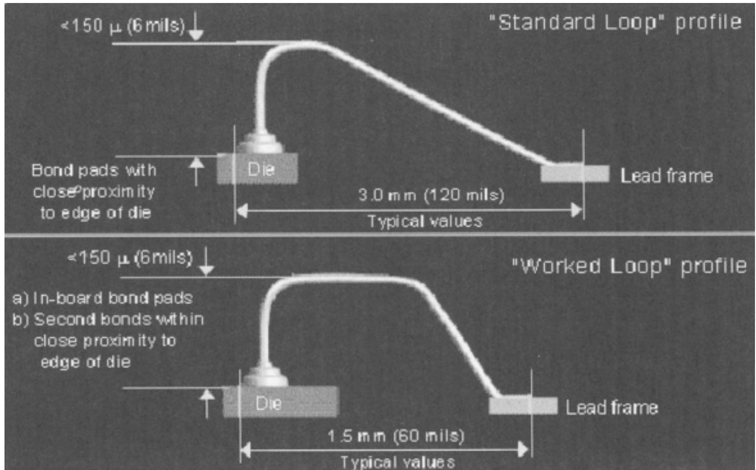


Figure 4.1.21 Loop profiles [Courtesy: Kulicke & Soffa]

To meet today's low loop requirements for fine pitch applications, we need precise and repeatable wire looping mechanism. This requires special algorithms and enhanced machine optics for maximum attainable yield. Since the bondpad pitch is getting smaller, the bonded wires must remain as

straight as possible. S-curves that exceed the specification will cause shorts and defects after molding. It is essential that the capillary on the bond head complete an exact trajectory between the ball and the wedge. Any disturbance in the trajectory can create a short between the sagging wires. In ultra fine pitch bonding, the looping trajectory depends on type of package that is being wire bonded. The looping trajectory for BGA and CSP packages is different from that of QFP packages. From figure 4.1.22 we can see that, in a QFP package where the lead frame is about the same height as the die, the loop trajectory is as shown in the figure, where as, on a BGA substrate the second bond is formed much below the die surface and therefore the looping trajectory is quite different. This will have an impact on the second bond formation as well as second bond strength.

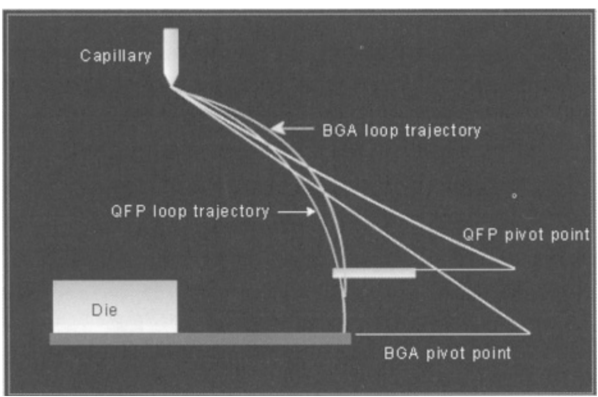


Figure 4.1.22, Looping trajectory comparison for QFP and BGA Packages
[Courtesy: SEMI]

New generation wirebonders have large libraries of standard loop shapes and capabilities. This enables them to process the latest packaging designs. Standard loop shapes include low loops, worked loops and BGA loops. Wires as long as 7.6 mm and loop heights as low as 100 microns are possible. In addition, options such as CSP looping, and more sophisticated BGA loop profiles, spider, and J-wire looping algorithms are also available.

4.1.6.1 Loop Control through Material Selection

In standard packages like SOP, PQFP and PDIP, the loop height is generally controlled by optimizing the equipment parameters such as kink height and reverse loop. In advanced thin packaging applications, in addition to controlling the machine parameters, the loop height is controlled by choosing the right bond wire material with a particular heat affected zone (HAZ) length. Shorter HAZ length gives shorter loop heights.

Wires that show very high strength at high temperature show short recrystallized region during the ball bond formation. As shown in figure 4.1.23, during the free air ball formation, if the re-crystallized region above the ball is long, it gives rise to high loop height and if the re-crystallized region is short, low loops are formed.

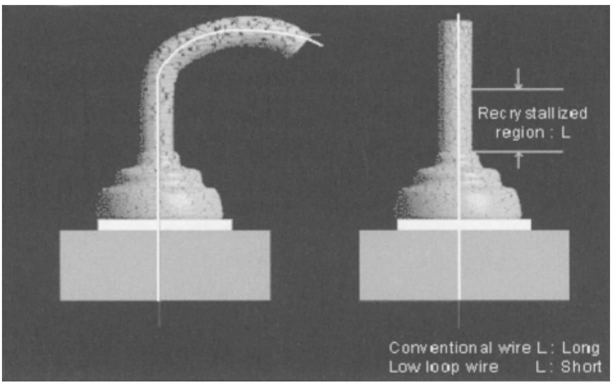


Figure 4.1.23 HAZ and loop height control [P-10]

The HAZ length for a particular gold alloy wire is also dependent on Electronic Flame Off (EFO) time and EFO current. As shown in figure 4.1.24, longer the EFO time, longer is the heat affected zone, and therefore higher is the loop height. During the free air ball formation, if the EFO current is high, the amount of HAZ is larger, even if the current is applied for a short time. This results in longer HAZ lengths and therefore higher loop height. The length of the HAZ depends on the type of wire material chosen. As discussed in the materials chapter, the HAZ length is controlled by

controlling the alloying elements and the grain size of the wire material. Usually, gold alloy wire materials with high breaking load at 250°C display shorter HAZ length.

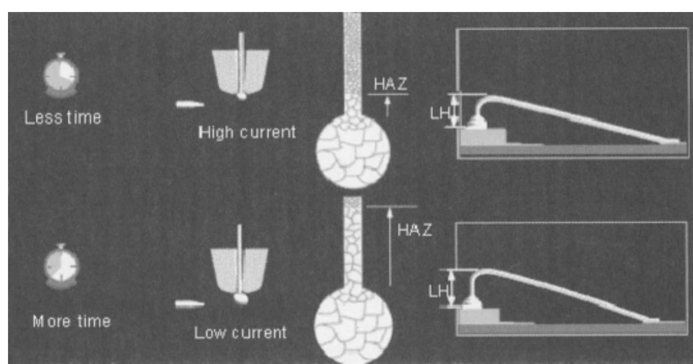


Figure 4.1.24 Effect of EFO time and EFO current on loop height
[VIEW-IN-CDROM]

From figure 4.1.25 we can see, the 25 micron gold wire with breaking load of 10 grams results in a loop height of 140 microns and a gold wire that has a breaking load of 6 grams gives a loop height of 200 microns.

Today, there are many wire materials that are available in the industry that can be chosen depending on the loop height requirement of the application. Here is an example of a 25 micron wire with different wire compositions, manufactured by one of the major bond wire supplier in the industry. For example NL3 type wire has a HAZ length of 130 micron, whereas the S1 type of wire has HAZ length of 260 microns. Figure 4.1.26 shows different HAZ length of different wires.

4.1.6.2 BGA Looping and Angle of Attack

During the loop formation in a BGA bonding process, the angle at which the wire approaches the lead finger (angle of attack) depends on the wire span as well as the loop height. From table 4.1.2 we can see that a 4.8 mm wire span makes an approach angle of 8.7°, where as 3.6 mm wire span makes an approach angle of 13.5°. This angle of attack that the wire makes

with the lead finger can also be controlled by choosing different loop options available with the equipment such as, standard loop or flat loop or worked loop.

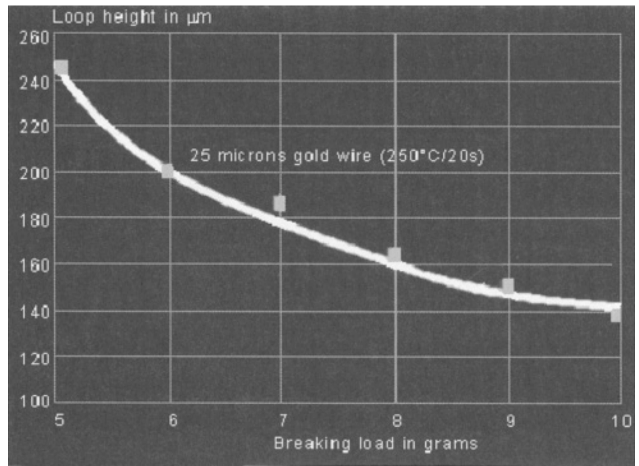


Figure 4.1.25 High temperature breaking load versus loop height [P-11]

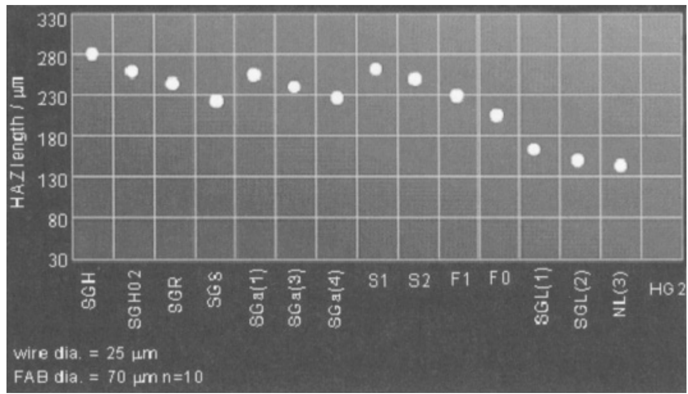


Figure 4.1.26 Different HAZ length of different wires [Courtesy: Sumitomo Metal and Mining]

4.1.6.3 Impact of Loop Profiles on Pull Values

The bond pull strength values of the second bonds on the lead finger depend on the loop height, the wire length and the angle of attack. If the device has inconsistent wire loop heights and loop lengths, the second bond pull values show a large variation and this will impact decision making during the process optimization. This issue will be addressed in greater detail in Section 4.2. (Process Optimization)

Table 4.1.2 BGA Looping [Courtesy: American Fine Wire]

Wire span (mm)	Loop height (μm)	β (°)
Long span (4.8 mm)	185	8.7
Medium span (4.1 mm)	185	11.6
Short span (3.6 mm)	183	13.5

4.1.7 Bondpad Metallization

Changes in the bond pad material and layers below the bond pad have altered the requirement for wirebonding. Different bond pad structures were investigated by statistically designed experiments to optimize bond strength and reliability. The ball shear test continues to provide the best measure of bond integrity, including failure mode information.

Despite its age, thermosonic gold ball wirebonding to aluminum metallization is still the dominant chip-to-package connection process. Though other processes like solder bumping are becoming widely used, gold ball bonding is expected to be used well into the future, particularly for lower-pad-count chips, where it has a cost advantage over solder bumps.

Thus the IC industry needs to make gold wirebonding continue to work reliably with IC and package interconnects as they continue to develop.

Because thermosonic gold wirebonding is such an old and trusted technology, there is a tendency to take its reliable performance for granted. However, the materials and structures to which the bonds are being made have changed dramatically since thermosonic bonding was developed, and they are continuing to change in an effort to make circuits denser and faster. To assure that the bonds are manufacturable and reliable, the effects of these changes on wirebonding must be understood and accounted for in the design of chip interconnects architectures, bonding pad structures, wirebonding setups, and packages. This section deals only with the mechanical reliability of the bond to the IC. The bond pad metal affects bondability as well as bond reliability . The factors that are crucial are:

- the types of bond pad metallization
- methods of preparation of bond pad metallization
- thickness of metallization
- surface hardness
- surface roughness
- cleanliness (Freedom from glass residues Oxide)

The bondability of a bond pad depends on the type of metallization, whether it is pure aluminum, Al-Si alloy, Al-Cu alloy, or aluminum-Cu-Titanium Alloy and so on. Similarly, the method of preparation of the metallization, such as sputtering, vapour deposition or CVD also impacts bonding. Other issues of concern are metallization thickness, surface hardness, cleanliness and reflectivity. The metal surface requirements for bonding are shown in figure 4.1.27.

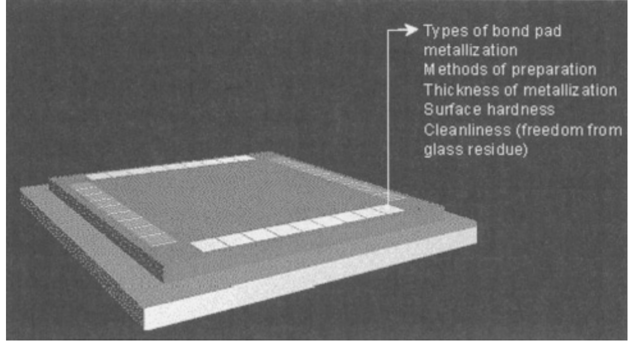


Figure 4.1.27 Metal surface requirement for bonding

Bondability is also affected by many structural parameters including: shape and dimensions of bonding pad, type of underlayer metallization, the number of underlayer materials, their thickness and the mechanical properties of the underlayer materials, integrity of underlayer interface (adhesion of underlayer materials) and the type passivation. These different factors are schematically shown in figure 4.1.28.

Let us review and discuss some of the above variables in detail to help us understand the effect of complexity of the bond pad metallization on the wire bonding process.

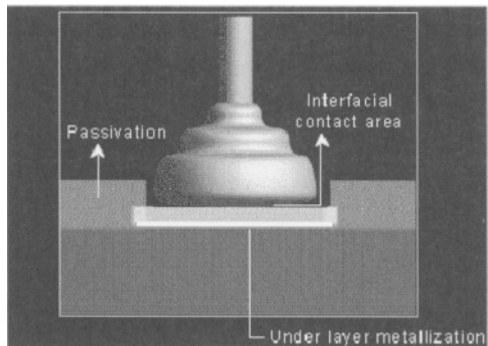


Figure 4.1.28 Bond pad structure parameters that impact bondability

4.1.8 Aluminum and Aluminum Alloys

Aluminum metal and its alloys are the most widely used conductor material in IC fabrication and the metal is used both as metallization on the bond pad and as the interconnection traces connecting all the transistors on the silicon chip. Al is predominantly used because of its high electrical conductivity and more importantly because of its ability to form a protective oxide layer on its top surface. For metallization although pure aluminum is seldom used (except in case of very high power devices), aluminum alloys and aluminum layered combinations with other metals has been the most widely used material for IC metallization, including the present day multilevel metallization structures. The features that make Aluminum so popular for metallization are:

- low sheet resistance
- good adherence to silicon oxide (SiO_2) and silicon nitride (Si_3N_4) passivation layers
- ease of metal deposition during wafer fabrication
- patternability
- good bondability
- easy availability and low cost

4.1.8.1 Compatibility of Aluminum Metal with Silicon Substrate

Why is Al metallization preferred over more conductive metals such as copper, silver and gold? To be able to understand this it is important to understand Al metal properties and interactions with Si and SiO_2.

Pure aluminum metal reacts readily with oxygen to form Al_2O_3. The energy of formation of Al_2O_3 is 399 kcal/mol as compared to 205 Kcal/mol for the formation of SiO_2. Therefore Al can reduce SiO_2 to Si by the reaction.

$$3\ SiO_2 + 4\ Al \rightarrow 3Si + 2\ Al_2O_3$$

When Al metallization is deposited on the silicon substrate, the Al atoms can react with the native SiO_2 that exists on the silicon surface. This reduction of SiO_2 by Al is very significant because it removes native SiO_2 existing on Si, leading to a better contact between aluminum and silicon and resulting in excellent adhesion between the Al metal and the silicon

substrate. This is also an important factor for the good adhesion to SiO_2 layers, which is a key property needed for metallization. Although the SiO_2 reduction reaction can take place theoretically even at room temperature, the actual processing of Al annealing is done at 400 - 450°C to ensure that complete reduction takes place.

Pure Al metal if used on silicon substrates gives rise to "Al spiking" problem, which is discussed in detail in the reliability chapter. Today, the industry uses Al-Si alloy and other Al alloys for wafer metallization. In the following sections, we shall discuss the important properties of Al alloys and other relevant materials used in multilevel metallization structures on a device.

4.1.8.2 Al-Si Alloy

Al-Si alloy is the most widely used metallization. The Si atoms are distributed uniformly throughout the Aluminum-silicon alloy matrix at high temperature. As shown in figure 4.1.29 as the alloy cools down, the silicon atoms tend to agglomerate, particularly at the silicon oxide interface, and grow themselves further to become large precipitates of Si, or as we call them 'silicon nodules'.

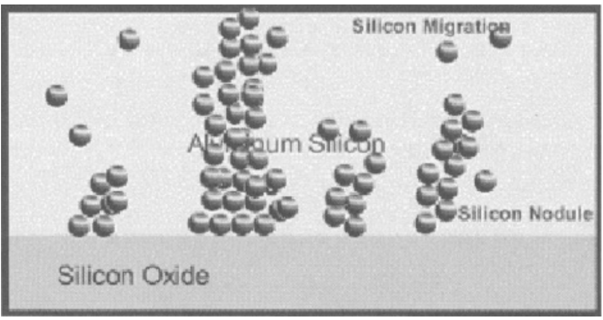


Figure 4.1.29 Silicon nodule formation [P-5]

Usually the Al-Si alloy composition contains approximately 1 to 2 percent of Si. If there is excessive silicon in the aluminum, it will precipitate and

form silicon crystallites or nodules on the bonding pad surface during heat treatment. These Si nodules can not only cause poor bonding but also potentially upset the atomic behaviour of the interconnects.

4.1.8.3 Aluminum-Copper

As interconnect dimensions shrink, current densities reach 10^6 A/cm² and the Al interconnects begin to fail due to a process called electromigration. And to minimize electromigration problem, Al-Cu alloys are used as chip metallization instead of Al-Si. Let us understand the phenomena of electromigration and the impact of use of Al-Cu metallization on wire bonding process.

4.1.8.4 Electromigration

Electromigration is the mass transport of a metal due to the momentum transfer between conducting electrons and metal atoms. Electromigration was discovered more than 100 years ago and it has been a problem ever since. As device features reduce in ultra-large-scale integrated circuits, current densities increase with the metallization layer complexity. These issues make understanding Electromigration (EM) essential to design more reliable bonding. A simple explanation of the Electromigration phenomena is explained in figure 4.1.30.

Under the influence of high current density, aluminum atoms are dragged by electrons. This atomic dragging creates voids (vacancy clusters) and cracks in the metallization as shown in the figure 4.1.30, these voids and cracks leads to an electrical open failure. The mass transport of the conductor materials is accelerated when the device is operating at high temperatures, and atoms move through grain boundaries, creating voids at one end and hillocks on the other [P-12].

Numerous research studies have been conducted to understand and to control electromigration. Some of the methods by which electromigration can be reduced include:

- decreasing grain boundaries (i.e. increasing grain size) and
- by reducing grain boundary diffusion by the introduction of a grain boundary pinning impurities such as copper

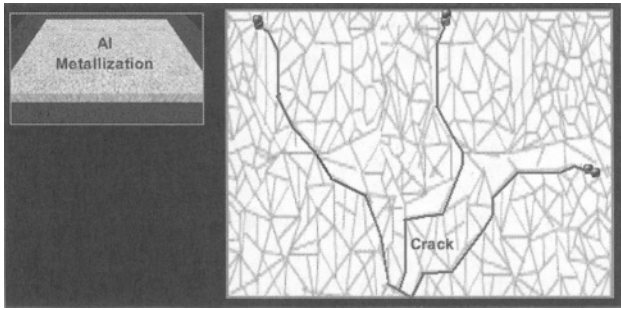


Figure 4.1.30 Electromigration

Copper is used to improve the electromigration resistance of the Al based interconnect. Cu enters the grain boundaries in Al and occupies several vacant sites. This reduces the grain boundary diffusion and hence the electromigration resistance is increased.

When copper is added to Al metallization, it can observed from the figure 4.1.31 that copper occupies positions along the grain boundaries. Under high temperature and high current density conditions, copper atoms act as diffusion barriers for the highly mobile aluminum atoms. By reducing aluminum diffusion, the electromigration resistance of aluminum metallization is increased. A typical aluminum alloy includes 4wt% copper and 1 to 2wt% silicon. Such alloys can increase the electromigration resistance significantly.

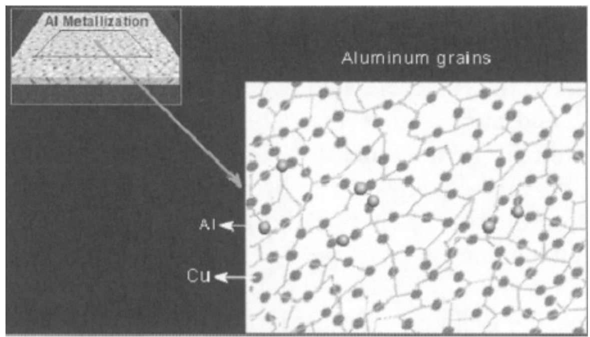


Figure 4.1.31 Copper atoms on the grain boundary

One of the key parameters to describe electromigration performance is the activation energy. The activation energy for electromigration of pure aluminum is 0.6 electron volts where as the activation energy for electromigration of alumium copper is 0.71 electron volts. And there fore the resistance to electromigration is much higher in the case aluminium- copper alloy. This is shown in figure 4.1.32.

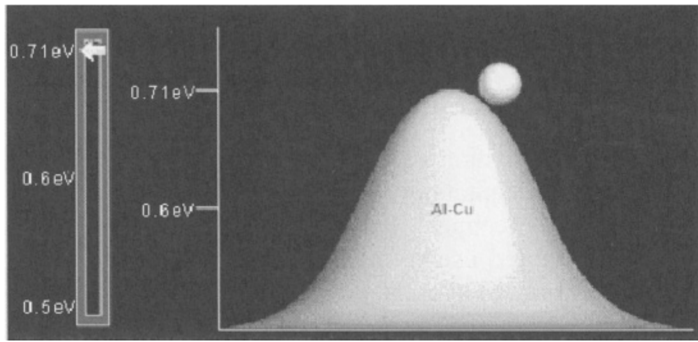


Figure 4.1.32 Activation Energy for Electromigration **[VIEW-IN-CDROM]**

At 1 μm passivation thickness, a reasonable estimate of MTF (Mean Time to Fail) at $1x10^6$ A/cm^2 at 150°C for the various aluminum alloys is given below.

Al+Si+Pd	20,000 hours
Al+Si+Cu	9,000 hours
Al+Cu	3,000 hours
Al+Si	600 hours
Al	150 hours

We can observe from the above table, that Al+Si+Cu is about 15 times more resistant to electromigration than Al+Si and about three times more resistant than Al+Cu [P-13].

The effect of copper content in aluminum on the electromigration lifetime has been investigated over a range of compositions and it is found that the lifetime increases with increase in copper content up to 4.0 percent copper.

This improvement is attributed to the $CuAl_2$ precipitates in the grain boundaries.

Copper atoms in the grain boundary not only act as diffusion barriers and minimize electromigration, they also attract aluminum atoms to form $CuAl_2$ precipitate as shown in figure 4.1.33. This preferential impetus to form $CuAl_2$ intermetallic compound reduces the mass diffusion of aluminum from one end to the other, and in this manner, minimize electromigration failure.

With further increase in copper concentration, there is little improvement in the electromigration lifetime.

This is because of retardation of the grain growth by the precipitate phase at high concentration of copper. The Copper content is limited usually to about 0.5% to 1.5% in the presently used aluminum alloys because:

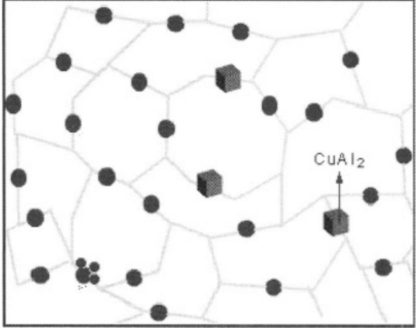


Figure 4.1.33 Formation of $CuAl_2$ pecipitate at the grain boundary

- the presence of copper in the aluminum metallization makes the plasma etch process more difficult because the reaction products of copper are not volatile at typical processing temperatures
- the Al-Cu alloys have increased susceptibility to corrosion in the presence of chlorine.

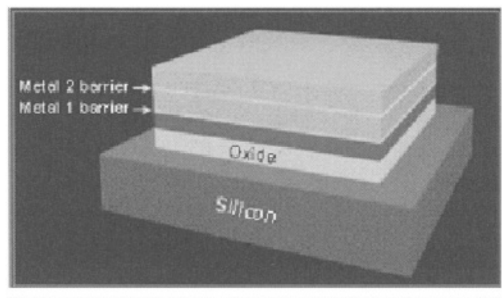
4.1.8.5 Al-Ti and Al-Si-Ti Alloys

The addition of titanium can further improve the electromigration resistance of the aluminum-copper-silicon interconnect system. These alloys obtained by both simultaneous sputtering of Al or Al-Si and Ti and by layering of Al-Si and Ti. They have been characterized with respect to composition, resistivity, hillock formation and other film characteristics. It is found that Al-Ti alloy does not yield smooth films while Al-Si-Ti does. The presence of Si yields to significant reduction in hillock formation. The addition of Ti, however, increases the resistivity of the alloys to about 4.5 - 5.5 μ - cm.

4.1.9 Under-Layer Metallization

In VLSI devices with very high integration, the interconnect metal structures are multi layered. That means underneath the bond pad there are extra layers of metallization. In figure 4.1.34 we can see an example of a vertical structure of bond pad with 2 metal layers and 2 barrier layers. Typically, these underlayer and cap layer metallizations are refractory metals/compounds. The most widely used being Ti, TiN, and Ti-W. These are conductors whose resistivities are not as low as that of the Al alloy; but they are more resilient to electromigration and stress voiding. The important features of the layered interconnects are:

- the under layer acts as a barrier layer between aluminum and silicon avoiding interaction and thereby preventing junction spiking and Si precipitation.
- the under layer provides a clean, uniform nucleating layer for aluminum which improves its step coverage and electromigration performance.
- the under layer and the cap layer reduce the effect of stresses in the underlying and overlying dielectrics on the interconnect.



Metal 2 - bondpad	1000nm AlSiCu
Metal 2 - barrier	100 nm Ti
Metal 1	500 nm AlSiCu
Metal 1 - barrier	Upper layer : 40...100 nm TiN Below layer : 40 nm $TiSi_2$
Polysilicon	250...350 nm
Oxide	400 nm

Figure 4.1.34 Vertical structure of bond pads

4.1.9.1 *Barrier Layers*

The following requirements are important to be satisfied by the barrier layers to act as under or cap layers. Obviously, those materials which meet most of these requirements are preferred.
These layers should:

- provide a good barrier against interactions between Al and Si/SiO_2 and their thickness preferably should be less than 2000 A°
- not react excessively with Al so as to lead a large increase in resistance
- not degrade the electromigration characteristics of the interconnect; if any, the electromigration resistance should increase
- adhere well to SiO_2 or Si_3N_4 films
- have good adherence of Al alloy on them
- be easily dry etched along with the Al conductor
- have deposition processes compatible with those used in IC technologies; and
- have low stress

The under layers and cap layers that are most commonly used are Ti-N and Ti-W refractory materials. It is found from various investigations that Ti-N and Ti-W are good barriers against Si diffusion into Al. These barrier layers are used for both horizontal and vertical interconnects. The important properties of these barrier metals and their interactions with other materials used in multilevel metallization are described below.

4.1.9.2 Titanium - Tungsten

This is an alloy of titanium and tungsten. The commonly used Ti-W contains about 10 wt% of Ti in the Ti-W film. The Ti-W films usually consist of columnar grains of tungsten without any free Ti phase. The titanium is in solid solution with some tungsten atoms distributed at the grain boundaries. The distribution of titanium is important for improving the barrier properties of Ti-W. The resistivity of Ti-W films is in the range of 50 to 80 μ - cm.

4.1.9.3 Titanium Nitride

Stoichiometric Ti-N has 50 atomic % each of N and Ti concentrations more than 50%, the excess N exists inn solid solution Stoichiometric Ti-N. Ti-N films have columnar grains with resistive range **50-100 μ cm**. The step coverage of TiN is similar to that of T contact resistance of Ti-N with p^+ and n^+ Si is large. To reduce the resistance a thin Ti layer is deposited prior to Ti-N deposition.

4.1.9.4 Titanium

Pure Ti is often used as an underlayer and for contact metallization on top of which a Ti-N layer is either formed in-situ, or deposited. Ti helps in reducing the interfacial oxide layer, improving the step coverage and adhesion of Al and Al alloy layers.

During the bonding process, these under layer metallizations may sometimes peel off if the adhesion between the layers is not good. It is also important to recognize that the bonding parameters have to be optimized according to the type of the barrier metallization and thickness of underlayer metallization that is present below the Al metallization. It has been observed that polysilicon layers under the bond pad tend to crack if the bond force is excessive.

4.1.10 Microstructure of Bondpad Metallization

Thin films of pure Al and Al alloys deposited by conventional physical vapour deposition processes are polycrystalline in all dominant orientations. The grain sizes and their distribution depend on the method of deposition and the process conditions used. The annealing of Al and Al alloy films generally increases the average grain size. Depending on the deposition techniques and annealing condition, the aluminum metallization on the bond pad can have variable grain sizes, as shown in figure 4.1.35. The grain orientations can also be different. This impacts some critical properties such as the hardness of the thin films, and reflectivity of metallization.

The orientations of the Al and Al alloy films obtained by different methods of deposition are different. The most dominant orientation in Al, AlCu and

AlSiCu films deposited on Si or SiO_2 is <111>. Small amounts of <200> orientation are also observed. The relative amounts of <111> and <200> orientations are dependent on deposition/annealing conditions and grain growth/suppression due to residual gases.

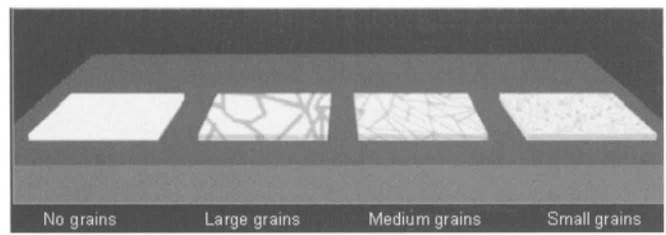


Figure 4.1.35 Schematic representation of aluminum grain Sizes

The grain size distributions, in as-deposited films and after anneal are narrower in AlCu and AlSiCu films are compared to pure aluminum films. TEM analysis of AlCu and AlSiCu films have shown that, when the copper content is in the range 0.8 to 2.0 wt%, precipitates $CuAl_2$ or copper-rich aluminum are found to be distributed in the films after annealing, predominantly at the grain boundaries

The sizes of these precipitates and their numbers increase with increase in copper content. In case of aluminum copper metallization, microstructure of the film contains aluminum grains and aluminum copper intermetallic compounds in the grain boundary Ref figure 4.1.33. The size of these precipitates and the number of these precipitates affect the mechanical, chemical and optical properties of the film [P-14].

4.1.10.1 Reflectivity

The specular reflectivity of Al and its alloy films is used as a measure of the film quality. The reflectivity of the deposited film depends on the grain size and grain orientation of the Al metallization. This in turn depends on the method of deposition and the deposition conditions. In today's automatic wire bonding machines, pattern recognition systems are used for locating and precision alignment of the chip and accurate positioning of the bonds. The

PRS is significantly affected by the reflectivity of the surfaces. It can be observed from the figure 4.1.36 that when the grain sizes are small, the reflectivity is low, with medium grain sizes, the reflectivity is better whereas with large grain sizes, the reflectivity is high. We get maximum reflectivity when there are no grain boundaries in the metallization. The reflectivity also depends on grain orientation. The reflectivity of a deposited Al alloy film can affect the PRS during the bonding operation.

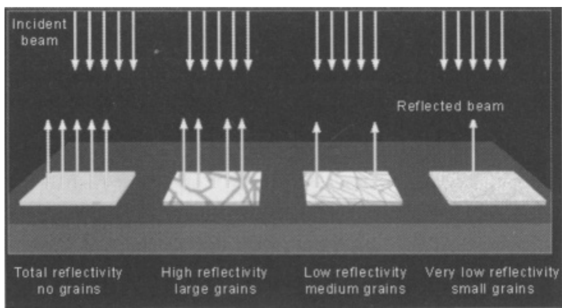


Figure 4.1.36 Reflectivity due to various grain sizes. **[VIEW-IN-CDROM]**

4.1.11 Alloying Elements and Impact on Bondability

The wire bondability of aluminum thin films depends on the alloying element. The Al alloys can significantly alter the bondability of the chip and force the development of new or optimized bonding parameters to ensure interconnect reliability. For example, copper is one of the most efficient hardening agents for aluminum. Such hardening effects are strongly dependent upon the degree of precipitation of the alloy as well as upon the nature and distribution of the precipitate. Thus, based upon the above-mentioned effects, one should expect a strong dependence of film deposition and process history on the resulting film hardness. This would be expected to have a marked effect upon the conditions required to effect a good thermosonic bond to the film.

4.1.12 New Aluminum Alloys for Bondpad Metallization

Several new aluminum alloys and different treatments of alloys have been suggested in the last few years to overcome various reliability problems of aluminum based metallizations.

The features of some of the important once are discussed below. It must however be remembered that in most of these cases the improvements claimed are only in certain characteristics and complete characterizations have not been done yet [P-13].

4.1.12.1 Al-Si-Pd

The Al-Si-Pd alloy has been proposed as an alternative to Al-Si-Cu. AlPd alloys have a high creep strength which leads to lower grain boundary diffusion of metal atoms. It also has high corrosion resistance. Electromigration and stress migration performance of Al-Si-Pd is also found to be superior to that of AI-Si-05%Cu.

4.1.12.2 Al-Si-Cu Alloys Doped with Hafnium and Boron

Addition of a few hundred ppm of Hafnium (Hf) and Boron (B) has been found to improve the performance of AlCuSi alloy interconnect material, without changing the manufacturing feasibility (same etching characteristics). The hillock formation is suppressed considerably. The electromigration lifetime improved by more than two orders of magnitude by addition of Hafnium and Boron. The void formation due to stress migration is also found to be greatly suppressed.

Aluminum-Samarium (Sm) Alloys: Al-Sm alloys are attractive for metallization because of the low solid solubility of Sm in Al which leads to low resistivity (about 3 μ -cm after anneal at 450°C). Al-1%Sm alloys also exhibit low hillock growth.

Al-Yttrium (Y) Alloys: Just as in the case of Al-Sm alloy, the AlY alloy is also found to be impressive from the point of its resistivity. Upon anneal at temperatures above 300°C, the resistivity of Al-0.7%Y alloy film is found to decrease to values very close to that for pure Al(~2.9 μ -cm). The addition of small amounts of Y is also sufficient to minimize the generation and growth of hillocks.

Corbon-Doped Al: Al films deposited by magnetron-plasma CVD and doped with carbon have shown superior characteristics in some respects. The in-situ carbon doping suppresses the growth of Al crystal grains, hillocks and spikes. Electromigration lifetimes are one order of magnitude higher than that of pure Al.

The resistivity is significantly higher than pure aluminum in as-deposited films. Resistivity decreases considerably after annealing at 450°C for 30 minutes. Beyond a carbon concentration of 10%, the resistivity increases steeply due to the formation of Al_4C_3.

Fluorine incorporation in aluminum: Incorporation of very small amounts of Fluorine (<0.1 atomic %) in aluminum and AlCu films is found to reduce the hillock formation considerably. The Fluorine incorporation is achieved by ion implantation with a dosage of about 10^{15} per cm^2, followed by annealing. At high dosages Fluorine incorporation gives rise to a significant reduction in hillock density. This is attributed to the reactive nature of Fluorine. The highly electronegative Fluorine forms much stronger chemical bond than Aluminum with itself.

Al-Scandium (Sc) Alloy: This new aluminum alloy containing 0.15% Sc has been proposed recently and characterized with respect to stress migration and electromigration. It is found that Sc addition to Aluminum gives rise to a much lower grain size as compared to AlSiCu, even after annealing. However, the stress migration resistance is far superior to that of AlSiCu. The electromigration lifetime is also enhanced by about one order of magnitude. It is known that, in general , smaller grain size is good for avoiding stress migration but gives poor electromigration resistance. But, it is also not clear how the AlSc alloy with smaller grain size has good electromigration resistance. It may be due to the formation of Al_3Sc or Sc precipitates in the grain boundaries [P-14].

4.1.13 Alternate Bondpad Metallizations

Semiconductor manufacturers's major challenge is how to increase chip speed beyond 1GHz. The overall speed of large, high density chips is not limited by transistor speed but by the on-chip “wires” that connects them. Specifically, it’s the resistance of the conductors and the capacitance (C) of

the insulators that together cause what are known as "RC" time delays, which limit chip speed. On-chip connections will present RC delays whether the underlying transistors are silicon - or GaAs- based.

To overcome these limitations, most believe it will be necessary to make a switch to conductors with lower resistance and insulators with lower dielectric constants (abbreviated by "k" or "e"). Copper, for example, is seen as the most promising alternative to aluminum.

The semiconductor industry - highly conservative by nature - will use aluminum based approaches as long as it can, possibly going to new Al-based schemes, such as aluminum alloy metallurgies, aluminum reflow, aluminum CVD or epitaxy- aluminum. Plasma-assisted aluminum PVD is another possibility.

In the long run, the industry's need for speed will force a switch to copper and to low k dielectrics. Before that can happen, however, decision makers at semiconductor manufacturers will have to be convinced that these new materials will provide better device performance, equal reliability and acceptable yield. When the technologies move to 0.18 μm regime and below, alternate metallization based on metals having resistivities lower than that of Al are needed to minimize the contributions of the interconnects to the speed performance in the ICs.

4.1.13.1 Cu-Based Metallizations

In the last few years extensive research has been carried out on copper based metallization. Most of the research on Cu in the last few years has been on the development of interconnect structures with appropriate barrier metals/adhesion promoters, and deposition techniques. Copper based metallization is discussed in greater detail in chapter 7

4.1.13.2 Gold-Based Metallizations

Gold based metallizations are used extensively for ohmic and Schottky contacts to compound semiconductor devices. Gold is attractive for metallizations because of low resistivity and superior electromigration performance. However, these films also require a barrier layer to prevent diffusion into the underlying layers or devices and to prevent void formation in Au at high temperatures.

4.1.13.3 Metallization for GaAs Devices

The metallization of gallium arsenide is a significantly more difficult problem. Metallization of GaAs can form either ohmic contacts or schottky barriers. Because GaAs decomposes into Ga and As_2 gas at 590°C, the formation of metal contacts is especially difficult. Similarly, the schottky barrier height on n-type GaAs is large (~0.8eV) and essentially independent of metallization type. $AuGe_2$ metallization schemes have formed the most stable GaAs contact material.

Bonding GaAs chip is as difficult as producing ohmic contacts with the metallization. The different bond pad alloys as well as the brittle nature of the semiconductor material itself (including thinned down die for improved performance) make selection of bonding parameters, especially force, extremely critical for successful bonding.

4.1.14 Metallization Deposition Technology

The metallization deposition technologies have an impact on the microstructure of the bond pad metallization. In this section the different technologies used for the deposition of types of conducting films will be discussed. Since aluminum is the most dominant metal in these metallization most discussion is on aluminum and aluminum-alloys.

Thin films of aluminum or aluminum alloys deposited primarily by two techniques, viz.,

- physical vapor deposition (PVD)
- chemical vapor deposition (CVD)

4.1.14.1 Physical Vapor Deposition (PVD) Technique

In the PVD technique, aluminum or aluminum alloys in bulk form, is used as the target. From this source, atoms of aluminum and aluminum alloys are transported to the substrate where they deposit on the surface, layer by layer to form a thin film. Two of the widely used technologies adopted in the PVD process are: electron beam (e-beam) evaporation and sputtering

In the electron beam evaporation technique, the aluminum or aluminum alloy atoms are produced by evaporating the source by heating it with an electron beam. As seen in figure 4.1.37(a) in physical vapour deposition, the aluminum target is heated to high temperature, using an electron beam. The aluminum gets vaporised, and the vaporised atoms get deposited on the silicon substrate as shown in figure 4.1.37(b). The microstructure of the vapour deposited film (bond pad) shown in figure 4.1.37(c) depends on the rate of deposition as well as the substrate temperature.

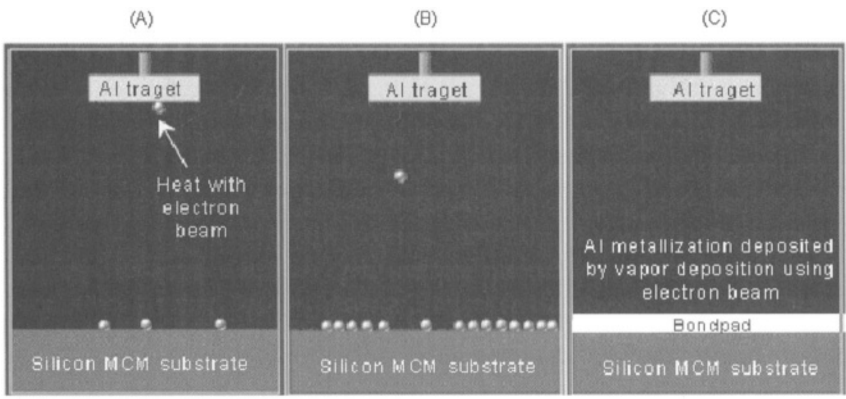


Figure 4.1.37 Physical vapor deposition on silicon substrate or MCM substrate

4.1.14.2 Sputtering Technique

In physical vapor deposition using sputtering technology, a high energy beam of argon atoms bombard the aluminum target, and dislodge aluminum atoms from the target. These sputtered atoms deposit on the silicon substrate and grow to form a thin film metallization. Usually, sputtering is a more preferred technique for aluminum deposition.

Of the two technologies discussed above, sputtering is the preferred technique for Aluminum deposition in VLSI technologies because of the following features:

- the composition (stoichiometry) of the target is closely reproduced in the deposited film.
- deposition rates are higher than in evaporation
- refractory metals like W and Ti films having high temperatures can be sputter deposited which are difficult to evaporate

4.1.14.3 Chemical Vapor Deposition (CVD) Technique

More recently, chemical vapor deposition technique is being used for metallization deposition. In CVD, the source is usually a compound containing Al. The common form of CVD is MOCVD where the MO stands for metal organic meaning the source is organo-metallic in nature.

In chemical vapor deposition, highly reactive organo-metallic compound of aluminum in gaseous form is introduced into the chamber as shown in figure 4.1.38. The molecule compounds are transported in vapour phase to the surface of the silicon substrate and the molecules undergo chemical reactions on the substrate at elevated temperature and under special ambient. These gaseous molecules deposit on heated silicon and decompose. Aluminum atoms, which are generated in these reactions, get deposited on the Silicon substrate to form the thin film and the organic molecules escape [P-12].

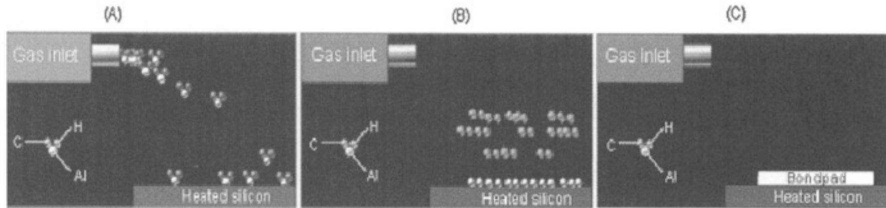


Figure 4.1.38 Chemical vapour deposition of bond pad metallization **[VIEW-IN-CDROM]**

4.1.15 Passivation Etching

The purpose of pad etch or passivation etch is to remove the passivating dielectric over bonding pads so that electrical connections can be made to them. Most passivation schemes use plasma deposited, (also called plasma enhanced) nitride (PEN) or phosphosilicate glass (PSG), or layered

combinations of the two. The combination of these two materials is intended to hermetically seal the die and provide a barrier to mobile ions. The passivation covering the bond pad area is shown in figure 4.1.39.

The passivation layer is etched to expose the bond pad. Depending on the type of passivation, dry plasma etching or wet chemical etching is used.

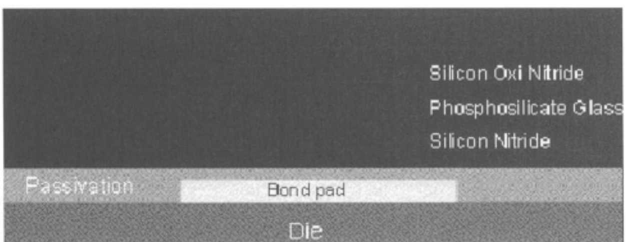


Figure 4.1.39 Bond pad completely covered with passivation

During passivation etching, both PEN and PSG are etched in fluorine based chemistries. The pad etch or passivation removal is done with flourine plasma, with equivalent flows of CHF_3 and O_2, as shown in the figure 4.1.40. This process exposes Al metallization on the bondpad for wire bonding.

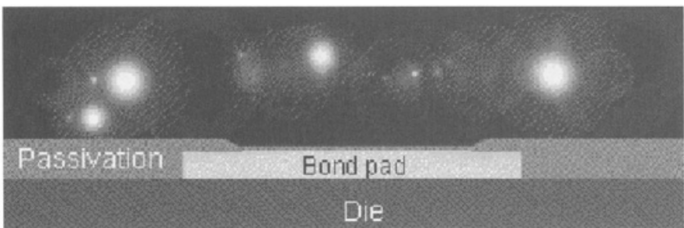


Figure 4.1.40 Plasma etching of the passivation

4.1.15.1 Etching and its Effect on Pad Pitch

Because bonding pads are large, critical dimensions (CDs) of the bond pad are not as critical as the interconnect lines on the chip. Because CD requirements are so lax, pad etch is often thought of as being trivial during

wafer fabrication. This has resulted in inconsistent pad openings and variable pad pitches, which is a serious concern in fine pitch ball bonding applications.

4.1.15.2 Passivation Residue

If low energy plasma is used and duration of plasma is short, it results in under etch of the passivation and leaves residual passivation on the bond pad resulting in bondability problems. The crucial problem to recognize here is that, even if a thin passivation residue is left on the bond pad, it is not at all easy to detect or to identify the residue. The residual passivation is shown in figure 4.1.41.

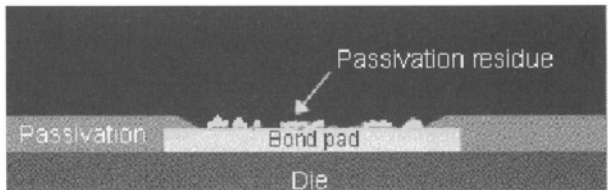


Figure 4.1.41 Passivation residue due to incomplete plasma etching

To make sure that there is no passivation residue, usually, the wafer back-end engineers tend to over etch during pad etch operation. Even the most experienced etch engineers in the wafer fab have had problems with pad etches at one time or another. For example, to increase wafer fab throughput, high powers are used to achieve fast passivation etch rates. High power results in high bias and high ion bombardment energies. Excessive ion bombardment tends to degrade the exposed metal surface, and sometimes results in embedding of fluorine atoms in the bond pad as shown in figure 4.1.42. In severe cases, over etching may also result undercutting of passivation.

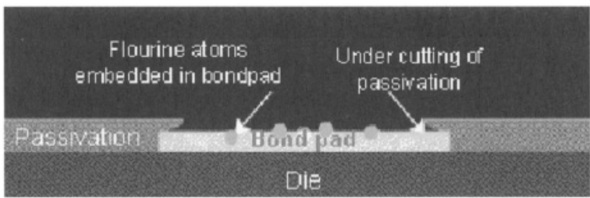


Figure 4.1.42 Flourine atoms embedded in bondpad

The surface of the metal is altered after a pad etch forming aluminum fluorides on the surface or by roughening the surface sufficiently to cause formation of relatively thick layer of (native) aluminum oxide. This has been found to result in unreliable wire bonds. Undercut of the PSG can cause reliability problems if it opens pathways for mobile ions to migrate into underlying layers.

4.1.16 Bondpad Contamination

Surface contamination, on the bond pad, has been cited often as source of bonding problem. The sources of contamination are: residual photo resist, water, corrosion products, tarnish, oxide layer, solvent residue and passivation residue. No real time detection methodology exists to identify the contamination and this makes the problem more severe. The same is true for bond pad metallization where pure aluminum is alloyed with copper, titanium, silicon, palladium and many other types of metals. The addition of these elements affects bondability due to formation of oxide layer characteristics of the alloy.

4.1.17 Method for Characterizing the Bondability of Chip Metallization Surfaces

Tarnish films or oxide layers on metallization surfaces have been known to cause degradation in bonding. If the tarnish films are insulating and thick enough so that their breakdown voltages can be measured, this breakdown

voltage measurement can be used to characterize the bondability and bond reliability. To perform such a measurement on a small part of the metallization surface, one can use a pair of microprobes, a thin gold wire having a ball terminal, and the other tungsten whisker.

The bondability of a metallization surface can be characterized by measuring the breakdown voltage of contaminating film or oxide on the metal surface. The schematic setup for measurement of surface breakdown voltage is shown in figure 4.1.43.

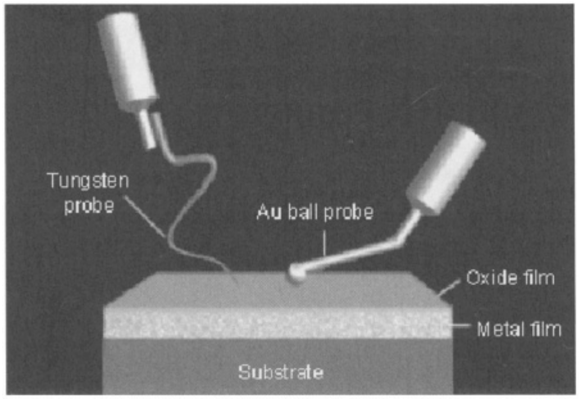


Figure 4.1.43 Experimental setup for measurement of surface breakdown voltage [P-15]

The measuring probe uses is a 25 micron diameter gold ball on the surface of the oxide film and a hard tungsten probe penetrating through the oxide film making electrical contact with the underlying metallization. The breakdown voltage (BV) of the surface tarnish film is measured with a diode curve tracer. Depending on the metal, it has been observed that, higher the oxide thickness, higher is the breakdown voltage.

Oxidized films of platinum, aluminum, titanium and nickel have been tested and it was observed that Pt did not show any significant oxidation, aluminum oxidation stopped after the initial layer has been formed where as both nickel and titanium showed parabolic growth rate.

In figure 4.1.44 we can observe that, when platinum thin film is heated at 500°C, even up to 30 minutes, we see no change in breakdown voltage. This

indicates no oxide growth. However, when we measure breakdown voltage of Titanium, heated at 500°C for 5 minutes, 15 minutes and 30 minutes, we can see that the breakdown voltage increases as a function of time. This indicates parabolic growth rate of oxide. Similar breakdown voltage measurements can be made to understand oxidation behaviour of metals and oxide thicknesses of metals. It has also been seen that the bondability of the gold wire to the Al film corresponds to the BV. Higher the BV, poorer is the bondability of the surface. This simple non-destructive method has been used for inspecting the surface condition of thin-film metallization on very small areas of wafers, chips or semiassembled components; the bondability of Au and Al wire to Al films and to understand the reliability of Au wire bonded to Ag-plated metal lead-frames.

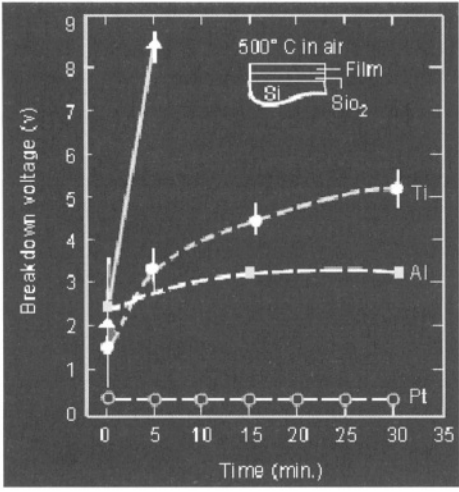


Figure 4.1.44 Surface breakdown voltage measurement at 500°C using positively polarised gold ball [P-15]

4.1.18 Hardness Measurement of Aluminum Bond Pad

If aluminum metallization is produced with variable hardness, then wire bonder parameters such as ultrasonic power and force must be correspondingly adjusted to create a bond with the same strength and

dimensions. If the wire bond equipment parameters are not changed to account for incoming hardness variability, there will be a change in the strength and geometry of the wire bonds. Therefore in fine pitch applications, it is imperative that the Al thin film hardness must be controlled and monitored. Film properties, which are often quite different from bulk properties, are difficult to measure with standard micro hardness testers such as Knoop and Vickers Hardness Testers, for several reasons. Even the lightest loads used by these testers can be large enough to either cause interactions with the underlying substrate or puncture the film entirely. In addition, inaccuracies of the tip geometry and optical measurements of the indentation size increase the error of those tests, especially with small loads.

4.1.18.1 Hardness Measurement with Depth Sensing

Today, indenters with increasingly accurate tip geometries are commercially available. They can apply lighter loads than standard micro-hardness testers. These indenters are also "depth sensing" so that optical measurement of indentation size is not required. With such tools and using data analysis software, accurate measurement of the mechanical properties of very thin films is possible. Where ever surface hardness is important for given application, depth sensing indentation may be the only way of making such measurements [P-16].

4.1.18.2 Continuous Loading Technique

The continuous loading technique is the most common method for measuring the properties of materials by all depth sensing indentation instruments. Hardness and elastic modulus measurements of metals such as copper leadframes and aluminum bond pads have been performed using this technique.

Typically, in depth sensing mechanical property measurement, a Berkovich triangular-base diamond pyramid indenter with a 65.3° face angle is employed. Microscopic measurements of the indentation are not required, because the shape of the indenter tip is known. In the continuous loading mode, a piezoelectric ceramic slowly drives the indenter tip into a sample and measures the penetration depth, at a series of force increments until the maximum desired force is reached. The sensor senses the amount of depth at

a particular face. The indenter will hold at the maximum load for a preset amount of time before unloading in a similar manner. Figure 4.1.45 shows depth sensing technique for hardness measurement.

The depth sensing is done in two different modes, while loading and while unloading. The maximum force is chosen so that the corresponding depth is no more than about one third of the film thickness. To a first approximation, this ensures that no substrate interactions affect the measured mechanical properties of the film. The measured indentation depth is comprised of both an elastic component and a plastic component.

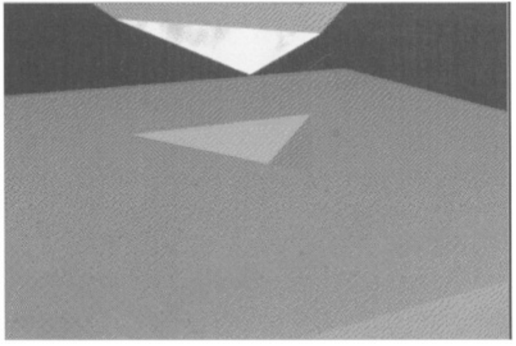


Figure 4.1.45 Depth sensing technique for hardness measurement
[VIEW –IN-CDROM]

The plastic depth alone is required by definition to calculate the hardness and elastic modulus of a material. There are two accepted methods for extrapolating the plastic component of depth from the initial slope of the unloading curve. The first method, known as the Doerner-Nix approximation, contends that if the initial portion of the unloading curve is linear, then the slope can be extrapolated to zero force, and the corresponding depth is the plastic depth. For many materials, however, the assumption of linearity is poor, and a curve fit better describes the initial unloading curve. This is the essence of the recently developed Oliver-Pharr method. Most depth sensing indentation analysis programs contain both techniques. Once the plastic depth is determined, hardness and elastic modulus calculations are straightforward [P-16].

4.1.18.3 Theory behind Thin Film Hardness Measurement

Hardness, defined as resistance to plastic deformation, is given by the formula:

$$H = F/A$$

where H is the hardness, F is the load (force) and A is the projected area of contact at maximum penetration. For an ideal Berkovich indenter

$$A = 24.5\, h_p^2$$

where h_p is the plastic depth. When the tip geometry correction factor is taken into account, h_p is replaced with the effective plastic depth, h_{eff}. Hardness is calculated and expressed in units of GPa. However, one can also express the hardness in Vickers Hardness Number (VHN), because the geometry of the Berkovich indenter is similar to that of a Vickers indenter.

Using the depth-sensing indentation method one can measure mechanical property of films ranging from hard oxides and nitrides to soft polymer coatings. This depth-sensing indentation method can also be used for measuring the elastic module of thin films [P-16].

4.1.18.4 Polyimide Die Coat Characterization

In many semiconductor devices, polyimide passivation or a polyimide die coat is used. During bonding, the bonds come in contact with the polyimide and the properties of the Polyimide may affect the bonding process. Depth-sensing indentation technique has been used to measure the hardness, elastic modulus and adhesion of polyimide die coat samples to determine whether variation in the mechanical properties of polyimide affects bond performance. [P-16]

4.1.19 Lead Frame and Substrate Metallization

After the first bond is formed on the bond pad on the chip, the second bond is placed on the lead finger on the package. The bondability of the wire and the reliability of the bond interface depend on the substrate metallization.

The substrate can be a leadframe, a ceramic or polymeric substrate. The lead frame used in either a plastic package or a cerdip package is made of a copper alloy or Alloy 42(iron-nickel alloy). In both these cases, the surface of the lead finger on the leadframe will have thin oxide layer as shown in figure 4.1.46. This oxide layer is a hindrance to good bonding. Similarly in a multi layer ceramic package, the Tungsten metallization can not be bonded with Gold or Aluminum wire due to the presence of an oxide layer.

Therefore careful selection of the final bonding metallization is absolutely necessary for lead frames used in plastic packages, polymeric substrate used in BGA and CSP type packages and ceramic substrates.

In this section we shall discuss in detail the different metallizations used for plating the lead finger, the impact of plating process on bondability, the morphology of the plated metallization and its effect on bondability and some of the analytical techniques used to characterize the metallization properties.

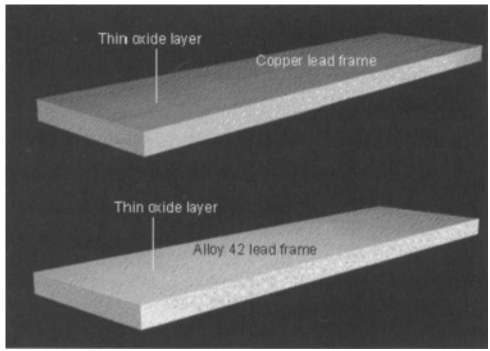


Figure 4.1.46 Thin Oxide Layer on Leadframe

4.1.19.1 Substrate Metallizations

The lead finger metallizations will be dependant on the package construction, whether it is a plastic package, a hermetic package, a cerdip package, a hybrid substrate or a special type of premolded package. The type of metallization on the lead finger is also determined by the bonding technology used for interconnection, thermosonic or ultrasonic. Let us review below different packaging technologies and the types of metallizations used. Majority of the lead-frames used for plastic packages are silver plated. The silver plating on copper leadframe usually has an undercoating of nickel, chromium, palladium or titanium. The silver plating on copper lead frame is schematically shown in figure 4.1.47. Usually the

thicknesss of the Ag metallization is about one micron with a 2 to 5 micron Ni metallization as under layer.

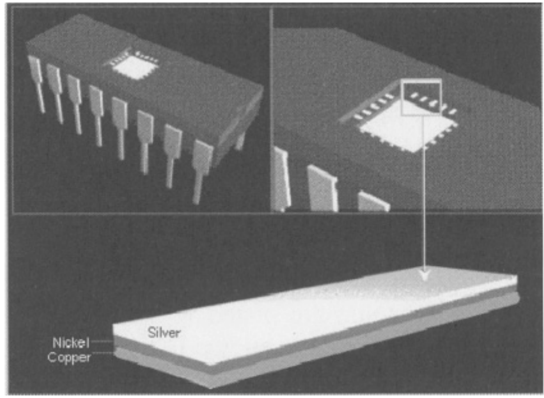


Figure 4.1.47 Plastic package – silver plating on the leadframe

Figure 4.1.48 shows a bond finger in a multilayer ceramic package which consists of top layer of gold with an under layer of nickel and tungsten metallization. Usually, the thickness of the gold is about 1 micron or 40 micro inches.

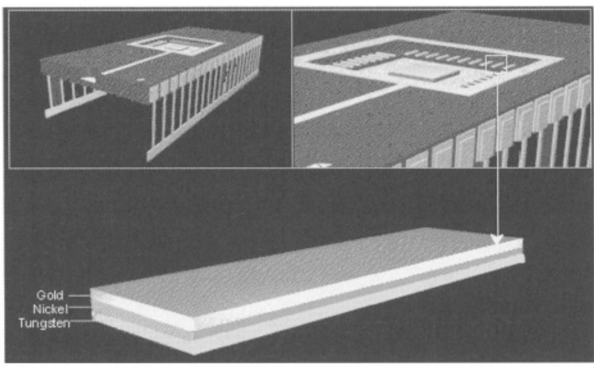


Figure 4.1.48 Layers of metallization on the leadfinger of a ceramic package

Hybrids packages or Multi Chip Modules based on ceramic substrate technology have thick films of Au or Pd-Ag. Hybrid substrates where an IC chip needs to be wire bonded have thick high temperature fired gold film as the bonding finger. The thick film is formed by screen printing and firing at temperatures around 900 C. The bondability of the Au thick film traces on the hybrid substrates depends on the thick film additives and porosity in the fired thick film. In hybrid applications, palladium-silver metallization is also used for wirebonding applications.

Cerdip packages are ceramic packages with glass sealants. A lead frame made of alloy 42 is sandwiched between the top and bottom ceramic layers with a hermetic glass sealant. The alloy 42 leadframe have aluminum metallization on the lead finger as shown in figure 4.1.49. Premolded plastic packages have lead frames that are plated with Gold or Silver on the lead finger with an underlayer of nickel as shown in figure 4.1.50.

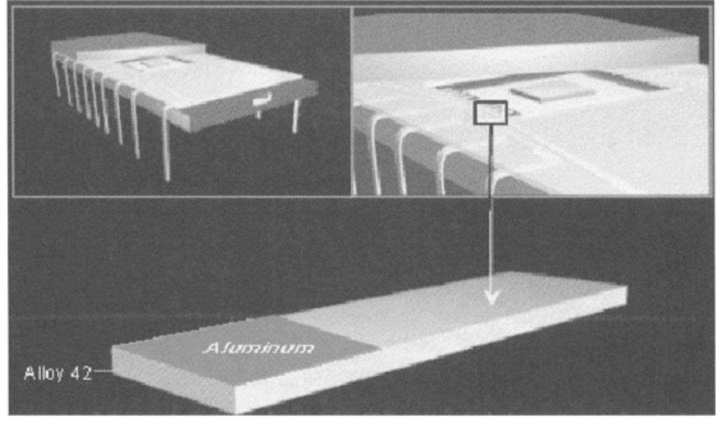


Figure 4.1.49 Layers of metallization on the leadfinger of a cerdip package

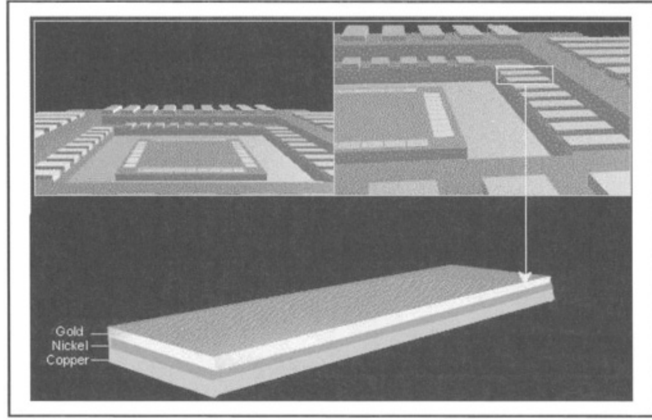


Figure 4.1.50 Layers of metallization on the leadfinger of a pre-molded package

In case of chip of board, BGA, CSP and MCM-L packages, the copper traces on the FR4 substrates is coated with Nickel and a thin film of gold for good bondability. Usually the nickel thickness is between 2 microns to 5 microns, and the thickness of gold layer is about 1 micron. Figure 4.1.51 shows COB - Layers of metallization on the leadfinger of a COB substrate.

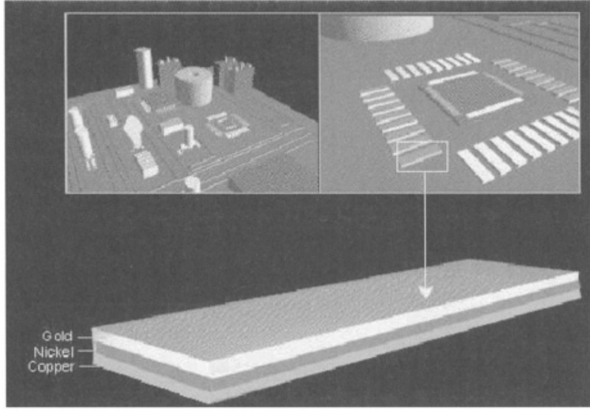


Figure 4.1.51 COB – Layers of metallization on the leadfinger

High end and complex Multi chip modules based on silicon or ceramic and polyimide technologies do not have plated metallizations on the lead finger. The bonding area of the lead fingers are coated with sputtered metallizations.

4.1.19.2 Precious Metal Plating on Lead Frames

The primary purpose of plating the lead frame with Ag or Au is to provide a bondable area on the lead finger for the second bond to form. This area needs to be slightly larger than the size of the second bond. Therefore the lead frame manufacturer is required to plate only the tip of the lead finger, the minimum area required for bonding. In addition, it is also observed that if the whole lead frame is coated with precious metals like Au, the adhesion of molding compound to the lead frame is drastically reduced. The molding compound adhesion is much better to bare copper or alloy-42 lead frame surface. Silver or gold plating on leadframe is done using different plating technologies to minimize the use of precious metal. The different plating technologies used to plate a lead frame are:

Ring plating : In ring plating, the inner leads of the package are plated on the top surface of the lead finger as shown in figure 4.1.52(a)

Ring-tip plating : As shown in figure 4.1.52(b), in ring tip plating, only the wire bonding areas of the lead finger are plated with silver metallization.

Spot plating both sides : As shown in figure 4.1.52(c), in spot plating both the die pad and the inner lead tip are silver plated on both the top and bottom surfaces of the leadframe.

Tip plating : As shown in figure 4.1.52(d), in tip plating , only the die pad and the wire bonding areas are plated with silver.

W-ring plating : In this technique, the die pad is plated only around the periphery and the inner lead of the lead finger is plated.

Overall plating: More recently, we have leadframes which are plated completely with palladium. Palladium plating not only provides good bondability, but it also provides a solderable lead finish. With this leadframe plating technology, IC assembly factories need not install a solder plating line for lead finish, and this saves significant amount of money. In this technology plating covers the whole leadframe area. In some situations, the leadframe may be quoted as having overall plating, but the rails will be

unplated in order to save plating costs. The overall plated lead frame is shown in figure 4.1.52(e)

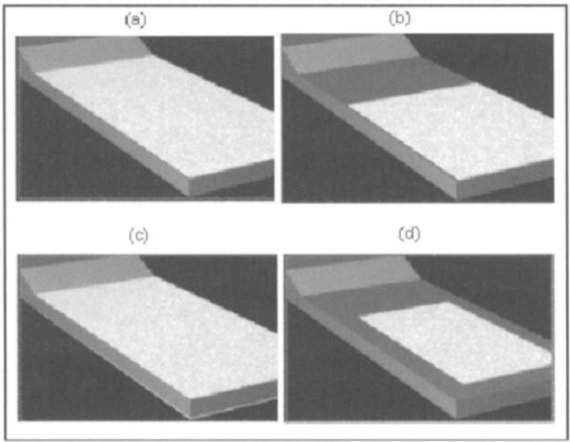


Figure 4.1.52 (a) Ring plating, (b) Ring-tip-plating (c) Spot plating (on both sides) (d) Tip Plating

Lead frame and substrate metallizations display many of the same effects on bondability as described above for bond pad metallizations on the silicon chip. The method of metallization deposition on the lead frame have the most significant impact.

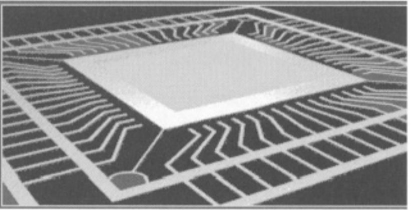


Figure 4.1.52 (e) Overall plating

4.1.20 Substrate Metallization Process

Lead frames and package substrates are metallized using different techniques including electro plating, electroless plating, immersion plating, cladding, and vapor deposition. Let us review these process technologies and their impact on metallization morphology and bondability.

4.1.20.1 Electroplating

Electroplating is the most widely used process technology for plating silver, nickel, palladium and gold metallization on substrates. Electroplating is the most economical of all the plating techniques. We can use electroplating for both thin and thick film plating. Electroplating is a high speed deposition technique. However film uniformity and purity are significantly affected by process parameters. The schematic representation of electroplating technique is shown in figure 4.1.53.

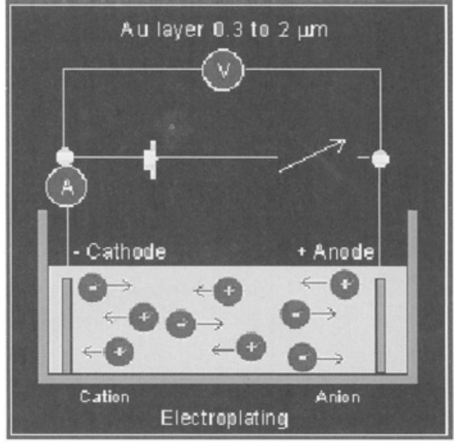


Figure 4.1.53 Gold deposition method with electrolytic plating

4.1.20.2 Electroless Plating

Many substrates can not be plated by electrolytic plating technique due to, the physical construction of the package or the inability to electrically connect the substrate for electrolytic deposition or the requirement of very high purity plating. In such cases, we use electroless plating technique.

In electroless plating there is no use of external current and the plating takes place by chemical reduction mechanism. The reducing agent reacts with gold ions and allows for fast gold deposition on nickel substrate. We can use electroless plating for coating very high purity coating of thickness ranging between 0.1 to 2.0 microns. The schematic of electroless plating is shown in figure 4.1.54.

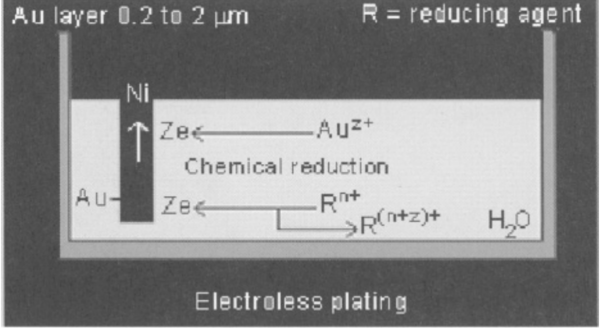


Figure 4.1.54 Gold deposition using electroless technique

4.1.20.3 Sputtering

In special MCM packages which require very high purity or fine line accuracy of the metallization, the metal can not be plated with a liquid electrolyte. The package substrate is sputter coated with the required metallization. Usually, sputtering is a preferred technique for aluminum deposition on MCM substrates.

4.1.20.4 Cladding

In a cerdip package application, alloy 42 lead frames are used and chip is bonded to the lead frame using Al wires. Since cerdip packages are sealed at high temperatures of greater than 400° C, the bonding area on the lead finger can not have Ag or Au metallization due to reliability concerns of intermetallic formation and voiding. Therefore in this situation, alloy-42 lead frame used in cerdip packages is usually clad with high purity Al foil.

Cladding is nothing but the process of joining a thin film of material onto a metallic substrate by mechanical rolling operation. This technique utilizes both high temperature and high pressure to bond a thin layer of metal to a metallic substrate. A bond forms between the coating and the substrate. Cladding typically takes place in a vacuum or a reducing atmosphere to prevent re-oxidation of the substrate. Figure 4.1.55 shows a schematic representation of the cladding technique.

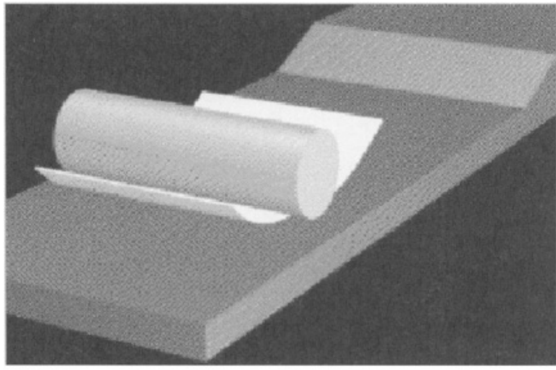


Figure 4.1.55 Schematic representation of cladding

4.1.20.5 Immersion Plating

In some special situations we use immersion plating technique. In Immersion platting there is no use of external current. Here the gold deposition takes place from the electrolyte on to the nickel substrate by a charge exchange mechanism.

In an immersion process you have a galvanic displacement in which a metal less noble, for example copper or nickel, is displaced by gold. As soon as the copper or nickel surface is no longer exposed, the process stops. A true immersion deposit is limited in thickness and typically does not adhere extremely well to the substrate.

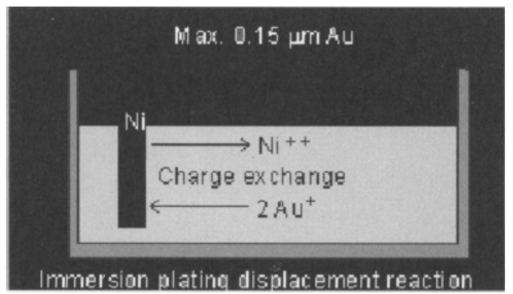


Figure 4.1.56 Gold deposition method without external current

The schematic of the immersion process is shown in figure 4.1.56.

4.1.20.6 Underplating

An important consideration during bonding is the surface morphology and surface chemistry of the plated metallization film. This surface condition of the plated metallization depends on the finish plating, the under plating and the base material. Underplating is defined as the plating layer that completes the required characteristics of the final plating layer and lies between the base material and final plating layer. Some of the reasons for depositing an underlayer nickel metallization are:

- if gold is plated directly on copper lead frame without an underplating, the surface morphology depends on the surface finish of the lead frame.
- copper lead frames or alloy 42 lead frame have a thin native oxide layer. Silver, gold and palladium being noble metals have poor adhesion to the copper lead frame if directly deposited.
- in addition, if thin layers of precious metals are plated directly on copper lead frame, copper atoms diffuse to the surface forming a copper oxide as shown in figure 4.1.57(a), particularly when the plating is exposed to high temperature. This oxidized top layer is not bondable.

Therefore a thin layer of nickel as underplating below the gold metallization is required both for adhesion enhancement and also as a diffusion barrier. As we can observe form the figure 4.1.57(b), when nickel is placed on top of copper it acts as a diffusion barrier and prevents copper from diffusing to the surface of gold and forming an oxide layer. The thin layer of nickel also acts as an adhesion promoter between the gold layer and the copper substrate. Proper selection of underplating material and thickness of underplating material is critical for good bondability.

The table 4.1.3 shows some of the underplating metallizations that are used in the industry.

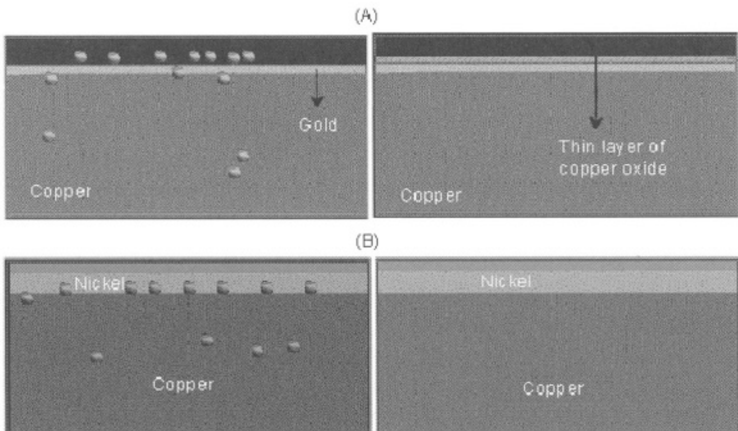


Figure 4.1.57(a) Copper diffusion through gold plating (b) Copper diffusion prevented due to nickel barrier

Table 4.1.3 Under plating and finish plating [P-17]

Finish plating	Under plating	Base - material	
		Cu - alloys	Fe, Ni - alloys
Au	-	N/A	X
	Ni	X	X
Ag	-	X	N/A
	Cu	X	X
Cu	-	X	X
	Ni	X	X
Ni	-	X	X
	Cu	X	X
Pd/Ni-alloy	-	X	X
	Ni	X	X
	Cu	X	X
Pd	-	X	X
	Ni	X	X
	Cu	X	X
	Pd/Ni-alloy	X	X

4.1.21 Morphology of Plated Films

The surface morphology of the plated films depends on many factors such as plating parameters, lead frame surface, under layer metallization morphology, and contamination. These factors in turn affect the bondability. If the top Au metallization surface is too smooth, it has been found to affect bondability. The bonding tool has a tendency to slide. On the other hand if the metallization surface is too rough the bondability is affected. Let us review some of the surface characteristics.

Usually the thickness of gold plated film is about 1 micron or less and this gold plating is done on top of a under plating metallization such as nickel. The surface morphology of the gold plated film is impacted by the surface morphology of a nickel plated film. So one must carefully monitor the plating process conditions of both the under layer metallization and the finish layer metallization process. It is not enough just to monitor gold plating conditions, but also one has to monitor uniformity of nickel plating. Figure 4.1.58 shows a gold plated film on top of a nickel plating, which showed good bondability.

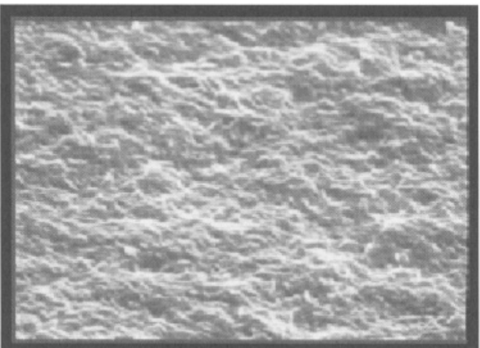


Figure 4.1.58 Surface morphology of gold plated film

Figure 4.1.59 shows some examples of surface morphologies which show inconsistent bondability.

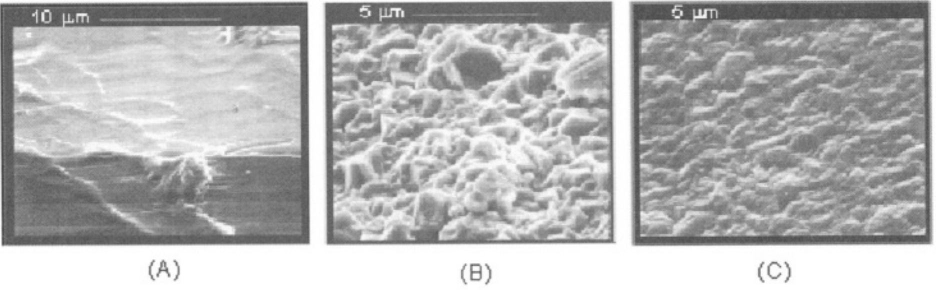


Figure 4.1.59 (a) Smooth gold surface (b) Rough gold surface (c) Lumpy gold surface

4.1.21.1. Surface Finish of Leadframe and its Effect on Bondability

The surface finish of the as-received Cu leadframes is also found to be critical to achieve excellent bondability. Leadframes with a coarse surface finish have been known to give excellent bonding strength as compared with a smooth surface which results in low pull strengths and bond lifts. The lead frame surface finish has an immediate impact on the surface quality of the plated metallization.

4.1.22 Alternate Substrate Metallization

The semiconductor assembly process for plastic molded packages typically utilizes copper based leadframes which are selectively plated with precious metal such as gold or silver. The elimination of precious metals in the leadframe manufacturing process contributes to significant reduction of material costs. To minimize the cost of precious metals on the lead finger, instead of plating gold or silver, copper has been plated on the lead frame. Current densities of 10 to 25 ASF, bath temperatures of 25 to 40°C, and bath constituents including H_2SO_4, $CuSO_4$, and HCl in appropriate concentrations, has been formed to provide a copper plated surface that gives consistent wire bondability.

Additional acid clean of the copper plated leadframes provides a surface with a passivation layer which inhibits oxidation of the copper plating. It has

been observed, that the bonding strength of thermosonic wedge bonding of gold wires onto copper plated leadframes was equal to the bonding strength of gold wire to silver or gold plated leadframes [P-18].

4.1.22.1 Palladium Plated Lead Frames

Over the last few years, new surface finishing processes have been developed to improve the performance of leadframes in wirebonding. Palladium plating is rapidly becoming the preferred finish for semiconductor lead frames. The primary reason for this choice is to meet increasingly strengthened environmental and legislative requirements for lead-free finishes improved package reliability reduce lead coplanarity problem on fine pitch leadframes, and eliminate lead bridges with solder plating and minimize associated yield losses. The thickness of palladium is quite thin, of the order of 5 micro inch. The palladium plating has an under plate of nickel barrier. The PPF technology is expected to bring 20% cost reduction in assembly [P-19],

The PPF (Preplated frame) technology will eliminate silver spot plating and solder plate operation after package molding. There is no need for chemical finish and cleaning after molding.

Conversion to Pd preplated frames is happening at a slow pace. The hesitation to convert traditional leadframe finishing processes (selective silver plating and post tin-lead plating) to palladium finishing has persisted in this cost-sensitive industry due to the inconsistency of palladium supply and price issues. The industry also has to still accept it as a totally reliable technology. The technology controversy is still going on whether the palladium plating should be 2 layer versus 4 layer. And some solder wettability issues remain. However, bonding on palladium plated lead frames has been found to be reliable and acceptable for commercial products. Some of the advantages and disadvantages of palladium plated lead frames are listed in this table 4.1.4

Table 4.1.4 Advantage and disadvantage of palladium plated lead frames

Advantage	Disadvantage
Quick turn around time by omitting solder plating process on outer-leads	Pd is expensive
Pb - free, good for environment	Plating hardness (Hv 250) difficult to plate thickly
Conventional assembly line can be modified easily and used	Copper-alloy materials are used mainly for PPF (Large elecrode potential difference between Pd and ferro-alloy)
No silver migration	Bondability not as good as Ag or Au plating
No solder bridges	
Selective plating mask is not necessary	
Dry assembly process	

4.1.22.2 Bonding to Pd-Ag and Pd-Au Metallization

Bonding to Pd-Ag and Pd-Au metallization on hybrid substrates was found to be a tolerant operation, although higher vibration amplitudes were required than for the gold metallized substrates. Presumably, these differences in weldability are due to the disparity between wire and film hardnesses. The Gold wire hardness is closest to the gold film (~ 27 and 38 Hμ_respectively) whilst the Pd-Ag and Pd-Au are substantially harder (65 and 90 Hμ) [P-20].

4.1.22.3 Nickel Plating

Usually Nickel is used as a barrier layer between the substrate metal (Cu or alloy 42 lead frame) and the final metal (Au or Ag). Nickel can be plated either by electrolytic or by electroless techniques. Nickel has also been used for bonding heavy wires particularly in power devices. The nickel plating morphology and microstructure significantly impacts the top layer metallization and affects bondability. For example gold plate over a bright nickel base has been found to peel. This problem of peeling may caused by passivation of the nickel during rinsing after plating. Passivation has been

often found to be worse when the rinse water is cold, because water can hold much more dissolved oxygen at lower temperatures. The quality of the nickel film is identified by such factors as porosity, adhesion strength and internal stress.

Table 4.1.5 Plating problems and possible cause for nickel plated film [P-21]

Symptom	Possible cause
Poor adhesion	Inadquate cleaning ; parts not acidified before entring nickel bath pH out of range (too high or too low);Nickel too stressed (may be due to metallic contamination or excess brightner) chromium contamination; nitrate contamination
Porous depositis	Current interrupted; nickel over nickel without proper activation; replating without complete stripping of chromium, deposit highly stressed; excess iron in solution
Poor adhesion involving peeling from copper	Failure to remove brightner from copper plate; copper tarnished in rinsing process
Deposit too highly stressed	Contamination with zink or cadmium; iron content too high; brightners out of balance or too concentrated, organic contamination, pH out of rnge, chloride content too high
Pitting of deposit	Solution contaminated with grease or oil; solid particles in solution; pH too low, metal too low, organic contamination inadequate agitation; temperature too low
Deposit dark	Metallic contamination, especially copper (zinc and cadmium first producer a bright stressed deposit, then at higher levels, black steaky deposits)
Deposit streaky	See above, chromium contamination; nitrate contamination, brightener imbalance; pH out of range, inadequate agiation, low wetting agent concentration; wrong wetting agent
Deposit rough	Solid material in solution smut not removed in cleaning; excessive current density; boric acid content too high.
Deposit hazy	organic contamination, immersion deposit on basis metal (usually from processing multiple alloys through the same acid dip); iron content too high; pH out of range; inadequate cleaning
Failure to plate	Faulty electrical system, contamination with chromium or nitric acid

Table 4.1.5 details some of the problems such as poor adhesion, porous film and stressed film and elaborates some of the causes for these problems. Table 4.1.6 details some of the problems such as poor adhesion, porous film and stressed film and elaborates some of the causes for these problems in case of silver plating.

Table 4.1.6 Plating issues and problems and possible cause for the silver plated film [P-21]

Symptom	Possible cause
Poor adhesion	Inadquate cleaning ; failure to use proper strike (immersion deposit); passive nickel layer; wrong cleaning cycle for alloy being processed
Porous depositis	Excess current density; lack of filtration
Rough deposits	Suspended solids in solution; conductive smut not removed in cleaning cycle
Hard dull deposits	Current density too low, temperature too low
Thin deposits (usually bluish-white)	Low temperature, low metal content; polarized anodes
Polarized anodes	Free cyanide too low, insufficient anode area
Anode bright and/or crystaline	Cyanide too high - usually also gives high current at normal voltage
Poor conductivity (low current at normal voltage)	Low temperature; low metal; low cyanide; poor electrical conditions; high carbonates
Brown stains or spots	Poor rinsing; spotting out
Patchy brightness	Organic contamination; brightner imbalance
Yellowish or pink deposits	High copper contamination combined with low silver content
Failure to cover nickel	Improper activation of nickel
Overall dullness	Low brightener content

4.1.23 Characterisation of Substrate Metallization Quality

The aluminum metallization on the IC chip is deposited with sophisticated clean room technologies like sputtering and PVD. Usually the quality of the

Aluminum metallization is consistent. Besides, since we do the first ball bond on the aluminum metal, the problem of non stick is very rare!!

However, the lead frame metallization processes such as electroplating is comparatively a “low technology process” and the process is not done in a clean room environment. Besides, the process is not easy to control in a mass manufacturing environment, unless very special care is taken to do so. If the bondability is affected by bad quality of the lead frame metallization, the impact on assembly yield is very high. Therefore testing the plated films for quality and consistency takes on tremendous importance.

4.1.24 Impact of Film Properties on Bonding

The properties of the plated gold, silver, Ni, palladium films that affect the bondability and the reliability of the bond are:

- plating thickness
- silver plating brightness
- breakdown voltage of silver plating
- plating cleanliness
- plating Impurities

Let us discuss and review each of the above parameters in detail.

4.1.24.1. Plating Thickness

If the Au or Ag plating thickness is too thin, or too thick it results in bondability problems. If the Au metallization is too thin, bondability is poor due to insufficient plastic deformation of Au during ultrasonic bonding. Secondly the under layer metallization could diffuse to top surface and form an oxide layer. If the metallization is thick, the softness of the metal may retard ultrasonic coupling during wedge bonding and the tool may slip during bonding. Secondly, the metal could form an intermetallic compound with Al wire and fail. Taking the above factors into consideration, the recommended thickness for silver including under plating is 5μm max and recommended thickness including under plating for gold, copper, nickel, Ni-alloy, palladium plating is 2 to 3 μm max

4.1.24.2. Effect of Plating Thicknesses on the Strength and Reliability of Substrate Metallization

When copper leadframe is plated with Au with an underlayer of Ni, the bondability depends on both the thickness of Au film and the thickness of Ni film. It has been observed that, increasing the nickel thickness decreases the initial bondability. Conversely, increasing the gold thickness increases the initial bondability with the median strength increasing linearly. Examination of the ratio of the gold thickness to the nickel thickness indicated a minimum preferred value of 2.5 µm.

4.1.24. 3. Plating Thickness Measurement Test Methods

Two major testing techniques namely X-ray fluorescence technique and beta backscatter technique. These tests are used for process control, for outgoing inspection at the supplier or for incoming inspection by the customer.

4.1.24.4. X-ray Fluorescence Technique

This method is based on the use of flourescent X-rays. This method is widely used because of the following reasons:

- requires a small measurement area
- high accuracy of the method for typical silver plating thicknesses used on leadframes
- the method is non-contact

Leading X-Ray fluorescence systems in the industry can measure on ultra-small areas less than 0.002" (0.05 mm) in width. When a beam of high energy X-rays impinges on the plated film the plated metal as well as the underlying metals release flourescent x-rays. These flourescent x-rays are characteristic of each individual element and depends on the atomic number. By measuring the intensity of the flourescent x-rays it is possible to measure the thickness of the film. The schematic representation of the measurement principles is shown in figure 4.1.60.

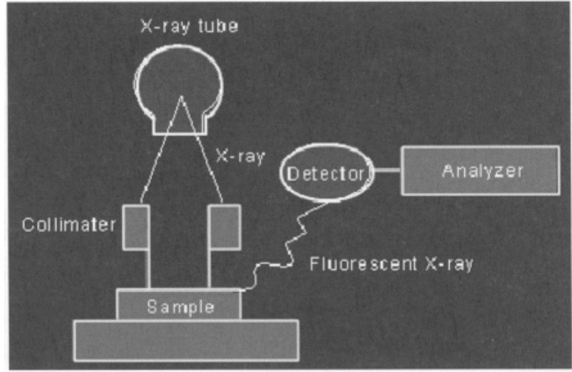


Figure 4.1.60 Film thickness measurement with X-Ray fluorescence [P-22]

4.1.24.5. Thickness Measurement Error Analysis

The measured thickness of the plated film depends on the measurement area. Smaller the area greater is the error. When we use X-Ray fluorescence technique to measure the silver thickness on a copper base material, the measurement error depends on measurement area, as well as thickness of the silver coating. We can observe from the figure 4.1.61, the measurement error increases as we decrease the thickness of the silver plating. The measurement error is 4 times higher when the measurement area is 0.1 millimeter instead of 0.3 millimeters. Other sources of error can be the type of underlayer metallization used. Usually elements with close atomic numbers have overlapping peak positions. And in case of elements which are far apart in the periodic table, the L-alpha lines of one element may overlap with the K-alpha line of a lower atomic number element.

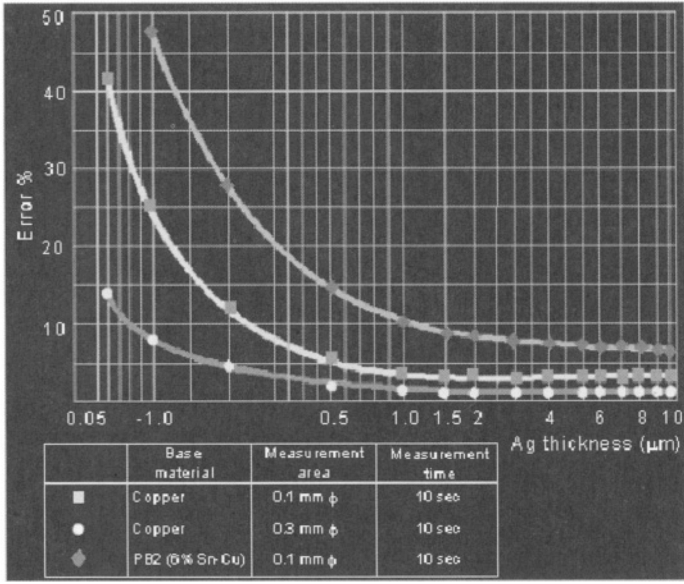


Figure 4.1.61 Error in silver thickness measurement [P-22]

Interferences during X-ray flourescence measurement are a major concern. Some example are given below.

- impurities in plating with atomic numbers between 42 (Molybdenum) and 52 (Tellurium) cause false readings for Silver.
- worn or abraded standards will affect calibration
- base material variations will affect results. Standard samples and leadframes must have the same base material and plating system conditions for accurate results

4.1.24.6. Measurement Procedure

Measurements shall be made on lead fingers and close to the center of the die pad, if possible. In those situations where the die pad is not plated, the measurement site shall be agreed between supplier and customer. The thickness data must be analysed for uniformity and consistency. Some of the

critical plating thickness values that are relevant are: individual measurement, mean value, standard deviation, Cp and Cpk values, lowest and highest reading, measurement uncertainty-percent or unit measurement, X Bar and R charts for each application with control limits and histogram with normal distribution curve for each application.

4.1.24.7. Silver Plating Brightness

Brightness values indicate surface roughness for given plating conditions. Brightness variations affect the ability of the pattern recognition systems used on bonding equipment to recognize the set points.

4.1.24.8. Silver Plating Brightness Measurement Methodology

The measurement method is based on the use of a GAM Densitometer. This method is chosen as the standard because of the small measurement area requirements and the high accuracy of the method for measuring typical silver plating brightness used on leadframes. This method is based on the measurement of the reflectance of light at 45° from a surface illuminated from a light source perpendicular to the surface. This value of reflectance gives a density value (D) based on the following formula

$$D = \log I/R$$

where density D is the measure of the brightness [P-23].

4.1.24.9 Interferences

Brightness values depend on surface roughness. A rough surface shows a low brightness value when compared to a smooth surface. Variable plating conditions, such as the addition of brighteners to the plating solution, may give brightness results which cannot be considered for the acceptance of plated leadframes.

Scratches and other flaws on the surface will also affect reflectance. The brightness results for leadframes are affected by storage time and storage conditions. A plated film with a rough surface becomes smoother as a function of time, and this is indicated by the increase in brightness of the

plated film, this can be observed in figure 4.1.62. Results have shown that both on copper and alloy42 lead frame the silver plating show degradation with time.

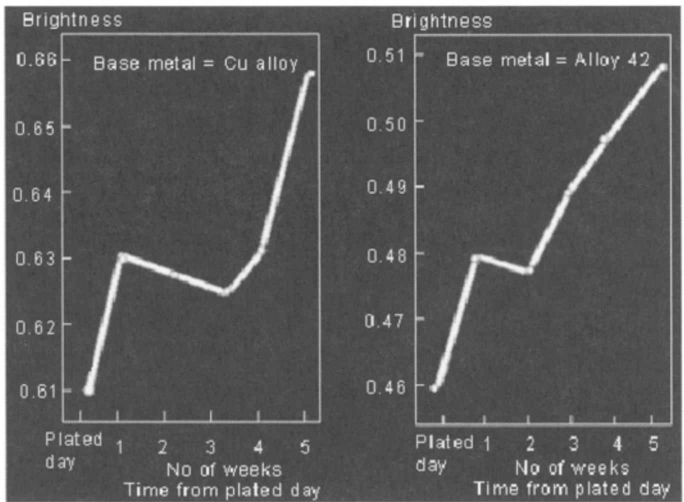


Figure 4.1.62 Changes of the brightness value as a function of shelf life for Cu and Alloy 42 lead frames [P-23]

Therefore leadframes should be stored in conditions agreed between supplier and customer in order to limit atmospheric tarnishing, and brightness measurements shall be taken within an agreed time of delivery. It is also important to note that degradation of the standards will affect calibration.

To make brightness measurements, no special preparation of the samples are necessary. Only precaution that one has to take is that the samples should not be contaminated by touching with bare hands. Brightness measurements shall be made close to the centre of the die pad. In situations where the die pad is not plated, the measurement site shall be agreed between supplier and customer. We must also be aware that this method determines quantitative measures of brightness which are not related directly to the traditional “Dull”, “Semi-Bright” and “Bright” descriptors for silver

plating. This test may be used for process control and outgoing inspection at the supplier or by the customer for incoming inspection.

4.1.24.10 Measurement of Breakdown Voltage of Silver Plating

Similar to measuring the breakdown voltage of aluminum oxide film on aluminum metallization, we can do the breakdown voltage measurement of silver film. This will indicate the ease of bondability on silver film. When the copper lead frame is heated, the Ag metallization oxidizes. Thicker the silver oxide, lower the bond pull strength. In figure 4.1.63 we see, as the breakdown voltage increases, the bond pull strength on the leadframe decreases and this is due to the increased thickness of the oxide layer.

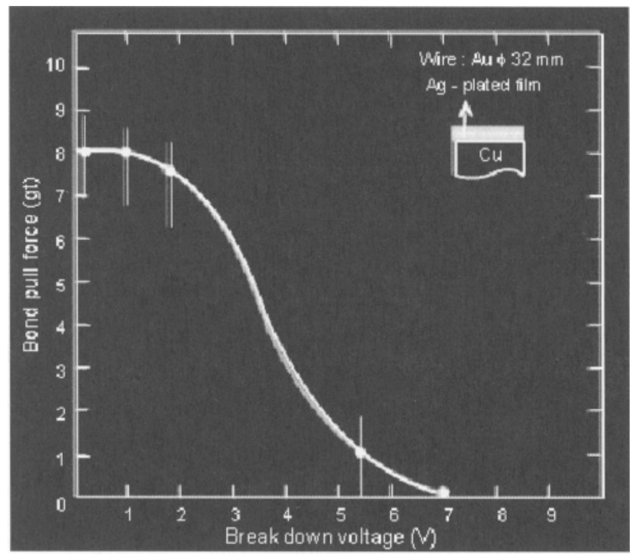


Figure 4.1.63 Relation between breakdown voltage of plated silver film and pull strength of wire bonded to lead-frame [P-15]

4.1.24.11 Bondabalility vs. Breakdown voltage

In case of silver film, there is direct correlation between bond failure rate and oxide breakdown voltage. For example, when gold wire is bonded to silver film, the failure rate is higher on silver films with higher breakdown voltage: Gold wire bonds on silver plated films show different failure rates depending on the breakdown voltage of the oxide. From figure 4.1.64 we can see, when the breakdown voltage lies between 0 and 0.15 volts, the failure rate after thermal shock remains zero. However, wires bonded on a surface with breakdown voltage of 3.1 volts, the failure rate increases with increase in number of thermal shock cycles.

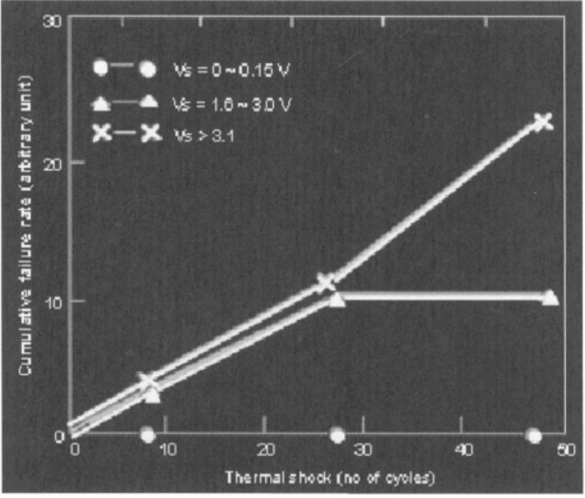


Figure 4.1.64 Impact of breakdown voltage on thermal shock failure of wire bonds [P-15]

4.1.24.12 Effect of Plating Cleanliness during Substrate Metallization

Bondability and bond strength are severely affected if the plated leadframes are not clean. Cleanliness is defined in terms of ionic conductivity. Generally, it is observed that if the ionic conductivity is less than 1.0μ Siemens/80cc., the bond strengths obtained are very good. Various

reliability tests reveal that cleanliness of lead frames plays a major role in the reliability of a package.

4.1.24.13 Impact of Plating Impurities on Bonding and Bond Reliability

Plating baths have impurities and these get trapped in the metallization. These trapped impurities may affect the bondability as well as bond reliability. For example, research work by Horsting et.al., shows that when impurities are present in plated Au film, the purple phase formation between Al wire and the Au metal is accelerated. However, when Al is bonded to pure Au, there are two phases, namely white phase and purple phase that are formed and no reliability failures are observed. This is a reliable interface. However when the gold is contaminated with impurity atoms, it has been found that only purple phase is formed at the interface. This is significantly less reliable. [P-24]

Other impurities that have been found to cause process problems as well as reliability concerns are: thalium, nickel, iron, lead and hydrogen. Hydrogen tends to migrate to the bonded interface and coalesce. This can result in a weak bond [P-25, 26, 27, 28, 29].

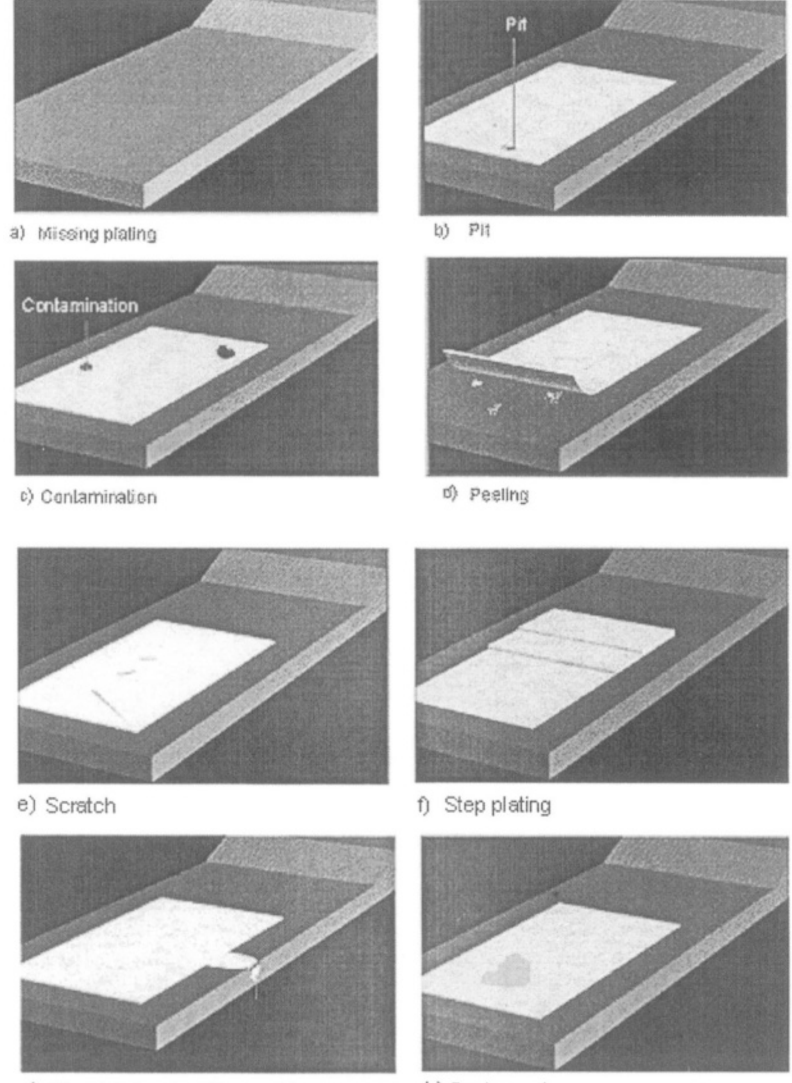
4.1.25 Visual Defects of Films

If the plated metallization is not uniform, it is a cause for concern during production and also reliability testing. The quality of plated film is checked by visual inspection. Usually visual inspection of the plating surface under a microscope is done at 10x magnification. Visual inspection may be performed with a microscope with up to 40 X maximum magnification, or as required to confirm results. Visual inspection is performed before and after functional testing.

The different problems of the plated Gold, Silver, Copper, Ni, Palladium films that affect the bondability and the reliability of the bond are:

- *Missing plating*: any bare spots, or missing plating in critical area as defined the coined areas or minimum flat wire bond are in the appropriate leadframe specification. This is shown in figure 4.1.65(a)

- *Pits*: a hole or depression extending blow the surface of the plating. Pit is also defined as any depression which exceed 0.008 mm in depth or 0.0127 mm in a surface dimension in critical areas or 0.0254 mm in depth or 0.051 mm in a surface dimension in non-critical areas. The pit can be observed in figure 4.1.65(b)
- *Contamination (Foreign material)*: a three dimensional alien material adhering to a surface other than parent material of the component, as shown in figure 4.1.65(c). Adherent denotes inability to be removed with an air or nitrogen blow-off at 20 psi.
- *Peeling*: The lifting of metallization from a surface as shown in figure 4.1.65(d)
- *Scratch*: any scratches or scrapes in the metallization plating which expose underplating base material (Scratches or scrapes in critical area which cause a build up of material in excess of 0.0127 mm in height). Scratches or scrapes can be seen in figure 4.1.65(e)
- *Step plating*: plateau-like plating having more than on level as shown in figure 4.1.65(f)
- *Bleed outside*: plating occurring on the sides of leadframe features as shown in figure 4.1.65(g)
- *Spot plating misalignment*: the variation between the defined and actual center lines of the plated area. The misalignment of the plate can be seen in figure 4.1.65(h)
- *Area variation:* the variation between the defined and actual plated area as shown in figure 4.1.65(i)
- *Incomplete plating*: plating is missing from any part of the designated area as shown in figure 4.1.65(j)
- *Attached silver particle*: small silver particle which is attached to the normal plated surface, this can be seen in figure 4.1.65(k)
- *Spot-sparing*: a stain-like discoloration occurring after the application of heat as shown in figure 4.1.65(l)


Pit
Contamination
a) Missing plating
b) Pit
c) Contamination
d) Peeling
e) Scratch
f) Step plating
g) Bleed out on leadframe side
h) Spot- sparing

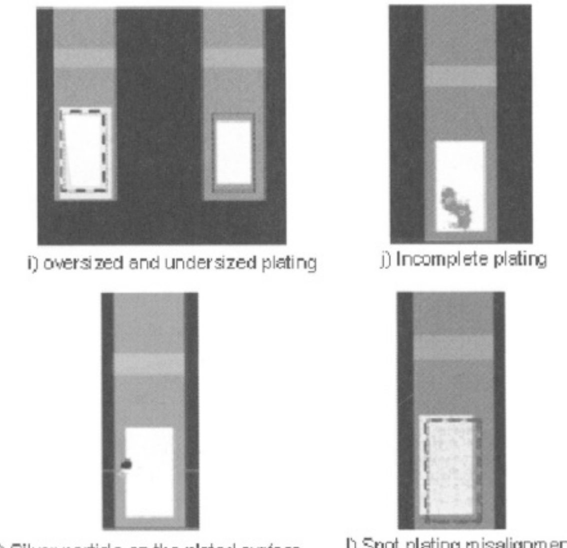


Figure 4.1.65 Visual defects

- *Blister*: an enclosed, localized separation of the plating metallization from the base material or from another layer of plating which can be depressed with a sharp instrument. This may occur during plating or after application of heat. Blister formation
- *Bleed out, back side*: plating on the back of leadframe caused by seepage of the plating solution beyond the mask
- *Bleed out surface*: seepage of the plating solution beyond the mask on the top surface of the leadframe so that the plated area increases
- *Corrosion:* electrochemical degradation of the material usually exhibited by discoloration such as rust
- *Discoloration*: any change in the color of the metallization, as detected by the naked eye. This may occur as plated or material after application of heat
- *Excessive plating*: plating exists outside the specified area
- *Nodule*: any nodules in critical area as defined the coined areas or minimum flat wire bond area in the appropriate leadframe specification.

Nodule is also defined as a protrusion or lump of plating material above the plated surface.

- *Plating non-uniformity*: the lack of consistency of brightness of plated Silver as plated or material after the application of heat

Let us study the test methodologies for some of the critical problems discussed above

4.1.25.1 Baking Test

Leadframes are plated with silver or gold films to improve bondability as well as bond reliability. However, if the quality of the plated film is poor, or if the plated film has a high level of contamination, when the lead frames are heated to 400°C, peeling, voids and blisters are formed. This clearly indicates the poor quality of the film. Such low quality plated films will affect bonding process as well as bond reliability.

The formation of voids and blisters can be observed in figure 4.1.66. Baking test is used to check for trapped hydrocarbon impurities and stressed film. Samples are heated in air on a hot plate or heater block. Using the baking test the goodness and integrity of a plated film can be checked.

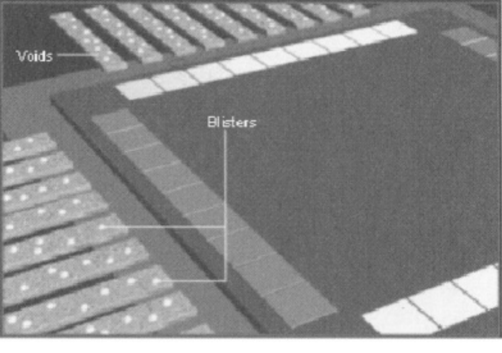


Figure 4.1.66 Bake test for checking plating quality

During the test, the samples are heated to temperatures between 200 and 450°C, and checked for blisters, voids, surface oxidation, discoloration and wire bondability.

Visual inspection after baking shall be performed according to the standard visual inspection criteria. The bake test conditions for plated films is shown in table 4.1.7

Table 4.1.7 Bake test condition for plated films [P-17]

Finish plating/base material	Cu -alloys	Fe/Ni - alloys
Au*	450°C x3 min	450°C x3 min
Ag	300° x 3 min	400°C x3 min
Cu**	200°C x1 hour	200°C x1 hour
Ni	400°C x3min	400°C x3 min
Ni / Pdalloy	200°C x1 min	200°C x1 min
Pd	300°C x1min	300°C x1 min

* May be changed by aggrement between vendor and customer to 400°C x 1 min or 450°C x 2 min or less, to account for changes in plating thickness, base material or other plating parameters

** Surface oxidation and discoloration detected by visual inspection are acceptable. Furthermore, parameter or solderbility evaluation for flux, dripping method, and etc. are to be determined by agreement between vender and customer

4.1.25.2 Adhesion Test

One of the simplest test to test the adhesion of the plated film is the Scotch tape test. In this test, we place the strip of tape (SCOTCH™ # 540, # 610, # 810, or equivalent) across the plated area, as seen in figure 4.1.67(a). The tape is pressed firmly with finger tips or other smooth object. The tape is peeled off the plated surface with very fine tweezers. On the other hand, if a lot of residue is left as shown in figure 4.1.67(b), then it indicates good adhesion. If the film comes off completely as shown in figure 4.1.67(c), it shows the poor adhesion of the film. Though this a qualitative test, it is widely used in the industry, the plating surface may be scored before the tape test.

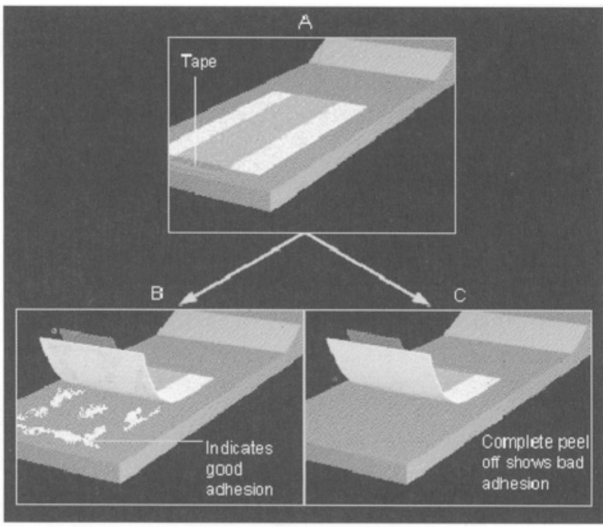


Figure 4.1.67 Scotch tape test to test adhesion of plated film **[VIEW-IN-CDROM]**

4.1.26 Bonding Wire as Process Variable

In this topic we shall discuss how bonding wire impacts process optimization, process reliability and eventually bond reliability.

4.1.26.1 Wire Selection

To achieve maximum yield and bond reliability, wire selection plays a very crucial role. The wire selection for any particular application depends to the particular chip metallization, package design, package constructions, and bonding machine configurations. Therefore, there is no "standard" bonding wire. This complicates the situation, particularly when optimizing the bonding process for:

- chips with different metallization
- packages with different lead frame design and metallization

4.1.26.2 Wire Parameters that Affect Bonding

To maximize assembly yields and to secure reliable bond, the important characteristics of the bond wire that one need to consider are:

- wire type
- wire size
- wire mechanical properties
- wire purity
- wire uniformity and consistency
- wire spooling
- wire surface conditions

Now let us discuss each of these in detail.

4.1.27 Wire Type

As we had already studied in the materials chapter about different types of wires used in wirebonding. The most widely used wire materials are Au and Al however, Cu is also used. Au was the original material used when wire bonding technology was developed. Al has become popular due to its good electrical performance and lower cost. Gold or gold alloy, aluminum or aluminum alloy is determined by the device requirements as well as by packaging requirements. Usually, hermetic packaging technology uses high temperature process and therefore it can be used only in aluminium wire bonding.

4.1.28 Wire Size

The wire size depends on the device characteristics. For a high power device, one needs to select a thick aluminum wire whereas for a high pin count fine pitch ASIC, we may need gold wire with 0.8 mil diameter. Device with low current requirement use thin gold or aluminium wire whereas devices requiring high current use only heavy aluminium wire. Similarly

wire diameter selection also depends on the chip design, lead frame (or package) design, and the size of the bond pad.

The diameter of the wire automatically determines the type of bond tool required, whether a fine pitch capillary for gold bonding or a wedge tool for thick aluminum bonding. Correspondingly, the bond process parameters such as bond force, time and ultrasonic energy need to be determined and optimized.

4.1.29 Effect of Wire Diameter on Free Air Ball

The consistency of the Free Air Ball (FAB) formation plays an important role for the eventual mashed ball diameter and ball height. A consistent free air ball determines the first bond diameter, first bond placement accuracy, as well as first bond shape and diameter consistency. Smaller the FAB, smaller can be the bond diameter. As we go towards finer pitch, the wire diameter is reduced to as low as 17.5 microns, and correspondingly the FAB diameter is also reduced. Figure 4.1.68 shows the variation of FAB as a function of wire diameter.

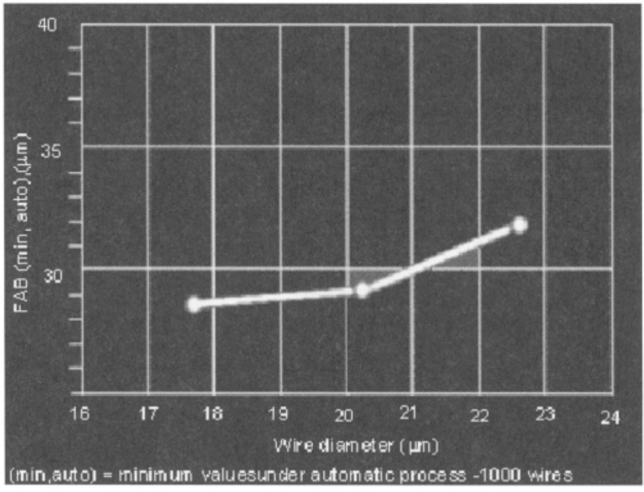


Figure 4.1.68 Free air ball size vs. wire diameter [P-11]

The bonded ball is larger than the FAB. The diameter of the bonded ball is determined by the amount of force, the ultrasonic energy, time and energy applied during bonding. The ball size ratio (BSR) is defined as “The bonded ball diameter divided by the FAB diameter”. Greater the ratio, larger is the ball diameter. As the diameter of the wire decreases, the FAB diameter decreases, and in order to obtain large bonded area on the pad, the ball size ratio needs to be high. To achieve strong first bond, the bonded ball area must be large. This means that the free air ball diameter must be large. As we can observe in figure 4.1.69, to achieve a FAB diameter of 35 microns the ball size ratio needs to be 2.6 for 18 micron wire, whereas with a 23 micron wire the ball size ratio is only about 1.5. We will see later, why an optimum BSR is necessary for bond reliability.

The same Free Air Ball diameter can be achieved by two methods:

- forming a larger FAB with a smaller diameter wire
- forming a small FAB with a large diameter wire

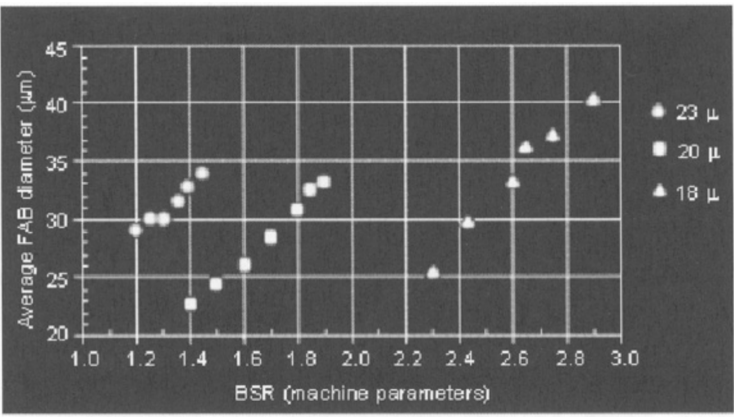


Figure 4.1.69 Free air ball size vs. ball size ratio [P-11]

The significant difference between the above two is the FAB to wire diameter ratio. As this ratio increases, the strength of the neck is significantly affected. To achieve the same free air ball diameter, with a 17

micron wire, the wire to ball ratio is much larger than with a 23 micron wire. We see in figure 4.1.70, the neck formation between the wire and the ball will be much weaker in 17 micron wire compared to the neck in 23 micron wire.

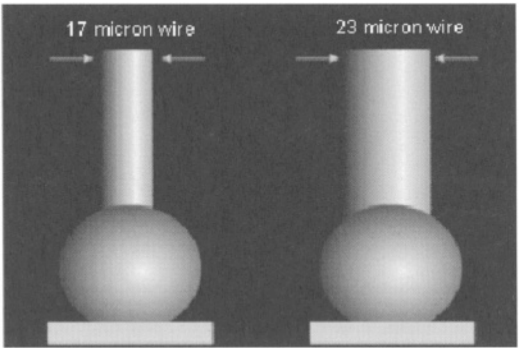


Figure 4.1.70 Free air ball to wire diameter ratio

In order to have a strong neck for the same bond diameter, we can use larger wire diameters with a small FAB to wire diameter ratio. In ultra fine pitch bonding thinner the wire, more difficult will be the process control. In addition, thinner wire is more susceptible to wire sweep problems. Therefore, one has to optimize the wire diameter for a particular pad pitch application and it is always recommended that we use largest wire diameter.

As the wire diameter increases, the first bond diameter also increases. The smallest possible first bond diameter is a function of wire diameter, Free Air Ball to wire diameter ratio and the bonding process parameters such as force and ultrasonic energy. In figure 4.1.71 we see the lowest first bond diameter achievable as a function of wire diameter. For example, we can observe in figure 4.1.71, when we go from a 25.5 micron wire to 23 micron wire, the first bond diameter is reduced from 48 microns to 40 microns. That means for a 2 micron reduction in wire diameter we effectively have almost an 8 micron reduction in ball diameter.

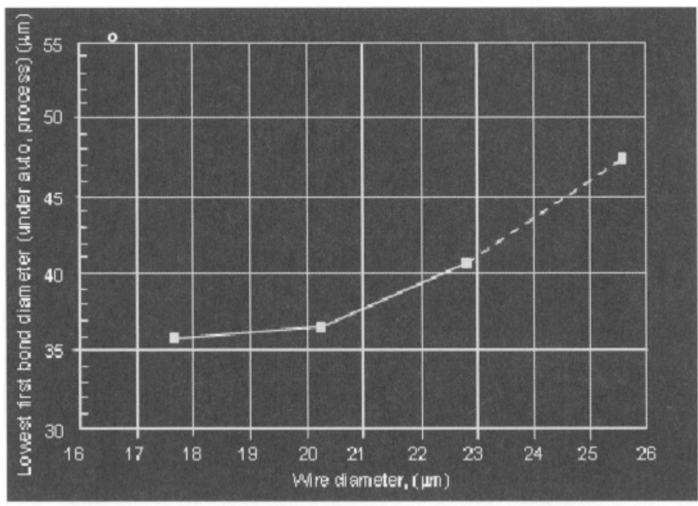


Figure 4.1.71 Wire diameter effect [P-11]

4.1.30 Effect of Wire Diameter on Shear Force

Shear force and shear strength per unit area are the two parameters that determine the goodness of the bond. It has been observed that as the wire diameter increases, the corresponding first bond diameter increases, therefore the associate shear force value increases. We can observe in the figure 4.1.72, as the wire diameter increases, the shear force value must increase in order to achieve constant shear strength per unit area.

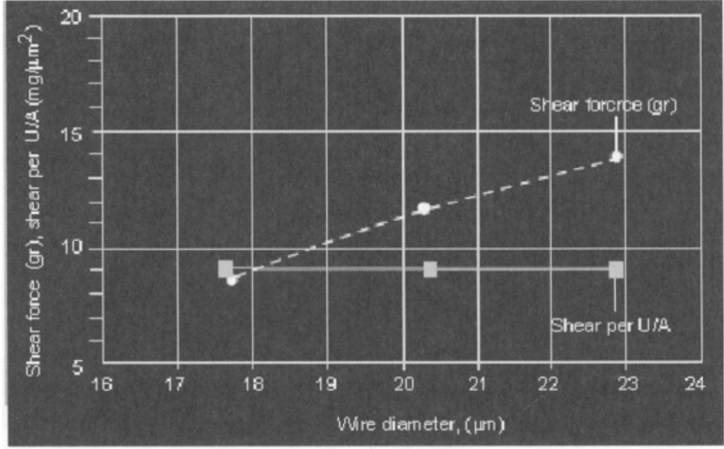


Figure 4.1.72 First bond properties strength [P-11]

However, we see that though the shear force value increases as the function of wire diameter, the actual shear strength per unit area remains reasonably constant. In any process optimization, one must achieve this minimum shear strength value for the process to be stable.

4.1.31 Effect of Wire Diameter on Breaking Loads

For a particular type of wire, it is natural to expect that breaking load of the wire during the bond pull increases with increasing wire diameter. For example, an 18 micron wire has a breaking load of 5 grams, whereas a 30 micron wire has a breaking load of 14 grams. As the wire gets thinner, the breaking strength decreases.

In order to have high breaking strength with thinner wires, one has to use different alloy composition wires. We can observe from figure 4.1.73, a 25 micron SGA3 wire has a breaking load of 12 grams and the same breaking load is achievable with NL3 wire with 23 micron diameter. Therefore in ultra finepitch applications, two to three micron reduction in wire diameter can have a significant impact on pad pitch design. One has to choose the right alloy which gives high breaking strength at smaller wire diameter.

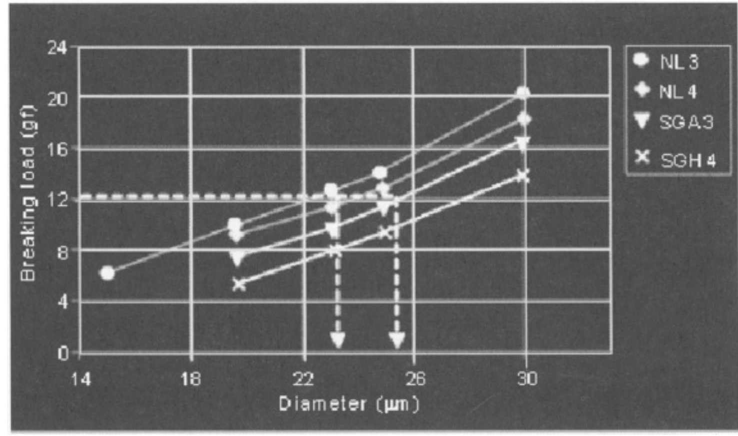


Figure 4.1.73 Comparison of breaking loads of different wires with diameter [P-30]

4.1.32 Wire Diameter: Effect on Neck Strength

In order to achieve high shear strength value on the first bond, we need a large bonded area. This can be achieved by forming a very large FAB with a 20 micron wire or a similar FAB with a 30 micron wire. As discussed earlier, the neck strength at the wire ball interface depends on the FAB to wire diameter ratio. As the wire diameter increases, and the BSR value decreases, it results in stronger neck strength. As discussed earlier, a smaller wire has weaker neck.

Figure 4.1.74 shows, a 20 micron wire which has neck strength of about 6 grams as opposed to a 25 micron wire which has neck strength of about 10 grams. Higher neck strength is crucial to minimize wire sweep.

The three bonding responses we need to monitor as a function of wire diameter are:

- ball contact diameter
- ball shear stress / unit area
- wire pull strength

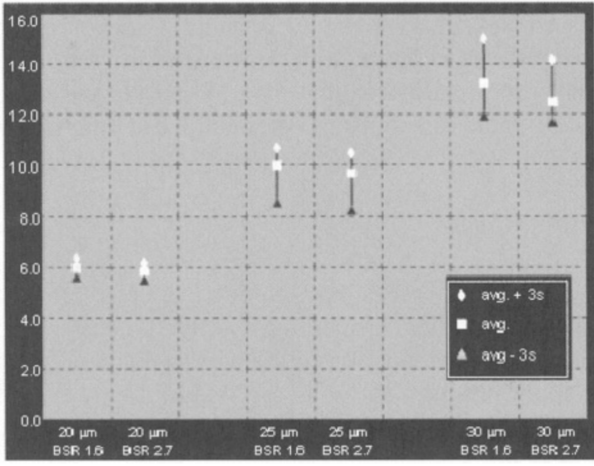


Figure 4.1.74 Wire diameter and its effect on neck strength [Courtesy: American Fine Wire]

From table 4.1.8, we can observe the variations of these three parameters for three different wire diameters. Here we see the bonding responses for 18, 23 and 25 micron wires.

Table 4.1.8 Bonding responses as a function of wire diameter [P-31]

Wire Ø	18 µm	23 µm	25 µm
Bonding responses			
Ball contact Ø, µm			
Average	37.6	37.2	38.4
Std dev.	0.6	0.5	0.6
Ball shear strength, gmf			
Average	12.7	14.2	14.2
Std dev.	0.6	0.7	0.9
Ball shear stress N/mm^2			
Average	119.4	128.3	120.5
Std dev.	7.2	6.7	6.4
Wirepull strength, gmf			
Average	2.2	5.7	6.5
Std dev.	0.1	0.4	0.5

The average ball contact diameter is about 37.5 micron in all the 3 cases. The ball shear stress is about 120 newtons/mm^2. But the only significant difference is in wire pull strength. The 18 micron wire shows average pull strength of 2.2 grams as against 6.5 grams for a 25 micron wire.

4.1.33 Wire Uniformity

The wire bonding process consistency depends on the consistency of bonding wire's mechanical properties, mainly elongation and tensile strength (breaking load). If the elongation of the wire is not consistent from lot to lot or spool to spool, the process will stop intermittently or wire breaks during bonding. Therefore, one must specify the acceptable elongation value and a tight 3 sigma value.

Pure gold wires are seldom used for wire bonding. Usually, the metals are alloyed with other elements to improve the mechanical properties of the wire. The alloying elements (also called impurity atoms) impact bondability, bond strength and bond reliability.

4.1.34 Effect of Wire Spooling

As discussed earlier, single layer and multi layer spools are used for bond wire manufacturing.

In single layer spool, the wire does not stick to the under layer and the wire release is smooth. But the length of wire on the spool is not sufficient to run an automatic bonding machine. We need to keep changing the spool and re-feeding the wire. This causes process inconsistency.

Today, bond wire manufacturing can provide the bonding wire spools up to 6000 meters of wire. The winding capability of the supplier plays a critical role in bonding process stability and consistency. Longer length of wire per spools provides better utilization through minimum spool changes. This assists in long term cost saving. However to achieve longer length of wire per spools one has to change the technology from a standard multi pitch to zebra multi pitch and the number of steps from 6 to 24.

Some of the problems encountered, when we use multilayer spools are : Wire may stick to under layer and wire may twist and curl. This results in inconsistency in wire feeding, bond positioning and wire breakage. The process has intermittent failures.

4.1.35 Wire Surface Condition

The surface condition of the wire plays an important role in the bonding process. Presence of lubricant oil from the wire manufacturing, dust particles while handling and presence of dust particles from the wire path in the bonding machine are some of the major causes of bonding problems. The clogging of the bond tool due to contamination will also affect the bonding process.

4.1.36 Second Source and its Impact

Yet, another complication is in selecting a second source for wire bond material supply, because wire from one wire manufacturer is not necessarily interchangeable with that from another, even when both products are produced to meet the same specification. The bonding parameters required for two different wires will vary. Therefore, it is very important that the second source qualification is performed with great diligence. Even with the availability of second source material, unless absolutely necessary, the second source wire material should not be used on the production floor when the first source is being used.

4.1.37 Ball Contact Diameter

When the free air ball is pressed with the capillary on to the bondpad, deformation of the ball occurs. The capillary dimensions, the bonding force and the ultrasonic energy determine the diameter of the deformed ball. It is important to recognize that the shear strength of the bonded ball is directly proportional to the bonded ball area also called ‘ball contact diameter’. For

the same deformed ball diameter, it is possible to have different ball contact diameters and this means different shear strength values.

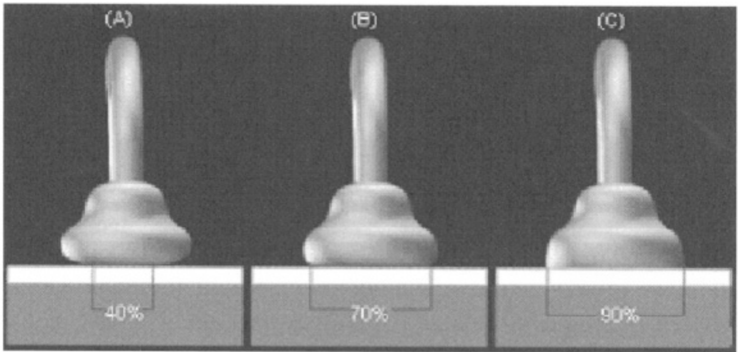


Figure 4.1.75 Bonded ball area of contact

Depending on the capillary design, the force, time and ultrasonic energy, the same free air ball can result in different ball contact diameters. For example, in figure 4.1.75 (a) we can see the bond contact diameter is about 40% of the total ball area, in figure 4.1.75 (b) it is about 70% and in figure 4.1.75 (c) bond contact diameter is about 90%. The ball contact diameter can be increased by optimum design of the capillary as well as controlling the bonding parameters.

4.1.38 Bonding Tool

The right choice of bonding tool (capillary or wedge) is crucial for successful wire bonding. One of the basic principles to achieve an optimized wire bonding process is through a proper capillary or wedge design selection. The synergy of different process variables coming from wire, substrate, bond pad metallization, and wire bonder is influential to final geometrical design of the bonding tool. Factors such as bond pad size, bond pad pitch, wire diameter and hardness, metallization, bonder speed and accuracy, loop height, loop length, and package layout will affect the tool

chosen for a wire bonding application. Proper bond tool selection is essential for successful wire bonding. The ceramic capillary is the tool most frequently used to make these interconnections. The ceramic capillary has undergone many changes as its usage has progressed from the manufacturing of 16 lead plastic packages to the more recent challenge of 500 lead BGA packages.

4.1.39 Bonding Tool Selection

Bonding tool action is so multi-faceted that purchasing a bonding tool involves more than simply selecting a tool from the catalogue. Expertise is a must to make an educated decision. If one chooses the right bonding tool, one can boost production and yield, reduce costs, and ensure consistency. Since the bonding wire must be delivered precisely onto the semiconductor bond pads, it is imperative that the wire be carefully located without wire damage, so that the wire, the bonding tool and bond pad locations are constant during all bonding positions.

The bonding tool must efficiently and consistently transmit the ultrasonic power to the wire bond pad interface to produce consistent and reliable interconnections. Between first and second bond, the high-speed looping and wire motion within the tool must be facilitated by minimal resistance, minimal plugging tendencies, and the elimination of potential stress concentrating sharp or acute edges within the wire guidance area.

In case of ultrasonic wedge bonding, the wedge tool pad front and back radii should be relatively large to minimize stress concentrations and maximize bond pull strengths. The bonding tool should be able to bond gold, aluminum, or copper wire at room temperature. Critical dimensions of capillary and its impact on bonding process are studied in the following section.

4.1.40 Capillary Dimensions

The critical capillary design parameters which affect the bonding process are: chamfer diameter, inner chamfer angle, capillary hole diameter, Tip diameter, outer radius, face length, face angle, capillary material, and

capillary surface finish. The different capillary design parameters are shown in figure 4.1.76

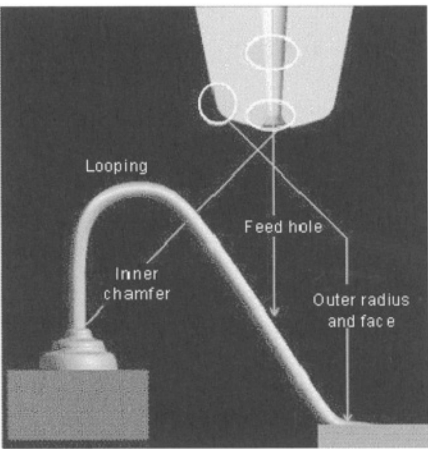


Figure 4.1.76 Capillary *parameters which affect the bonding process* [P-11]

The important dimensions in the capillary design are the face angle, the outer radius, the amount of inner chamfer, and the inner chamfer angle. The inner chamfer determines the size of the FAB, the final ball diameter as well as the ball height. The outer radius and face impact the smoothness of second bond transition and interfacial area of the wedge bond. The feed hole has an impact on looping profile as well as consistency. Figure 4.1.77 shows details of the standard tip dimensions of a capillary.

As the pad pitch decreases, there is a tendency of the capillary to touch the already bonded wire. This necessitates a very thin and slim capillary design in ultra fine pitch bonding application. Figure 4.1.78 shows the capillary touching the wire.

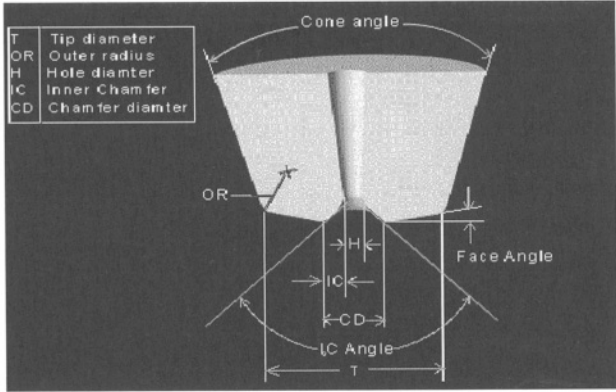


Figure 4.1.77 Capillary showing standard tip dimensions [Adopted from product catalog : Gaiser Tool]

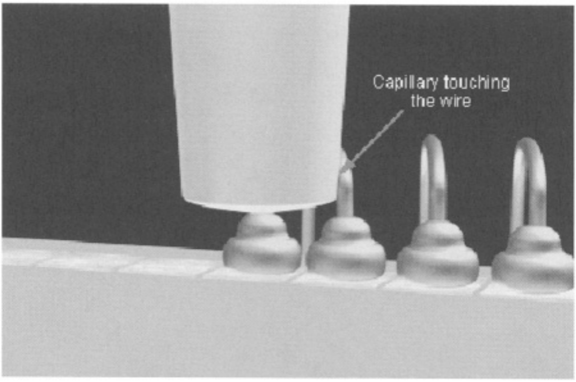


Figure 4.1.78 Capillary touching the wire

4.1.41 Capillary Tip Diameter

Tip diameter is the diameter of the capillary face at its intersection with the forming line of the cone. Usually the tip diameter is between 2 mils to 10 mils (50 - 250 microns) in size. The larger tip diameter provides a longer

bond length and larger surface area for a successful second bond. In ultra fine pitch bonding, in addition to smaller pad pitches, the size of the bond pad itself is small. In this situation, the capillary tip diameter must be as close to the bondpad size as possible. Figure 4.1.79 shows the tip diameter of a capillary. As the device pad pitch decreases, one must reduce the capillary tip diameter. Figure 4.1.80 we see, as the device pad pitch decreases, the capillary tip diameter decreases correspondingly.

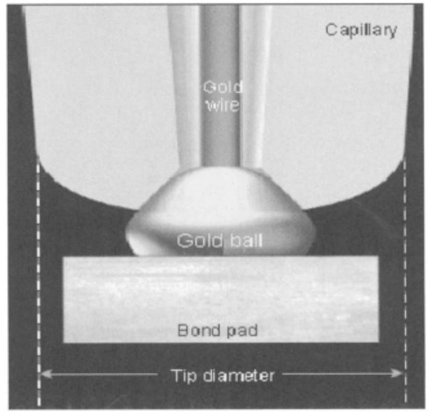


Figure 4.1.79 Tip diameter [P-7]

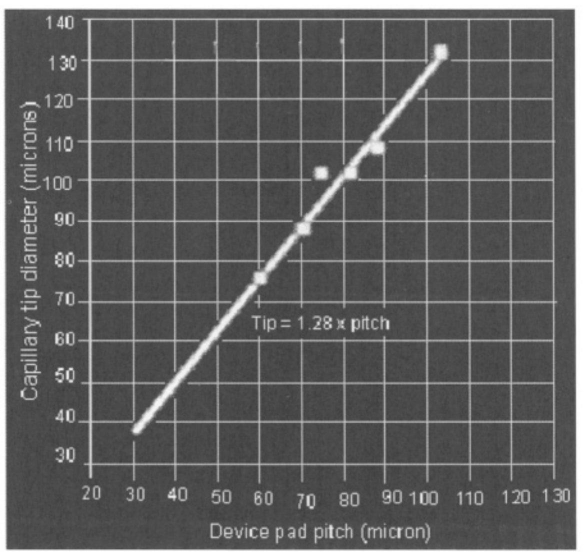


Figure 4.1.80 Pad pitch versus capillary dimension [P-11]

The length of a stitch bond depends on the tip diameter. We can see in figure 4.1.81 a stitch bond made with capillaries, with 3 mil tip diameter and

larger than 3 mil tip diameter. Larger the tip dimension, larger is the intermetallic area and higher is the bond strength.

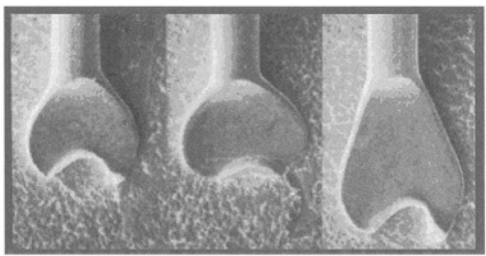


Figure 4.1.81 Effect of capillary tip diameter on weld diameter
[Adopted from product catalog : Gaiser Tool]

The tip diameter of a capillary is usually 25 to 50% larger than the bondpad. In table 4.1.9, we see that as the pad pitch decreases from 100 microns to 50 microns, the tip diameter of the capillary changes from 5.5 mils to 2.8 mils, (140 microns to 70 microns)

Pad Pitch (Microns)	Tip Diameter (Mil)
100	5.2 - 5.5
90	4.3
80	4.0
70	3.0
60	3.0 - 3.3
50	2.8 - 3.0

Table 4.1.9 Pad pitch vs. tip diameter

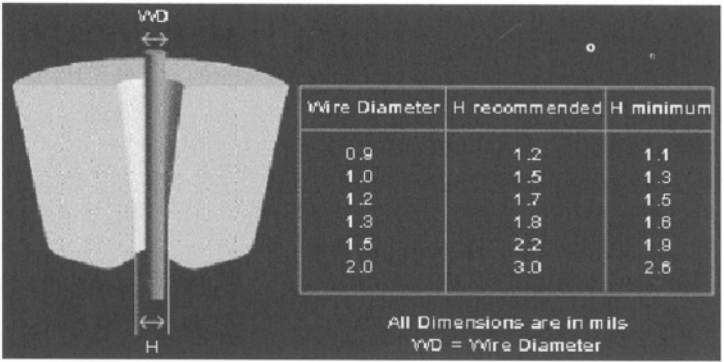
4.1.41.1 Tip Diameter Tolerance

The manufacturing tolerance for the tip diameter is critical. Usually manufacturers attain tolerance of between 0.2 to 0.4 mils.

4.1.42 Capillary Hole and Its Effect

The diameter of the capillary hole must be closely controlled. If the hole is too tight, wire movement is hindered. If the hole is too large, loop profile and wire bond positioning are significantly affected. For example the figure 4.1.82 shows that for a 1 mil wire, recommended hole diameter will be 1.5 mils, and the minimum hole diameter is 1.3 mils.

A larger hole dimension is preferred in a high speed bonder because it assists easy flow of wire. However, a smaller hole dimension may be required to produce small ball bonds and for more precise bond placement.



Wire Diameter	H recommended	H minimum
0.9	1.2	1.1
1.0	1.5	1.3
1.2	1.7	1.5
1.3	1.8	1.6
1.5	2.2	1.9
2.0	3.0	2.6

Figure 4.1.82 Recommend capillary hole diameter [P-11]

During capillary design for a particular wire diameter, one can determine the ideal hole diameter as well as the chamfer diameter to achieve good bond placement as well as minimum first bond diameter.

Table 4.1.10 Capillary configuration for different wire diameter [P-31]

Wire Ø	18 microns	23 microns	25 microns
Hole diameter, microns	25	28	30
Chamfer diameter, microns	31	33	35

In table 4.1.10, we see that the hole diameter requirement for 18, 23, and 25 micron wires is correspondingly 25, 28 and 30 microns. The required chamfer diameters are 31, 33 and 35 microns.

4.1.42.1 Tip-Bore Concentricity Tolerance

This is the tolerance of how exact the bore is centred inside the capillary. The tolerance is usually not published by the capillary manufacturer, however it is available upon request.

4.1.43 Chamfer Diameter and Chamfer Angle

The chamfer diameter is the inner cone at the opening of the bore. The chamfer aids in centring the ball. The chamfer diameter should not be larger than the bond diameter, because formation of a strong bond will not be possible. An example of a capillary with small chamfer diameter versus a capillary with large chamfer diameter is shown in figure 4.1.83.

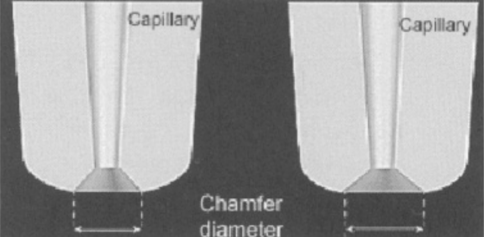


Figure 4.1.83 Chamfer diameter

It is important to recognize that as the FAB diameter increases, the chamfer diameter needs to be increased. The diameter of the FAB determines the volume of the FAB. When the capillary presses the ball on the bond pad, the FAB volume is distributed in three areas which are volume of chamfer diameter, volume of squashed ball, volume of neck as shown in figure 4.1.84.

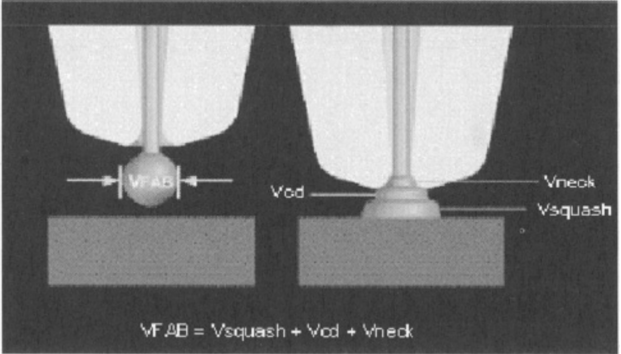


Figure 4.1.84 Capillary design consideration [P-11]

Depending on the first bond diameter requirement, and the FAB, one can determine what the chamfer diameter should be. As the FAB diameter increases, a larger chamfer diameter is required to get the same first bond diameter.

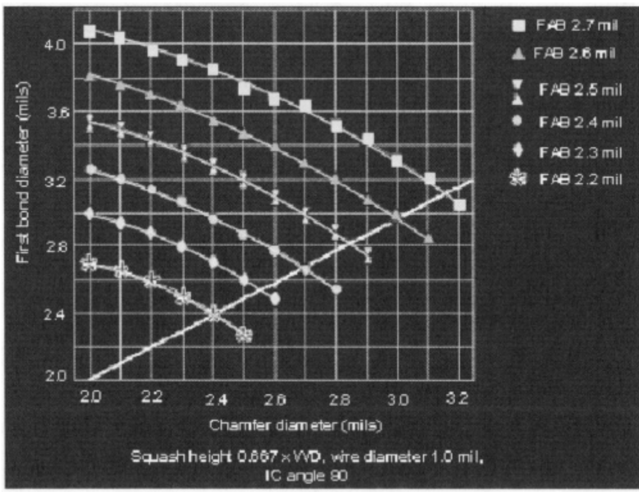


Figure 4.1.85 First bond diameter vs. chamfer diameter [P-11]

For example as shown in figure 4.1.85, in order to get a first bond diameter of 2.8 mils, one can either use:

- a 2.85 mil chamfer diameter when the free air ball size is 2.5 mils or
- one can use a 2.6 mil chamfer diameter when the free air ball is 2.4 mil or
- one can use a 2.3 mil chamfer diameter when the free air ball is 2.3 mil

4.1.43.1 Chamfer Angle and its Effects

The chamfer volume depends on the chamfer angle. Larger the angle higher the volume of the material in the chamfer. For example ball bonds made with 90° chamfer angles have taller ball bonds and smaller ball bond widths. This is due to the upward deformation equalling the outward deformation of the ball during bonding. Ball bonds made with 120° chamfer angle will be wider due to increased outward deformation of the ball. We can observe from figure 4.1.86 the volume differences between a 90° chamfer and a 120° chamfer.

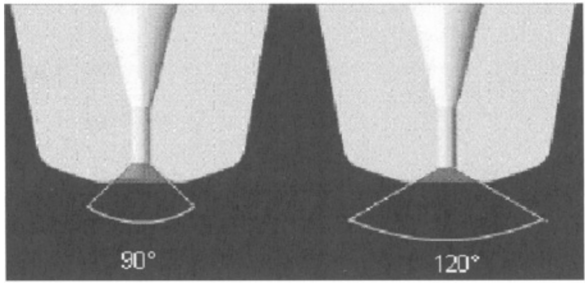


Figure 4.1.86 Volume difference between chamfers **[P-11]**

A 120° inner chamfer angle results in a sharp transition of the wire into the hole. This sharp edge can cause considerable drag which can cause sagging or S-ing. Whereas, a 90° inner chamfer angle does not have a sharp transition, and therefore, there is less drag on the wire, and better looping.

In order to determine the chamfer diameter and the chamfer angle, we need to look at first bond requirements as well as the second bond requirements. Larger the chamfer diameter, lower is the shear strength per unit area. At the same time, larger the inner chamfer angle, larger will be the ball diameter. 90° chamfer angle is preferred for fine-pitch applications where small ball bonds are desired. Determining chamfer diameter for first bond and tail bond requirement is schematically shown in figure 4.1.87.

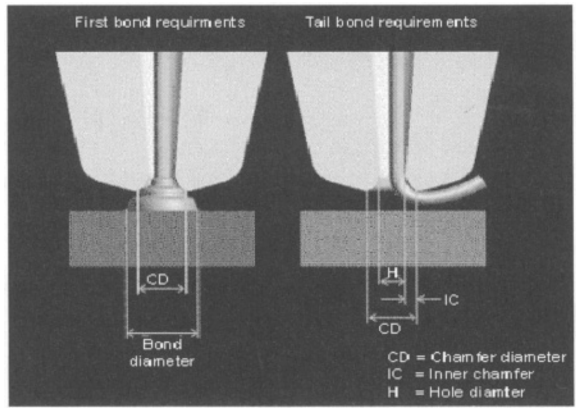


Figure 4.1.87 Capillary design consideration (Determining chamfer diameter and chamfer angle) [P-11]

The 90° chamfer angle capillary minimizes tailing by cutting through the wire more efficiently. The second bond formed with 90° chamfer angle is not as strong as the second bond made with the 120° chamfer angle capillary. When the chamfer angle is 90° or below, the wire transition from the hole to the chamfer is almost straight. When the chamfer angle is 120° the capillary provides the sharpest transition from the chamfer to the hole. The sharp edge that is created may cause considerable drag which can cause sagging or wavy wires.

4.1.44 Face Angle

Face angle is the angular value of the forming line of the outside of the chamfer diameter in reference to a horizontal plane. A comparison between two capillary is shown in figure 4.1.88. One with 4mil tip diameter and 20 degree face angle versus 7mil tip diameter and 8 degree face angle.

Capillaries have face angles ranging between 0-30 degrees. For example, a flat face capillary has a face angle of ZERO degrees. The face angle determines the weld interface. Smaller the face angle greater is the contact between the capillary and the second bond.

Three different types of face angle are shown in figure 4.1.89, here we can observe, with an 11 degree face angle, the weld area is very small, whereas with an 8 degree face angel, the weld area is much larger, with a 4 degree face angle, the weld contact areas will be very high.

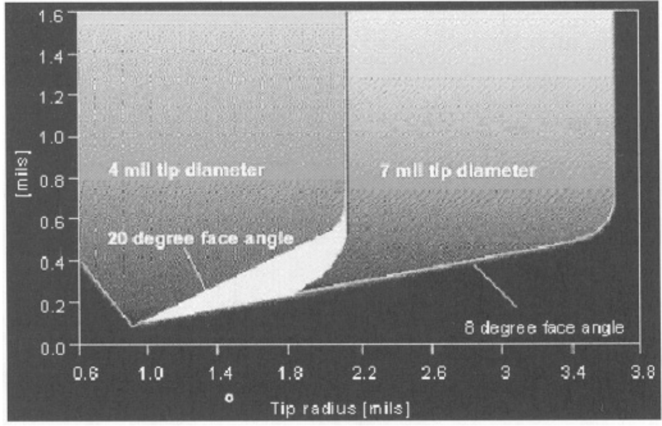


Figure 4.1.88 Capillary design consideration [P-11]

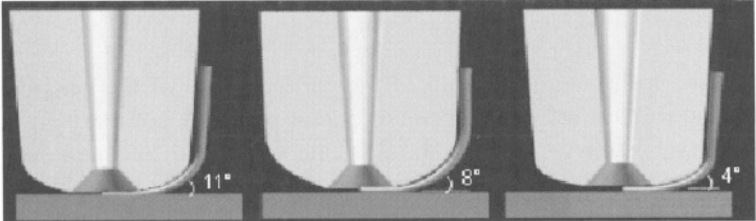


Figure 4.1.89 Face angle

The weld length increases if the tip diameter is larger and the face angle is smaller. This results in higher second bond strength. If the capillary has very small face angle and a small outer radius, then it results in micro cracks at the heel. Crack on second bond can be seen in figure 4.1.90. This is due to very small face angle and smaller outer radius of the capillary.

To avoid the micro crack, we can increase the outer radius and also increase the face angle. This gives a smoother transition from wire to weld and also increases the area of the weld interface.

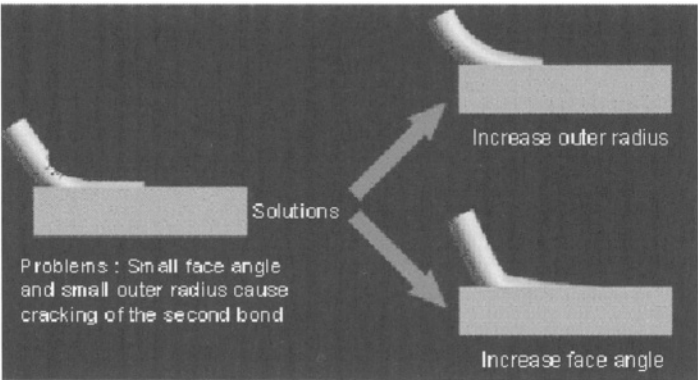


Figure 4.1.90 Cracked second bond [P-11]

4.1.44.1 Impact of Tip Diameter on Face Angle

As the tip diameter decreases, face angle increases. If the tip diameter is 5 mils or greater, the face angle can vary between 0 to 8 degrees. If the tip diameter is below 5 mils, then the face angle increases, and should be between 11-15 degrees.

4.1.44.2 Impact of Plating Thickness on Face Angle Selection

Softer plating requires higher face angle, whereas thick films need 8° face angle, and palladium film requires 0° face angle.

4.1.44.3 Face Length

The face of the capillary determines the extent of contact that the capillary makes during the ball bond formation and during the second bond formation. Larger the face length higher is the contact. The face length is determined by the equation shown in figure 4.1.91.

The face angle of a capillary determines the extent of contact that the capillary makes during the ball bond formation as well as during the weld formation. In general, when the capillary tip diameters are reduced, the face angle of the capillary is increased to maintain higher pull strength values.

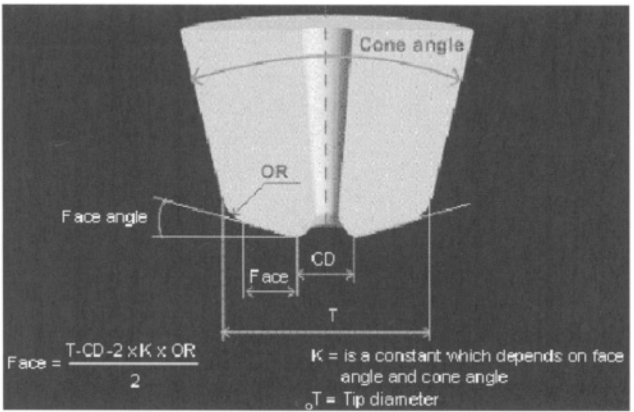


Figure 4.1.91 Capillary face calculation [P-11]

4.1.45 Outer Radius of the Capillary

This is the radius of the filet between the cone and the face of the capillary tip. The function of the outer radius (O.R) is to form the transition to the wire from the weld. Usually the outer radius value lies between 0-75 microns (0-3 mils). When the outer radius is too small, stress on the heel can result in a fracture or heel crack. Most capillary designs have outer radius larger than the wire diameter to be bonded. Figure 4.1.92 shows stitch bonds made with a small and large outer radius dimensions tools. For flat face capillary designs, the outer Radius is typically two to four times the diameter of wire to be bonded.

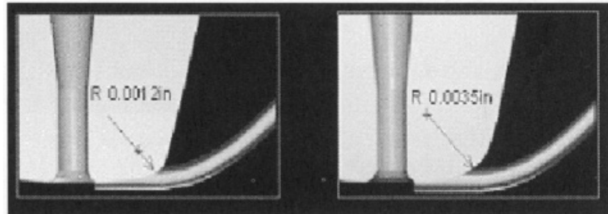


Figure 4.1.92 Stitch bonds made with a small and large O.R dimension tools
[Adopted from product catalog: Gaiser Tool]

As the tip diameter is reduced, the outer radius (the radius between the capillary face and the cone angle) is also reduced. Reducing the outer radius, increases the length of the face, maximizes the bond length for high pull strength.

4.1.46 Capillary Shapes

With a decrease in bond pad pitch, the tip diameter of capillary needs to be smaller. As we can see in figure 4.1.93, when the bond pad size is small, the capillary tip diameter will be small and correspondingly the bottle neck diameter can also be minimum. When the bond pad size is larger the bottle neck diameter can be large.

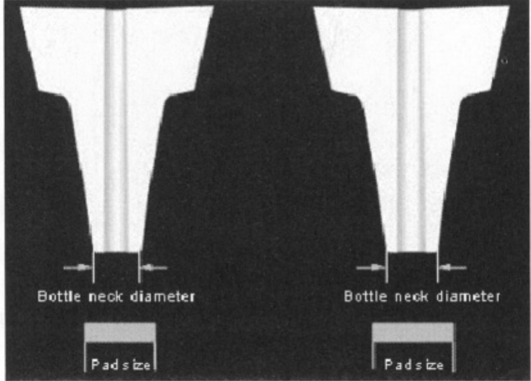


Figure 4.1.93 Bottle neck capillary diameter

With conventional bottle neck capillaries there is reduction in the wall thickness. And this gives rise to two main problems.

- inconsistency of ultrasonic coupling
- breaking of the tip

Let us briefly discuss each of the above mentioned problems.

4.1.46.1 Inconsistency of Ultrasonic Coupling

It is important to recognize that as the wall thickness becomes smaller, the capillary becomes more fragile and looses rigidity and this affects consistent ultrasonic coupling. We can observe from the figure 4.1.94, for the same bottleneck diameter, if the cone angle inside the capillary is 10 degrees, the corresponding wall thickness of the capillary will be about 3.6 mils. Where as, if the cone angle is 20 degrees the wall thickness is reduced to 2.2 mils.

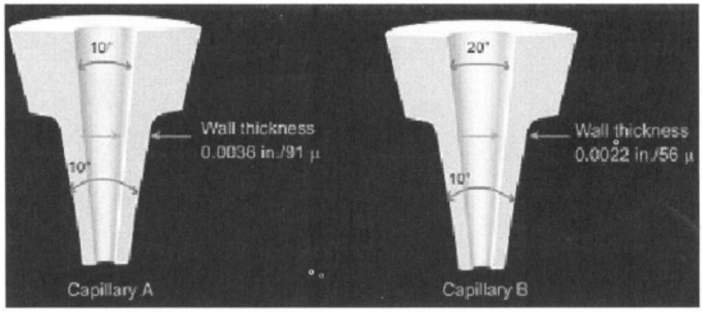


Figure 4.1.94 Cone angle

4.1.46.2 Breaking of the Tip

In conventional bottle neck capillaries, due to the reduction in wall thickness, the bottle neck capillary's tip is prone to breakage particularly during wire threading. When an operator threads the wire from the top of the capillary and comes down to grab the wire at the bottom tip of the capillary, the tweezer tip jumps at the transition of the bottleneck and this can create a tiny scratch or micro crack as shown in the figure 4.1.95.

During high speed bonding the capillary is undergoing constant pounding during touch downs and this leads to possible tip breakage of the already damaged capillary.

It is also important to recognize that in conventional bottle neck capillaries, the taper is achieved through wheel grinding technique. During bottleneck capillary manufacturing, a grinding wheel grinds the capillary and forms the bottleneck. Due to wearing of the wheel with time, the grinding process will not be consistent. This affects repeatability, accuracy of the wall thickness and the radius of transition. Figure 4.1.96 shows the bottle neck capillary manufacturing.

This tapering of the bottle neck capillary using a grinding process sometimes may also result in a weakened bottle neck taper. Variations in the main taper tip diameter "T" and variations due to wheel wear as well as

bottle neck height (BNH) tolerance produces variation in tip mass which could contribute to variation in ultrasonic power required.

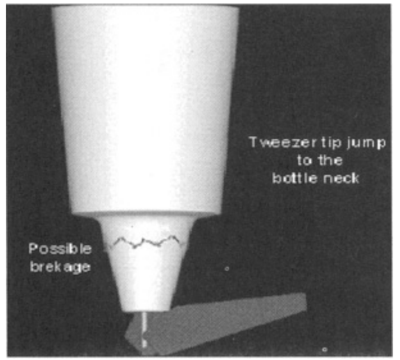


Figure 4.1.95 Breaking of the tip

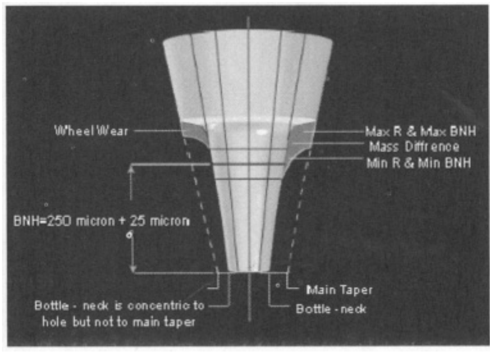


Figure 4.1.96 Bottle neck capillary manufacturing [Courtesy: Small Precision Tools]

4.1.47 Slim Capillaries

In order to overcome some of the drawbacks of bottle neck capillaries, a new technology of capillary manufacturing has been developed. Today, ceramic injection molded technology is used to produce bottle neck capillaries which do not have ground line due to wheel grinding.

In slim line bottle neck capillaries, the tip diameter, the bottle neck height and the wall thickness can be very tightly controlled and have very little variation. This results in minimum variation in ultrasonic coupling. In conventional bottleneck capillary, the wall thicknesses are much smaller compared to the wall thickness in a molded slim line capillary and secondly the sudden transition in tapering that we observe in a conventional capillary is replaced by a smooth tapering in a slim lime capillary. Figure 4.1.97 shows comparison of bottle neck and slim line capillary.

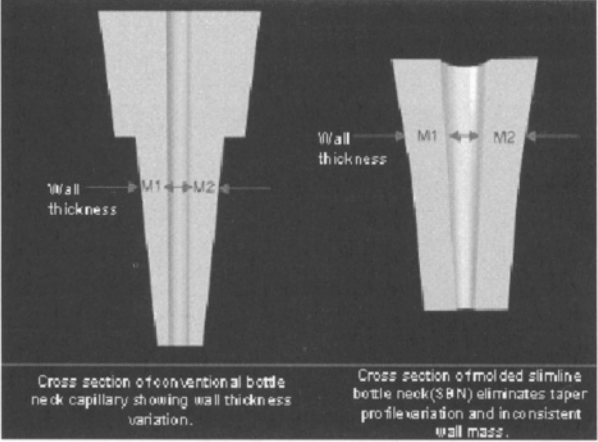


Figure 4.1.97 Molded slim line capillary [Courtesy: Small Precision Tools]

4.1.48 Capillary Materials

Earlier Tungsten Carbide was used as capillary material because of its resistance to breakage. Recently, ceramic capillaries have become very popular. The smooth surface of the ceramic capillary coupled with non-porosity at the surface is a good combination for a capillary that has long life.

Aggressive pitch reduction is forcing a reduction in capillary dimensions. To support this reduction, the capillary must have high mechanical properties during bonding and good machinability during manufacturing. Capillary design and the ceramic material used are important considerations in meeting the requirements of today's ultra fine pitch packaging technology. One of the known methods of achieving this is to reduce the ceramic grain size. The grain size reduction increases the fracture toughness, and thereby strengthens the capillary break-resistant capability. For ultra fine pitch applications, wirebond capillaries made with zirconia composite material with special additives (AZ) are used. Each material has its advantages and disadvantages depending upon its use.

Tungsten Carbide: Tungsten carbide has the advantage of being the most resistant to breakage and is recommended for use in capillaries with tip diameters of less than .005". It has some disadvantages also. Since Tungsten carbide is a cemented material of small particles of pure tungsten carbide held in a matrix by a cobalt binder, under high temperature, the binder tends to leach out. The carbide then breaks down resulting in a roughened bore and bonding face and may result in process reliability problem. Figure 4.1.98 shows capillary surface of tungsten carbide and surface finish of ceramic capillary. The dark areas in the photo show the cobalt binder.

Thermal conductivity of tungsten carbide is higher than alumina and therefore they must be heated to prevent them from acting as heat sinks, drawing heat away from the bond pad during bonding. Wear life of tungsten carbide capillaries approaches 500,000 bonds, depending upon the temperature used.

Alumina Ceramic: unlike tungsten carbide, alumina ceramic has no binder and does not break down under high temperature, nor does it react with most chemicals thereby permitting chemical cleaning. Bore and surface finishes obtainable with ceramic capillaries are superior to those obtained with carbide.

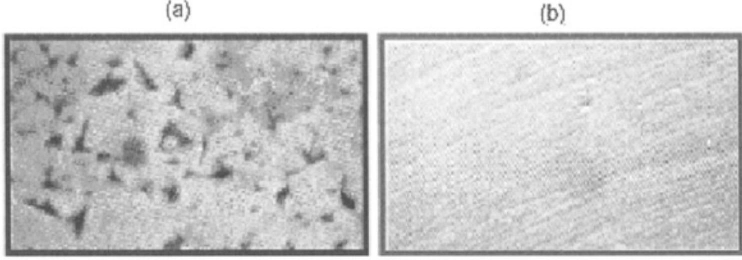


Figure 4.1.98 (a) Tungsten carbide capillary surface (b) Ceramic capillary [P-32]

Ceramic capillaries are also not susceptible to hole plugging. Ceramic capillaries have lower thermal conductivity and can be used with or without heating. Wear life of ceramic capillaries have been known to exceed one million bonds when used in automatic bonders. In special cases where long term durability is required even ruby capillaries have been used.

Zirconia Composite (AZ) : It has been observed that the strength of the zirconia composite (AZ) material is greater than the ceramic high-density material, where AZ exhibits higher fracture values than standard high-density material. Today, AZ material is being used to produce slimline bottleneck capillaries using ceramic injection molding (CIM) process.

Capillary tip breakage problem is a major issue for capillaries with tip diameter less than 110 micron, where the capillary breaks during wire bonding process. Zirconia composite (AZ) material can withstand the ultrasonic force applied for T less than 110 micron. The grain size reduction increases the fracture toughness, strengthening the capillary's break-resistant capability.

Table 4.1.11, shows the comparison of high-density ceramic material used for conventional capillary making versus a zirconia composite material used for ultra fine pitch application.

We can observe here, that the average grain size is 0.25 microns for AZ material versus 2 microns for high density ceramic, and correspondingly the material strength is higher.

Table 4.1.11 Comparison of high density ceramic and zirconia composite material. [Courtesy: Small Precision Tools]

Material	High density ceramic (C)	Zirconia Composite (AZ)
Chemical composition	99.99% Al_2O_3	ZrO with additives
Color appearance	Translucent white	White
Density (g / cm^3)	3.99	5.5
Average grain size	< 2 μm	<0.25 μm
Bending strength (MPa)	850	2400
Finishing	Fine matte and polished	Fine matte and polished

Similar to AZ material, some other companies use a toughened alumina material for capillary tool manufacturing. Stress tests have shown that toughened alumina material is far more superior to alumina. In figure 4.1.99 we can observe the results of a capillary breakage test.

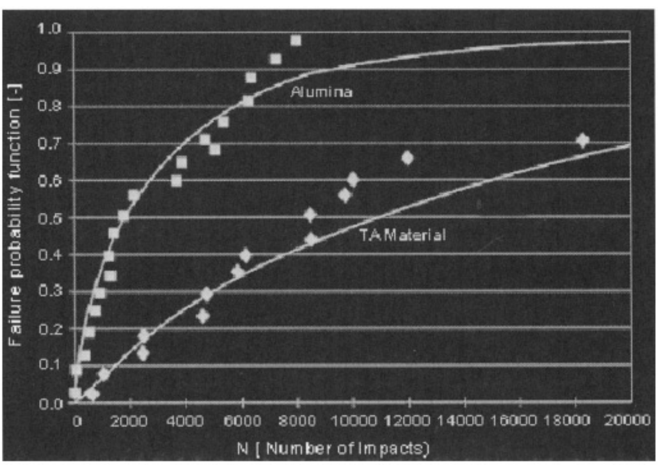


Figure 4.1.99 TA material and alumina capillary breakage test
[Courtesy: SEMI]

The results show that the failure probability of a capillary with a conventional alumina is much higher compared to the failure probability of a capillary with toughened alumina.

4.1.49 Capillary Manufacturing with CNC Machining

The conventional CNC grinding process uses an abrasive diamond wheel that wears out with time. This directly affects the consistency of meeting the critical dimensional tolerances and final finishing of the product. Ceramic Injection molding process eliminates this problem.

Another disadvantage of any grinding technology is the amount of micro-fractures it generates into the ceramic material after it has been grounded.

These micro-fractures are inherent to the grinding process and cannot be eliminated even if the finest diamond-grinding wheel is used.

Unlike the manual or CNC grinding technology, the capillary produced using the CIM process is molded net to shape. There is no need to do grinding or major external finishing process

4.1.50 Ceramic Injection Molding (CIM) Process

Today's ceramic injection molding process is a combination of powder metallurgy, injection molding, and sintering technologies. To obtain the necessary chemical and physical properties, powders are selected by size, shape and combined with additives. Figure 4.1.100 shows the process flow of the CIM process.

Every particle of the ceramic powder is coated with an inorganic binder, and then transported for molding which gives the final form rigidity. Evaporation and exothermic reaction remove the binder, leaving only a small fraction behind. The formed part, depending on the powder used, is then sintered in an oxidizing or reducing atmosphere, or in a high vacuum at temperatures of up to 2400° C.

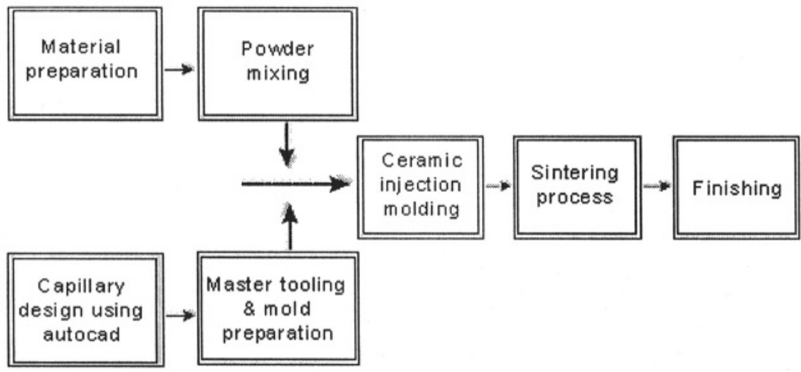


Figure 4.1.100 Ceramic injection molding (CIM) process [Courtesy: Small Precision Tools]

4.1.51 Advantages of Ceramic Injection Molding

Ceramic injection molding process offers a high degree of reproducibility. Complex capillary parts in ceramic can be shaped in one operation with diverse geometry and different wall thickness. Some of the other advantages are:

- economically cost effective in manufacturing of complex parts which are difficult to CNC machine
- molding to net shape
- consistent dimensional measurement readings
- tighter tolerance specification than powder pressing
- consistent repeatability and reproducibility
- superior surface finishing

4.1.52 Capillary Material Selection Criteria

Important criteria in the selection of the suitable capillary material for an optimum bondability are:

- small grain size
- higher density
- higher bending strength
- resistant to tip breakage and
- sleek material finish

4.1.52.1 Small Grain Size

Materials which have small the grain sizes gives smoother finish. This helps in reducing the wire drag in the wire passage. This also helps in the long wire / low loop requirements of today's high lead count packages. Typically, for high density ceramic material, the small grain size will be less than 2 microns and for zirconia composite (AZ) material, the small grain size will be 0.25 microns. Figure 4.1.101 shows SEM photo of ceramic and zirconia material.

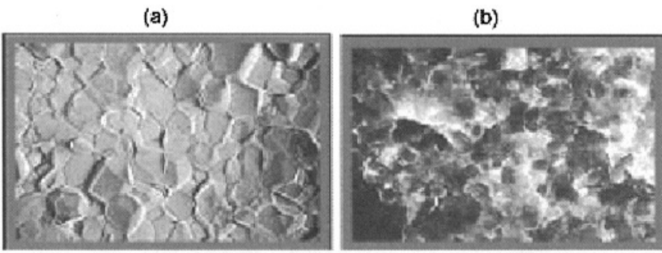


Figure 4.1.101 (a) High purity density material (b) Zirconia composite
[Courtesy: Small Precision Tools]

4.1.52.2 Higher Density

Because of higher density, the material's grain boundaries are not visible under a standard metallurgical high power microscope. The ceramic material surface finish is non- porous, and this reduces gold build-up and degradation due to grain losses during bonding. This increases the capillary life (in terms of number of capillary touchdowns or tool wear), which is important in the ultra-fine pitch package application. An increased tool life yields lesser machine down time.

4.1.52.3 Higher Bending Strength

Higher the bending strength of the material, higher the capacity of the capillary material to withstand mechanical stress. Bending strength property is important because this gives a measure of material's capability to withstand tip breakage during actual bonding process. The higher the bending strength value the better, because the material is more resistive to breakage problem.

4.1.52.4 Resistant to Tip Breakage

As we go towards smaller tip diameter, the capillary should be designed to withstand tip breakage. This is specifically necessary for molded slimline bottleneck capillaries.

4.1.52.5 Sleek Material Finish

This is an important consideration for ultra-fine pitch applications. A smaller hole size is essential for better bond placement accuracy, as well as maximizing the inner chamfer (IC) design. Sleek material finish also resolves problems such as open wire and loose tail after second bond.

4.1.53 Capillary Surface Finish

Capillaries are designed with polished finish surface or with matte finish surface.

4.1.53.1 Polished Finish Capillary

The capillary tip with a smooth or polished finish produces a shiny or smooth looking second bond. After 1500 to 3000 bonds, the capillary becomes 'seasoned' and has a very light matte finish. For longer capillary life and general applications, polished capillary is used. This provides shiny second bond and longer capillary life due to less gold build-up. A capillary with polished finish is shown in figure 4.1.102(a). This kind of capillary is typically specified for surfaces with very good bondability.

4.1.53.2 Matte Finish

The matte finish texture is done on the face and on the outer radius. Only the inner chamfer remains highly polished. This combination allows for strong second bonds, while first bonds are shiny and smooth. Matte finish produces a textured stitch bond and is always necessary for smaller tip diameter. A matte finish is used when the bondability of a surface is poor. This allows for better coupling between the capillary and the wire and

resulting in better transference of ultrasonic energy. Figure 4.1.102(b) shows a capillary with matte finish.

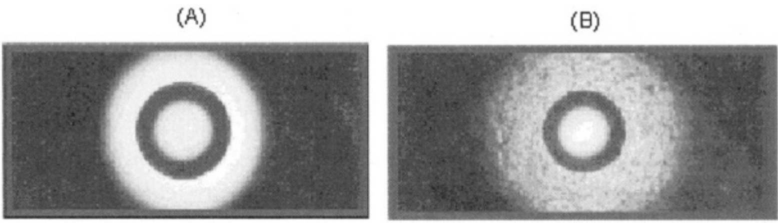


Figure 4.1.102 (a) Polished finish (b) Matte finish [Adopted from product catalog: Gaiser Tool]

4.1.54 Capillary Damage

A new capillary has a smooth surface finish with no cracks, pits, or attached foreign particles. However, on continuous use during bonding, the capillary tends to pick up contamination particles and also gets damaged. The use of damaged capillary will affect the bonding process and result in reliability failures. If we continue to use damaged capillary, it will affect both the first bond and the second bond.

When an over used capillary is continuously used, the ball has a rough surface, but the shear force may not be affected. This worn out capillary can give stitch bonds which have slight heel damage. An SEM image of ball formed with worn out capillary is shown in figure 4.1.103

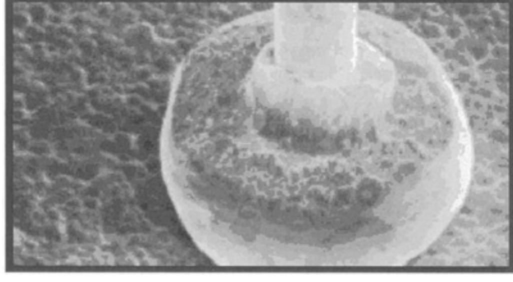


Figure 4.1.103 Ball bond formed with worn out capillary [Adopted from product catalog: Gaiser Tool]

4.1.55 Wedge Tool for Ultrasonic Bonding

Small wire ultrasonic wedge bonding is a long established assembly interconnect technique in the semiconductor industry. Commonly referred to as wedge bonding. The wire material used is critical for wedge material selection and design due to the different material properties of aluminum versus gold wire. Wedge tools are available in a variety of materials, such as tungsten carbide for aluminum wire applications, titanium carbide for gold wire wedge bonding and fine grain metals for fine pitch applications.

The effect of tool geometry on the strength and reliability of a bond is important, as the foot geometry is imprinted on the weldment. The bond shape of a wedge bond depends on the wedge geometry. The basic bonding tool foot consists of a front radius (FR), and back radius (BR). As shown in figure 4.1.104 the front radius, the back radius of the wedge foot determines the shape of the bond, length of the bond as well as the smoothness of the heel.

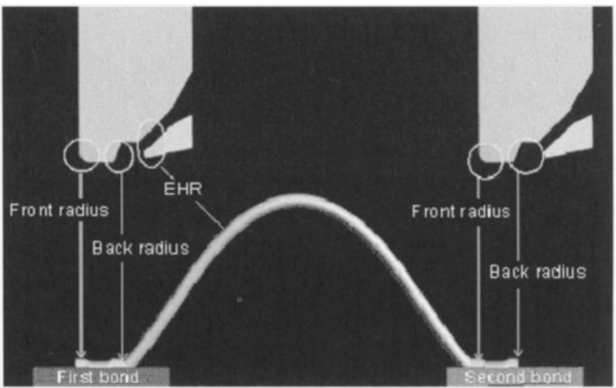


Figure 4.1.104 Wedge design considerations [P-11]

The front radius assures a gentle transition from the wire into the weldment of the second bond. The major portion of bond weldment occurs under bond length. A gentle transition from the wire into the weldment of the first bond is assured by the back radius, and permits wire termination after the second

bond. Figure 4.1.105 shows the schematic view of a wedge tool for aluminum wire bonding.

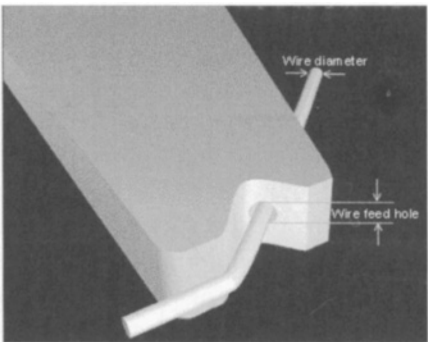


Figure 4.1.105 Wedge tool for ultrasonic bonding [Adopted from product catalog: Gaiser Tool]

There are many tip configurations of wedge. Figure 4.1.106 shows a cross-sectional view of a V-notch wedge. Different critical dimensions such as the back radius, the front radius, the bond length, the foot length, the hole diameter, and the wire feed angle are also shown here.

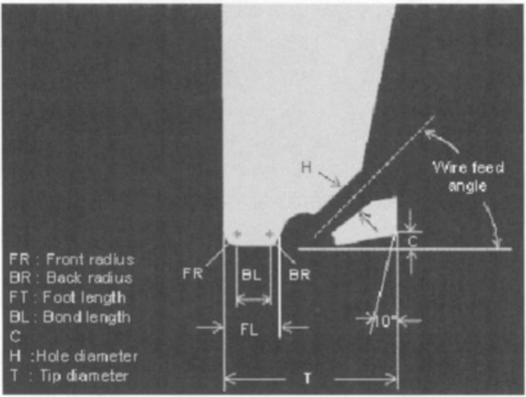


Figure 4.1.106 Cross sectional view of a V-notch wedge identifying the standard dimensions [Adopted from product catalog: Gaiser Tool]

The design of wedges over the last ten years has changed very little with the exception of the introduction of deep access wedge bonding. Most bonder manufacturers now offer a wedge bonder that enables the wire to travel through the centre or down the back of the wedge vertically. The tip configurations on these deep access wedges are generally the same as those offered for conventional bonding.

4.1.56 Back Radius

The Back Radius has two functions. The first function is to provide the transition between the wire and the first bond. The second function is to provide the area on the wedge where the wire will terminate on the lead bond.

A normal back radius will range between 50 - 100% of the wire diameter. This depends on the wire, bond length, and device requirement without affecting the ability to terminate the wire after second bond. Usually, the back radius is smaller than the front radius, making the weakest point in the system at the wire weldment transition of the first bond. Figure 4.1.107 shows a SEM photograph of a wedge bond on the die, formed with a tool with a straight back radius. The straight back radius helps to provide consistent tailing.

During aluminum wedge bonding, it is typical to-have a certain amount of heel damage. Usually, larger the back radius of the tool, the lesser is the heel damage in the bond. Microcracks in the heel are due to smaller back radius or worn-out wedge or high bonding parameters. Figure 4.1.108 shows a SEM photomicrograph of heel microcracks.

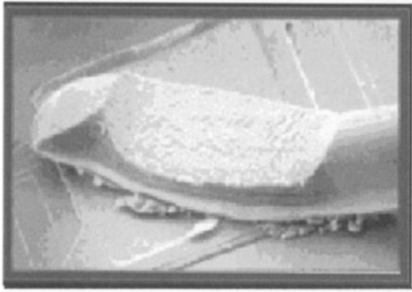


Figure 4.1.07 Wedge bond formed with straight back radius [Courtesy: Gaiser Tool]

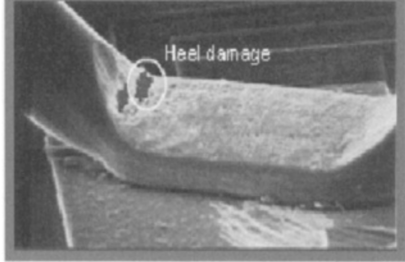


Figure 4.1.108 Micro- cracks in the heel [Courtesy: Gaiser Tool]

4.1.56.1 Elliptical Back Radius vs. Chamfer Back Radius

An elliptical back radius on a wedge provides a stronger bond by increasing the cross-sectional area of the heel. This helps in reducing heel cracks often associated with standard wedges. The elliptical back radius may cause inconsistent tailing as it creates a stronger heel area. Figure 4.1.109(a) shows a SEM photomicrograph of a wedge bond made with elliptical back radius. This provides a stronger bond by increasing the cross section area of the heel. This also helps to reduce heel cracks that we normally see in standard wedges. However, one disadvantage with elliptical back radius is that it may cause in-consistent tailing. Figure 4.1.109(b) shows a SEM photomicrograph of a wedge tool with a chamfer back radius. The chamfer produces a slope to the back radius and helps to reduce heel cracks. It may cause inconsistent tailing due to a stronger heel area.

Wedge tool are designed with polished front and back radii to help reduce aluminum build-up from occurring. The polished front and back radii provide a smooth appearance at the heel of the 1st bond and the toe of the 2nd bond. The polished back radius can also aid in reducing heel cracks. Figure 4.1.109(c) shows a SEM photo of a bond formation with wedge tool with polished front and back radii.

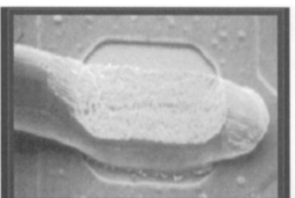


Figure 4.1.109 (a) Wedge formed with elliptical back radius tool [Courtesy: Gaiser Tool]

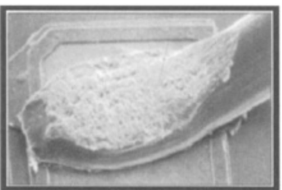


Figure 4.1.109 (b) Wedge bond made with chamfer back radius tool [Courtesy: Gaiser Tool]

Figure 4.1.109 (c) Bond formation with wedge tool with polished front and back radii [Courtesy: Gaiser Tool]

4.1.57 Face of Wedge

The first bonding tools in general use were, flat-faced tools with front radius, a bonding flat, and sharp back radius of .0002 inches. When wires are ultrasonically bonded, optimum bonding is achieved when the deformed width is between 1.5 to 1.8 times the wire diameter. We can use either a flat faced wedge or a concave shaped wedge as shown in figure 4.1.110. Usually, the deformed width is less with concave tools compared to flat faced tools.

4.1.57.1 Concave Tool

A concave tool design is the most reliable bonding tool design. It incorporates a highly polished front and back radius, assuring a smooth, gentle transition from the wire into weldment. Concavity depth is normally 20-30% of the wire diameter across the width of the tool. A satin finished bonding length assures minimal movement between the wire-tool interface and the slightly concave face across the tool width assures low deformation and highest bond pull strength.

The deformed wire strength is less for either a concave or flat tool with a very sharp back radius. The larger the back radius, the greater the deformed wire strength, due to a stronger transition at the heel.

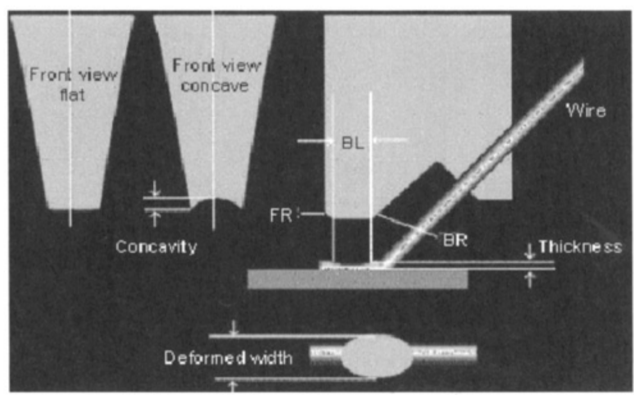


Figure 4.1.110 Flat vs. concave faced wedge tools [P-32]

4.1.58 Deep Access Bonding

In Ultrasonic wirebonding, it is best to make the first bond on the die, and the second bond on the lead finger. However, when we do ultrasonic bonding in deeply recessed package, using a wedge with a 30 degree wire hole, the bonding will be very difficult because of interference between the wire and the side wall of the package, or the tool and the side wall of the package.

Therefore, we can use 60° bonding in deep recessed packages. Here, when the wire enters the hole at 60°, there is no interference between the package side wall and the bondwire. Figure 4.1.111 shows 30° and 60° bonding in deep recessed package.

Using a wedge with 30° wire hole, there exists a continual problem of the wire touching the top corner of the package, thereby causing the wire to nick, break, or drop out of the bonding tool, increasing machine downtime and reducing reliability.

Depending on the feed angle the dimension of the side of the wedge changes. For example as shown in figure 4.1.112, a 60° feed angle wedge has a much smaller ‘S’ size compared to 30° feed angle wedge.

A standard solution to ultrasonic bonding into deeply recessed packages has been to “Reverse Bond”.

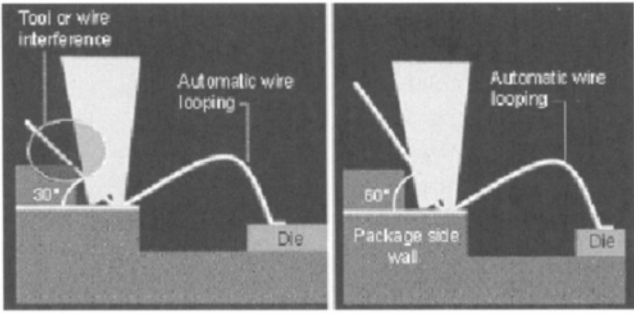


Figure 4.1.111 Standard 30 and 60 degree bonding in deep recessed package [P-32]

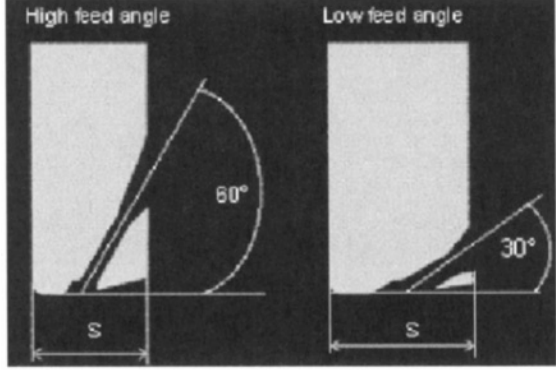


Figure 4.1.112 Feed angle effect on S size [P-11]

4.1.59 Reverse Bonding

When we have problems bonding into deeply recessed packages, one solution is to perform reverse bonding, where we place the first bond on the lead and the second bond on the bond pad on the die. As shown in figure 4.1.113. However, with reverse bond technique, there is increased possibility of wire sagging and shorting of the wire with the die edge. Therefore, special instructions must be given to the operators when we use reverse bonding technology with any package.

Some attempts have been made in the past to solve the problem of bonding into deeply recessed packages by using bonding tools with a 60 deg. hole rather than the standard 30° hole. This was normally done without changing the wire feed system or wire clamp and proved to be a poor solution because of the continual wire nicking and wire feeding problems experienced. Since the automatic looping of the wire by the machine cannot be utilized. In making the second bond on the die, the wire tends to lay down flat on the die, the longer the wire run, the more severe this problem becomes.

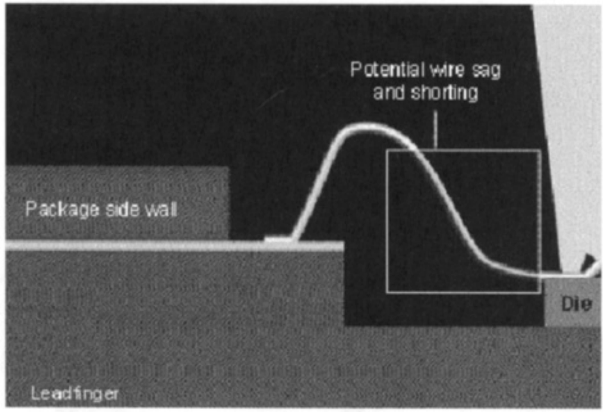


Figure 4.1.113 Reverse bonding [P-32]

4.1.59.1 Advanced Deep Access Bonding

The new deep access wedge bonding utilizes a through-the-wedge design. The wire feeds down through the centre of the wedge, exits the wedge and then re-enters the wedge at the tip. This design allows for accessibility similar to a capillary. In conventional wedge bonding, the wire feed occurs at 30 degrees or 60 degrees angle. The wire and the clamp are located behind the wedge. This limits accessibility into deep packages. However, in deep accessed wedge bonding, we can have wire feed through the wedge. In this case, the wire feeds down the centre of the wedge, exits the wedge, and then re-enters at the tip of the wedge. This wedge design allows deep package accessibility almost like a capillary. Figure 4.1.114 (a) shows a conventional

wedge tool with a 60 degree feed angle and Figure 4.1.114 (b) shows a deep access wedge tool.

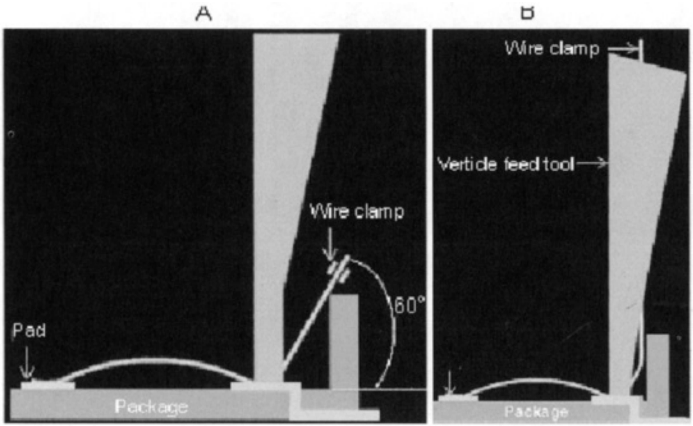


Figure 4.1.114 (a) Conventional wedge tool (b) Advanced deep access wedge tool
[Adopted from product catalog: Gaiser Tool]

4.1.60 Wire Feed and Impact on Bond Position

The wire feed hole in the wedge must control wire motion. If the wire has too much movement within the wedge, the bond positioning will not be accurate. Special designs are attempted to minimize wire movement and maximize bond position accuracy. In designing wedges, it is important to accommodate easy wire threading as well as minimum wire movement inside the hole. Here is an example of a key hole design where the large opening allows easy wire threading while the smaller slot keeps the wire aligned. Figure 4.1.115 shows the SEM photograph of key hole design.

Better wire placement accuracy can be achieved also by using wedges with in-line groove. Figure 4.1.116 shows an example of a wedge tool with an inline groove. This groove helps in improving wire placement accuracy as well as ultrasonic coupling.

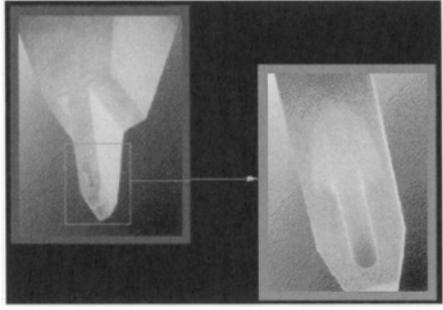


Figure 4.1.115 Key hole design [Courtesy : Microminiature Technology]

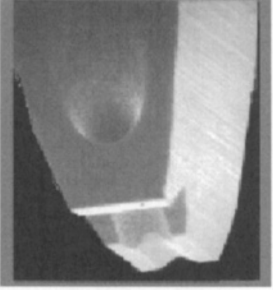


Figure 4.1.116. Wedge tool with an in-line groove

4.1.61 Materials for Wedge Tool

Wedge tools are available in a variety of materials. For increased durability and superior quality of gold wire wedge bonding wedges are manufactured using titanium carbide. Whereas for aluminum wedge bonds, wedges are manufactured with high quality tungsten carbide and osmium. Fine grain metals are used to manufacture wedges used in fine pitch applications

4.1.62 Surface Finish

Most movement during bonding should occur at the wire substrate interface, rather than at the wire-tool interface. Tools having a highly polished bonding length normally have to make several hundred bonds before making consistent bonds. Tools with an extremely fine satin finish on the bond length eliminate this problem and reduce movement between the wire-tool interface. The satin finish of the highly polished front and back radii are controlled so that aluminum build-up on the tool is not increased.

Depending on application, bonding wedge tools with wide variety of surface finishes are manufactured. They are:

- “Soft” for Al wire (just enough roughness to couple with wire)

- "Frosted" standard for Au wire (rougher surface than for Al)
- "Super frost" finish is coarsest standard finish, for TAB tools for Cu tape

For example, a wedge tool with a surface roughness of about 0.13 microns is used for standard aluminum wire. This roughness is just enough to couple with the wire. However, for gold wire wedge bonding, a wedge tool surface with a roughness of 0.58 microns is used. Other rough surfaces used are 0.20 and 0.36 micron roughness. For special applications such as TAB bonding tools roughness as high as 0.97 micron is used.

Table 4.1.12 Surface profile of standard finishes [Courtesy : Microminiature Technology]

Finish	RMS Roughness (Rq)	
	Microns	Micro-inches
Soft	0.13	5.1
Tempered	0.20	7.9
Textured	0.36	14.2
Frosted	0.58	22.6
Super frost	0.97	38.2

In table 4.1.12 we can see the surface roughness value changing from 0.13 microns value for soft finish and 0.97 microns for super frost finish. The choice of the surface roughness depends on the type and diameter of the wire.

4.1.62.1 Cross Groove Tool

Cross groove tool increases ultrasonic coupling and therefore it is recommended for hard bond wires. Wedge tool with a cross groove design improves ultrasonic coupling and is generally used for gold wire wedge bonding. Because aluminium is a soft metal, this type of tool is not usually

recommended for aluminum because of possible build-up of aluminum in the groove. Figure 4.1.117 shows the SEM photograph of cross groove design of a wedge tool.

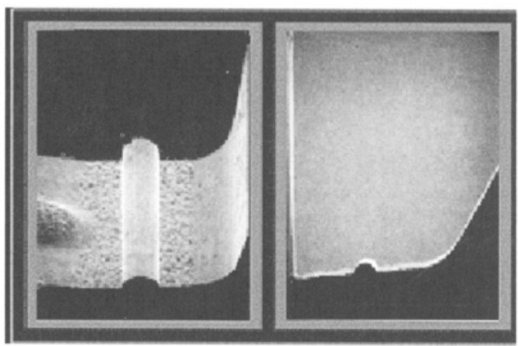


Figure 4.1.117 Wedge tool with cross groove design [Courtesy : Microminiature Technology]

Cross groove tools are generally used where the metallization is difficult to bond and a normal concave design is not effective. Figure 4.1.118 shows a SEM microphotograph of a wedge bond made with a cross groove tools.

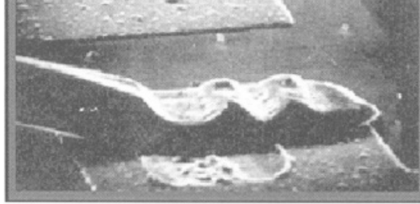


Figure 4.1.118 Typical bond made with a cross groove tools [P-32]

In a wedge with cross groove design the back radius must be sharp enough and the bond length long enough for the wire to terminate correctly.

If the back radius is too large or the Bond length is too short, the wire will have a tendency to terminate at the cross groove. When this happens, the 2nd bond will be short and the 1st bond will have an extra-long tail. A closer look of a wedge bond performed with grooved wedge tool is shown in figure 4.1.119.

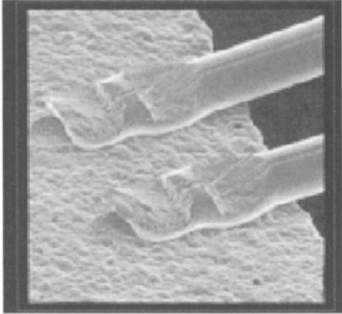


Figure 4.1.119 Another example of wedge bond with grooved wedge tool [Courtesy: Gaiser Tool]

4.1.62.2 Wedge Tool of Heavy Wire

Choosing the right wedge with either a V-groove or a round groove is critical for reliable heavy wire wedge bonding. Wedge dimensions such as foot length, hole angle, groove style, and back radius determine the accuracy of bond placement as well as reliability of the bonded interface. Figure 4.1.120 shows an example of wedge with a 60 degree angle V-groove generally used for heavy wire bonding.

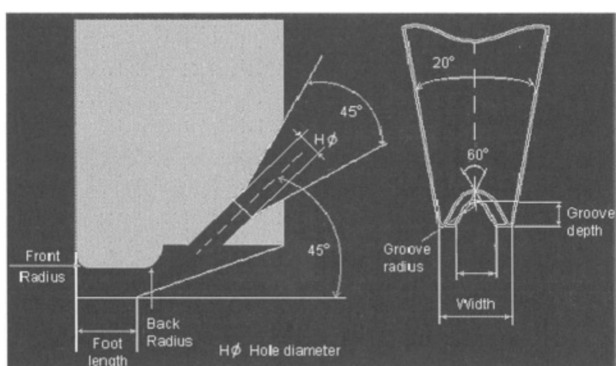


Figure 4.1.120 Heavy wire wedge tool design with V-groove [P-11]

4.1.63 Other Wedge Tools

4.1.63.1 Ribbon Bonding Tool

Ribbon wire bonding is used in microwave applications and in some high power applications. Ribbon bonds exhibit little wire deformation or heel damage and therefore smaller front and heel radii are typical. A heel radius of 0.2 mils is common in order to achieve consistent termination. Figure 4.1.121 shows wedge tool used for ribbon bonding.

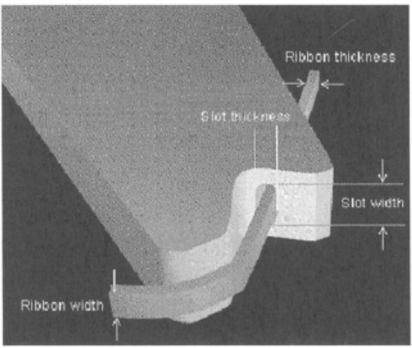


Figure 4.1.121 Ribbon bonding wedge tool

4.1.63.2 Special Bonding Tool

The protruding cross used in single point TAB type application provides excellent coupling and is today used in CSP type application. Figure 4.1.122 shows a SEM photograph of a wedge tool with protruding cross.

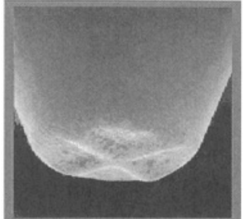


Figure 4.1.122 Wedge tool with protruding cross

4.1.64 Other Variables that Impact Bonding

The major contributors to bonding process consistency and reliability are the bonding parameters, the type of metallization, the wire and the bonding tool. However, there are a host of other variables that contribute to bonding process inconsistency and process reliability. Here we discuss some of those "noise factors". It is important to recognize that to achieve a bonding process with 99.999% process yield, these "noise factors" must be controlled rigorously.

4.1.65 Wire Bond Equipment and Work holder

During the bonding process, the equipment parameters and equipment stability play an important role in determining the final process yield and bond reliability. Some of the variables are: PRS recognition, EFO consistency, wire feed consistency, synchronization of all movements, stability of settings, transducer, software related bugs and missing bond detector. In addition the heater block, work holder design and operation also impact the bonding process. Some of the variables are: heater block, leadframe clamp, package vacuum clamp and leadframe transport system.

4.1.66 Pattern Recognition System

The pattern recognition system on the automatic wire bonders must recognize the bondpads on the chip and the fiducial marks on the package. The variability in brightness of the bondpad metallization or inconsistency in fiducial mark will induce inaccuracy in PRS recognition and this may result in reduced MTBA. Reduced MTBA means decreased productivity and decreased yield. (PRS is discussed in greater detail in the equipment chapter). The output of Pattern recognition system for different chip varies depending on the brightness of the bondpad metallization. We can observe from figure 4.1. 123(a), the reflectivity is high in case of a bright bondpad, whereas, the reflectivity is low in case of a dull bondpad as shown in figure

4.1.123(b). In designing a package for optimum bondability, it is important to design for pattern recognition. In figure 4.1.124, is an example of a two tier ceramic package, where, fiducial marks are placed on each shelf and a recommended design of the fiducial is shown here. It is important that one should not use lead fingers as fiducial marks for pattern recognition.

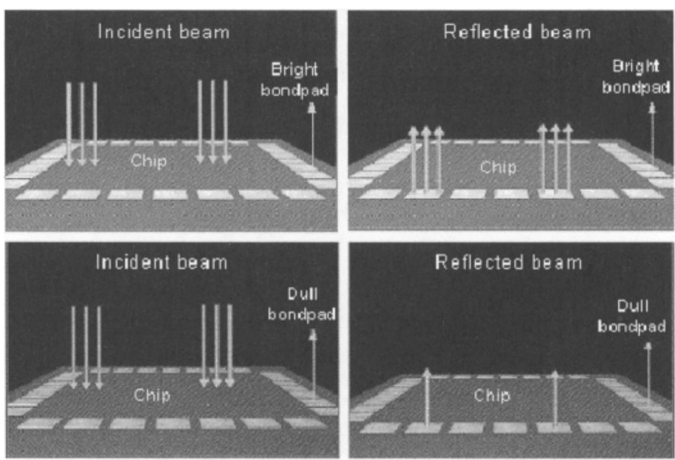


Figure 4.1.123 Pattern recognition system for different chips

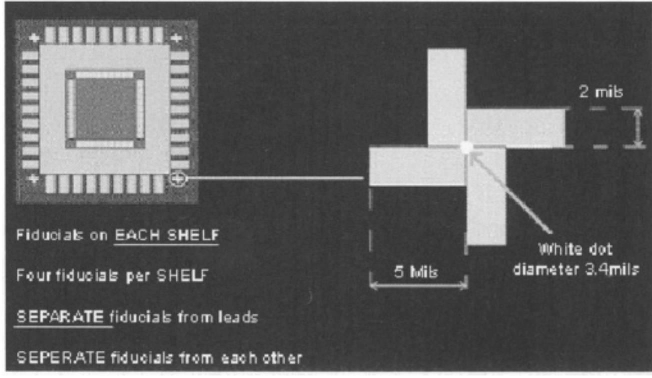


Figure 4.1.124 Fiducial mark design guidelines [Courtesy: Kulicke & Soffa]

4.1.67 EFO Consistency

The EFO parameters such as EFO current, EFO time and EFO gap have a significant impact on the ball formation at the capillary tip. If the EFO time is short, the ball formed will be small. If the EFO current is too small the ball formation is incomplete and if the current is high the ball formed will not have optimum sphericity.

The EFO gap is the gap between the electrode and the capillary tip. This is very crucial for optimum free air ball formation. If the gap is not optimum, the ball formation is not uniform this may result in ball non stick or inconsistent second bond. The EFO gap variation as shown in figure 4.1.125, may give rise to inconsistent FAB and result in first bond and second bond problems.

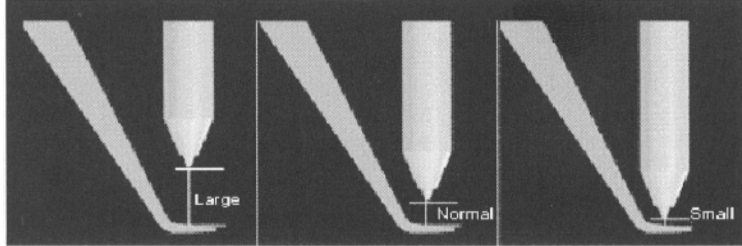


Figure 4.1.125 EFO gap

4.1.67.1 Positive vs. Negative EFO

The polarity of the EFO electrode may be positive or negative. It has been found that positive EFO has a tendency to sputter molten gold ball and the fine particles can contaminate the capillary as well as the EFO tip. Deposited gold on capillary will affect the bond process. In the last decade or so companies are using negative EFO technology. This is supposed to minimize deposition of carbonaceous material on the capillary and also maintain uniform sphericity of the ball.

4.1.67.2 Impact of EFO on Looping

As we already discussed, the free air ball size is dependent on EFO parameters such as EFO gap, the EFO current and the wire diameter. For the same wire diameter, as the free air ball size increases the heat affected zone (HAZ) length also increases. This is shown in the figure 4.1.126.

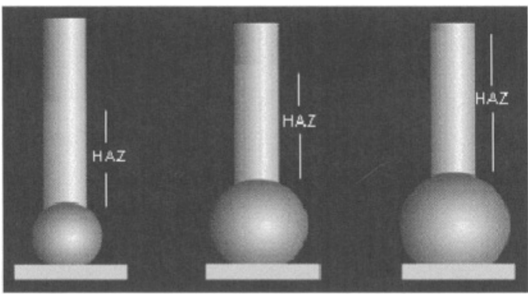


Figure 4.1.126. HAZ formation as a function of FAB diameter

Different heat affected zone lengths give rise to variable loop heights. One must also recognize that the heat affected zone is not a constant value, but for a particular free air ball size the heat affected zone range will have a maximum and minimum value. This also contributes to loop height variations during bonding.

Table 4.1.13 Minimum and maximum length of heat affected zone
[Courtesy; American Fine Wire Corporation]

FAB Size	Minimum HAZ	Maximum HAZ
43.0	71.0	89.0
50.0	99.0	130.0
76.0	148.0	175.0
EFO gap = 254 microns Wire size = 25 microns		

In table 4.1.13, we see for a particular FAB diameter of 43 microns, the heat affected zone has a minimum value of 71 microns and a maximum of 89 microns, correspondingly the loop height will be shorter or taller.

4.1.68 Wire Feed Consistency

After the second bond is formed, the amount of tail length determines the ball bond size of the next bond. For example, in ball bonding the tail length determines the size of the molten ball. If the wire is not fed consistently the length of the wire under capillary determines the size and shape of the air ball. Here in figure 4.1.127, we see 3 situations of the wire feed - under feed, normal feed and over feed.

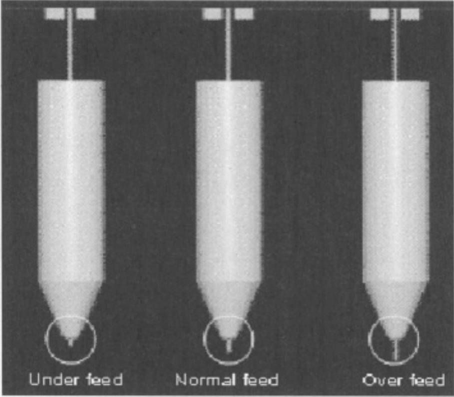


Figure 4.1.127 Wire feed consistency

The amount of wire under the capillary tip is a result of ease of tearing at second bond and the amount of wire that is fed from the spool. If the wire feed is not uniform, because of wire sticking on the spool or jamming of the wire clamp, then the amount of wire below the tip is inconsistent.

The length of the tail as well as the shape and configuration impact the ball diameter and roundness. Figure 4.1.128 shows, three different ball shapes depending on the tail parameters.

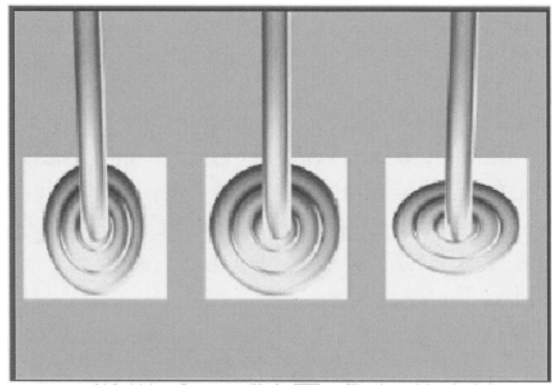


Figure 4.1.128 Different ball shapes

4.1.69 Accurate Touchdown Detection and Impact Control

Today's equipments precisely detect the connection of the capillary with the free air ball at the tip and the bond pad on the chip. An exact and repeatable touchdown detection and stringent impact control are essential for consistent bond force, and controlling the deformation of the gold ball on the aluminum pad. The bond pad size is just a few microns wider than the deformed ball diameter. Slight variations in the deformed ball size can cause yield loss.

4.1.70 Synchronization

The motions of the bonder, such as the bond head, the capillary, the wire feed, and the workholder movement under the capillary must all be synchronized perfectly. Lack of synchronization will result in incomplete

bonds, missed bonds, inconsistent looping, misplaced bonds and many other defects.

In high speed automatic bonders, the motions of the bond head, the x-y table, the leadframe transporter and the capillary trajectory need perfect synchronization. Otherwise, it may result in non stick bond, inconsistent loop profile, wire breakage, misplacement of bonds and many other defects. Therefore a thorough understanding of the machine capabilities and machine limits is necessary before optimizing a product on a particular machine.

4.1.71 Stability of Settings

Equipment settings may drift as a function of time, usage, handling, environmental conditions (temperature and humidity) and variation in material specifications. Periodic calibration and checking must be done on all parameter settings. Below is an example of drift due to high intensity illumination. In automated wirebonding equipments multiple high intensity lamps are used to illuminate the device for pattern recognition. However, these high intensity lamps can heat up the transducer by 5 or 10° C. This increase in temperature will change the resonance frequency of the transducer and may cause process inconsistency. The illumination of the transducer is shown in figure 3.1.22.

As the transducer warms up, the resonant frequency has been found to drift downward. Thus to obtain reproducible bonding conditions with a particular ultrasonic system, it is necessary to preheat the transducer by turning the lights on for several hours prior to bonding or to put heat absorbing filters in front of the lamps.

4.1.72 Software Related Bugs

As newer machines are introduced, the equipments are easier to use and have lot more capabilities. All these are due to advancement in machine control through microcontrollers and software technology. Recently, software bugs have been found to cause more down time of the bonding

machines on the manufacturing floor, than failures due to hardware related problems. We must recognize that software BUGS are:

- difficult to solve by a maintenance technician
- not easy to explain over the phone to the supplier
- the algorithms and software codes are proprietary

Many times the bonding machines are idle till a new software copy is reloaded or the software fix is installed in the bonding machine computer.

4.1.73 Missing Bond Detector

The present day bonders have a new feature called the missing bond detector. The machine stops if it does not complete the bond formation. This feature works only with leadframe packages or substrates that are electrically conductive. The missing bond detector does not work with packages that have an electrically non-conductive surface. For example, COB and BGA packages which are made of non-conducting polymeric substrates may not benefit from the missing bond detector accessory.

4.1.74 Heater Block

In thermosonic bonding, the substrate temperature must be kept at an optimized temperature. The substrate is heated using a heater block. If the heat transfer from the heater block to the substrate (say leadframe or BGA substrate) is not uniform, the actual temperature of bonding will be below the optimized value. This leads to non-stick of bonds. The incomplete heat transfer to the bonding area may be due to warpage of the substrate, improper clamping of the package to the heater block and insufficient time for heat transfer. If there is no preheat stage and the package starts bonding immediately after placement on the heater block, this leads to non stick problem.

4.1.74.1 Non Uniform Heating

In large substrates, the temperature may not be uniform all across the substrate, if the heater block design is not optimized for the specific substrate. This is particularly true in case of COB and CSP substrates which are bonded as one large unit and then singulated to individual package, as shown in figure 4.1.129. It is imperative to make temperature measurements at various predetermined points on the COB or CSP leadframe and monitor this regularly.

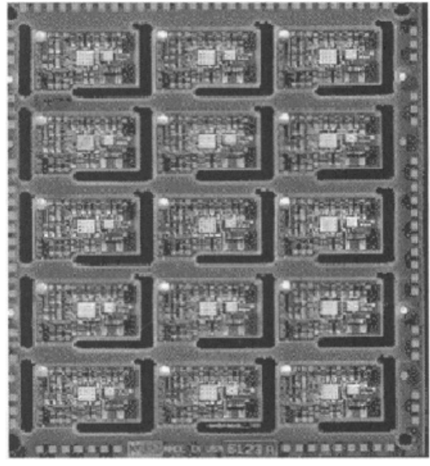


Figure 4.1.129 Chip on board panel

4.1.75 The Lead Frame Clamp

The leadframe is transported from the magazine on to the work holder and is clamped with a clamp during bonding. This clamping is done to hold the lead fingers in place to avoid any vertical or horizontal movement during bonding.

When the lead frame is held properly with the clamp the lead fingers and the die pad are held flat on the heater block, as shown in figure 4.1.130(a). If the clamp pressure is not sufficient then the lead fingers will be floating in air without any rigid support underneath, as shown in figure 4.1.130(b). During bonding, this leads to incomplete ultrasonic coupling and non-stick bonds.

If the clamp force is excessive, the leadframe has a tendency to spring back when the clamp is released after the bonding process. This spring back causes the second bond to fail.

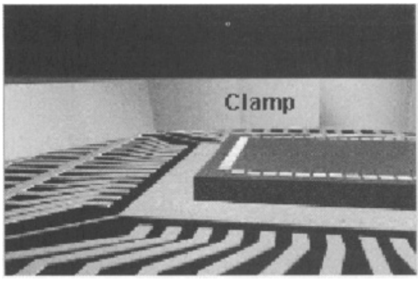


Figure 4.1.130(a) Lead frame clamped with a clamp

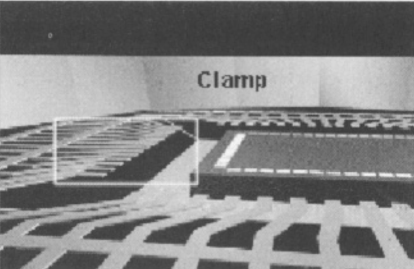


Figure 4.1.130(b) Insufficient clamp Pressure

The rate of spring back is dependent on the leadframe material. Usually the harder the leadframe, greater the spring back. The spring back also depends on the amount of clamp pressure. The wedge bond lift due to leadframe spring back is shown in figure 4.1.131.

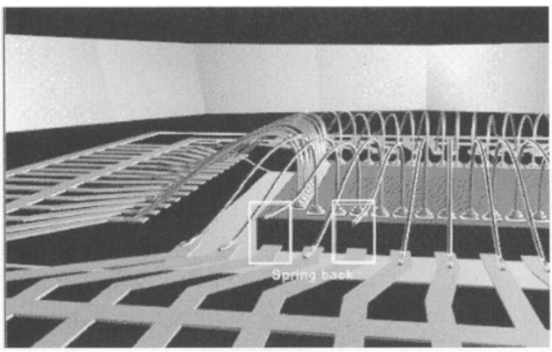


Figure 4.1.131 Wedge bond lift due to leadframe spring back **[VIEW-IN-CDROM]**

4.1.75.1 Package Vacuum Clamp

In case of Ultrasonic aluminum wedge bonding of high pin count ceramic packages, the units are bonded individually. For example, a PGA or a

CERDIP package is mounted on a special workholder during bonding. For many packages the workholder is a vacuum clamp. If the vacuum is not strong enough, the package may have slight vibration and this may lead to improper ultrasonic coupling during bonding. The figure 4.1.132 shows the vacuum clamping of a package.

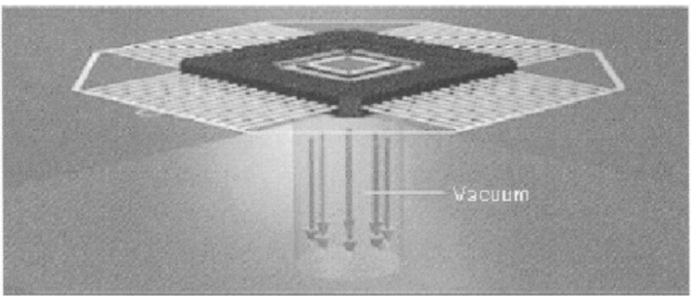


Figure 4.1.132 Vacuum clamp **[VIEW-IN-CDROM]**

4.1.76 Tool Resonance

The Ultrasonic generator transmits the ultrasonic vibrations through the transducer horn to the capillary which in turn transmits through the wire to the bondpad interface. The bond tool must possess uniform resonance characteristics. The material selected for bond tool manufacturing must exhibit high transmissibility and must possess a “high sonic profile”

The resonance amplitude also depends on the loading on the capillary. When the capillary is not loaded with the force, the vibration amplitude is high whereas when we apply a bonding force on the bonding tool, the ultrasonic vibration amplitude becomes smaller.

4.1.76.1 Effect of Tool Slimness

When we compare the free amplitude vibration modes for three different bond tools, when the tool is extended 0.25" below the transducer horn, we

see that the slimmer the tool, the greater the vibration amplitude and therefore the less bonding time or ultrasonic power that is required for bonding.In figure 4.1.133 we see, three different wedge tools with different dimensions. As the tool gets slimmer, the vibration amplitude becomes higher. However the disadvantage of very slim tools is their fragility.

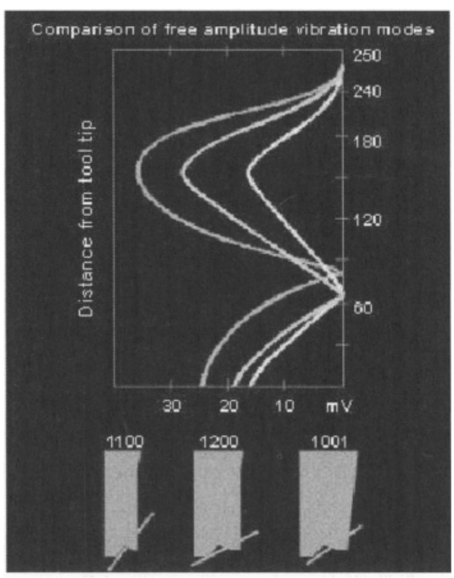


Figure 4.1.133 Tool resonance as a function of tool slimness [P-33]

4.1.76.2 Capillary Length Effect on Tool Resonance

The free amplitude vibration of a wedge tool depends on the extension of the tool below the transducer. When we measure the free amplitude vibration modes for a bond tool with the tool extended at 0.250", 0.242" and 0.235" below the transducer horn, we see that the amplitude changes with length.

We can observe from figure 4.1.134, that the vibration amplitude is not the same for different tool extensions, and this will lead to inconsistent bonding

parameters, and therefore, it is imperative that we use a tool length gauge when we replace a wedge tool in a transducer horn.

Capillary length is defined by the wire bonder in use and in standard lengths of 0.375" and 0.437". The latter allows deeper access below the package wall. Small tolerance on capillary length usually allows for consistent ultrasonic response when capillary is inserted flush with the transducer.

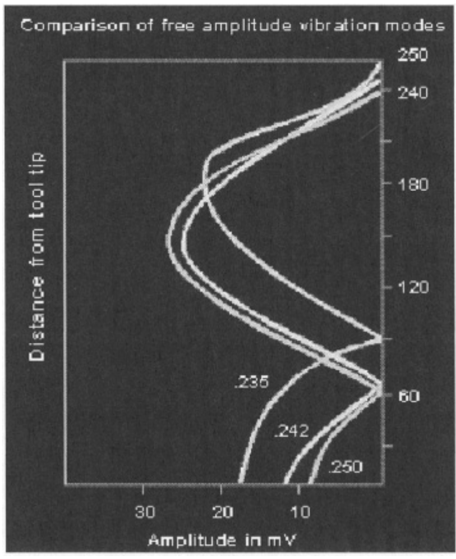


Figure 4.1.134 Tool resonance [P-33]

4.1.77 Special Bond Tool Features

Dimensional uniformity must be maintained for all manufactured capillaries and wedge tools using tight Statistical Process Control (SPC). Only bond tools produced with SPC maintain consistent bonding quality for the duration of the tool lifetime. This reduces the need to recalibrate

machine parameters when bonding tools are replaced and thus increasing overall yield.

Heated tip capillaries can be used in specific bonding applications, where the package cannot be heated to high temperature (e.g. plastic packages, MEMS) and this improves bondability.

4.1.78 *Thermocompression Bonding*

Thermocompression bonding is less often used. The process variables are the same as we encounter with thermosonic bonding. Below, we discuss some issues related to thermocompression bonding.

Plastic flow and diffusion occurs during a controlled time, temperature and pressure cycle. At least one of the two materials to be joined must be ductile to eliminate elastic "_spring-back" which could degrade the joint when the bonding tool is removed. Heating the bonding tip and/or the substrate promotes intimate contact with a minimum of applied force, by lowering the compressive yield strength of the ductile material. Heating, also, accelerates the diffusion process. Some of basic requirements for developing thermocompression bonding procedures are:

- choose appropriate lead materials such as soft, fully or partially annealed metals to minimize undesired elastic 'spring –back'
- assure that adequate deformation of the wire occurs. The cross section thickness of the bond region should be approximately one-half the original thickness of the wire. Under normal conditions, pressure should not exceed the compressive yield strength of the ductile bonding wire
- radiused wedge bonding tools require the tip to have a radius of 1 to 4 times that of the wire, to prevent the formation of stress risers. The size and shape of the tool should produce bonds of adequate contact area and configuration when a moderate force (10 to 200 grams) is applied
- choose an appropriate temperature within the annealing range of the ductile metals, but below the eutectic or alloying temperatures

- precautions must be taken to ensure that undesired films (oil, Oxides, etc.,) do not exist on the bonding surfaces

4.1.79 Process Variables affecting COB Packages

Let us to discuss the various process variables that influence the bonding process in a chip on board package. Both ultrasonic aluminum bonding and thermosonic gold ball bonding are used in COB assembly. Many factors such as type of substrate, solder mask, die attach material; influence the wire bond quality and reliability of COB devices. Thermosonic bonding is preferred because of the higher wire bonding throughput.

One disadvantage of the thermosonic bonding method is the need for substrate heating upto 250° C. Lower temperature is needed for COB because of the low glass transition temperature of the PCB. While defining the bonding process, the temperature at the interface between the wire to be bonded and the surface of the device is very critical.

In Thermosonic bonding methods, the interface temperature reflects not only material and size differences but also the kinetics of the bonding process, i.e., the rates at which the devices are fed to the bonding station and the time duration of bonding.

When gold thermosonic bonding is used in chip on board application, the quality of the bond and wire bond process yield depend on the temperature of the substrate. Lower the substrate temperature, lower is the shear strength of the ball bond, and higher is the 'non stick' problem. Therefore it is imperative that the substrate must be heated to as high a temperature as the PCB can withstand. Generally the highest temperature is just below glass transition temperature of the PCB. To heat the substrate, the wire bonder work holder is accommodated with a heater system. When the heater heats a copper lead frame, because of the high thermal conductivity, the lead frame temperature (T_S) is close to that of the setup temperature (T_H) of the heater. Figure 4.1.135 shows substrate heating for thermosonic bonding.

When gold wirebonding is performed on a metallic leadframe, the substrate temperature is the same as the heated temperature. However, when wirebonding is performed on a PC board, the actual COB substrate

temperature, (Ts), is generally much less than the setup temperature of the heater, (Th). The causes for the substrate temperature to be less than the setup temperature are:

- low thermal conductivity of the PCB material,
- larger thickness of the PCB, and
- small air gaps (caused by PCB warpage) between the PCB substrate and the heater top surface.

Generally, the average actual temperature of the substrate is atleast 20 to 40 deg. C below the setup temperature. Therefore it is important to calibrate the heater setup temperature to the actual temperature measured on the COB substrate.

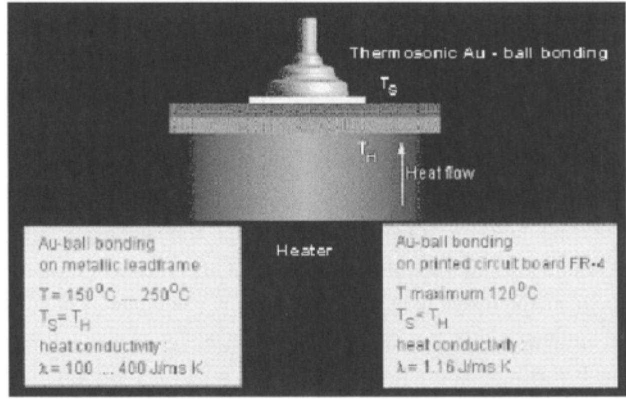


Figure 4.1.135 Heating of substrate during thermosonic bonding

Such dramatic variation in process temperature will certainly result in non-stick problem. The non stick becomes quite evident at the second bond or the wedge bond on the PCB bonding finger and less evident at the ball bond site because of the higher temperature ball bonding on the chip pad. Figure 4.1.136 shows the variation of actual substrate temperature as a function of set temperature of heater.

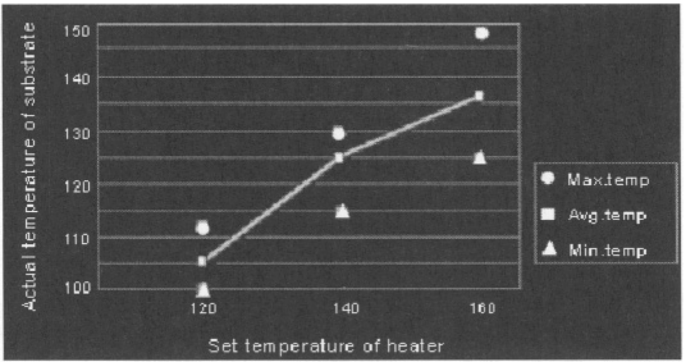


Figure 4.1.136 Calibration graph for COB substrate.

4.1.79.1 PCB Mechanical Properties and Effect on Ultrasonic Coupling

Ultrasonic and thermosonic bonding use ultrasonic power to achieve the best bonding adhesion. The PCB and other substrates are able to vibrate and reduce the effective ultrasonic power which penetrates into the bonding wire. High vibration of the substrate means low ultrasonic coupling between the bonding tool and the substrate, and low deformation of the bond. A high PCB vibration results in poor bonding. The stability and thickness of the PCB influence the bond adhesion.

The PCB dimension, its density, p, and the Young's modulus, Y, influence vibration during ultrasonic process. The ratio of Young's modulus of the PCB material (Y) to the density of the PCB (p) is an indication of the stability of the PCB and its ability to vibrate. This ratio is the material component of the vibration:

$$\omega_0 \propto \sqrt{\gamma/\pi}$$

In general, a high ratio of Y/p, indicates high stability and low vibration of PCB substrate. This gives high bond pull forces. A lower ratio Y/p leads to higher vibration of the PCB and lower bond pull forces. Figure 4.1.137 shows the influence of young's modulus on pull force. Vibration of the PCB

may be neglected if the thickness is greater than 1 mm or the ratio Y/p is high enough.

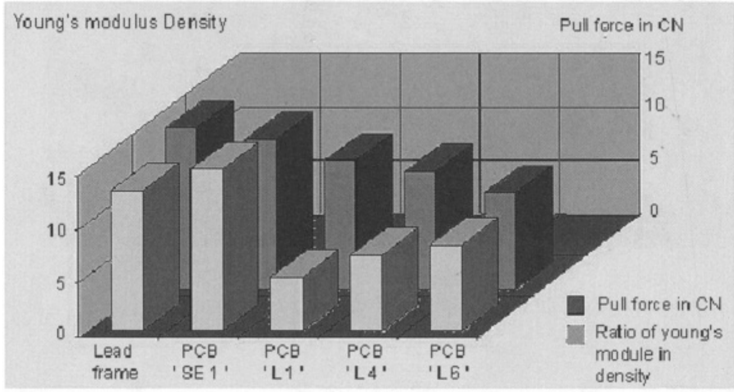


Figure 4.1.137 Effect of Young's modulus on bond pull force

4.1.80 Operator Skills

There are thousands of bonding equipments operating in hundreds of factories around the world. They range from manual bonders to the most sophisticated bonder of today with PRS, user-friendly operation manual and on demand equipment trouble shooting guide. Bonders from different suppliers have different methods of set-up, calibration and operation. The key to successful bonding is a knowledgeable operator with excellent skills and experience. Operator skills include :

- wire threading
- capillary mounting
- teaching the bonder the bond program
- set-up of proper sequence of bonding
- loop profile control
- bonding Speed control
- temperature set up
- bond pull testing

- bond shear testing
- interpretation of results
- modification of process based on pull/shear data
- recognizing a serious problem by visual inspection

Even with the introduction of the latest bonders with new technologies, the operator is the key to defect free high yield bonding process. As much effort should be spent on training the operator as is spent in optimizing the process; because, an optimized process in an inexperienced hand is as good as a non-optimized process.

4.2 Process Optimization

Optimization of the wirebonding process significantly improves the yield and quality of the product and enhances the productivity of a factory. The factors that need to be considered for wirebonding process optimization are discussed in this chapter.

Before optimizing the wirebonding process for a particular device package combination, it is assumed that the required materials and the prebonding assembly processes meet all necessary specs. For example we must ensure that

- the bondpad design and positioning of pads on the chip meets the design specification
- the chip metallization meets the bondability criteria (no contamination, no passivation residue etc.)
- the leadframe design meets the bond design criteria such as angle of approach, the leadframe width, the wire length etc
- the leadframe metallization thickness and purity meet the required specifications
- the right kind of capillary for the application has been selected
- suitable bonding wire has been selected
- the prebonding assembly processes, such as wafer saw and die attach, have all been performed according to specifications

- the right workholder with proper heating stage and clamp system is used

4.2.1 Purpose of Process Optimization

The optimization of the Au ball bonding process is done in order to achieve

- maximum shear strength on the first bond
- maximum pull value on the second bond
- minimum ball size (ball 100% within the pad)
- ball consistency
- minimum second bond size
- consistent loop height
- uniform loop profile
- no heel breaks
- no non stick
- no cratering
- no excess intermetallic
- no aluminum metal squeeze out
- zero defect process

Figure 4.2.1 shows the different criteria involved while optimizing the Au bonding process.

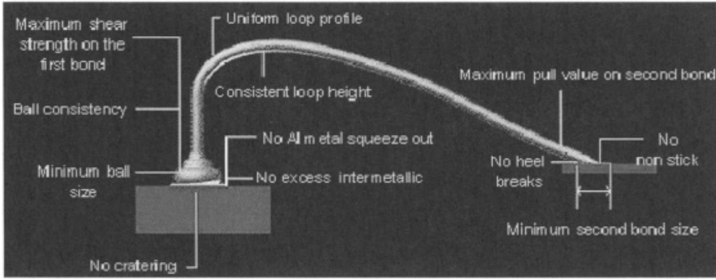


Figure 4.2.1 Optimization of the Al ball bonding process

The optimization of the utrasonic aluminum wedge bonding process is done in order to achieve

- maximum bond pull strength
- minimum wedge size
- non stick
- no cratering
- consistent loop height
- no Aluminum squeeze out
- zero defect process

Figure 4.2.2 shows the different criteria involved while optimizing ultrasonic Al wedge bonding process.

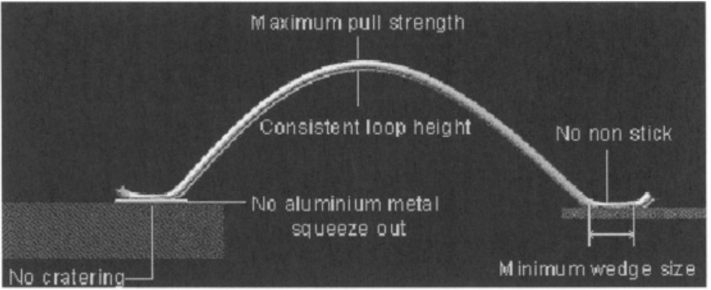


Figure 4.2.2 Optimization of ultrasonic Al wedge bonding process

4.2.1.1. Process Optimization Sequence for Thermosonic Bonding

The process optimization sequence involves, choosing the right capillary, adjusting the bond parameters, adjusting the EFO parameters, and the loop parameters. The three major optimizations are wedge optimization, ball optimization and loop optimization. Figure 4.2.3 shows a basic flow chart of optimizing a bonding process. The optimizing process starts with starting the machine, carrying out the preparation of the materials, evaluating the right capillary, calibrating the capillary offset and the EFO, adjusting the loop parameters, optimizing the wedge with time, force and power, checking the wedge visually and testing for maximum pull force, free air ball

optimization, if free air ball is okay, then optimizing the ball with time, force and power, checking for ball height, bonded ball diameter and shear force and finally loop optimization.

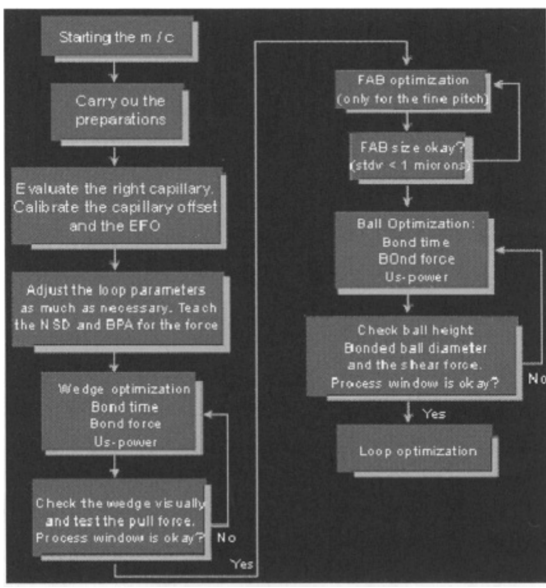


Figure 4.2.3 Flow chart of optimizing a bonding process [Courtesy: ESEC]

4.2.2 Au Ball Bond Optimization

In optimizing a gold ball bond process, we need to consider all parameters that need optimization. Parameters are classified into two types, they are control parameters and noise factors. Control parameters are those variables that can be adjusted readily or easily.

Noise factors are variables which are known to influence the process (or response) which either we choose not to control or cannot be controlled. There are many noise factors which have a significant impact on the out come of the process such as type of metallization, equipment stability, type of capillary and so on.

For example, the main control factors are equipment parameters that have the most influence on the Au bond quality, viz:

- ultrasonic energy
- bond force
- bond time
- bonding temperature

With these input parameters, the bond quality is measured in terms of response outputs; namely maximum average bond shear strength and bond pull value. But we must remember that in any bonding process optimization none of the parameters act alone in determining the quality of the bond. The parameters have an "interactive effect" on the outcome.

For example, as we increase the bond force and ultrasonic energy, there is an optimum region where the bond is good. If the force or the ultrasonic energy falls outside of this region, the bond quality deteriorates. An illustration of two typical process windows, using power and force as the process variables is shown in figure 4.2.4. Similar plots can be drawn for every combination of parameters.

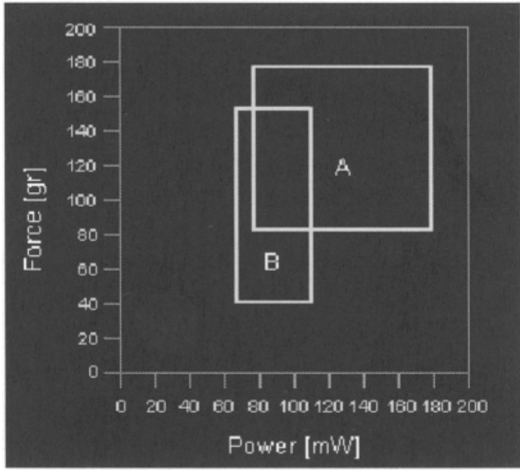


Figure 4.24 Illustration of two typical process windows

4.2.3. Optimization of Free Air Ball

In gold thermosonic ball bonding, before we optimize the ball bond on the bondpad, we need to optimize the Free Air Ball (FAB); i.e. the shape and size of the molten Au ball at the tip of the capillary. The final ball size on the bondpad depends on the FAB characteristics. The FAB diameter is controlled by many factors. As shown in figure 4.2.5, the formation of the ball at the tip of the capillary depends on parameters such as electronic flame off time and electronic flame off current. In addition, the gold wire, the electrode parameters and the atmosphere surrounding the ball influence the size, uniformity, as well as the shape of the ball.

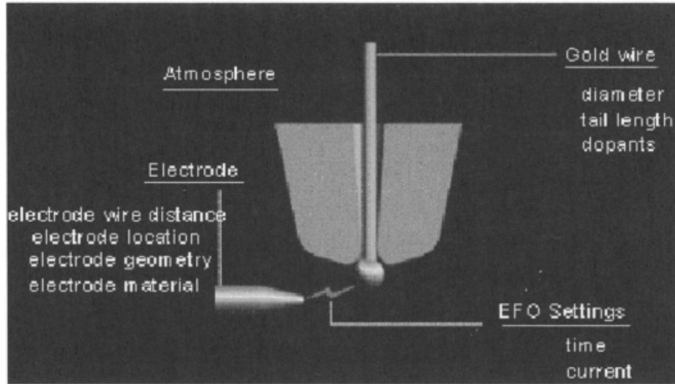


Figure 4.2.5 Ball formation influencing factors

It is also important to know that the FAB diameter also depends on the amount of wire (tail length) below the capillary. For the same EFO parameters, small tail length results in smaller free air ball size, whereas larger tail length results in a large free air ball size. Figure 4.2.6 shows ball size as a function of tail length.

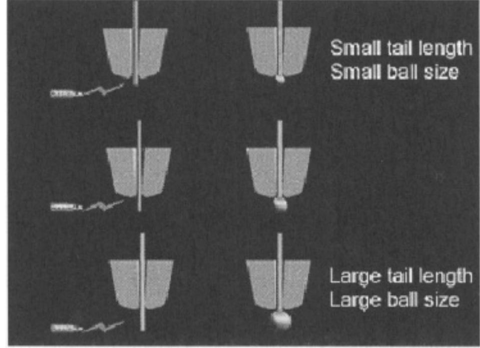


Figure 4.2.6 Ball size as a function of tail length

The tail length not only depends on the wire feed, but also on the "tear characteristics" of the second bond. This is a crucial factor dependent on wire material, second bond parameters, leadframe metallization bondability and clamp consistency.

4.2.4 Design of Experiment

In today's factory environment, there are various types of devices, substrates, wires and capillaries. The productivity and yield of a factory depends totally on how optimized the wire bonding process is. Like numerous other microelectronic processes, wire bonding is ideally suited for the application of experimental design techniques for process optimization [P-34].

In any Design of Experiments (DOE), we need to consider the factors, the levels and the responses. Factors are typically evaluated at two or more settings. Setting for factors is referred to as levels. Factors can be classified into two types, control and noise. Control factors are those variables one wishes to learn more about that can be adjusted readily or easily. Noise factors are variables which are known to influence a response which, either cannot or we choose not control. Noise factors are of four types:

- customer imposed (e.g. bondpad metal)
- supplier imposed (e.g. substrate material)
- internal (e.g. building vibration)
- degradation (e.g. wire bond tool wear)

For the wire bond process optimization the idea would be to set the bonder machine settings to maximize the average bond pull or ball shear values or both.

4.2.4.1 Example of Au Wire Bond Optimization Using Taguchi Method

Conducting a DOE requires a detailed plan, and a clear understanding of what the experiment is to accomplish. For example, in Au bonding optimization, we optimize the first bond (ball) as well as we optimize the second bond (wedge).

4.2.4.2 Ball Bonding Parameters Optimization

In this example of design of experiment we have selected 4 parameters which are bond time, bond force, ultrasonic energy and ball impact. The levels selected are minimum, mean and maximum. These values must to be selected based on prior history or technical analysis of the response parameters. Table 4.2.1 shows the ball bonding parameters and the levels selected.

Table 4.2.1 Ball bonding parameters selected for DOE

Window		Minimum	Mean	Maximum
Bond time	BT	12	15	18
Bond force	BF	250	300	350
Bond US	US	10	15	20
Bond impact	Imp	300	350	400

For the parameters and the levels that we have selected for the first ball bond optimization, table 4.2.2 shows the response parameters which are:

- ball shear failure mode acceptable or non acceptable
- mean ball shear force and
- standard deviation of the ball shear force values

Table 4.2.2 Response parameters

Type of ball shear	ACC/Not Acc
Mean BS-force	BSMEAN
Std dev Bs-force	BSSTDEV

This DOE set up is called L9 matrix with a 3 level factor. In the Taguchi method of design of experiment we set up the experimental design in this fashion. In table 4.2.3, we see how the parameters are distributed in the L9 matrix.

Table 4.2.3 Setup : Matrix L9 with a 3 level factor

Test	BT	BF	US	Imp
1	12	250	10	300
2	12	300	15	350
3	12	350	20	400
4	15	250	15	400
5	15	300	20	300
6	15	350	10	350
7	18	250	20	350
8	18	300	10	400
9	18	350	15	300

Once the DOE is set up, the bonding experiments need to be run systematically. Many texts on design of experiments give little or no information about this stage. This is one of the biggest reasons why people get poor results from an experiment. It is important to realize that during a DOE evaluation program, the only changes to be made are those called out in the orthogonal array. All other potential sources of variation must be held constant, or as close to constant as possible. That means, in the present set up, we will perform 9 experiments with the specified values of bonding time (BT), bonding force (BF), ultrasonic energy (US) and ball impact (IMP). All other variables are held constant.

The results are shown in the table 4.2.4. We can see which values have what effect on the ball shear as well as on the standard deviation values. After the experiment is completed, from the response output you see that test no 3 gives high ball shear value, with minimum standard deviation resulting in very high C_{PK}, similarly test no 5 also gives good results. This DOE gives us a set of parameters which we can use for further optimization of the process.

Table 4.2.4 Ball bonding parameters response

ACC/Not ACC	BSMEAN	BSSTDEV	CPK
Not ACC	15.36	1.25	1.65
ACC	25.44	1.13	3.31
ACC	33.34	1.04	4.86
ACC	27.34	1.61	2.52
ACC	35.18	1.57	3.42
Not ACC	16.13	1.42	1.54
ACC	32.75	2.09	2.37
Not ACC	17.25	1.21	1.97
Not ACC	24.45	1.58	2.27

We can also plot the data graphically and see which factor has the greatest influence on the mean shear value as well as on the standard deviation. From the figure 4.2.7, we see that among all the 4 parameters ultrasonic energy has greatest impact on the ball shear force. We can also see bond time has no significant effect, bonding force does not have a significant effect and neither the ball impact.

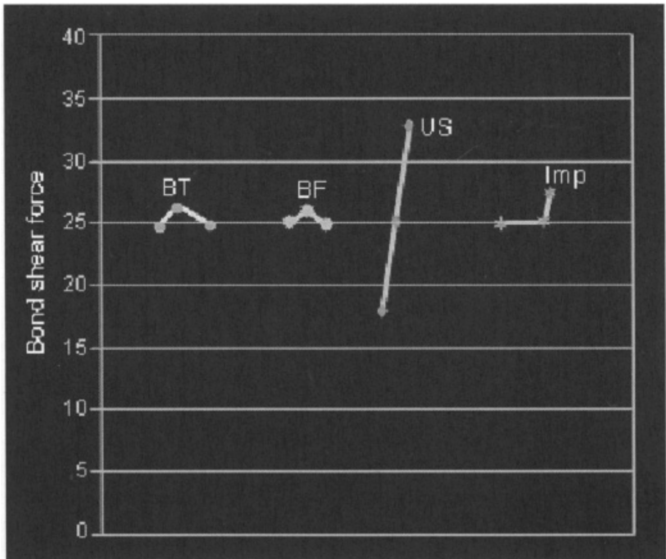


Figure 4.2.7 Influence of process parameters on mean

4.2.4.3 Optimization of Wedge Bond

Similar to ball bond optimization, we can set the parameters and levels for second bond optimization. In order to optimize the wedge bond parameters the four factors that we select are bond time, bond force, ultrasonic energy and ultrasonic compensation (from longitudinal to transverse). The three selected levels are minimum mean and maximum. Table 4.2.5 shows the parameters and the levels selected.

Table 4.2.5 Wedge bond process parameters for DOE

Window		Minimum	Mean	Maximum
Bond time	BT	5	10	15
Bond force	BF	500	550	600
Bond US	US	25	30	35
Comp US	US comp	0	0.1	0.2

The response parameters in wedge bond DOE which are Number of weld lifts, Mean pull force value, Standard deviation. Table 4.2.6 shows an example of L9 matrix for Wedge bond DOE.

Table 4.2.6 L9 matrix for wedge bond DOE

Test	BT	BF	US	US comp
1	5	500	25	0
2	5	550	30	0.1
3	5	600	35	0.2
4	10	500	30	0.2
5	10	550	35	0
6	10	600	25	0.1
7	15	500	35	0.1
8	15	550	25	0.2
9	15	600	30	0

The result of the DOE is tabulated in table 4.2.7. As you can observe, test no 2 has high mean value with minimum standard deviation resulting in C_{PK} of 2.61.

Table 4.2.7 Wedge Bond Process parameters

w lift off	WP MEAN	WPSTDEV	CPK
OK	5.43	0.42	1.93
OK	5.51	0.32	2.61
OK	5.66	0.38	2.33
OK	5.52	0.39	2.15
OK	5.65	0.54	1.64
OK	5.47	0.51	1.61
OK	5.4	0.39	2.05
OK	5.53	0.46	1.83
OK	5.55	0.53	1.60

4.2.4.4 Response Surface Model

What we discussed in the previous section is a simple but effective DOE program for wire bond optimization. But nowadays many companies adapt complex optimization programs such as response surface model. The response surface models program gives us a 3 dimensional multi variant plot. An RSM plot of aluminum wedge shear data is shown in figure 4.2.8 (a) and 4.2.8(b). For wire bonding we may also choose other response variables (e.g. percent cratering, average pull after a high temp bake, positional accuracy, etc.) and conduct DOE.

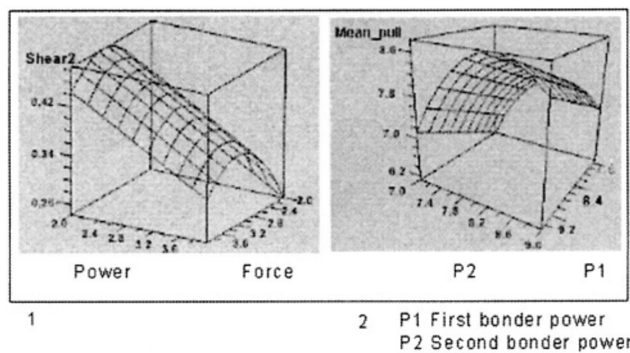


Figure 4.2.8(a) RSM plot of aluminum wedge shear data
4.2.8(b) RSM plot of aluminum wedge shear data [P-35]

4.2.4.5 Confirmation of DOE

The last stage, confirmation and conclusions, is the proof of the pudding step. Here we take the optimized settings from the analysis stage and run those combinations few times, depending on the budget. If the results of the confirmation match the predicted values, then the DOE has proven right and all goes well. The experiment has been confirmed. If not this shows that one or more of our assumptions is invalid. Failure to confirm directs us to look for and find reasons for the unpredictable behavior before starting more experiments.

4.2.4.6 DOE Software

Several excellent software packages are available to support the set up and analysis of designed experiments. For the sophisticated user with some statistics background, RS discover is a useful tool. For those users who demand windows and low cost, the software package DOE wisdom is recommended.

4.2.5. Aluminum Wedge Bond Optimization

In optimizing a Al wedge bond process, we need to consider all parameters that need optimization. As discussed earlier parameters are classified into two types, they are Control parameters and Noise factors. The equipment parameters that have the most influence on the Al bond quality are ultrasonic energy, bond force, bond time. With these input parameters, the bond quality is measured in terms of response outputs; namely maximum bond pull value. In case of Al wedge bonding we observe

that as we increase the force and ultrasonic energy, the bond pull value increases in the beginning, and then the pull value begins to decline. We can observe form figure 4.2.9, in Aluminum wedge bonding, when the deformed width of the wire is small, the bond pull strength is also small and the failure mode is lift-off of the bond. As we increase the deformed width, we reach a peak value of bond pull strength, where the failure mode changes from lift-off to heel break. Further increase in deformation width decreases the bond pull strength and the failure mode is heel break.

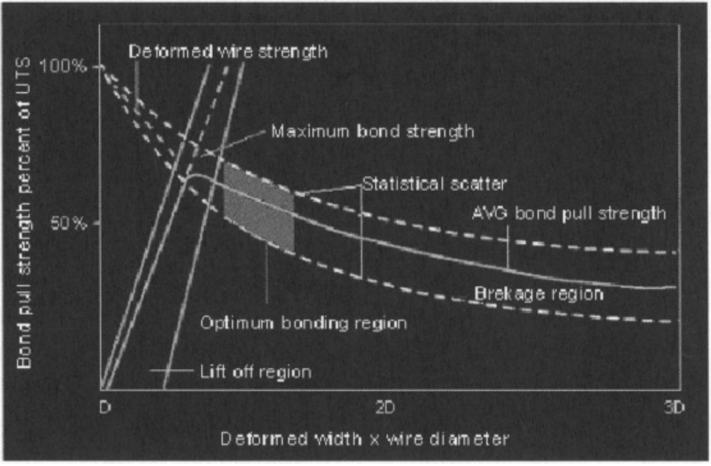


Figure 4.2.9 Variation of pull strength as a function of deformed bond width **[P-32]**

The point at which the pull value peaks, is the optimum "parameter settings" for that wire and wedge combination. It has been observed that beyond the highest point, the wedge bond has micro cracks at the heel (due to over bonding) and therefore has reduced pull strength.

4.2.6 Second Bond Optimization

As we move towards finer pitch and thinner wire packages, it is becoming difficult to optimize the second bond using bond pull technique. The bond

pull technique is NOT a foolproof test methodology for testing the "goodness" of a second bond. Therefore we need to use visual data, such as "width of the second bond" to monitor the process consistency and to optimize the second bond. Optimized second bonds provide assurance that subsequent ball bonds are not affected. Let us see how to optimize a wedge bond in case of Au thermosonic bonding.

Usually as the force and the ultrasonic energy are increased, the amount of deformation of the second bond increases and therefore the width of the second bond increases. Depending on the width of the second bond, the failure mode can be either a wire bond lift or heel break.

- smaller the width, higher the second bond lift
- larger the width, higher is the heel break

4.2.6.1 How to Optimize Bond Width?

Optimization is done by collecting second bond width data for the same wire diameter from different bonders. Then the X-bar and standard deviation for each is calculated. Then the normal distributions from many bonders is used to create a "nominal composite" distribution plot. Based on this composite distribution one can determine a lower specification limit and an upper specification limit for second bond width. This gives an additional tool for process control and monitoring. The factors that affect the results are:

- the type of bonder used (manual or automatic)
- the type of capillary
- direction of bonding (longitudinal or transverse)
- wire diameter
- wire type

Al wedge bond can also be optimized by using similar bond width measurements. In the figure 4.2.10, we see how the bond pull value changes as a function of bond width.

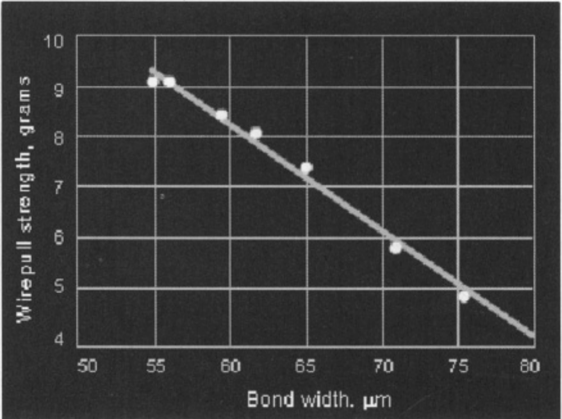


Figure 4.2.10 Wire pull strength vs second bond width [P-36]

In ultra fine pitch wire bonding, there is a significant interaction between the second wedge bond and the first ball bond. A bad second bond can result in an irregular shaped and undersized or oversized FAB being formed prior to the next first bond. The result will be inconsistent or miss positioned first bond on the next wire following the bad second bond. Because of this interaction, the best practice is to conduct a second bond optimization experiment before the first bond optimization.

4.2.6.2 Optimization of Second Bond with Pull Test

In ultra fine pitch bonding, since the wire is very thin, the second bond is more vulnerable, therefore optimization of the second bond is performed with great care. A normal bond pull test, where the hook is positioned close to the ball does not provide a realistic picture of the quality of the second bond. Therefore the hook is placed close to the second bond and the optimization is carried out with this pull test data. As we can see in figure 4.2.11, the second bond pull strength depends on the tip diameter of the capillary. As the tip diameter increases, the second bond strength increases.

Therefore, one of the optimization parameters in ultra fine pitch bonding will be the capillary dimensions.

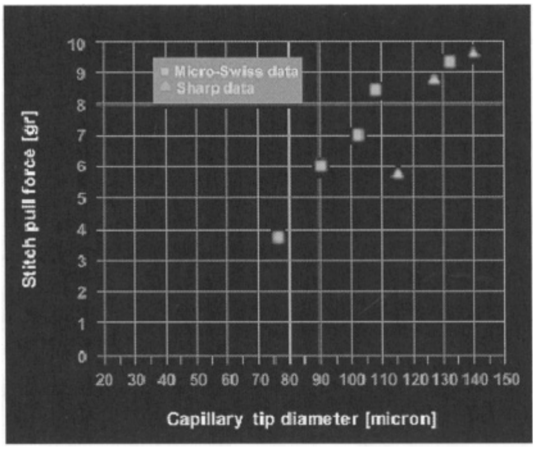


Figure 4.2.11 Second bond strength vs. capillary tip size [P-11]

During second bond optimization with bond pull test method, we encounter that, the bond pull values have 2 distributions. One is the bond pull values distribution in the y bonding direction and the other is bond pull value distribution in the x bonding direction. The pull force is slightly higher in the y direction compared to the x. Figure 4.2.12 shows second bond optimization.

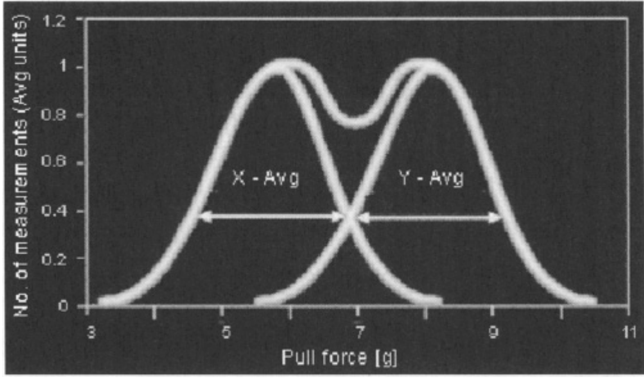


Figure 4.2.12 Second bond optimization using bond pull force in longitudinal and transverse direction [P-11]

4.2.6.3 Looping Optimization

The wire bonder plays the primary role in loop formation. New generation wire bonders have large libraries of standard loop shapes and capabilities. This enables them to process the latest packaging designs. Standard loop shapes include multiple loop shapes; low, worked and BGA. Wires as long as 7.6 mm and loop height as low as 100 microns are within their capabilities. In addition options such as CSP looping, more sophisticated BGA loop profiles, spider, and j-wire looping algorithms are also available. It is desirable for a wire bonder's programmable control parameters to serve as the dominant factors controlling loop shape. Boundary conditions, such as capillary friction, should have a minor effect in the process. The hole diameter and chamfer angle also play a secondary role in controlling the loop shape.

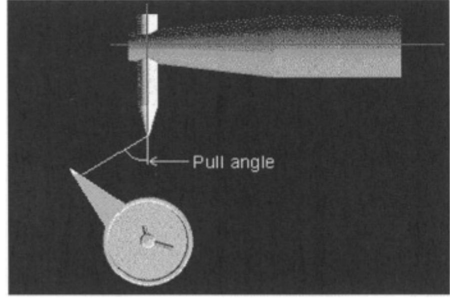


Figure 4.2.13 Capillary drag force test [P-11]

The friction exerted by the capillary on the wire which is also called drag force should be minimum.

Low drag capillaries, with an inner radius instead of the standard double inner chamfer, are available to minimize capillary friction. Drag force test is used to measure the friction of the capillary at different pull angle depending on the shape of the loop. Figure 4.2.13 shows how drag test is performed to check for drag force.

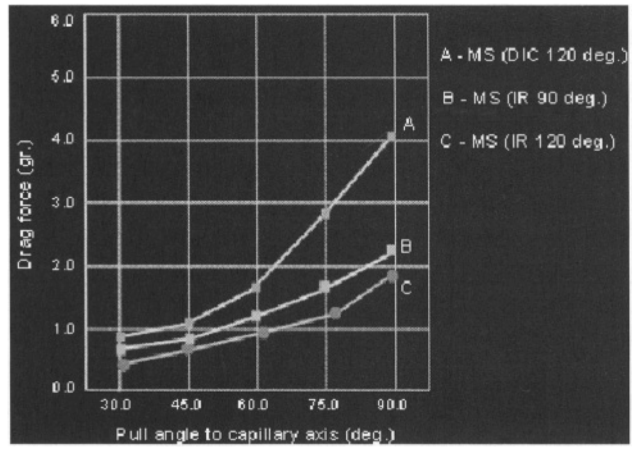


Figure 4.2.14 Variation of drag forces as a function of pull angle [P-11]

We can observe from figure 4.2.14, as the pull angle increases, the drag force increases. At the same time, the capillary chamfer design also has an impact on drag force. A 120° chamfer angle with a double inner chamfer shows a very high drag force. Whereas a normal chamfer design, the drag force is higher when the chamfer angle is small.

4.2.6.4 Capillary Design Optimization Considerations

For the ultra-fine pitch bonding, the deformed ball size needs to be controlled at much tighter dimensions. Therefore, optimum capillary design must be selected. In addition, the reduced tip diameter to provide sufficient clearance between adjacent wires would further reduce the strength of the

stitch bonds. Various empirical formulas and simulations have been used to quantify critical capillary diameters [P-31].

For standard bonding application, a hole to wire clearance of 10 microns or 40% has been the usual practice for a robust bonding process. For the ultra-fine pitch application, the shrinkage in ball size results in a smaller chamfer diameter, which indirectly affects the hole diameter. In addition, for a wire diameter of 23 microns, a sizable hole to wire clearance is necessary to prevent any serious wire drag during bonding. Wire drag can affect the wire feed and the looping characteristic. Evaluation on the wire drag force with hole variations are performed to determine the minimum possible hole size.

We can observe from figure 4.2.15, the drag force increases with increase in wire feed out angle and there is a significant increase at a wire feed out angle of 70°. When the hole diameter is equal to wire diameter plus 7 microns, the drag force is minimum. Whereas, when the hole diameter is equal to wire diameter plus 4 microns the drag force increases moderately. From the experimental result, a minimum hole to wire clearance of 5 micron is still considered acceptable for the ultra finepitch application.

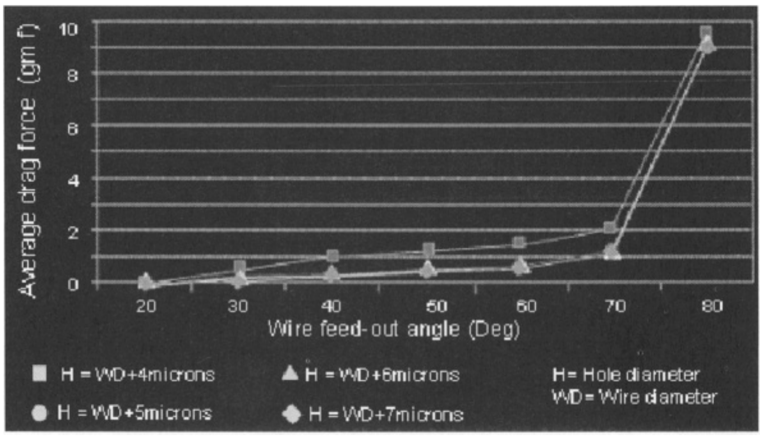


Figure 4.2.15 Drag force for different hole diameter with different wire feed–out angle [P-31]

4.2.6.5 Tip Diameter Optimization

The selection of the optimum tip diameter for ultra finepitch bonding is largely dictated by the bondpad pitch for that device. In general, the optimum tip (T) dimension can be calculated using the equation

$$T\,(max) = 2BPP\text{-}WD\text{-}(2LH\text{-}WD)$$

where
T : tip diameter
BPP : bond pad pitch
WD : wire diameter
LH : loop height

4.2.6.6 Capillary Tolerance

Not just the dimensions of the capillary but also the tolerances of capillary dimensions are crucial to achieve zero defect bonding process. The stringent ball size control due to the smaller bond pad opening requires the various critical dimensions for the capillary to be controlled within much tighter tolerances. This means that the standard tolerances can no longer be applied. The figure 4.2.16 shows the comparison of tolerances used for the ultra finepitch, standard finepitch and the non-finepitch application.

For example, the tip diameter tolerance for ultra fine pitch capillary is ± 3microns when compared to ± 5 microns for a standard fine pitch and ± 8 microns for a non-fine pitch capillary. Similarly the tolerance of chamfer diameter for standard fine pitch is ± 4 microns whereas, for ultra fine pitch only a positive tolerance of 2 microns in allowable.

In order to optimize the final dimension of the capillary, it is recommended that few experiments are done with critical capillary dimensions and review the impact of these parameters on the second bond non-stick failure. For example, in an analysis with a 1.1 mil wire, it was observed that, as the tip diameter increases, the failure rate decreases.

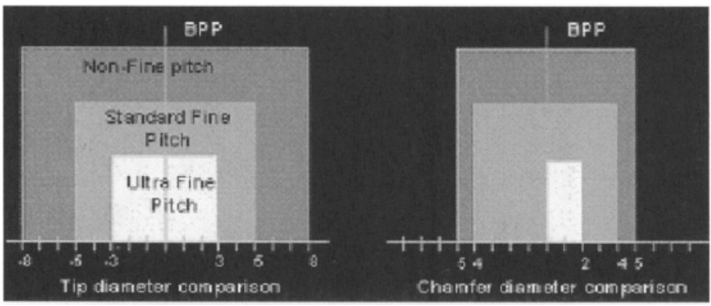


Figure 4.2.16 Comparison of tolerances used for the ultra finepitch, standard finepitch and the non-finepitch application [P-31]

Figure 4.2.17 shows, how in an ultra fine pitch bonding application, as the tip diameter increases, the percent of heel failure decreases. Similarly, as the face angle increases, the number of failures decreases. In figure 4.2.18, we see the effect of face angle on heel failure rate. The heel failure rate depends on 3 major components of capillary design, the tip diameter, the face angle and the outer radius. Combining the failure rates observed with different tip radii, face angles and outer radii, we can select the optimum capillary for that particular application.

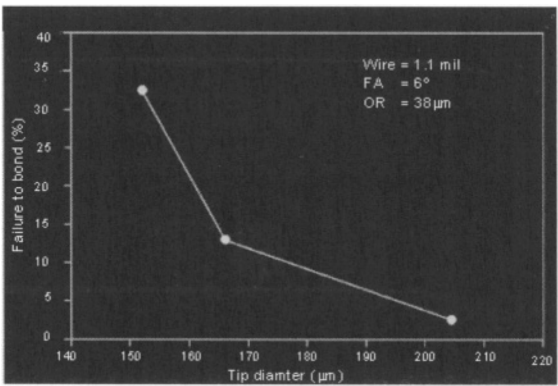


Figure 4.2.17 Rate of failure as a function of tip diameter [Courtesy: Sumitomo Metal Mining]

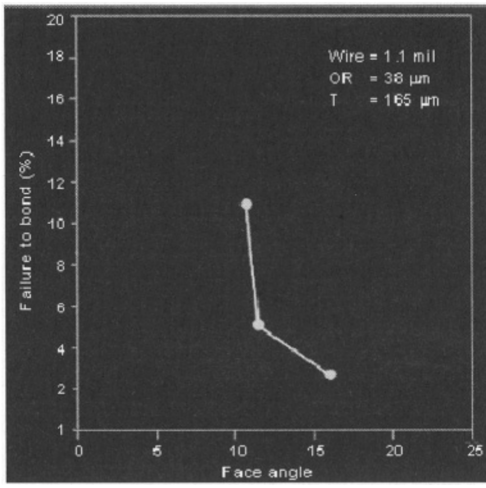


Figure 4.2.18 Heel failure as a function of face angle [Courtesy: Sumitomo Metal Mining]

We can observe from figure 4.2.19, with a tip diameter of 152 microns a face angle of 6 degrees and an outer radius of 38 microns, the failure rate is 33 percent. The failure rate is reduced to 13 percent, when the tip diameter in increased to 165 microns with face angle and outer radius remaining same. Finally, the failure rate is zero, with a tip diameter of 165, face angle of 15 degrees and an outer radius of 70 microns.

The capillary diameter selection can also be made based on the Shear strength requirement of the bonded ball. If we need to optimize, the ball bonding process and if the requirement demands minimum shear strength value, then the capillary needs to be selected based on the ball diameter requirement. For example, a ball diameter of 80 microns can have different shear strength value of 80,100 and 125 N/mm^2. This depends on the shear force value obtained from the bond shear test and the bond shear result, which is directly correlated to the type of capillary that was used to form the 80 micron diameter ball. Therefore, it is possible to select the right capillary depending on the shear strength value required for a particular ball diameter. Figure 4.2.20 shows capillary selection based on shear strength.

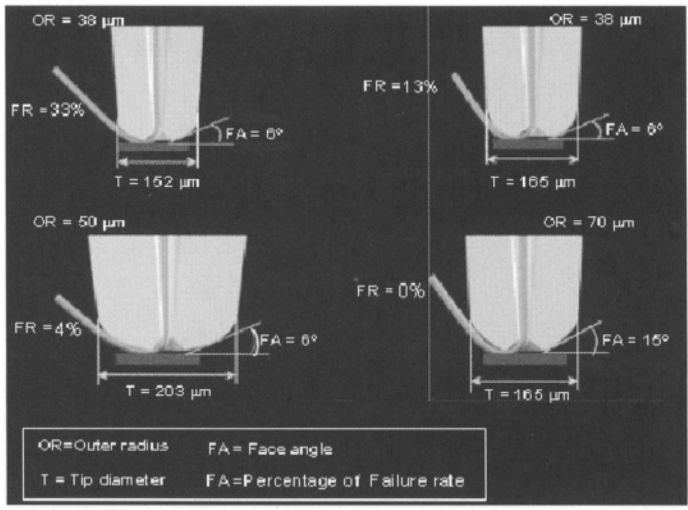


Figure 4.2.19 Comparison of capillary shape and dimensions and their impact on failure rates [Courtesy: Sumitomo Metal Mining]

Based on the discussion so far, we recognize that in ultra finepitch wirebonding, selecting the capillary dimension is dependant on many parameters, such as type of package, loop requirement, pad pitch, placement accuracy, speed of bonding, shear strength requirement, second bond consistency and many other issues.

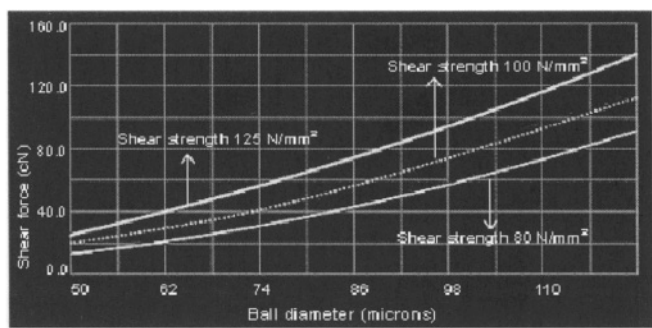


Figure 4.2.20 Selection of capillary based on shear strength [Courtesy: ESEC]

In ultra fine pitch bonding, since capillary plays a very crucial role, the selection of the capillary is an important step. The capillary selection depends on pad pitch, wire size, pad size, type of packages and many other parameters [P-35]. (An interactive flow-chart showing a step by step approach for selecting the appropriate capillary for a particular application is given in the CD). **[VIEW-IN-CDROM]**

4.3 Process Control

Once the process has been optimized and the production of the device starts, the process needs to be controlled to make sure the bond strength, bond shape and other critical attributes are within the specified window. There are a variety of techniques for measuring the quality and reliability of bonds. The most frequently used techniques are:

- visual inspection
- bond Pull
- bond shear test
- bond etching
- electrical testing
- bake test
- thermal cycle/thermal shock testing

But for real time process control application we generally use

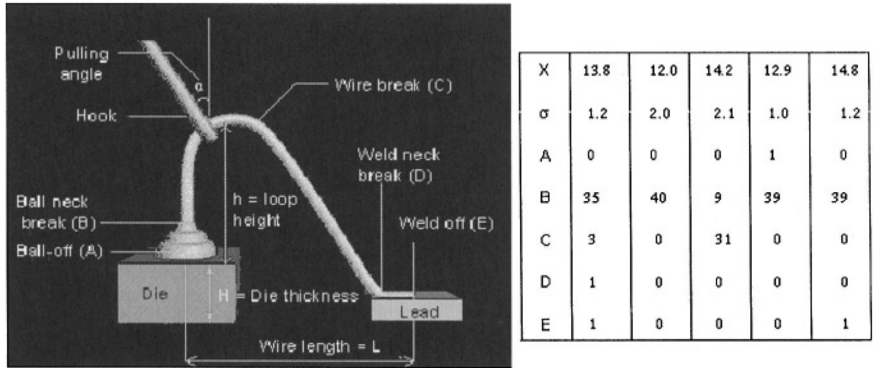
- bond pull
- bond shear
- visual inspection
- bond etching

Let us discuss each of these in greater detail.

4.3.1 Bond Pull

The bond-pull strength test is a primary method used by many manufacturing plants for process control. The pull test is a relative test for a particular package configuration. Test results must include bond strength and mode of failure. When using bond pull test it must be remembered that getting the highest bond pull value is important, but more important is the fact that no A type, D type and E type failures should occur. We can observe from figure 4.3.1, after performing a bond pull test we get X-bar and sigma values and also the different failure modes. Take a look at different data present in the table. (Refer Quality chapter for more details about wire bond pull test methodology)

In ultra fine pitch bonding, since the wire is very thin, the second bond is more vulnerable, therefore, process control using wirebond pull technique is focussed more towards the wedge bond. A normal bond pull test, where the hook is positioned close to the ball does not provide a realistic picture of the quality of the second bond. The pull value must be as high as can be with minimum standard deviation.



X	13.8	12.0	14.2	12.9	14.8
σ	1.2	2.0	2.1	1.0	1.2
A	0	0	0	1	0
B	35	40	9	39	39
C	3	0	31	0	0
D	1	0	0	0	0
E	1	0	0	0	1

Figure 4.3.1 Pull test failures modes and bond strength values **[VIEW-IN-CDROM]**

4.3.2 Use of Control Charts

Control charts are used to control the bonding process. The primary objective is to make timely decisions about whether the bonding process is in statistical control or not. In any process there will be variation from one measurement or unit produced to the next. If the variation is due to purely random or chance causes, the bonding process is said to be in "statistical control". If variations occur because of bonding machine changes, material inconsistencies, operator or inspector error, or other "assignable" causes, the process is said to be "out of control". Control charts are an aid in a "management by exception" approach to maintaining quality. A manager does not want to stop a process when it is operating in a stable manner within its natural tolerance but, on the other hand, when it is likely that the process has changed, attempts to identify the causes of the change should be made. There are two basic types of control charts, they are control charts for variables and control charts for attributes

Variable control charts are used to control a measurable characteristic such as bond pull value or bond shear value; whereas attribute control charts control a countable characteristic such as number of non-sticks. Control limits are drawn on a control chart to indicate the extremes of acceptable behaviour of a process. In most applications, they are set at plus and minus three standard deviations from the process mean.

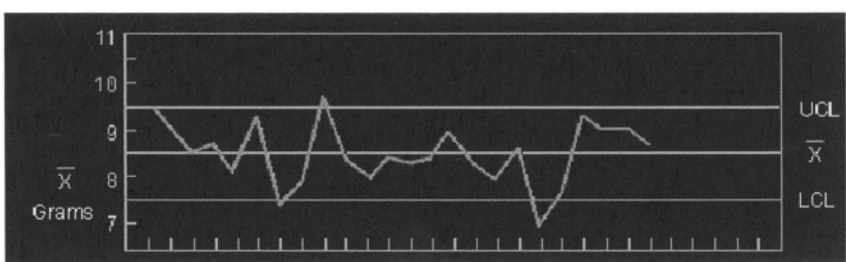


Figure 4.3.2 Control chart [P-37]

In the control chart shown in figure 4.3.2, we see that the mean pull value X-bar is 8.5 grams, and the upper control limit is at 9.5 grams and the lower

control limit at 7.5 grams. When the process starts to deviate and falls below the lower control limit, it is time to re-optimize the process and bring it back within the two control limits. One can also monitor the consistency of the process by generating a Range Chart also called 'R-Chart'. Here we see, when the mean R value fluctuates significantly, that is an indication that the process needs optimization. An R-chart is shown in figure 4.3.3.

4.3.2.1 Control Limits should not be confused with Specification Limits

Control limits are nearly always a natural consequence of the variability of the process itself. Whereas specification limits are most often specified by the customer or the quality management. If a process starts out in statistical control and always stays in control, there is no need for a control chart and the process will be quite predictable. However, few processes fit this category. Often, assigning of new operators, use of different materials, occurrence of machine wear and tear, and innumerable other changes will cause the process to go out of control. Control charts help to differentiate between changes caused by natural variability in the process and influences that have caused the process to change. It is this power to detect real changes versus natural variability that makes control charts so important.

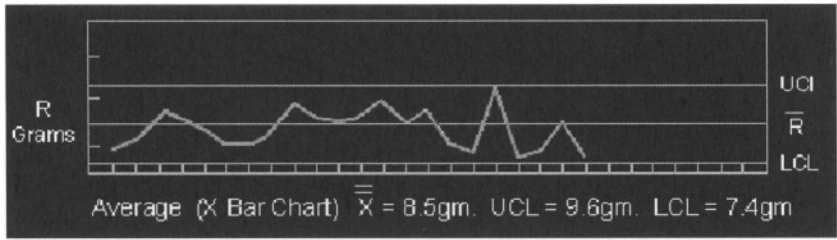


Figure 4.3.3 R-Chart [P-37]

4.3.3 Bond Pull Force as the Measurable Characteristic

Bond pull force is one of the measurable characteristics. Once the measurable characteristic has been decided, the next step is to determine the

sub group sample size. When bond pull data is used for process control, the critical issue that has to be taken care is selection of wires for bond pull test.

4.3.3.1 Selection of Wires for Bond Pull Test

Selection of wires for pulling is a critical step, because not all wires in a device are similar. Some are long, some are short, some have higher loop height, some are bonded in longitudinal direction and some in transverse direction. And the bond pull value depends on a particular wire configuration. If the chip designer has not designed the chip according to bonding design rules, or, if the bonding engineer has not programmed the looping profiles and wire lengths correctly, we will end up with a device with different wire lengths and loop heights. For example, from figure 4.3.4 we can see there are some short wires with low loop, medium length wires with medium loop, and long wires with very high loop. When we perform bond pull test on these wires, the pull values will vary considerably and therefore the standard deviation, sigma, will be very high and in some cases, even the failure modes will differ.

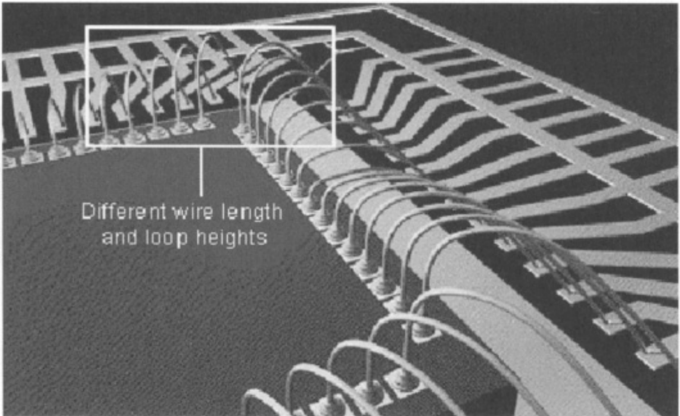


Figure 4.3.4 Different wire length and loop heights

The more the variation among all the wires, the greater the spread in bond pull values and greater is the standard deviation (3 sigma) value.

Therefore for optimum process control methodology, we must select all the wires in a device for performing pull test; but this is cumbersome and time consuming, particularly in case of a high pin count device. The other recommended option is to select specific wires which have specific behavior patterns.

For example, in a 60 lead CSP package shown in figure 4.3.5, we may select two wires from middle region of each side of the device and three wires from each corner of the device. This gives a spectrum of wires that have all the variables incorporated in them. By performing bond pull test on a single device and only 40 wires, we will be able to recognize any deviation in process.

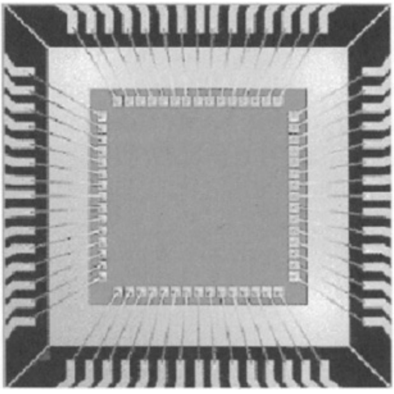


Figure 4.3.5 Selection of wires for bond pull testing

And every hour or every two hours (as the requirement demands) we can perform bond pull tests on the same set of wires, and we will be able to see drifts in the process if:

- the X-bar value is changing
- the standard deviation value is changing
- if the failure mode is changing

4.3.4 Creating a control chart

When controlling a measurable characteristic (such as the bond pull force), we need two charts

- one to monitor the mean or average
- one to monitor the variability

An X-bar (mean) chart is used to monitor the mean, whereas a R (range) chart is used to monitor the variability. X-bar and R charts are examples of variable control charts. They are usually used together. As previously discussed, a variable control chart controls a measurable characteristic, such as bond pull strength. X-bar charts control the process average, whereas R charts control the process dispersion or variability. A change in the process average will usually show up on the X-bar chart but may not be a detected on the corresponding R chart, and a change in variability in the process may not show up on the X-bar chart but should be apparent on the R chart. The centreline of an X-bar chart is usually set at the overall or grand mean that can be calculated using the equation [P-38].

$$\bar{\bar{X}} = \bar{X}_1 + \bar{X}_2 + \bar{X}_3 + \ldots + \bar{X}_g = \frac{1}{g} \sum_{i=1}^{g} \bar{X}_i$$

Where g= total number of subgroups

The range R for each subgroup can be calculated as the difference between the largest and smallest value for each subgroup. The following equations are commonly used for computing three sigma upper and lower control limits for X-bar charts.

Upper control Limit : X-Bar Chart

$$UCL_{\bar{X}} = \bar{\bar{X}} + A_2\bar{R}$$

$A_2\bar{R}$ is an estimate of $3\sigma_{\bar{X}}$ and A_2 is a constant that depends on the subgroup sample size.

Lower Control Limit : X- Bar Chart

$$LCL_{\bar{X}} = \bar{\bar{X}} - A_2\bar{R}$$

The centre line of the R chart is set at the mean of the subgroup ranges [P-38]

$$\bar{\bar{R}} = \bar{R}_1 + \bar{R}_2 + \bar{R}_3 + \ldots + \bar{R}_g = \frac{1}{g} \sum_{i=1}^{g} \bar{R}_i$$

Where g= total number of subgroups

The upper and lower control limits set at three standard deviations are usually computed from [P-38].

Upper Control Limit : R Chart

$$UCL_R = D_4\bar{R}$$

A_2R is an estimate of $3\sigma_{\bar{x}}$ and A_2 is a constant that depend onthe subgroup sample size.

Lower Control Limit : R Chart

$$LCL_R = D_3\bar{R}$$

A_2, D_4 and D_3 are factors that are tabulated in the table 4.3.1 and 4.3.2

Table 4.3.1 S chart [P-38]

		S Chart	
Subgroup size n	$\bar{X}$ Chart A_3	Lower control limit B_3	Upper control limit B_4
2	2.659	0	3.267
3	1.954	0	2.568
4	1.628	0	2.266
5	1.427	0	2.089
6	1.287	0.030	1.970
7	1.182	0.118	1.882
8	1.099	0.185	1.815
9	1.032	0.239	1.761
10	0.975	0.284	1.716
11	0.927	0.321	1.679
12	0.886	0.354	1.646
13	0.850	0.382	1.618
14	0.817	0.406	1.594
15	0.789	0.428	1.572
16	0.763	0.448	1.552
17	0.739	0.446	1.534
18	0.718	0.482	1.518
19	0.698	0.497	1.503
20	0.680	0.510	1.490

Table 4.3.2 R Chart [P-38]

		R Chart	
Subgroup size n	$\overline{X}$ Chart A_2	Lower control limit D_3	Upper control limit D_4
2	1.881	0	3.267
3	1.023	0	2.575
4	0.729	0	2.282
5	0.577	0	2.115
6	0.483	0	2.004
7	0.419	0.076	1.924
8	0.373	0.136	1.864
9	0.337	0.164	1.816
10	0.308	0.223	1.777
11	0.285	0.258	1.744
12	0.266	0.284	1.716
13	0.249	0.308	1.692
14	0.235	0.329	1.671
15	0.223	0.348	1.652
16	0.212	0.364	1.635
17	0.203	0.379	1.621
18	0.194	0.392	1.608
19	0.187	0.404	1.596
20	0.180	0.414	1.586

4.3.5 Procedure for Calculating Parameters for an X-Bar and R Chart

- assemble 20 to 30 subgroups of data for consecutive time intervals.
- calculate the mean, X-bar and range, R, (X_{max} - X_{min}) for each subgroup.
- calculate the average of the means, (X) and the average range (R)
- plot X vs. time chart
  a. the center line is X.
  b. the upper control limit (UCL) is $X + A_2R$
  c. the lower control limit (LCL) is $X - A_2R$
- R vs. time chart
  a. the center line is R
  b. the UCL = D_4R
  c. the LCL = D_3R

In bond pull testing, there is no maximum pull value. Therefore the UCL does not have to be adhered to as critically as one must to LCL value.

4.3.6 Interpretation of Control Charts

In the control chart shown in figure 4.3.2, we see two points below the LCL. The first point is attributed to a "new pull test operator". But the second point is attributed to a weak weld heel break. This is not an acceptable failure mode. The cause of the heel break was found to be due to excessive deformation of the second bond. This can be corrected by slightly reducing the second force and power.

When the process starts to deviate and falls below the lower control limit, it is time to re-optimize the process and bring it back within the two control limits". It is important to keep in mind that the X-bar and R values of bond pull testing are very product specific. That means these values depend on the chip design and the corresponding package design. When a control chart is plotted, it must be plotted for the same device/package combination.

4.3.7 Process Control using Bond Shear Strength

The bond pull test does not test the quality of the ball - bond pad interface strength. The bond adhesion strength of gold ball bonds is controlled by using the shear strength test. The failure mode and bond strength are used to measure the bond quality and reliability.

Shear testing gives better assessment of the ball or weld strength. However, attention to shear test equipment capability is more critical than pull testers. The equipment must be capable of positioning the shear tool with precision (0.0001" or less) and repeatability; and the shear arm must remain static (no bending or moving) during the shearing operation. We can observe from figure 4.3.6, the larger the bond diameter, higher is the shear strength; and therefore as we increase the ball size, we must set the lower acceptable specification limit to a higher shear strength value.

Recently, however, the industry is using shear force per unit area as the standard representation of shear values. Though bond shear test can be used for process control, it is seen from experience that the failure of the ball bond interface is a very rare phenomenon, and thus process control with shear testing may be an effort without significant outcome.

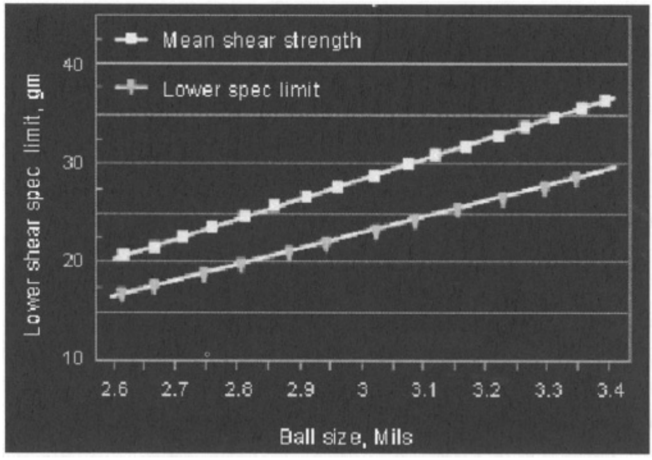


Figure 4.3.6 Variation of lower spec limit with ball size

4.3.8 Visual Inspection

Visual inspection is used to determine bond quality problems such as smashed bonds, skinny bonds, misplaced and deformed bonds, as well as wire conditions.

4.3.8.1 p CHARTS

If on visual inspection, a wire bonded device can be classified as either "conforming or nonconforming," "good or bad," "defective or not defective," "passing or not passing," "acceptable or not acceptable," and so on, then a p or np chart can be used to monitor and to control the process. Some examples of characteristics of a bonding process that are candidates for p charting include:

- ball bond positioning 100% within bond pad
- wire linearity (S-ing)
- shape of the second bond

The key element in determining whether p charting is appropriate is that inspected items fall into one of two categories. Typically, the fraction nonconforming is plotted on the p chart. A QC manager is usually more interested in ways to decrease failures and nonconforming units; hence, it seems more appropriate, in most instances, to concentrate on the negative rather than the positive characteristic. The only difference between a p chart and an np chart is that a p chart shows the fraction of nonconforming items, whereas an np chart indicates the number of nonconforming items.

4.3.9 Intermetallic Area Measurement

Intermetallic area coverage can be considered a complement of shear testing and in many instances it provides a better picture of the behaviour of different metal systems used in the bonding pads.

The testing begins by etching a sample in KOH solution (25/75 by weight KOH/H_20) for 10 minutes at 50 deg. C or for 30 to 60 min at 25 deg.C, then carefully lifting the bonds and exposing them perpendicular to the objective lens of a 350x or 500x microscope. Looking through the microscope, one can observe the reacted area on the bond not on the I.C. Then using any available method (i.e. a scaled grid) the area can be calculated.

It is possible to analyse the amount of area that has reacted at the ball bond interface by placing a grid on the lifted ball. For example figure 4.3.7 shows reacted zones of a ball with grid superimposed. We can observe that, only 15% of the ball area has reacted with the bondpad when the reaction occurred at low bonding temperature. Whereas, when the reaction occurred at higher temperature, more than 40% of the ball area has reacted with the bondpad.

A minimum area of 50% of the total area is considered acceptable. Lack of growth can then be traced to surface contamination or poor bonding parameters. Correlation between shear force and area coverage is possible if one knows the shear strength of the metal system used in the sample or samples analyzed. The process engineer will have to develop his own correlation tables between shear force, intermetallic growth and the metal systems used in his products.

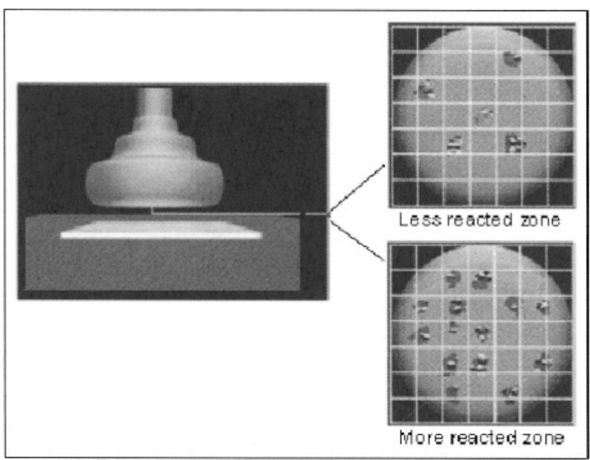


Figure 4.3.7 Schematic representation of reacted zones of a ball with grid superimposed

4.3.10 Bond Etching

Bond etching measures the condition of layers under the bond pads after bonding. With this technique, the ball and pad metallization is removed, and the condition of underlayer materials is examined for defects. This particular method not only allows detection of subsurface damage caused by equipment parameters, but can also serve as a tool for optimization of the bonding parameters. Typically, NaOH, $HCl+HNO_3$ or KOH are the chemical solutions of choice used to remove the interconnection material and expose the underlying structure.

4.3.11 Process Capability (C_{pk}) Analysis

Another way to look at if the process is under control is to calculate the C_{pk} value for the process. The C_{pk} value determines whether the process is within 3 sigma, 4sigma or 6sigma limits. C_{pk} is calculated with the equation:

$$C_{pk} = (\text{X-bar} - \text{LSL})/3\sigma$$

X-bar : mean value of bond pull or bond shear
LSL : low specification limit
σ : standard deviation

The C_{pk} index basically relates product tolerance to the customer's specification with consideration of overall product distribution. A C_{pk} value of one generally indicates that virtually the entire product (99.73%) just meets the customer's specifications.

The C_{pk} value depends on the LSL value. Choosing a very low spec limit will automatically give a very high C_{pk} value. Therefore the value of LSL must also be determined by observing the behaviour of the process over a period of time. C_{pk} is used primarily for variable data analysis when such data are not available, C_{pk} can be applied to attribute data on the basis of certain essential statistical criteria.

4.4 Process Monitoring

The critical parameters in bonding namely bonding force, ultrasonic energy, time and temperature must be calibrated on a regular interval. If the actual values are different from the set values on the equipment then the process will never be under control. Therefore calibration and monitoring of bond force, bonding temperature (heater stage as well as the temperature on the package), ultrasonic frequency and bond time is absolutely necessary. In addition to calibrating the bonding equipment, the bonding test equipment such as the pull tester and shear tester must also be calibrated.

In this section on process monitoring we study how to monitor the process parameters for accuracy, precision and consistency to control the quality of the bond, and what are the different techniques available for monitoring.

4.4.1 Monitoring the Bonding Responses

Once the bonding process is optimized, the machine will be producing bonds at very high speed. The consistency of the bonding responses must be monitored at different intervals. For example we must check the long term stability of the ball contact diameter, ball shear strength, ball shear stress, wire pull strength, free air ball diameter, bonded ball diameter and ball height.

In high speed ultra fine pitch bonding the bonding process may drift from the optimized condition as the number of bonds increase. One must monitor the process to see this drift and understand stability of the process. Table 4.4.1 shows the bonding responses at 50,000 bonds and 1.25 million bonds.

Table 4.4.1 Bonding response comparison at 50k and 1250k bonds [P-31]

Bonding Responses	50k	1250k bonds
Ball contact ϕ, μm		
Average	40.9	39.4
Std Dev.	0.5	1.3
Ball shear strength, gmf		
Average	15.2	13.6
Std Dev.	1.5	1.2
Ball shear stress N / mm²		
Average	114	109
Std Dev.	10	6.712
Wire pull strength, gmf		
Average	4.3	4.5
Std Dev.	0.34	0.5

Here we can observe when that the ball contact diameter after 50,000 bonds is 40.9 microns with standard deviation of 0.5 microns, whereas after 1.2 million bonds the ball contact diameter is reduced to 39.4 and standard deviation has increased to 1.3. Similar degradation is observed with shear strength and ball shear stress.

The goodness of a fine pitch wire bonding process is determined by the long term stability of the process without any drifts or sudden shifts. The

long term stability of geometric dimensions of Free Air Ball [FAB], Bonded Ball Diameter [BD] and Ball Height [BH] are indicated in the image 4.4.1. Here we can observe, the geometric dimension of the free air ball, the ball height, and the ball diameter remains consistent even after 400,000 bonds. The constancy of the parameters even after 400,000 bonds indicates long term stability of the process.

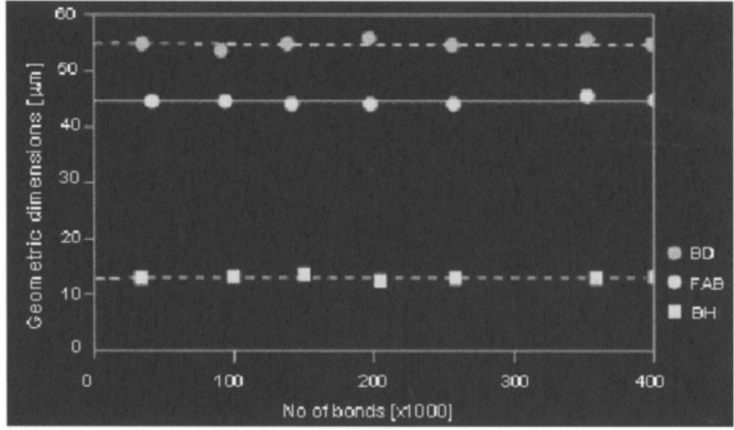


Figure 4.4.1 Long term stability of geometric dimensions versus number of bonds [Courtesy: ESEC]

This type of analysis is required in order to confirm the robustness of fine pitch wire bonding process. The bonding machine quality control is done by monitoring the process parameters for accuracy and consistency. The critical bonding process parameters viz.: force, temperature and ultrasonic energy must be monitored in order to achieve perfect quality of the bond, high yield and maximum machine uptime. Bonding machine quality control procedures falls into two main categories which are:

- maintenance of bonding machine consistency, by incorporation of design features (such as automatic frequency control) and periodic calibration
- in-process monitoring of parameters associated with bond formation.

4.4.2 Ultrasonic Frequency Control and Monitoring

All bonding machines rely on a highly resonant electro-mechanical system, to deliver energy to the bond zone, and minor changes in system parameters result in considerable changes in response. For example, any temperature drift (e.g. caused by the heating effect of viewing lamps) can produce a relatively small resonant frequency shift which causes a large reduction in tool vibration amplitude. The frequency of the ultrasonic energy is usually set at 60 KHz and any drift is automatically corrected by special features such as

- automatic control of generator frequency to the system electrical resonance - the phase lock method or
- programmed frequency modulation (FM) within a fixed range, to ensure matching of the generator resonance for at least part of the bonding period

Most of the bonding equipment developed in the USA, Europe and Japan are largely of the automatic frequency control type.

4.4.3 Bonding Tool Amplitude Measurement

Force and time are variables in the wire bonding process that are relatively easy to measure. Ultrasonic energy is, however, a complex and difficult variable to measure. From the conception of ultrasonic bonding, it has been difficult to measure and control ultrasonic energy at the lower tip of a bonding tool. Most ultrasonic bonding machines have variable ultrasonic efficiency and make it difficult to transfer bonding schedules from one bond to another.

As device bond pads get smaller and silicon and gallium arsenide devices get thinner, ultrasonic energy control at the bond interface becomes very critical. Bonding tool vibration amplitude is the most important machine parameter which influences the energy delivered to the bond zone. Periodic monitoring of machines in terms of the tool tip or horn end vibration amplitude during unloaded operation must be done to minimize bonding equipment variability for quality control. There are many methods for

ultrasonic amplitude measurements; some are qualitative and some are quantitative.

- qualitative methods rely on capacitor microphones or magnetic devices such as transducers, but are relatively insensitive
- quantitative methods capable of absolute vibration amplitude determination use either reflected optical intensity or laser beam interferometry

Some of the systems that are used for monitoring different parameters are:

- capacitive microphone technique
- impedance measurement system
- ultrasonic measurements using laser interferometry
- wedge tool vibration measurement using optical sensor

Let us discuss each of the above mentioned monitoring methods in detail.

4.4.4 Capacitive Microphone Technique

It is important to realize that simply changing a bonding tool in a bonder can change the ultrasonic power at the tip of the bonding tool. The piezoelectric transducer bonding horns, phase locked loop ultrasonic power supplies and laser interferometer measurement of horn displacement do not address the fact that ultrasonic energy must be measured at the lower tip of the bonding tool. The solution to this measuring problem is the capacitive microphone tuning process. [P-39].

The use of a capacitive microphone sound meter to measure the compressional sound waves at the lower tip of a bonding tool has helped to control these critical energy settings. The measurement system is based on a process that measures compression sound waves at the lower tip of a bonding tool with a microphone probe. The compressional sound waves are displayed on a precision sound level meter in dB pressure level units.

This process is accomplished by positioning a microphone probe tube at the ultrasonic power node just above the lower tip of an ultrasonic bonding tool. The bonder is then cycled through its bond cycle. The probe tube picks up small variations in ultrasonic amplitude and the energy level is measured and stored on a sound level meter in units of dB pressure level. The signal is then amplified and is displayed on a cathode ray oscilloscope. The sound level reading is not an absolute value, only a relative value (Energy Per Unit Area). However, it is a value that is repeatable when measuring the same shape and type of bonding tool. A schematic of capacitive microphone measurement technique is shown in figure 4.4.2.

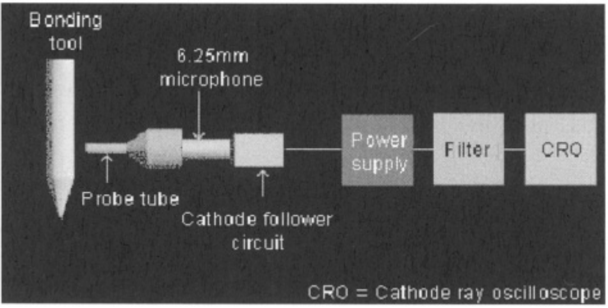


Figure 4.4.2 Capacitive microphone system for ultrasonic bonding tool displacement monitoring [P-39]

4.4.5 Impedance Measurement System

Impedance changes during bonding have long been accepted as an indicator of bonding quality. With industry available systems, we can now have a means to measure the impedance changes during bonding. With it's built in statistics based on variational analysis, the system contains a form of artificial intelligence that allow it to analyze the bonding process for consistency [P-40].

The BQM system uses the transducer as a sensor and passively monitor the changes occurring in the transducer during the bonding process. Any change in the process will cause the bonder to be stopped and thus prevent further bonding errors.

4.4.6 Ultrasonic Measurements using Laser Interferometry

Each ultrasonic transducer reacts differently and provides varied outputs (excursion amplitudes) for a given input. Therefore bonding schedules can not be easily transferred from one bonder to the other. Therefore calibration of transducers with a reliable methodology is very critical. Using the focused beam of a low power helium-neon laser, it is possible to monitor the excursion path of a transducer as it expands and contracts under power and can be precisely measured down to a micro inch using the technique of interferometry [P-39].

In the laser interferometer system it is possible to measure the bonding tool displacement consistency. A very fine beam of the laser is focused on the bonding tool and the vibration amplitude of the bonding tool is accurately determined by using a reflective laser beam. The laser interferometer utilizes a 3mW helium-neon laser (wavelength 0.63μm), which is aligned perpendicular to the ultrasonic horn or bonding tool. The beam is focused to a 25μm diameter spot which impinges upon the target, and reflected light re-enters the front of the laser. The unit consists of laser head, X-Y mount and monitor/power supply. The laser head is of a cold cathode coaxial design with hard seal construction for environmental protection and long storage life. A rugged X-Y mount is used for fixturing the laser power supply, a signal strength indicator for focusing the beam and an LED display. A schematic of the laser interferometer system is shown in figure 4.4.3.

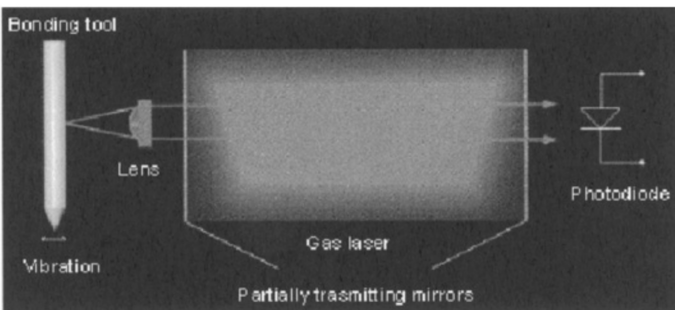


Figure 4.4.3 Schematic of laser interferometer system [P-39]

4.4.6.1 Measurement Procedure

First the laser is mounted on the bonder so that its beam may be directed onto the front face of the transducer. The focused laser beam is aligned on the vibrating horn of the transducer using micrometer adjustment on the mount until a sharp signal is indicated on the analog meter. A specific ultrasonic level is applied to the transducer and the ultrasonic generator's gain is then adjusted until the output displayed on the laser monitor is equal to the input level applied. Every time the vibrating horn moves through half a wavelength of laser light, a pulse is created. The pulse rate is automatically converted to vibration amplitude and digitally displayed in microinches. In this way the transducer may be calibrated so that there is a close correspondence between programmed input value and actual transducer output. Using a laser interferometry system, we can perform the following with a high degree of accuracy: They are: measure the amount of ultrasonic energy, duplicate the optimum values on other bonders, inspect the machine set-up, inspect all incoming transducers for efficiency and detect defective transducers or inadequate mechanical coupling.

With laser interferometry it is possible to match the ultrasonic performance of all bonders on the assembly line. Since the measurement takes place at the transducer horn, it is an accurate measure of the performance of the entire ultrasonic system, and because there is no physical contact with the ultrasonic source, the monitoring has no effect on the system being measured.

4.4.7 Wedge Tool Vibration Measurement using Optical Sensor

In ultrasonic bonding, the elastic vibration of wedge bonding tool and vibration of wedge tip determines if welding between bonding wire and bonding pad takes place. Therefore, it is very important to confirm if a wedge tool desirably vibrates. Inadequate tool setup like a wedge mis-alignment provides low amplitude of wedge tip and results in insufficient bond. Optical displacement sensor is used to measure the ultrasonic amplitude. [P-39]

In this case, the reflected optical intensity of a beam of light determines the vibration amplitude. As shown in figure 4.4.4, light from a tungsten filament goes through an optical fiber, hits the bonding tool, and then gets reflected

back. The intensity of the reflection is measured using a photodiode. The intensity is a function of the distance between the fiber optic probe and the bonding tool.

Before monitoring the vibrations of the bonding machine, it is necessary to perform a static calibration. If the tool has strong resonance at a desirable frequency around 60 kHz which is a designed frequency of a bonding machine, it indicates that the machine is calibrated. As we have already discussed in ultrasonic wedge bonding, the vibration of the wedge tip is instrumental in welding the bonding wire to the bonding pad. Therefore, it is very important to confirm if the wedge tool vibrates as required. Improper tool setup results in low amplitude of wedge tip and results in poor bonding. Figure 4.4.5 shows the frequency response of tool vibration, and we can observe that the tool has a strong resonance at a desirable frequency of 60 KHz.

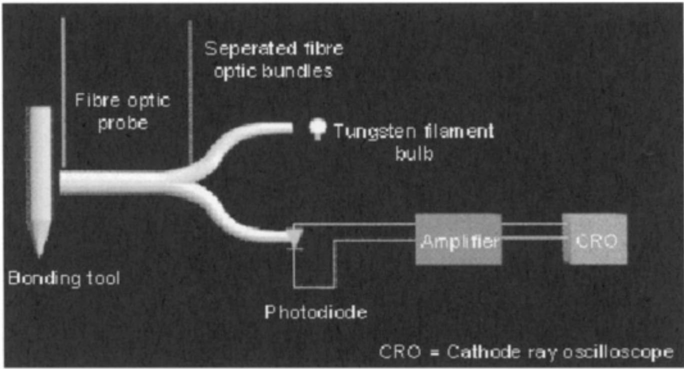


Figure 4.4.4 Principal of operation of the optical displacement sensor [P-39]

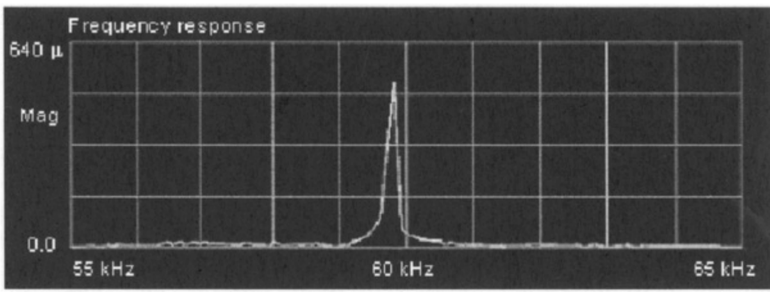


Figure 4.4.5 Frequency response of tool vibration [P-41]

Tool vibration should be measured not only at the tip, but also at each point of entire wedge. The vibration amplitude of each point of wedge at the resonance frequency is measured. The free amplitude vibration of a wedge tool depends on the extension of the tool below the transducer. (Refer figure 4.1.133 in process variables)

4.4.8 Effect of Loading on Tool Vibration Mode

Although the above discussed monitoring techniques can reduce bonding variability, the unloaded tool displacement cannot by itself, represent actual bonding amplitudes, since the bonding tool vibration may be sensitive to loading. Therefore, machine consistency monitoring techniques cannot provide a complete answer to process control problems. The ultrasonic vibration amplitude is dependent on force applied on the bonding tool. When the capillary is not loaded with force the vibration amplitude is high whereas when we apply a bonding force on the bonding tool the ultrasonic vibration amplitude becomes smaller, as shown in figure 3.1.24 in Equipment.

It is to be expected that the vibration characteristics of the tool set to a normal extension will be modified somewhat during bonding because of the loading on the tool. The vibration amplitude of the sonotrode in unloaded condition is different from the actual vibration amplitude during bonding, and this deviation is sensitive to variations in tool mounting, and the type of tool. Greater the deviation, higher is the impact on bond quality. Figure 4.4.6 shows the deviation in vibration amplitude before loading and after loading.

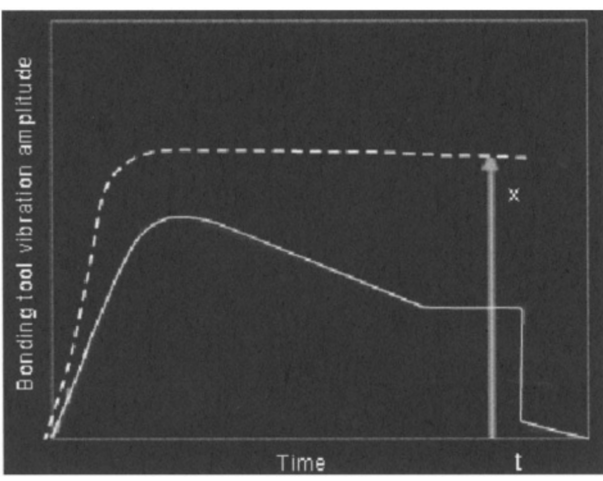


Figure 4.4.6 Deviation in vibration amplitude and impact on bond quality **[P-39]**

4.4.8.1 Impact of Extension of the Tool on Resonance

As can be seen in figure 4.4.7 a dramatic indication of the effect of tool extension can be seen from the frequency dependence of the tip vibration amplitude. For the 0.375-in. (9.5-mm), tool extension there is a double resonance peak with very large amplitudes at the resonances. After removal and reinsertion of the tool to an extension of 0.325 in. (8.2 mm), the curve with a single peak which has amplitude, resonant frequency, and shape typical of normal bonding observed.

The resonance of the bonding tool depends on the extension of the tool below the transducer hole. For example if we take a tool and its extends 0.375 inches below the transducer the tool exhibits a strong resonance peek at 59 KHz and strong resonance peek at 62KHz. where as the same tool when it is extended to 0.325 inches below the transducer hole it exhibits a single resonance peek at frequency of 60.5 KHz . This shows how critical bonding tool mounting is from the point of view of process consistency.

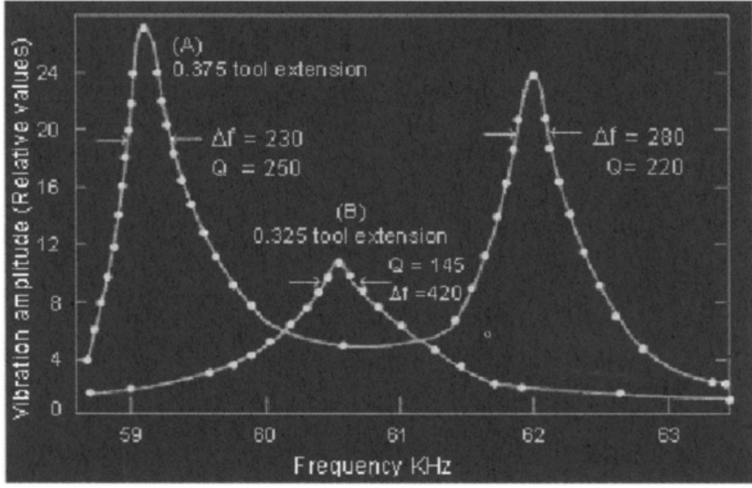


Figure 4.4.7 Mechanical resonance curves for the same tool set at two different extensions below the horn [P-42]

The figure also shows that the normally stated unloaded electrical Q of a transducer has no significance in so far as the vibration characteristics of the bonding tool are concerned. Not only does the mechanical Q of a particular transducer-tool combination depend on the method of electrical drive but it also depends on the length and extension of the bonding tool. The mechanical Q may be changed as much as a factor of 2 by varying the tool extension within the range specified by the manufacturer [P-42].

4.4.9 Bond Force Monitoring

The bonding force is the most critical parameter in the ultrasonic bonding schedule. Small changes in the value of the bonding force can markedly affect the nature of the bond. Yet the bonding force is measured on most bonding machines by a hand-held gauge, and the value of force obtained depends greatly on the skill of the operator.

More recently, there are special force gauge mounting fixtures that have been developed. To calibrate and adjust the force, the force gauge assembly

is clamped onto the work stage, and the power to the bond is switched off. The bonder cam assembly is turned by hand through the first search position until the bonding tool touches the substrate, then the force gauge arm is positioned horizontally in front of the transducer horn close to but not touching the bonding tool. It is essential to measure the actual force applied to wire and metal surfaces or leads during bonding.

The applied force usually consists of two distinct elements: dynamic and static components. To measure the actual force applied to the work piece during the bonding cycle, one technique uses a dynamic force measurement system (DFM) [P-43]. The heart of the system is a very fast-response transducer with extremely high sensitivity to small force changes of ± 1 gram. The DFM system allows one to measure the actual applied force in real time.

With this technique, we can identify the actual bond force duration and amplitude, dynamic and static portions of the force curve, repeatability of applied force from one bond to another, machine-related problems affecting the force curve and timing for the application of ultrasonic energy as compared to the force curve and methods for duplicating the optimized force from one machine to another.

4.4.10 Bonding Time Monitoring

Another important bonding parameter is bonding time, which controls the level of plastic deformation in wire and substrate metallization. During the selected time, ultrasonic energy and force are applied to the wire and substrate. The application of ultrasonic energy to the work piece at the desired time, during the application of force, is called the timing factor. This parameter ensures consistent bond quality and reliability. The timing factor can be adjusted using the DFM system.

4.4.11 Other Bond Monitoring Techniques

Changes in mechanical impedance at the bonding interface generally cause changes in the transducer driving system. Monitoring has been achieved by

measuring current flow in constant voltage systems and vice versa. Texas Instruments have patented a bond energy monitor which terminates the bonding process when the second derivative of the transducer impedance (determined as a result of monitoring changes in transducer driving current) passes through zero and becomes negative. TI has a successful missing wire detector for automatic bonding machines, based on in-process measuring of a bonding frequency shift which is characteristic of acceptable wire bonds.

Another commercial instrument produces chart recordings of transducer driving current during the bonding period and offers fault diagnosis based on visual interpretation of these records, but this gives no possibility of in-process control. A closely related device is the amplitude deviation detector, which indicates bond quality on the basis of the deviation in sonotrode vibration amplitude after a fixed bonding time compared with the initial (unloaded) amplitude at the full power condition.

The vibration amplitude of the sonotrode in unloaded condition is different from the actual vibration amplitude during bonding, and this deviation is sensitive to variations in tool mounting, and the type of tool, and greater the deviation, higher is the impact on bond quality [P-44].

4.4.12 Siemens Process Monitoring Methodology

For the real-time recording of essential bond parameters, bond force, ultrasonic amplitude and bonding time during the bonding process, Siemens' has developed a technique where the sensors are applied to the bond arm. Strain gauges are fixed to the bond arm and provide a signal proportional to the applied bond-force. A piezo-ceramic sensor is attached to the horn of the bond arm. The strain gauges fixed to the bond arm measure the bond force, whereas the piezo-ceramic sensor measures the amplitude of the ultrasound. Figure 4.4.8 shows the sensorized bond arm with piezo sensor.

The methods (measuring procedures) and necessary hardware and software for the monitoring of the measured values have also been developed. [P-45]

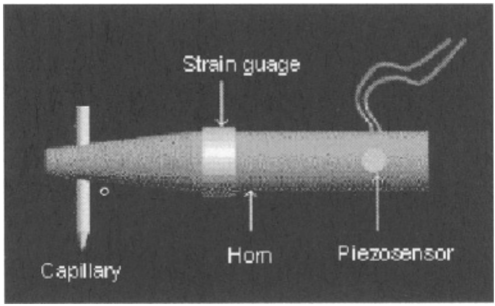


Figure 4.4.8 Sensorized bond arm with piezosensor **[P-45]**

4.4.12.1 Quality of Bond

It is possible to detect the quality of wirebonding by analyzing the shape of the second harmonic of the ultrasound. We can observe from the figure 4.4.9, if the bond is good, the shape of the second harmonic has constant amplitude over the bonding time of say, 50 milliseconds. If the bond is non-sticking, then there is a rapid drop in amplitude in the first 10 milliseconds and the signal is near the baseline.

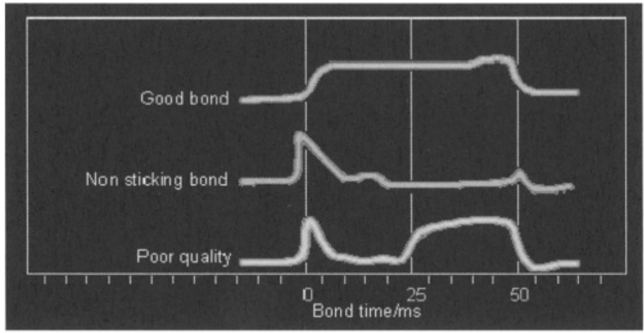


Figure 4.4.9 Amplitude of 2nd harmonic related to bonding quality **[P-45]**

However, for poor quality bonds, the signal shows a decrease in amplitude, but after approximately 20 milliseconds, we see a recovery. A

bond with good sticking the second harmonic behaviour is shown in Figure 4.4.10(a). Here, we see the amplitude of the fundamental 60 kHz frequency is constant over the bonding time of 50 milliseconds, and the second harmonic also has a constant amplitude over the bonding time. This results in a perfect position bond. Figure 4.4.10(b) shows the photo of a perfect positioned bond.

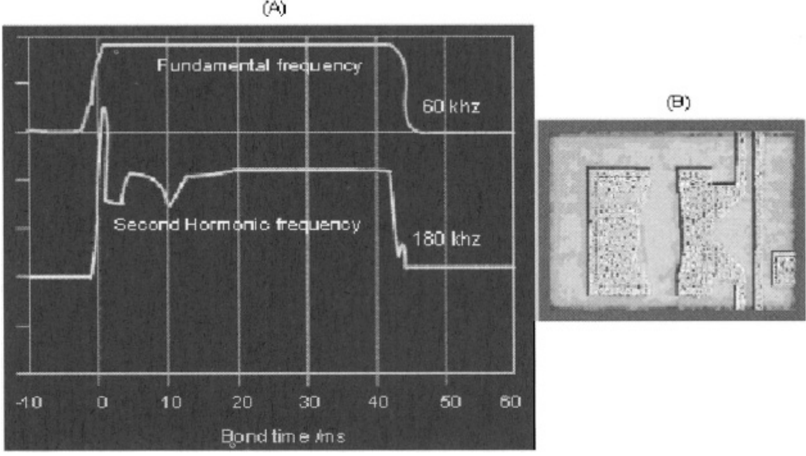


Figure 4.4.10(a) Ultrasonic amplitude of a perfectly placed bond. (b) A perfectly positioned bond [P-45]

However, in case of improperly positioned bond, the fundamental frequency shows constant amplitude, whereas the second harmonic shows a dramatic decline in the initial 20 milliseconds and a slow recovery later. For a bond that is imperfectly positioned, the corresponding drop in second harmonic amplitude is dramatic. Figure 4.4.11 shows the ultrasonic amplitudes of half hit bond pad.

By observing the drop in the second harmonic amplitude, it is possible to stop the bonding machine whenever the border values are exceeded.

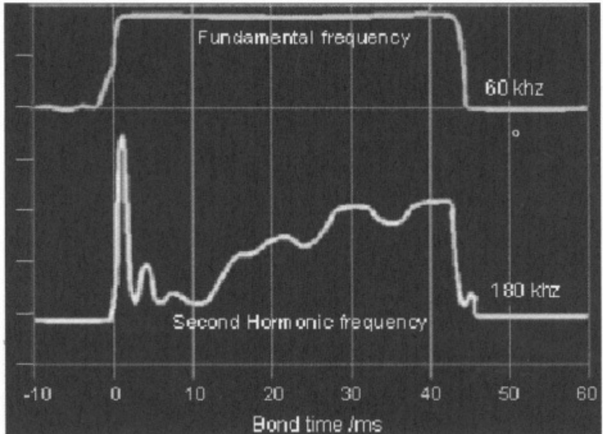


Figure 4.4.11 Ultrasonic amplitude of half hit bond pad **[P-45]**

4.4.13 Temperature Monitoring

Another major bonding parameter is thermal energy which is applied to the substrate. If the temperature of bonding is too high it can result in softer metallization, which causes metal splash and bond pad fracture. A temperature that is too low can result in harder metallization and consequently cause non-sticking. The bond temperature can be monitored with an infrared system or a thermocouple.

4.4.13.1 In-situ Measurement of Stress and Temperature

Recently, new test chips have been developed to monitor the physical parameters during bonding. Microsensors are based on doped silicon, polysilicon or metal and are integrated directly under the bond pad. The test chips can measure by the mechanical stress induced by the force, heat transfer between the bondpad and the gold ball and heating of chip by the ultrasonic energy. Figure 4.4.12 shows a sensor located directly under the bondpad which will measure the exact temperature at the bonding interface

as well as the actual force experienced by the bonding pad at the time of bonding [P-46].

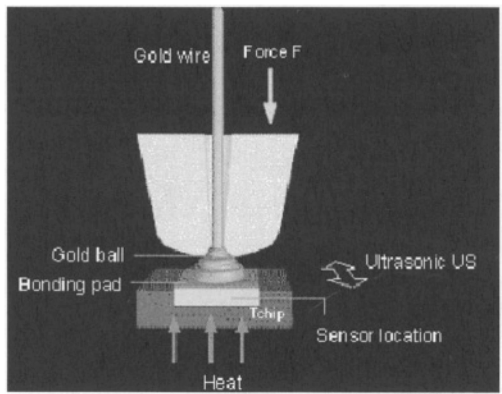


Figure 4.4.12 Sensor location under bondpad **[P-46]**

4.4.13.2 Microsensors for Stress Measurement

Two kinds of structures, Line and Serpentine, are fabricated for stress measurement. Diffused serpentine resistors are best suited for force measurements. Figure 4.4.13(a) shows a microsensors used for stress measurement under the bondpad. Figure 4.4.13(b) shows another example of microsensor in a serpentine format for stress measurement under the bondpad.

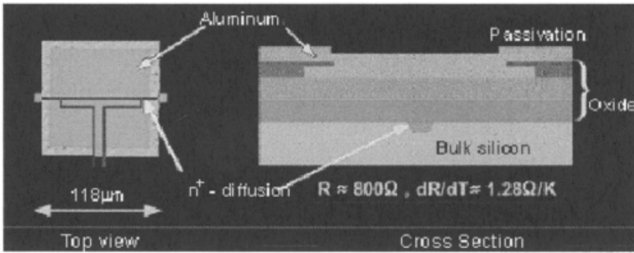


Figure 4.4.13(a) Microsensors for stress measurement

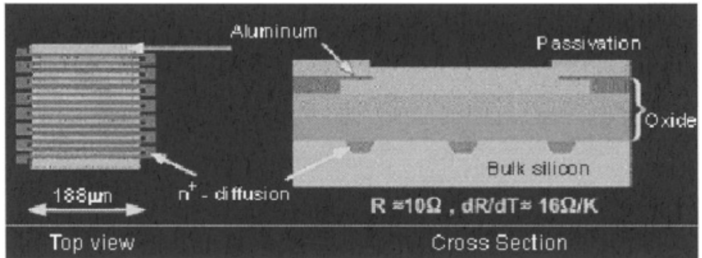


Figure 4.4.13(b) Microsensors for stress measurement [P-46]

It is possible to measure the stress on the bondpad during bonding by placing stress sensors underneath the bondpad. The stress sensor is calibrated using four point bending technique or by applying perpendicular press pressure on the bond pad.

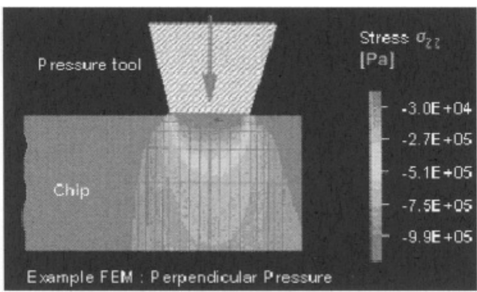


Figure 4.4.14 Finite element modelling of perpendicular stress on bond pad [P-46]

The actual measured value can also be correlated by performing finite element modelling of the stress distribution using simulation technique. Figure 4.4.14 shows a FEM of perpendicular pressure on the bondpad.

4.4.13.3 Microsensors for Temperature Measurement

The metal structure is the best choice for temperature measurements. Metal sensors have temperature coefficient of resistance and have low stress

sensitivity. The sensors can be located below the bonding pad as shown in figure 4.4.15(a) or below the passivation as shown in figure 4.4.15(b).

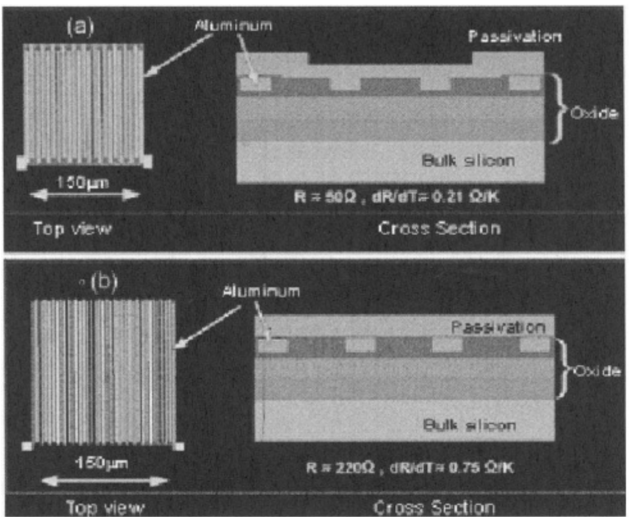


Figure 4.4.15 (a) and (b) Microsensors for stress measurement placed below the bondpad [P-46]

The chip gets cooled when the capillary makes contact with the bond pad during bonding. The capillary acts as a heat transfer agent. Higher the temperature of the chip, greater is the temperature drop. When the Capillary touches the bondpad, it acts as a micro heat sink, and has a cooling effect on the chip. In figure 4.4.16 we see, that when the chip is 60°C, the temperature drop due to capillary contact is about 3°C. However when the chip temperature is higher at a 140°C, the temperature drop due to capillary contact is as much as 8°C. This is of significance particularly in high speed bonding.

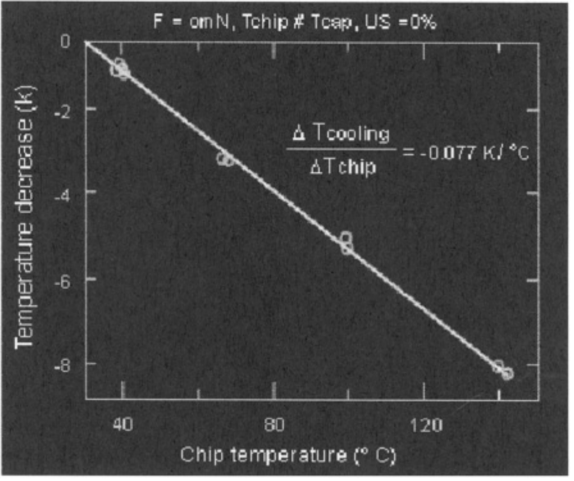


Figure 4.4.16 Cooling of chip by capillary [P-46]

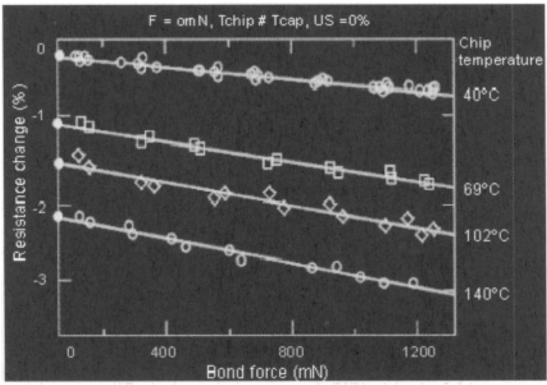


Figure 4.4.17 Bond force vs temperature [P-46]

Similarly, the temperature drops when higher bond force is used. Higher the bond force greater is the contact between the hot gold ball and the bond pad. This results in more cooling. Figure 4.4.17 shows the variation in temperature as a function of bond force.

4.5 Process Mechanism

In this section on bonding process mechanism, we will dwell into the intricacies of how interfacial bonding occurs. We will understand how atomic diffusion, dislocation motion and intermetallic formation impact the strength and reliability of a gold ball bond as well as Al wedge bond.
The different types of bonding mechanism discussed here are:

- ultrasonic bonding mechanism
- thermocompression and thermosonic bonding mechanism
- high frequency bonding mechanism

Here we shall also try to understand some of the different issues involved during bonding such as growth of bonded interface, impact of tool on weld strength, causes that lead to metal softening when ultrasonic energy is applied, impact of ultrasonic bonding on reliability, different stages of high frequency bonding, impact of alloying on intermetallic phase formation and many other important issues related to wire bond mechanism.

4.5.1 Ultrasonic Bonding

Ultrasonic bonding is the most common bonding technology used for Al bond wires. To bond the wire to the bond pad, we apply force and Ultrasonic energy. Here we shall discuss the mechanism of bonding between the wire and the bond pad.
As shown in figure 4.5.1, we can observe that on the surface of the aluminum wire and on the surface of the aluminum bond pad as well as on the lead frame metallization, a thin layer of native oxide exists, along with a monolayer of moisture and a thin layer of hydrocarbon contamination. To bond these two surfaces (the wire and the metallization) the layers of oxide have to be removed exposing the nascent metal.
Ultrasonic bonding is a solid-state metals joining method which uses no fluxes or other materials. When ultrasonic energy and force are applied to the joining members, the metals in contact are plastically deformed at the mating surfaces in such a way that oxide films or minute foreign materials

are dispersed, and the irregular surfaces are made to conform to each other to ultimately produce a metallurgical bond. Ultrasonic bonds are produced by pressing the wire against the bonding surface to which it is to be joined. The pressure is applied, generally, by the tip of a transducer that is vibrating at about 60 kHz per second. The mechanical force and scrubbing action cause molecular mingling of the two surfaces, in contact, and thereby form a bond.

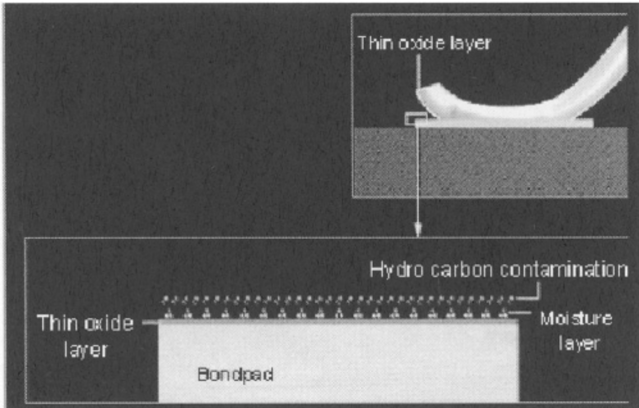


Figure 4.5.1 A thin layer of oxide on wire and the bond pad is broken to create the interfacial bond

When ultrasonic energy is applied, the scrubbing action breaks the oxide layer on the bondpad. Simultaneously, the ultrasonic waves dislodge the dislocations from their pinned locations as shown in figure 4.5.2(a). These dislocations move resulting in microplastic deformation at the interface resulting in a mechanically interlocked interface as shown in figure 4.5.2(b). This method is adaptable to the joining of dissimilar materials, as well as sections having different thicknesses. Ultrasonic bonding is a cold bonding technique in which no external heat is applied. The transducer supplies the ultrasonic energy to the wire through the wedge tip and the wire lies in the groove in the wedge tip to avoid complete mashing of the wire. The force between the tip and the work can be controlled. During vibration, dynamic stresses are induced which are sufficiently intense to cause plastic deformation of the interface material. Moisture and oxide films are broken

up and dispersed, and irregularities in the surfaces are eliminated. This causes intimate nascent metal contact, and the result is a metallurgical bond, formed in the solid state, with no melting of the metals.

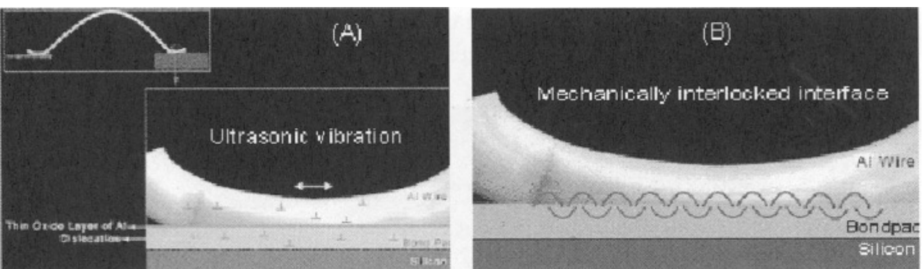


Figure 4.5.2 Molecular mingling of two surface due to mechanical force **[P-47, 48, 49]**

4.5.1.1 Ultrasonic Bondability of Metals

Face Centered Cubic (FCC) metals have better ultrasonic bondability at room temperature. This is attributed to number of slip systems available in a FCC structure. Because of the presence of large number of slip planes, metals with FCC structure (like aluminum, gold, copper, palladium and nickel) deform plastically very easily when compared to metals with body centered cubic (BCC) structure (like tungsten). Figure 4.5.3 shows a FCC and BCC lattices.

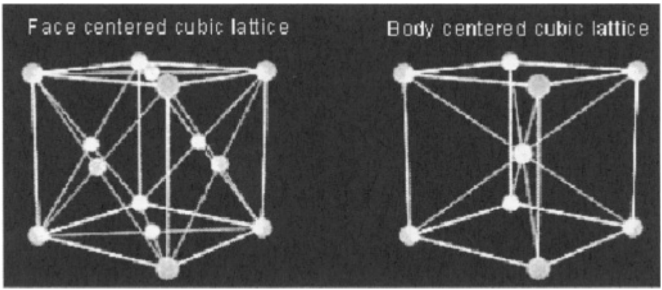


Figure 4.5.3 Face centered and body centered cubic structures
[VIEW-IN-CDROM]

Therefore, ultrasonic welding is best suited to ductile metals such as aluminum, gold, silver, copper.

4.5.1.2 Growth of Bonded Interface

Experiments have shown that the when ultrasonic energy is applied between the wire and the bond pad, the initial reaction occurs along the periphery of the bond. The surface area of reaction is directly proportional to the time for which the ultrasonic energy is applied.

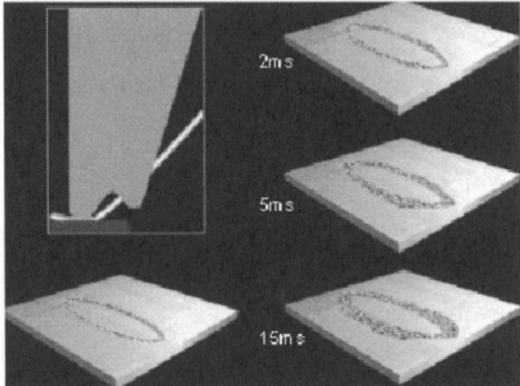


Figure 4.5.4 Schematic representation of the amount of interface reaction with respect to time for which the ultrasonic energy is applied. **[P-50]**

We can observe from figure 4.5.4, when the ultrasonic energy is applied for 2 milliseconds, the surface area of reaction is small, whereas when the ultrasonic energy is applied for 15 ms, the surface area of reaction is much larger.

At very short times of ultrasonic application, the bonded area is weak and easily peelable. As the time of bonding is increased, there is greater area of interaction along the periphery and the bond becomes stronger. Figure 4.5.5 shows a SEM micrograph which clearly indicates the area under the bond that is actually welded. The centre portion of the bonded region is not welded.

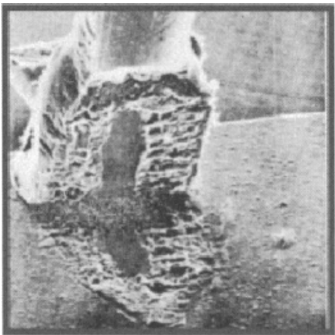


Figure 4.5.5 SEM photomicrograph 1000X if lift-off pattern of a aluminum wedge bond [P-32]

4.5.2 Impact of Tool on Weld Strength

In ultrasonic wedge bonding, the amount of reaction during the application of the ultrasonic energy is higher with a concave tool when compared to a flat tool. Weldment strength is greater for a concave tool than for a flat tool, due to a more complete weld. The weld starts at random points within the bond, beginning at the heel or front of the bond, progressing along the sides of the weldment.

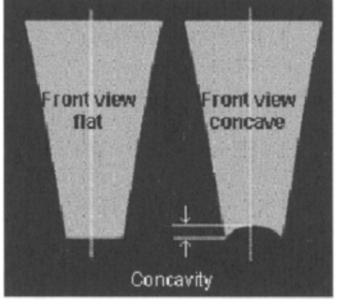


Figure 4.5.6 Concave tool vs. flat tool

Bonding in the center of the weldment occurs last, if at all. More welding in the center of the bond occurs with a concave tool. Figure 4.5.6 shows the comparison of flat tool and a concave tool.

4.5.2.1 Why do the Metals "Soften" when Ultrasonic Energy is Applied?

The mechanism of ultrasonic softening and deformation in metals has been studied by Langenecker. He has studied the stress - strain curve of aluminum

metal when ultrasonic energy is applied and compared it to the stress - strain curve of aluminum when thermal energy is applied. He has shown that that either ultrasonic energy or thermal energy can independently cause equivalent deformations in aluminum.

Figure 4.5.7 shows a comparison of aluminum single crystal under ultrasonic stress as well as thermal stress. We can see here, at 18 degree centigrade, aluminum shows very high tensile stress and high elongation. However, as we increase the temperature to 200 degrees, 400 degrees, and 600 degrees centigrade, the tensile stress value decreases. This is due to easy plastic deformation at high temperature. When 20 KHz ultrasonic energy is applied to aluminum single crystal, the plastic deformation increases as the ultrasonic power is increased or 15 to 35 and to 50 watts per centimeter square. Most importantly, this decrease in tensile stress occurs at room temperature [P-51].

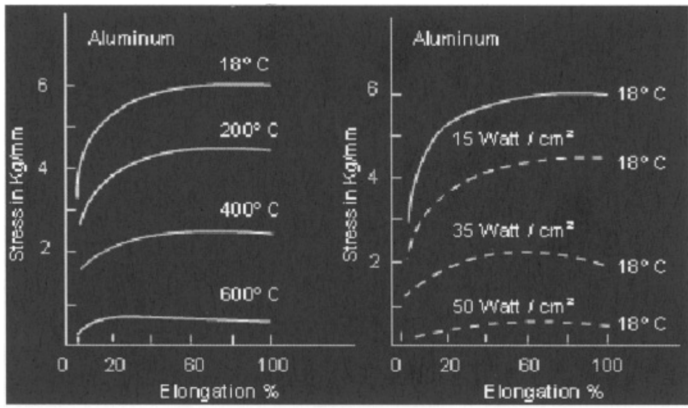


Figure 4.5.7 Stress vs. elongation for aluminum single crystals [P-51]

Here we can observe that the stress elongation is essentially equivalent to deformation under a compressive load, such as occurs in ultrasonic welding. However, two major differences exist between ultrasonic deformation and thermal deformation, which are:

- the ultrasonic energy density required to produce deformation in aluminum with no applied stress is about 10^7 times less than is required for an equivalent deformation resulting from thermal energy
- ultrasonically deformed aluminum is work hardened (acoustic hardening) whereas equivalent thermal deformations leave the metal permanently softer (annealed)

When ultrasonic energy is applied to a FCC metal, the acoustic energy is preferentially absorbed at dislocations. The dislocations are freed from their pinned sites and the metal deforms under relatively low stress.

4.5.2.2 Is there Heat Generation during Ultrasonic Bond Formation?

Perhaps the major controversy concerns the amount of heat generated during ultrasonic bonding, and the importance of heat in deforming the weldments. Some experimental measurements have shown that there may be a rise in local temperature due to the combined effects of plastic deformation, elastic hysteresis, and localized slip. But accurate measurements of temperature have not been made. But it is certain that the temperature of the interface is much below the melting points of the metals being bonded. Another theory has been put forward to explain the formation of ultrasonic weld and the role of wire and substrate deformation in ultrasonic bonding. According to this rationale, when one examines the growth of a weld or some completed welds, it is observed that the perimeter welds first. This suggests that it is the wire deforming against the bonding pad that cleans the surfaces, permitting intimate metallic contact and thus welding. After ultrasonic bonding, the resulting welded joint (bonded interface) has low-resistance and is a low-noise junction, because the bonded interface is free of intermetallics and voids.

4.5.2.3 Mechanism of Ultrasonic Wedge Bonding of Au

Gold is a harder metal than aluminum. During Au wedge bonding, a hard wire is bonded to a soft metal. This is not easy, for two reasons

- greater force and ultrasonic energy is required to plastically deform Au wire
- excessive force and ultrasonic energy will cause aluminum metallization to squeeze out of the bond pad

Unlike aluminum wedge bonding it is not possible to generate a mechanically interlocked interface between Au wire and Al bond pad. Therefore in order to minimize Al squeeze out and to increase the strength of the bonded interface, it is required to have a metallurgical bond. Therefore during Au wedge bonding one uses a higher than room temperature during bonding.

4.5.2.4 Impact of Ultrasonic Bonding on Reliability

The ultrasonic energy and force on the bond wire create a strong bonded interface. However, the same parameters also induce micro cracks in the wire during the bonding process.

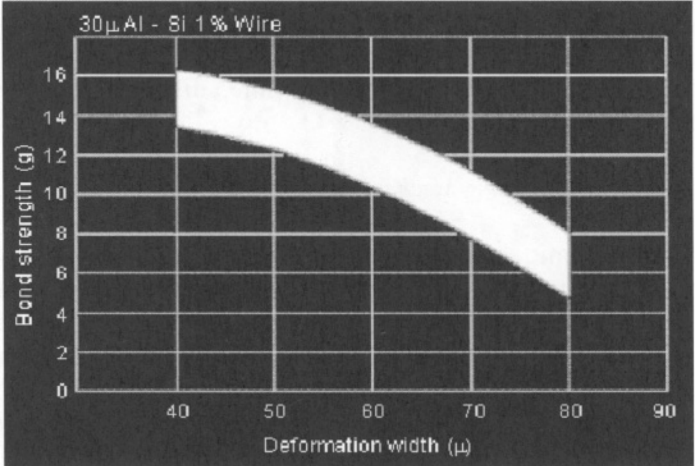


Figure 4.5.8 Deformation and bond strength [Adopted from product catalog: American Fine Wire Corporation]

The generation of microcracks at the heel of the wire is directly related to the amount of force and ultrasonic energy. For a particular diameter of Al wire, we can observe from figure 4.5.8, as we increase the wedge deformation width, the bond strength tends to decrease. This is because, the increased amount of force and ultrasonic energy used in wedge bonding induces microcracks that propagate a fracture at lower stress values during bond pull test. Therefore one must take necessary care in choosing the optimum force and ultrasonic energy values for maximum bond strength and minimum heel crack.

4.5.3 Thermocompression Mechanism

During thermocompression bonding when Au ball is bonded on Aluminum metallization, the atoms of Au and Aluminum inter diffuse and form a metallurgical bond. Depending on the type of Al metallization, the rate of inter diffusion between Au and Al varies and therefore, the type of intermetallic formed at the interface can be different. Thus, the failure rate due to Au and Al intermetallic is significantly affected by the type of bond pad metallization and its structure. Depending on the bond force, bonding temperature and the length of bonding time, different intermetallic are formed at the interface.

4.5.3.1 Thermosonic Bonding Mechanism

During thermosonic bonding when gold ball is bonded on aluminum metallization, the atoms of Au and Al inter diffuse and form a metallurgical bond. Thermocompression bonding has long been replaced by thermosonic bonding. In thermosonic bonding, in addition to the force and temperature, Ultrasonic energy is applied during bonding. Thermosonic bonding accelerates the diffusion process for Au and Al and, in times as short as a few milliseconds, creates a strong, welded intermetallic structure. Ultrasonic energy absorption occurs preferentially at dislocations, grain boundaries, impurities, etc., and activates or frees dislocations from pinned positions. This produces metal softening and allows slip and low stress deformation to take place. The use of ultrasonic energy during bond formation enhances

diffusion phenomena and other chemical activity. Reaction between contacting species also accelerates.

4.5.3.2 Effect of Time

The reaction at the interface between the ball and the aluminum metallization depends on bond time. The duration of the applied ultrasonic energy, and the level of energy absorption has a significant influence on diffusion activity and on material properties. All other parameters being same, shorter bond time results in smaller reaction zone, and, larger bond time results in larger reaction zone. We can observe from figure 4.5.9 the intermetallic reaction for different bonding times of 2ms, 4ms and 15 ms. It is evident that the reaction zone is highest when the bonding time is 15 ms.

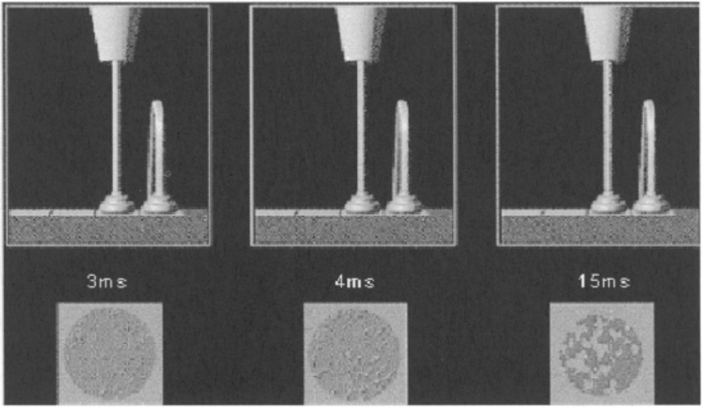


Figure 4.5.9 Schematic representation of variation in intermetallic reaction with respect to bonding time

When Au ball is bonded thermosonically to Al bondpad, the two metals react at the bonding temperature and usually Au2Al intermetallic compound is formed. This provides the adhesion strength to the ball bond. When Au and Al diffuse into each other, depending on the temperature and the duration of exposure at that temperature many other intermetallics are also formed. During thermosonic bonding process, usually, Au_5Al_2 is the phase

that is formed. However, during thermal annealing, many different phases are formed depending on concentration of Al and Au. The different phases that are formed in regions where Au concentration is far less than Al and different phases that are formed in regions where Al concentration is far less than that of Au are shown in figure 4.5.10.

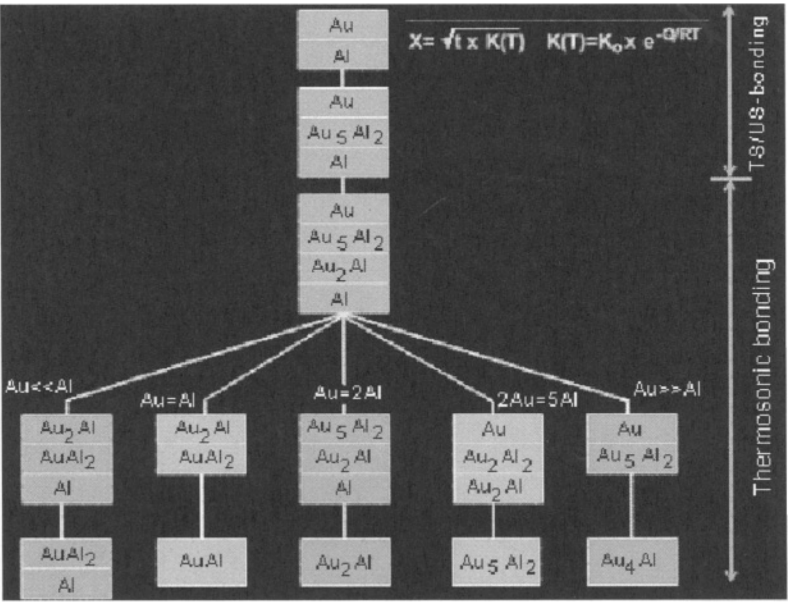


Figure 4.5.10 Diffusion and intermetallic phase formation in Au-Al system [P-11] **[VIEW-IN-CDROM]**

When gold and aluminum react to form intermetallics, the electrical resistance, the thermal expansion coefficient and the hardness of the intermetallics is dramatically different from either aluminum or gold, for example

- the Specific resistance of Au_4Al is 15 times higher than that of Au
- the coefficient of thermal expansion of $AuAl_2$ is half of that of Al

- hardness of Au_4Al is 10 times that of aluminum

We can observe from table 4.5.1, hardness of aluminum is between 20 to 50, whereas that of Au_4Al is 334 and similarly, the specific resistance of aluminum is 2.3, whereas that of Au_4Al is 37.5.

Table 4.5.1 Properties of intermetallic phases [P-11]

Phase	Al	$AuAl_2$	AuAl	Au_2Al	Au_5Al_2	Au_4Al	Au
Spec-Resistance [$\mu\Omega$ cm]	3.2	7.9	12.4	13.1	25.5	37.5	2.3
CTE [10^{-5}]	2.3	0.94	1.2	1.3	1.4	1.2	1.42
Hardness [HV]	20-50	263	249	130	271	334	60.90

These intermetallics can be a major cause of reliability problems (For more information refer Reliability chapter under purple plague).

4.5.3.3 High Frequency Bonding Mechanism

In Thermosonic Bonding, the mechanism of bond formation is diffusion controlled and thus bonding time plays a significant factor. But in high frequency bonding, it has been observed that force, temperature, and scrubbing due to ultrasonics play a much more important role. In BGA and CSP type packaging, the bonding temperature are very low and therefore the primary energy input is achieved using high frequency [120 KHz] transducer which increase the mechanical scrub due to ultrasonic input. If the displacement of any two ultrasonic transducers is equivalent, the one operating at high frequency will have a large mechanical scrub component. When the ultrasonic frequency is increased, the reactivity and intermetallic growth is enhanced due to higher energy transfer. The better absorption of energy provides higher percentage of gold-aluminum chemical reaction, thereby giving a stronger weld.

As material flow occurs, microscopic slip planes shear across each other. At the surface, this slipping provides new surfaces that are metallurgically clean. Because these clean surfaces on the bond site and wire are in contact, they diffuse and weld to each other. Higher ultrasonics also increase the strain rate and enable the material to transfer energy from the capillary tip through the wire to the bond interface more efficiently.

Considering that bonding times are shorter for higher frequencies, it can be inferred that at higher ultrasonic frequencies the efficiency of converting the acoustic energy into intermetallic reactivity at the bonded interface is increased.

4.5.3.4 Stages of High Frequency Bonding

In 60 kHz wedge bonding, deformation occurs during the first 10 to 15 ms, after which the wire strain-hardens. Once the wire is strain-hardened, the energy is transmitted to the wirebond pad interface, opening up new metal surfaces. At this point, diffusion bonding, enhanced by ultrasonics, occurs at the newly exposed metal surfaces. The bond is now complete.

During 120 kHz, almost immediately after the ultrasonic generator board fires, the wire behaves as a strain-hardened material. The table 4.5.2 shows the stages of bonding at 2 different frequencies: Low frequency of 60 kHz and high frequency of 120 kHz. In the low frequency region first the deformation occurs and that results in strain- hardening, whereas in the high frequency region first there is a high rate of strain- hardening but with very slight deformation. At the next stage the metal slips and then there is formation of diffusion bond and finally increase in the bonded area.

In high frequency bonding less energy is used in bond deformation, whereas most of the energy is transferred to the wire pad interface. And therefore the bonding occurs even without much deformation. And this is the advantage of using high frequency ultrasonic or ultra fine pitch application. In low frequency bonding more energy is used in deforming the bond and less energy is transmitted to wire bond pad interface. This results in large ball diameter with low interfacial strength and this is unsuitable for ultra fine pitch wirebonding.

Figure 4.5.11 is a schematic representation of the bonding mechanism in low frequency and high frequency bonding. Here we can observe that, to get similar bond strength with 120 kHz frequency it takes only 10

milliseconds and addition wire deformation is small, whereas in case of 60kHz frequency the bonding time is almost 20 milliseconds and wire deformation is large.

Table 4.5.2 Stages of bonding in low frequency and high frequency bonding [P-52]

Stage	Frequency	
	60 kHz	120 kHz
0	Deformation resulting in strain hardening	High strain rate hardening with slight deformation
1	Slip	
2	Couple formation with ultrasonic enhanced diffusion	
3	Bond area increase	

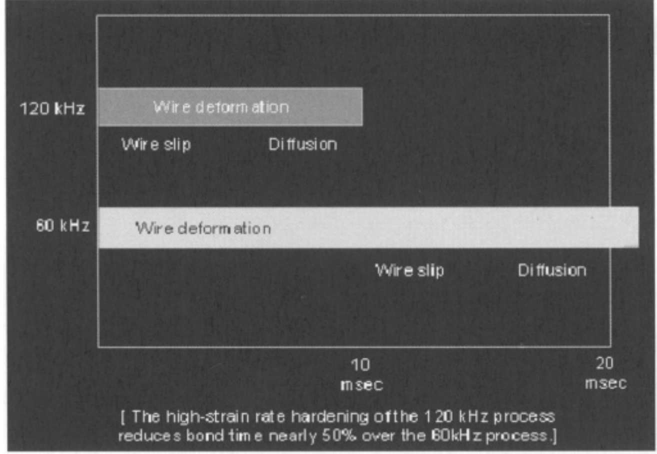


Figure 4.5.11 Schematic representation of bonding mechanism in low and high frequency bonding. [P-53]

4.5.3.5 Intermetallic Formation at Different Frequencies

Figure 4.5.12 shows an SEM view of the bottom side of the squashed balls after they have been released from the aluminum pad in a KOH solution. For each frequency the process parameters which resulted in the highest shear strengths have been taken. It may be difficult to judge from the reproductions the percentage of area where a growth of an intermetallic can be seen. From the originals, it can be estimated that at 60 kHz about 60% of the squashed surface is coated with an intermetallic alloy. We can also observe that intermetallic formation at 140kHz it is about 75% and at 240 kHz the intermetallic coverage is about 90%.

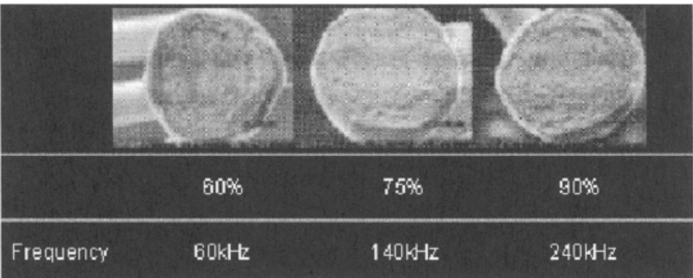


Figure 4.5.12 Intermetallic formation at different frequencies [Courtesy: Small Precision Tools]

4.5.3.6 Shear Strengths as a Function of Amplitude

The shear strength of the ball bond increases as the frequency of the ultrasonic energy increases from 50 to 140 to 240 khz. We must also recognize that at each frequency the particular amplitude gives the highest shear strength. The free air amplitude decreases as we increase the ultrasonic energy. The shear strength at 50° C, shear value per contact as a function of different frequencies and amplitudes can be seen in figure 4.1.134 in process variables. It can be seen that higher the frequency, the lower is the amplitude required for an optimum bond. The higher Shear strengths - 110 N/mm^2 are obtained at a frequency of 240 kHz (improvement of around 25% compared to the lower frequencies) [P-54].

4.5.3.7 Shear Strength as a Function of Time

For optimum bond strength the timing is shorter at higher frequencies can be seen in figure 4.1.10 in process variables. As we go towards higher frequency the shear strength peaks at an optimum time value For example at 240 khz frequency the shear strength increases when we increase the time from approximately 2 sec to 5 sec. After that any increases in time decreases the shear strength and similar phenomena is seen at 140 khz and 100khz. While the higher Ultrasonic frequencies give better results at room temperature, they have the disadvantage that the process window gets tighter, i.e., little variation of Ultrasonic power or time will result in completely deformed nail-heads or non sticking balls. Therefore, the equipment for high frequency applications requires the capability of precise parameter control or closed loop operation.

4.5.3.8 Impact of Alloying on Intermetallic Phase Formation

Due to the special material requirement of ultra finepitch wirebonding, material suppliers are developing special wires with specific alloying elements. These alloying elements in the gold wire have a significant impact on the intermetallic phase formation. Special alloys wires used in ultra fine pitch bonding have different intermetallic phase growth phase. Figure 4.5.13 shows an example of intermetallic growth of FP2 wire which is 99% gold. Even on long exposure at 175°C the FP2 forms the intermetallic phase slower than high purity gold, this result in lower contact resistance and increase bond reliability. [P-55]

Unlike the case of Pd -Au alloy described above, in some alloy compositions of Au wire, rate of formation of Intermetallic Phase is much higher than 4N gold. This is a cause for concern from the point of view of reliability which we shall discuss in the reliability section.

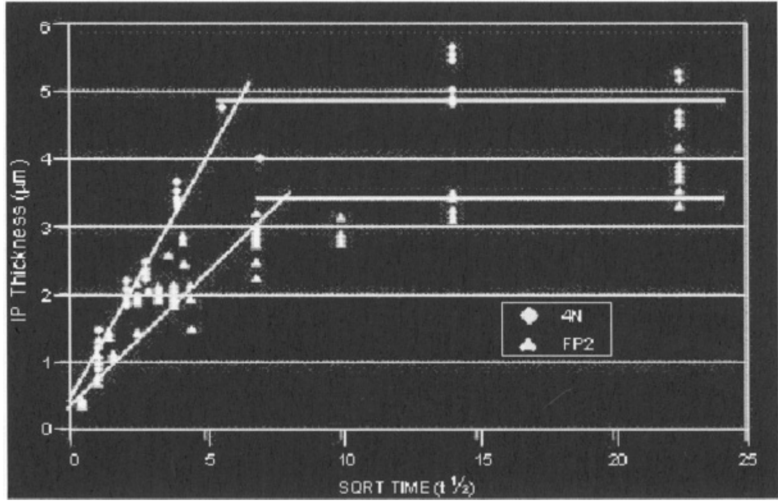


Figure 4.5.13 Comparison of intermetallic phase growth of 4N and FP2 wires [Courtesy: American Fine Wire]

4.5.3.9 Mechanism of Formation of Second Bond on Lead Frame

During thermosonic ball bonding, the first bond on the bond pad is between the Au ball and the soft aluminum metallization on bond pad. The second bond is formed on the lead frame with a metallization which is usually Au or Ag. The mechanism of bonding is metallurgical bond between Au-Au or Au-Ag. When Au wire is thermosonically bonded to Au metallization, there is metallurgical bonding between same metal. When Au is bonded on to Ag, a metallurgical bond is formed between the two metals. Both these metals are soluble in each other and can form a solid solution. When gold wire is bonded onto silver metallization on a copper leadframe, there is no formation of intermetallic compound. Since both gold and silver have similar crystal structure, and they are noble metals, they form a solid solution, by diffusion of gold atoms into silver and silver atoms into gold. Thus the interfacial alloy is uniform and has similar properties as the two metals.

4.6 Designs for Bondability

In order to achieve high yield and a reliable bonding process, we need to make sure that the IC chip is designed to meet the assembly manufacturing requirements as well as that the package is designed to meet the assembly manufacturing capabilities. Practical constraints of wirebond tooling and properties of the wire generally limit wirebonding to a perimeter footprint. For optimum bonding results the bond pads on the chip and the lead fingers of the lead frame have to be appropriately designed. Therefore we need to consider two important factors and they are:

- die design rules
- assembly and packaging design rules

These design rules are based on IC design performance requirements, wire diameter, pad spacing at the chip, pad spacing at the substrate, die size, package size, reliability requirements, bonding machine capabilities and many other parameters.

All the design parameters that have been mentioned in this section are just guidelines and are provided here as example only. The author is not liable for use of this information by any individual. The actual design values must be decided by the design engineers and the packaging engineers in every company for every device-package combination.

To maintain control over assembly operations and achieve the highest possible yields in assembly, it is important to comply with an established set of design rules. The basic design considerations include: die design considerations, substrate design considerations. In die design, we consider bondpad opening, position of the bondpad on the chip, bondpad pitch, scribe street dimensions and other such factors. In substrate and package design, we need to consider dimensions of the substrate or package, loop height, wire length, wire angle, bond angle range, crossing wires, maximum number of bonds per slot, die to cavity clearance, and many other parameters. In substrate or package design, the minimum die size, that can be accommodated is governed by the maximum wire length allowed, whereas, the maximum die size that can be accommodated is governed by the closest bondable area. Figure 4.6.1 shows other dimensions that are critical in

substrate designs which are, the angle of the wire, width of the ground ring, gap between the ground and power ring, width of the power ring and minimum bonding area on the lead finger.

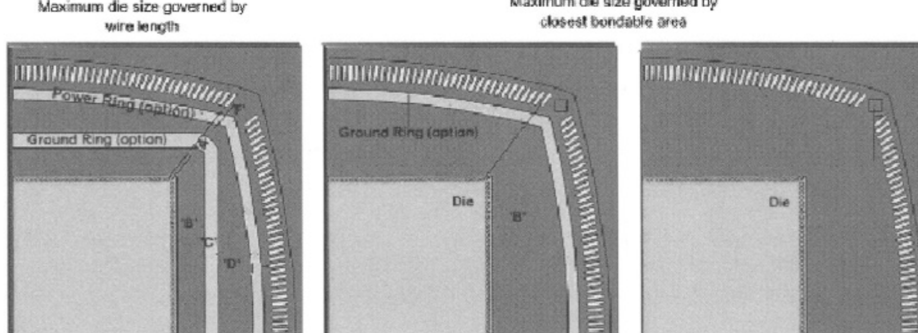


Figure 4.6.1 Substrate design guidelines: A=180 mils max @ 45° for FPP 200 mils max @ 45° for STD , B= 0.88 mm, C= 0.35 mm nom, D=0.2mm min, E=0.35mm nom, F=0.2mm [P-56]

4.6.1 Die Design Rules

A die designer has to follow certain layout guidelines to accommodate easy device assembly with the package. The die bond pads should be lined up in a center row or two or four-edge rows. The first and last bond pad of each row should maintain a minimum distance from the die edge. Die design rules are required in the layout of a new die so as to avoid yield-loss and quality-loss and to insure compatibility with the latest assembly materials, equipment, processes, quality and reliability requirements. When die redesign occurs, the metal mask should also be redesigned to meet these die design rules.

The die design rules provide the designers with layout design rules for wire size selection, bonding pads (geometry and location). Passivation, metallization spacing, and die size, in order to ensure manufacturability at optimum assembly quality, yields, and productivity with minimum silicon usage. One must be aware that as device geometry continues to shrink and

the die pad pitches become smaller, mechanical wire bond limitations will affect package availability.

4.6.2 Bond *Pad Rules*

4.6.2.1 Bond Pad Placement on Die

General rule in bonding pad lay out is that the bond pad must be located around the die periphery and on the intersecting axis connecting the pad centre to the corresponding wire connection. A clearance of +/- 15 degrees may be accepted on pad position.

The bond pads must be located on the perimeter of the die, and they must be positioned within the area defined by the lines extending inwards from the lead frame to the centre of the die. Usually, equal number of pads, symmetrically arranged around the die is suggested. The recommended and not recommended bond pad placement is shown in figure 4.6.2.

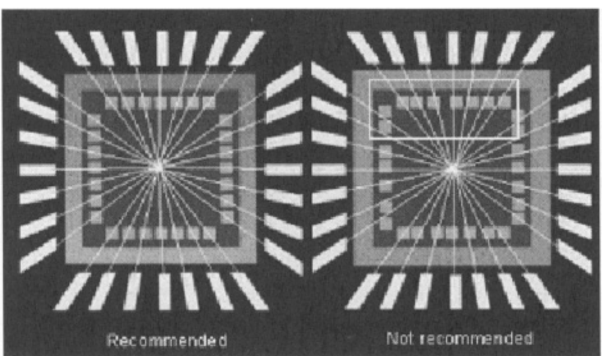


Figure 4.6.2 Bond pad placement on the die

With some lead frame or package configuration this rule may be slightly waived in order to give priority to more important wire bonding rule, such as:

- minimum distance between wires
- centered wire bonding on lead frame

- non-placement of bonding pad at the die corner

The bond pad size, pad pitch and pad gap depend on the ball diameter. The pad pitch is defined as the "centre to centre" distance between to bond pads, and the pad gap is defined as the "edge to edge" distance between two bond pads. The pad pitch and the pad gap are shown in figure 4.6.3

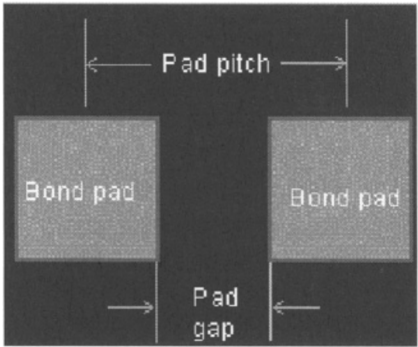


Figure 4.6.3 Bond pad design

In ultra fine pitch bonding, the bond pad pitch is determined by the capability of the wire bonder as well as the capillary design. The bond pad pitch in-turn determines what the pad size should be and the size of the bond pad opening. From table 4.6.1, we can see, for example for a 70 micron pitch the bond pad size is 65 microns, the bond pad opening is 60 microns.

Table 4.6.1 Single In-Line pads microns(mils)

Bond pad pitch	80 (3.2)	70 (2.8)
Bond pad size	74 (2.9)	65 (2.6)
Bond pad opening	67 (2.6)	60 (2.4)

Distribution of bonding pads along die side should be in accordance to the following ratio:
(Number of pins of lead frame/Number of side of lead frame +/-1)
Examples:

14L 14 pins : 4 sides = 3.5 (min 3 - max 4)
15L 15 pins : 3 sides = 5 (min 4 - max 6)
28L 28 pins : 4 sides = 7 (min 6 - max 8)

Bonding pads should ideally be located on the perimeter of die and within an area that is close to the lines extending from lead to centre of die.

Table 4.6.2 Staggered pad pitch with resultant effective pad pitch. [P-56]

Straggered pad pitch	150 (5.9)	140 (5.5)	120 (4.8)
Effective pad pitch	75 (3.0)	70 (2.8)	60 (2.4)

When the bond pads are placed in a staggered fashion, the pad pitch is much larger, and the effective pad pitch is also correspondingly increased. In case of staggered bond pads, the staggered pad pitch can be 120 microns but the resultant effective pad pitch is actually 60 microns. In this case, the bonding parameters used need not be very tight. Table 4.6.2 shows staggered pad pitch with resultant effective pad pitch. In figure 4.6.4 we can see the staggered bond pitch is 120 microns, but the effective pitch is 60 microns.

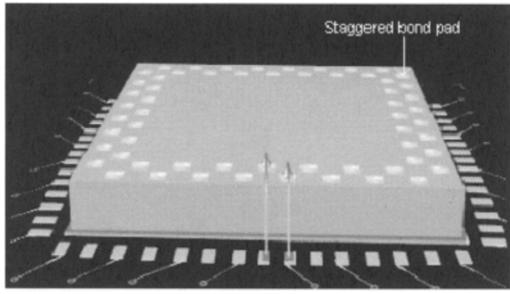


Figure 4.6.4 Staggered bond pad pitch and effective bond pad pitch

4.6.2.2 Bonding Pad Placement Relative to Pins

Wire bonding path must come to lead finger edge in such a way that it crosses the edge of lead finger facing (parallel) to die side. In establishing bond design rules for a package, the bond angle range should be within the lead frame corners. The path of the wire must not cross the left corner (lower limit) or the right corner (upper limit) of the lead finger, and the allowable range must be within this angle. For the leads shown in the figure 4.6.5, we can see the ideal bond pads that are within the range. The bond pads to the left and to the right are out of range.

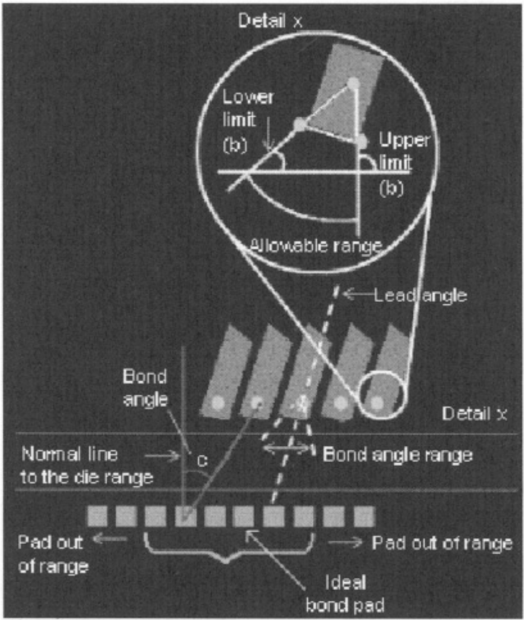


Figure 4.6.5 Determining ideal bond pad, bond angle and bond angle range **[Adopted from product catalog: LSI Logic]**

4.6.2.3 Bonding Path Inclination or Wire Approach Angle

Wire approach angle is the angle formed between the bonding path and lead finger edge facing die pad side. Minimum acceptable bonding path inclination is 45 degrees.

The wire bonding on the lead finger or pin must be centered on the bonding area. The bonding area is the area contained within lines 50 μm from edges of coined area of the lead.

4.6.2.4 Maximum Length of Wire over the Die

Clearance between bond pad and the die edge: The length of the wire from die edge and axis of the bond pad must be no more than:

- 15 mils (381 microns) for plastic package with undepressed lead frame
- 20 mils (510 microns) for plastic with depressed lead frame and hermetic packages
- 50 mils - 1300 microns for power plastic and power hermetic packages

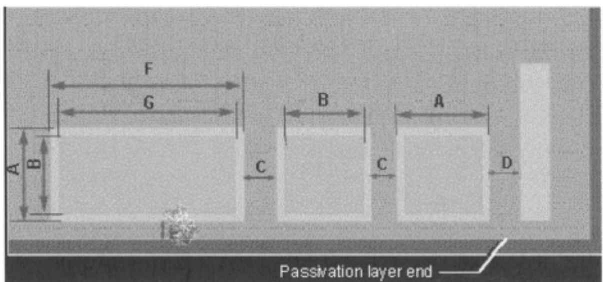
Before the design of die lay-out the compatibility with blank bonding diagram must be checked. For IDF lead frame it is compulsory to check the compatibility of bonding pad lay-out with the blank bonding diagram.

4.6.2.5 Bondpad Size Requirements

Critical dimensions to be taken into consideration when positioning the bonding pad are shown in figure 4.6.6. The important considerations in the location of the bond pad are:

- the pad must be located on the perimeter of the die and should be located within an area defined by the lines extending inward from the package post to the center of the die.
- an equal number of pads on each side of the die is preferred.
- pad locations that cause the wires to cross, appear to cross, or come with in 2 wire diameters of adjacent wires or bond pads are not acceptable. For fine pitch, less than one wire diameter is not acceptable.
- active metallization must be no closer than 13 microns (0.5 mil) from the bonding pad.

- to achieve the 80 microns (3.2 mil) bond pad pitch, no active metallization can be between the bond pads



A : Aluminum pad dimension, B :Passivation window, D :Distance between bond pad and Al, C : Distance between two aluminum pads metallization, E : Distance between bond pad and scribe line, F : Al bond pad for double wire, G :Passivation window for double wire

Figure 4.6.6 Critical dimensions for positioning the bondpads on the die

In die design guidelines, the scribe street design plays an important role. We can observe from table 4.6.3, if the scribe street has no test patterns or alignment targets, then the minimum width should be 51 microns. If the scribe street has test patterns, then the width should be a minimum of 64 microns.

Table 4.6.3 Die design guidelines

Scribe street width (no test patterns, metal pads or alignment tragets)	Scribe street width (with test patterns etc.)
Width microns (mils) min	Width microns (mils) min
51 (2)	64 (2.5)
76 (3)	89 (3.5)
102 (4)	114 (4.5)

4.6.2.6 Calculation of Bond Pitch as a Function of Chip I/O

The pad limited chip designs require more pads with finer bond pitch. The finest bond pitch is limited by many factors including wire diameter and ball diameter, bonding capillary, wire length, bond finger pitch and the minimum distance between wires as determined by the wire sweep for the

molding process. Figure 4.6.7, shows the bond fingers at constant pitch P, bonded to pads on the die.

Here we see that the pitch of the bond fingers on the substrate is constant. However, to accommodate this constant pitch P, the bond pad pitch on the die increases from the center towards the die edge. For example, E1 is the minimum pad pitch at the center of the die and it changes to E2, E3 and to EN as we go towards the die edge. This variation in pad pitch is a function of minimum wire length J and the minimum angle allowed between the wire and the edge of the die.

The finest pitch fingers achieved by most substrates including lead frames and PCBs is in the range of 120 to 180 microns which is more than twice the pad pitch on the die in the range of 60 to 90 microns. As a result the distance Tn = EnSinAn between wire centers decreases with the angle An from the center to the corners of the die.

If a fixed distance $T \geq 2R$ (Q+1) must be maintained then the pad pitch has to gradually increase, limited only by the minimum angle An = 45° allowed between the wire and die edge [P-57].

Q is the factor used to determine the minimum distance desired between wires and depending on the bonding process can have values Q=1 to 3.

Considering a die with 2n+1 bond pads per side and a minimum pitch E_1 = T and minimum wire length J at the center of the die, then it can be deduced that the pad pitch of the nth pad E_n should be:

$$E_n = E_1 \left(1 + \left(nP - \sum_{m=2}^{n} E_m\right)^2 / J^2\right)^{1/2}$$

E_1 = Minimum pitch

J = Minimum wire length

E_m = Pad pitch on the die

P = Pad pitch on the substrate

E_n =Pad pitch of nth pad

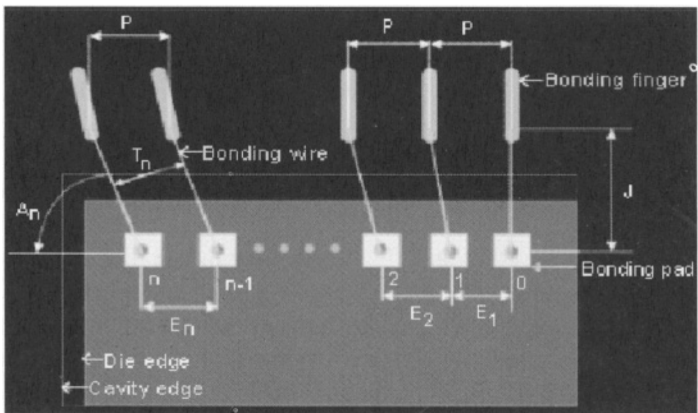


Figure 4.6.7 Bond fingers at constant pitch P, bonded to pads on the die [P-57]

The pad pitch increase as a function of the pad number is shown in figure 4.6.8, for three cases. When the bond finger pitch is 125 microns and the wire length allowed is 2 millimeters, the impact on the bond pad pitch on the die is not very significant. The slope $\Delta E_n/\Delta n$ is about 0.6 microns per pitch. However, when we use a substrate with a large pitch of 180 microns between the bond fingers and the wires are short, say about 1 millimeter, then the pad pitch of the bond pads on the die change dramatically. We see here the slop $\Delta E_n/\Delta n$ is 3 microns per pitch. So in any ultra fine pitch application, the die design and the substrate design has to go hand in hand in order to achieve reliable bonding process. On the substrate, the pitch between the bond fingers is limited by the substrate manufacturing technology.

The pad pitch increase slope $\Delta E_n/\Delta n$ is practically constant depending on the values of E_1, P and J. Comparing cases #1 and #2 with the same wire length J = 1080 microns and E_1= 80 microns, when the finger pitch is decreased by ΔP=30% the number of pads is increased 300% subject to the restrictions described above. It is for this reason that any decrease in bond finger pitch is highly desirable to maximize pad count and minimize pitch.

Comparing cases # 2 and # 3 with the same finger pitch P = 125 microns, the number of bondable pads increases only proportionally to the wire length increase. Though higher pad count is desirable longer wires with higher inductance is not particularly desirable in high frequency applications. Furthermore the increased wire sweep not accounted for in this calculation will force a larger wire spacing T and larger pad pitch E_1.

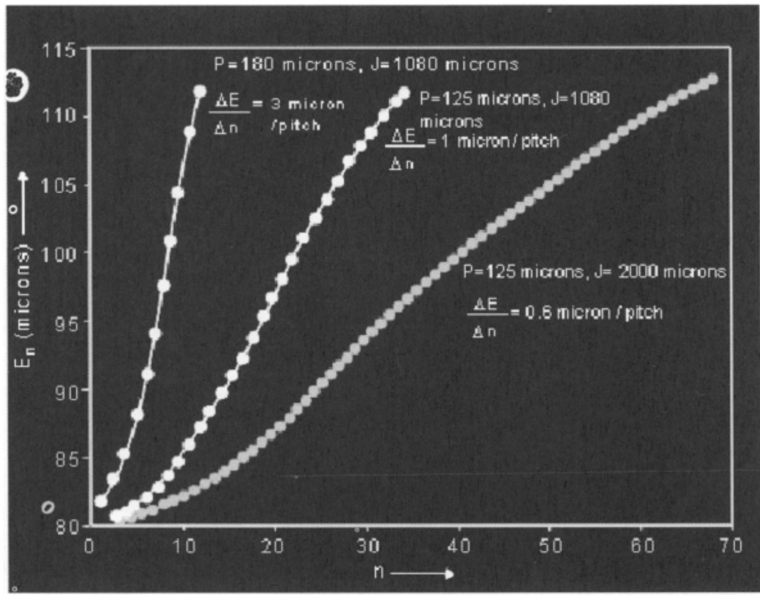


***Figure 4.6.8** Bond pitch calculation as a function of pad number as counted from the die center. Centre padpitch E_1: 80 microns, minimum angle A_n: 45°* [P-57]

4.6.2.7 Pad Pitch Determination for Ultra Fine Pitch Bonding

The pad pitch is a function of many parameters, including wire diameter, free air ball diameter, capillary dimensions capability, bonding parameter control and bond on pad capability. Let us take a look at how each of the above parameters impacts the pad pitch.

In ultra fine pitch bonding, the ball bond must be placed precisely in the bond pad opening. However, the consistency of displacement is not possible 100% of the time. The accuracy of placement depends on a host of factors, such as operator error, machine error and diameter variation and thus the bond is displaced by a certain margin as shown in figure 4.6.9. Taking into consideration, all this errors, one has to decide what the bondpad opening and pad pitch should be.

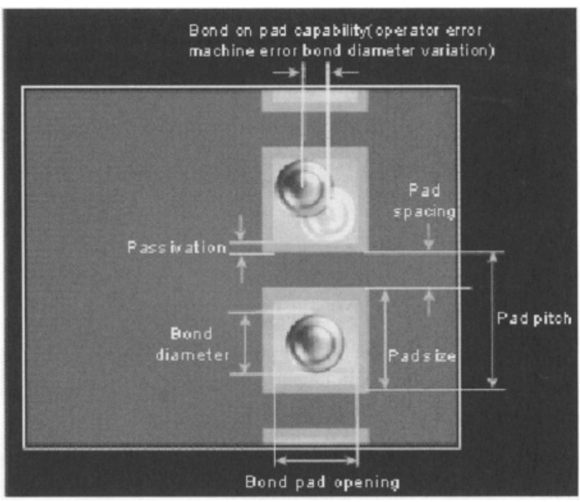


Figure 4.6.9 Consideration for determining the permissible pad pitch in ball bonding

4.6.2.8 Effect of Wire Diameter on Bond Pad Pitch

It is well established that the wire diameter and the free air ball diameter determine the pad pitch on a die. We can see in the figure 4.6.10, the impact of wire diameter on minimum pad pitch requirement. As the wire diameter decreases, the pad pitch can correspondingly be reduced. For example, a one-mil wire diameter requires a minimum pitch of 63 microns, whereas a 0.7 mil wire diameter requires 51 microns.

Table 4.6.4 gives approximate values of ball diameter, the required pad opening, and the pad pitch achievable for that particular wire diameter. In

this table we see if the ball diameter is 53.6 microns using a 1 mil wire, the corresponding ball diameter contact will be about 48 microns, the minimum pad opening should be about 59 microns that results in a pad pitch of 70 microns.

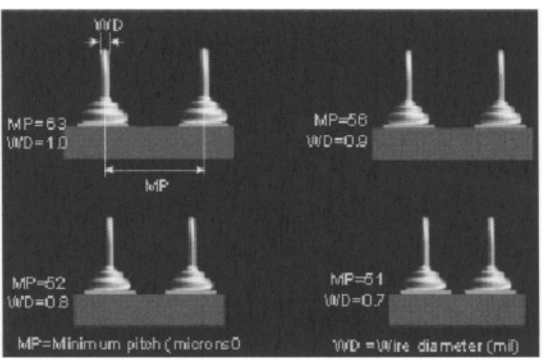


Figure 4.6.10. Wire diameter effect on pad pitch

Table 4.6.4 Bond pad design consideration for fine pitch ball bonding [P-56]

		Fine pitch	Ultra fine pitch		
Pad pitches	Microns	90	80	70	60
Pad opening	Microns	75	69	59	49
Ball Diameter contact (BDC)	Microns	59.3	53.3	48.2	42.7
Ball diameter	Microns	65.9	59.2	53.6	47.4

4.6.3 Maximum Admissible Current Through the Wire

Wire bonding is the operation that allows the electrical connection between die and the leadframe. Regarding gold wire dimensioning, the following empirical law shown in table 4.6.5 is used for the maximum current (in A) that can flow on one bonding wire as a function of the wire

diameter. Aluminum wire is used in hermetic package and in special cases of plastic package. Max current allowed in aluminum wire is given in table 4.6.6.

Table 4.6.5 Maximum current allowable as a function of gold wire diameter [P-56]

Wire		I Max allowable
Microns	Mils	
25	1.00	1.25A
32	1.25	1.60A
38	1.50	1.90A
46	1.80	2.25A
51	2.00	2.50A

Table 4.6.6 Maximum allowable current in aluminum wire diameter [P-56]

Wire		I Max allowable
Microns	Mils	
32	1.25	0.7A
127	5.00	5.4A
178	7.00	8.9A
254	10.00	15.2A
381	15.00	27.9A
508	20.00	42.9A

The maximum current is more often limited by area defined with the ball bond circumference and the metal thickness around bondpad.

$$S = D \times E$$

where,
S : section through which the current is passing by
D : 2x wire diameter
E : metal thickness

Higher the current requirement of the device, larger is the diameter of the bond wire. However, it is important to remember that the maximum current that can be carried is limited by the area defined with the ball bond circumference and the metal thickness around the bond pad. Figure 4.6.11 shows the bond pad design for high current optimization.

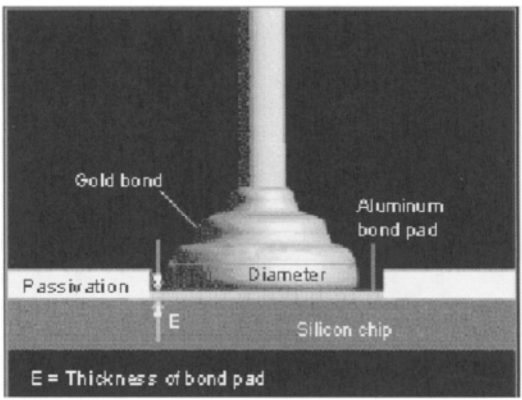


Figure 4.6.11 Bond pad design for high current optimization

4.6.3.1 Bondpad Design for High Current Application

The bondpad dimensions for power devices are different from the bondpad dimensions that we normally come across in case of low power ICs. In high current applications large diameter Al wire is used which is wedge bonded to the die. Due to large wire diameter, greater than 50 microns, bondpad on the die must be rectangular in shape corresponding to the longer foot of the Al wedge bond. Nevertheless to optimize the bonding quality, the wedge bond axes and the bondpad axis are parallel and the length side of the rectangular bondpad must be parallel to the wire path.

As we can observe from figure 4.6.12, the length side of the rectangular bond pad must be parallel to the die pad, and usually, for large diameter wires, the value I is approximately, three times the diameter of the wire, and the pad opening B is between 2 and 2.5 times the diameter of the wire.

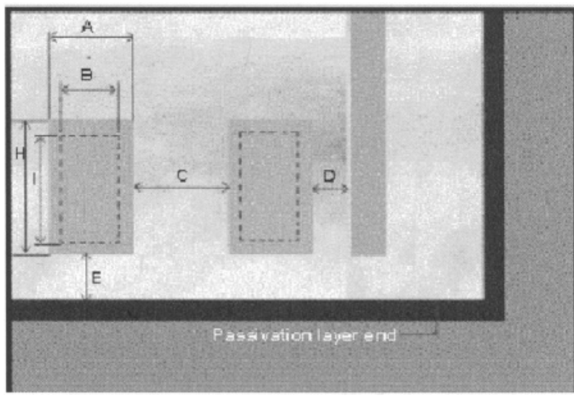


Figure 4.6.12 Bond pad design for high current application

4.6.3.2 Bond Pad Design to Improve Wire Bond Reliability

In wire bonded IC products bond pad, peeling has been recognized as dominant weakness on bonding reliability. There have been several methods proposed to overcome this problem, including:

- to use special oxides, in the layer dielectric and metal composites to improve adhesion
- to use different device structures to improve bond wire adhesion
- to increase bonding force to enhance adhesion
- to increase bonded area by increasing bond pad size

Recently, development work has been done [P-58] to modify the layout patterns of the metal layer beneath the top metal, and this new pattern has been shown to enhance adhesion.

Cross-sectional views of the conventional bond pad structure and the proposed new layout design in a 0.6- μm single-poly triple-metal CMOS process are shown in figure.4.6.13(a) and 4.6.13(b) respectively.

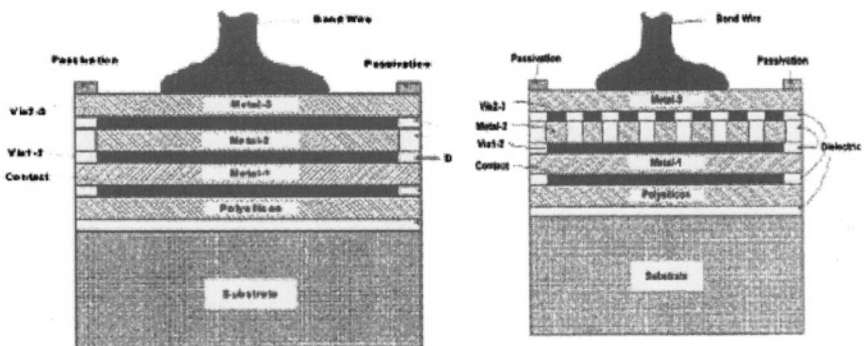


Figure 4.6.13(a) Conventional bond pad structure with the layout pattern of each metal layer is realized by one flat plate and the electrical connection between two metal layers is only a large area of via plug

Figure 4.6 13 (b) Cross-sectional view of the proposed layout design method realized in a single-poly triple metal CMOS process

In the conventional pad structure, the layout pattern of each metal layer is one large square area of flat plate (96 μm X 96 μm) and the electrical connection between each two metal layers is performed by only one large size via plug. This bond pad structure is generally fabricated to be a flat plate on its top surface, which the adhesion of the bond ball with the bond pad is not good enough and bonding reliability is then lowered. In order to increase the adhesion of the bond ball on the bond pad, the surface of the top metal denoted by Metal-3 in Fig.4.6.13 (a) should be designed to be rough. To make a rough surface on the top metal of the bond pad, the Metal-2 layer beneath the top metal in Fig.4.6.13(b) is designed with relatively very small pieces (i.e., 5μm X 5 μm) of varied regular or irregular layout test patterns on each single bond pad area for investigation. The electrical connection between Metal-3 and Metal-2 is performed by a plurality of via-plugs (named as Via2-3) with area (0.7μm 0.7 μm) smaller than the mentioned small Metal-2 pieces. This arrangement will create a ragged surface of the metal-2 layer in the cross sectional view of the bond pad structure. The interface layer dielectric deposited on the ragged Metal-2 then has an undulating surface.

Therefore, the top metal deposited on the undulating interface layer dielectric is formed as a rough surface that is able to improve the stiffness of bond ball on the bond pad. Several experimental layout patterns of Metal-2

and Via2-3 have been designed and fabricated in a 0.6- m single-poly triple-metal CMOS process to investigate their performance.

It has been found that the top surface of the bond pad would be rough enough to improve the bond wire adhesion on the bond pad. Figure 4.6.14 shows the layout patterns of conventional bond pad.

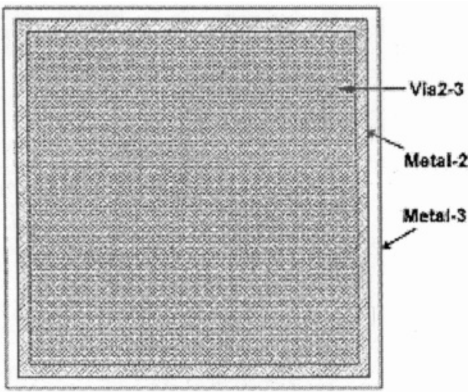


Figure 4.6.14 Conventional layout patterns of Metal-2, Vias 2-3, and Metal-3 layers on a bondpad.

Figure 4.6.15 shows the varieties of layout patterns that have been experimented with.

Without any extra fabrication cost in CMOS processes, a layout design method has been proposed to increase the bond wire reliability for packaged IC products. Just by changing layout patterns on the bond pad, the bond wire reliability can be effectively improved. Besides, the total area of the metal layers and via plugs of the proposed layout design method is less than that of the conventional bond pad layout. This indicates that the new proposed bond pad can also deliver lower parasitic capacitance and a better circuit performance for high- frequency circuit application [P-58].

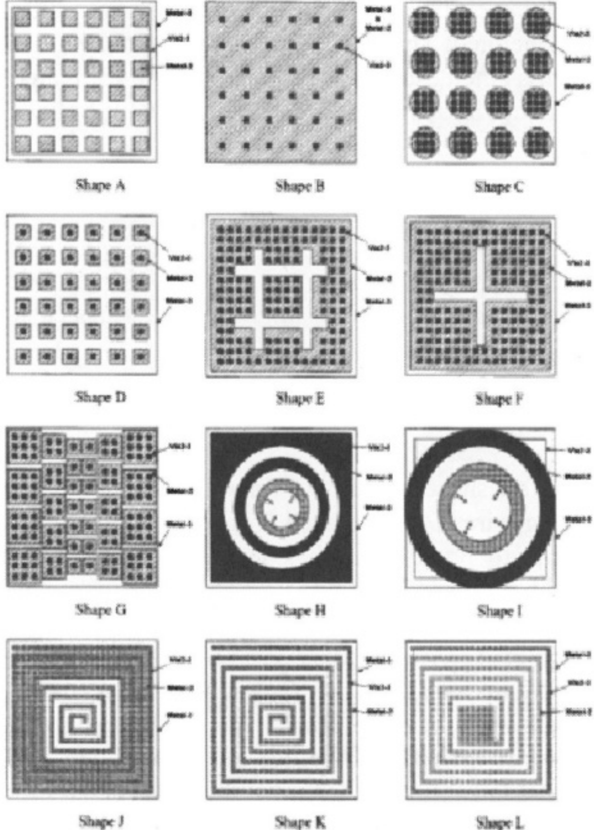


Figure 4.6.15 Designed layout patterns of Metal-2, via2-3, and metal-3 layers are defined as the shape names at the bottom of these layout patters for the experimental test chips.

4.6.3.3 Non-conformance to Die Design Report

If a die does not meet the "die design rules" specification, then the design engineer must generate a "Non-conformance to die design report". Proper die designs as well as substrate designs are crucial in high pin count ultra fine pitch packaging. And one must learn from the mistakes committed on one design, so that similar mistakes do not recur, and therefore it is

recommended that each time there is a design violation a non-conformance report must be generated. The non-conformance report must include some of these details such as the description of the violation, estimated yield loss due to violation, productivity loss, cost increase and quality-reliability concerns.

4.6.4 Assembly and Package Design Guidelines

Similar to die design rules, there are specific design rules in package design for optimum assembly processing. Let us discuss each of the design rules and study as to why they are important.

4.6.4.1 Pad Design Rules on CSP and BGA Substrates

Fine pitch on the substrate allows finer pad pitch on the die without having to use long wires. As discussed earlier, the maximum number of in-line pads possible to bond on each side of the die with the finest pitch depend on the bond finger pitch and wire length at the center of the die, assuming the angle of wire to the die edge is not less than 45 degrees.

As can be calculated from the equation in section 4.6.2.6, starting with 80 microns pad pitch and 1.08 mm long wire at the center of the die, when the bond finger pitch is decreased from a typical 180 microns possible on a PCB substrate to 125 microns on the flex substrate allows 3x more bonding pads at a significantly finer pitch. As the pad pitch on the substrate decreases, it allows for higher number of bond pads on the die. However, there are certain design guidelines that control the pad structure on the substrate.

The pad size determines the pad pitch of the lead fingers on the substrate. We can observe from figure 4.6.16, for the second bond to be accurately placed on the lead finger, the minimum required width is 90 microns. In order to achieve 90 microns on the top surface, the minimum width of the copper foil must be 125 microns at the bottom, taking into consideration, the etching factor. As the copper thickness increases, the etching factor becomes larger. And between 2 copper lines, we need a minimum gap of 60 microns to achieve good yield during the substrate manufacturing process. Taking all these factors plus the 5 micron nickel gold plating on

top of the copper, we see that the pad pitch achievable is 185 microns. If we need to reduce the pad pitch to say 125 microns, correspondingly, all these other factors need to be reduced and this demands a dramatic improvement in process technology as well as process accuracy.

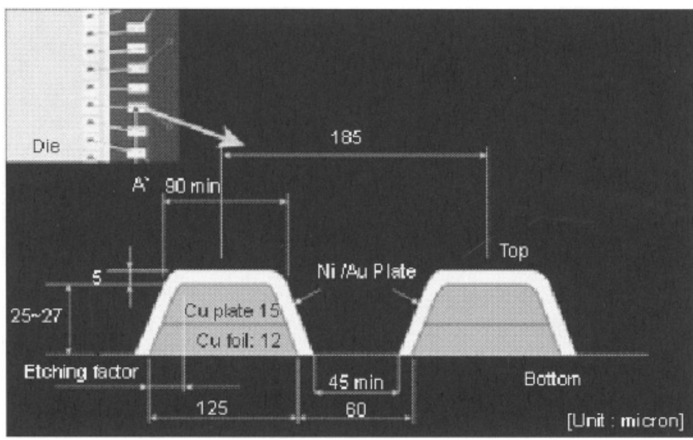


Figure 4.6.16 Lead finger design rules [P-59]

The bonding flat width has been found to be at least 90 microns wide, in order to obtain good bond on pad accuracy. As the bond wire placement on the substrate pad goes from orthogonal structure towards a radial structure, the required flat width increases.

Since the pad pitch of the lead fingers is determined by width of the bonding flat, we can see in figure 4.6.17, that if the package is designed with orthogonal leads, where the wire is parallel to the lead finger, the bonding width is small and correspondingly, the lead finger width can also be small. However if we design the package with radial lead structure, the bonding wire approaches the lead finger at an angle and therefore the bond flat width has to be larger in order that the second bond is completely within the wedge of the lead finger. This automatically increases the bond finger width and correspondingly the pad pitch.

Assuming that for consistent second bond placement, the required flat width is a minimum of 90 microns, one can calculate the pad pitch for different substrate technologies. We see here in table 4.6.7., how manufacturing technology can reduce the pad pitch. For example, in a PBGA application, where we use electroplated gold on a FR4 substrate, in order to achieve 90 micron flat width, the base width is 110 microns, the space width is 75 microns and the resultant pad pitch is 185 microns.

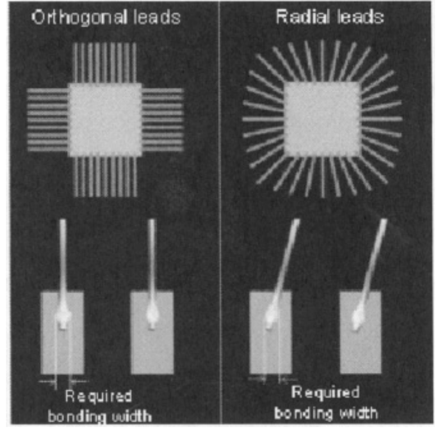


Figure 4.6.17 Orthogonal and radial lead layout [Courtesy : Kulicke & Soffa]

Whereas, in a 2 layer tape ball grid array, the same flat width of 90 microns can be achieved, with a base width of 95 microns, space width of 35 microns, resulting in a pad pitch of 130 microns.

Table 4.6.7 Pad design rules on substrate [P-60]

BGA substrate	Flat width (F)	Base width (B)	Space width (S)	Pad pitch (P)
2 layers GS TBGA	90	95	35	130
3 layers GS TBGA	90	100	35	135
2 ML TBGA	90	95	50	145
EPBGA	90	110	75	185

The technology of substrate manufacturing is changing to meet the needs of high pin count smaller size packages with finer pitch. Today, on a BT-

resin substrate, it is possible to achieve less than 120 micron pad pitch with a bond finger flat of 60 microns.

4.6.4.2 The Cost Impact of Line Spacing and Line Width

On the substrate, in order to achieve fine pad spacing and smaller pad pitch, one has to use more advanced technologies which in turn impacts cost of the substrate. In order to achieve smaller pad pitch one has to decrease the pad spacing and that means the chemical etching technology must be very controlled and very precise on large PCB panels of almost 50cms x 50cms.This high level etching technology will increase the cost automatically. For example, for a pad spacing of 120 microns, manufacturing cost is much lower than pad to pad spacing of 70 microns.

4.6.4.3 Package Design Consideration

To achieve absolute precision in ultra fine pitch bonding, the other packaging dimensions and placement accuracies must be very closely controlled. Factors such as die thickness, die attach thickness, substrate thickness, loop height, wire clearance allowed and many such factors need to be considered for zero-defect bondability.

An example of such package design criteria is represented with TBGA package in figure 4.6.18. Here we can observe, when the loop height is say 100 microns, if the heat spreader is a little bit too thick and if the die-attach thickness is higher than the design and encapsulation material is a little bit thinner than the design then the loop will be exposed outside the package. And on the same lines, if the die-placement precision is not consistent, then the short wire of 0.5 mm loop length can be either misplaced or it could be stretched. Yet another example, when there are bond wires at 2 different heights if the loop control parameters are maladjusted, the gap between the wires can reduce affecting the electrical performance of the device.

As discussed above, in packaging, the dimensions and the tolerance of every component of the package affects the wirebonding process. Different factors such as die thickness, die attach thickness, substrate thickness, loop height, wire clearance allowed and many such factors need to be considered

for zero-defect bondability. Let us discuss some of the important factors to be considered in detail.

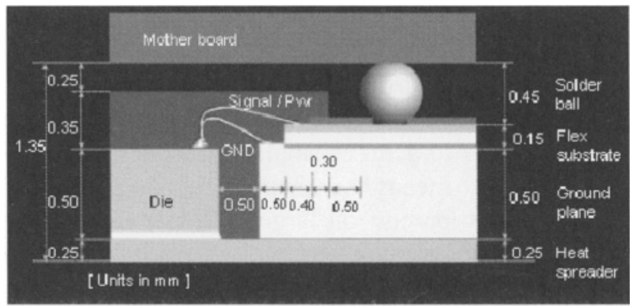


Figure 4.6.18 An example package design criteria in a TBGA package [P-57]

4.6.5 Design of Loop Height

The shape and length of the bonded wire are quite important to its reliability. For example, too taut a loop can lead to thermal cycle failures; and at the other extreme, too large a loop can cause the wires to lean over and short each other thru wire sweep.

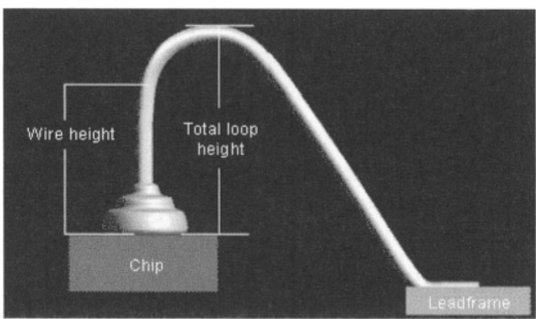


Figure 4.6.19 Wire height and loop height

The definition of wire height and the loop height are slightly different. Wire height is the vertical distance from the die to the point where the wire is about to touch the capillary during the loop formation. This point is slightly lower than the top of the loop. The total loop height is measured from the top of the die to the top of the loop. Figure 4.6.19 shows the wire height and the loop height. Some of the typical loop height for different packages are given in table 4.6.8

Table 4.6.8 Loop height values of various packages

TQFP	6 mils (0.15 mm) max
TSOP Type 1	6 mils (0.15 mm) typical
MQFP, SOIC, PDIP	12 mils (0.30 mm) typical
PLCC	15 mils (0.38 mm) typical
CSP	4 mils

4.6.5.1 Wire Gap Requirement in Design

Adequate clearance (25 to 50 microns) between the wire near the second bonds and the ground/supply pads is critical to avoid shorting. In order to achieve this clearance, one can modify the loop shape, however this can cause the loop shape to become "humped" and difficult to control. Wire lengths, shortest to longest, can vary as much as 2.54 mm (100 mils). This situation requires that the looping algorithm provide consistent loop heights. The die may have staggered bond pad layout, which challenges the capabilities of even the most flexible wire bonder software. For example in multilayer wirebonding shown in figure 4.6.18, the ground bonds are usually shorter, where as the signal and power wires are longer. When the same bonder is programmed to handle short wires with a particular loop profile and long wires with different loop profile we must recognize that

there will be process inconsistency and therefore, problems of wire touching and wire sagging.

4.6.5.2 Die Size Rules in Packages

The die size and die clearance values depend on the type of package, length of wires in the package, maximum wire length allowed in the package and whether a die attach fillet is required or not. Important features to be considered in die design are: die clearance per side without substrate bond and die clearance per side with substrate bond. In packages, where there is a substrate bond on die pad, the die clearance value C depends on the distance between the ball bond and the die edge. In figure 4.6.20 for example, if the value A is 5 mils, the minimum C value for a TSOP package is 25 mils. If the A value is 15 mils, the minimum C value must be 40 mils, and this particular design rule is to make sure that the wire loop does not short with a die edge. As the thickness T of the die is reduced, the value C can also be made smaller.

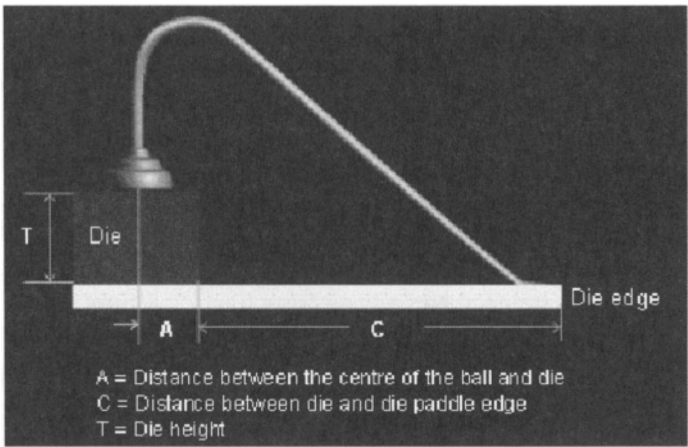


Figure 4.6.20 Die clearance per side with substrate bond [P-56]

For example from figure 4.6.21, if the die thickness is greater than 20 mils, the minimum C value is 30, and if die thickness is less than 20 mils, then the minimum C value must be 25 mils.

In case we create a down bond from the die attach paddle to the lead frame, then, the minimum value of C, which is the distance between the die edge and the die pad edge depends on the die thickness

In case of worked loop formation, to avoid potential wire short at the die edge, the maximum value of A is determined by the wire diameter. As we can observe in figure 4.6.22 for wire less than 1 mil diameter, the maximum "A" value is 80 mils, and for wires greater than 1.5 mils diameter, the maximum "A" value is 120 mils.

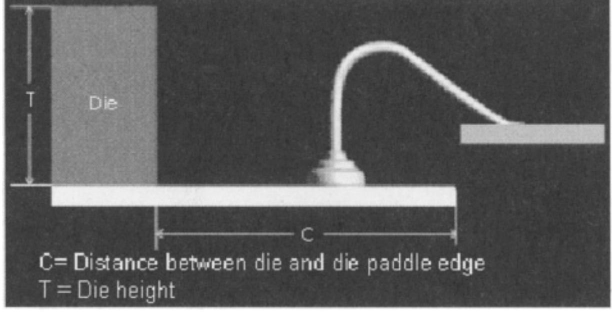


Figure 4.6.21 Down bond from die attach paddle [P-56]

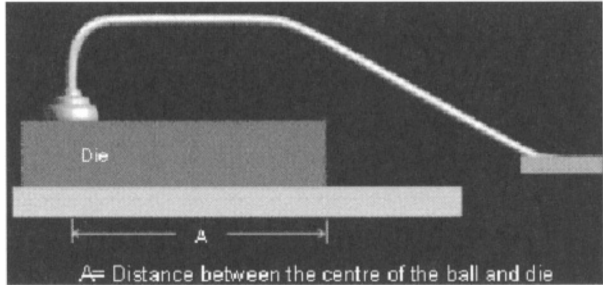


Figure 4.6.22 In-board bond from die edge [P-56]

4.6.5.3 Minimum/Maximum Die Sizes Allowed in a Package

Each package size has a maximum and minimum die size it can accommodate and this limitation arises due to wire bonding. If the die is too large for the package, then the wires are too short, or if the die is too small for the package, the wires are too long. In figure 4.6.23 for example, for a 10 millimeter by 10 millimeter TQFP package, the smallest die size allowed is 1.8 millimeter side, and the largest die allowed is 7 millimeter side. Similar design rules hold good for CSP and BGA packages also.

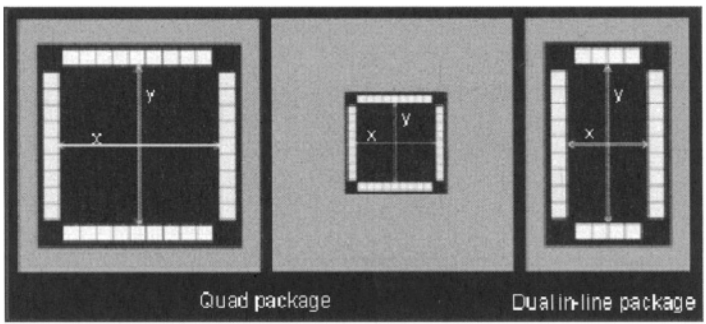


Figure 4.6.23 Minimum / maximum die size allowed in packages [P-56]

4.6.5.4 Die to Cavity Fit

Another design criterion that one has to check is the die to cavity fit, and this is applicable to both premolded plastic and ceramic cavity type packages. A clearance is required from the edge of the die to the edge of the cavity to ensure high yields at die attach. To determine the largest die which will be allowable in a given cavity, a minimum spacing between cavity edge and die edge must be maintained. Maximum wire length dictates the smallest die allowable. The longest wire is typically connected to the outside corner bond-finger. On a multitier designed cavity, the longest wire will be from the furthest corner bondfinger on the top tier.

4.6.6 Staggered Pad Layout

Some designers choose to shrink die size by staggering the rows of bond pads. For high pin count devices, we require staggered bond pads. Staggered bond pad layout can have same pad pitch or variable pad pitch. Whenever a staggered bond pad is designed, it must be in conjunction with a standard lead frame, to avoid wire crossing. If the die is not designed in conjunction with the lead frame, then, we may have to design a custom lead frame. Bond pad layout for staggered bonds with same pad pitch and variable pad pitch is shown in figure 4.6.24. A staggered-pad die can easily be assembled in hermetic packages where the wires remain undisturbed during encapsulation.

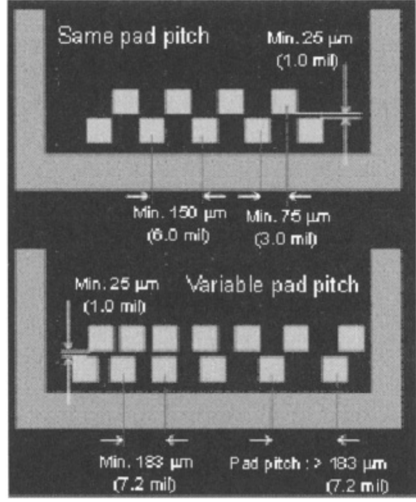


Figure 4.6.24 Bond pad layout for staggered bonds [P-56]

But plastic encapsulation of staggered pad devices have proven a sticky challenge because of wire sweep during the molding process.

4.6.6.1 Wire Rules

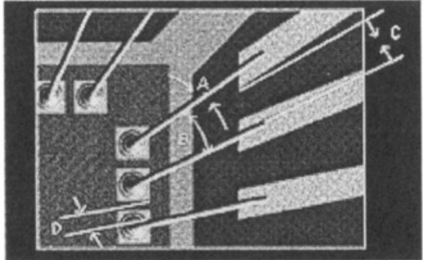
In every company the package design guidelines must establish wire rules. These rules are based on performance and reliability requirements and manufacturing capability. Some of the wire rules are discussed below.

4.6.6.2 Maximum Number of Wires on a Pad

More than one wire connected either to one pin or one bonding pad are accepted only if the electrical continuity on each wire can be detected at electrical test.

4.6.6.3 Wire Clearance Rules

In any die design, we need to consider the lead frame design also. We can observe from figure 4.6.25, some of the wire clearance rules.



Symbol	Description	Requirement	
A	Wire angle	30deg. to 90deg. max	
B	Wire separation	Min 2x wire diameters for normal pad pitch Min 1x wire diameter for the pad pitch	
C	Wire to adjacent lead	Min 4mils (102 μm)	
D	Wire to adjacent bond pad	SOIC,PDIP,SSOP TSOP,TSSOP	Min 2.8 mils (68 mm) for normal pad pitch Min 1.0 mil (25mm) for fine pad pitch
		Other package	Min 1.0mil (25mm) for normal pad pitch Min 0.5mil (13mm) for fine pad pitch

Figure 4.6.25 Wire clearance rules [P-56]

They are:

- the wire angle must be between 30 to 90 degrees
- wire separation should be minimum of 1 wire diameter
- wire to adjacent lead should be minimum of 4 mils, and
- wire to adjacent bond pad should be minimum of 1 mil

4.6.6.4 Bond Angle Range

The angle formed by the wire and the normal line, from the die edge defines the wire angle. The maximum wire angle allowed is dependent on the die pad pitch and bonding technique used. Bond angle range controls the lead tip exit angle and assures that the bond wire passes over the tip rather than the side of the bond finger. The pad closest to the line, directly along the bondfinger, is defined as the ideal pad. Using the ideal pad is the optimum pad for manufacturing. Following design options are generally accepted in the industry:

- 30 degrees - Ideal for maximum yield
- 45 degrees - Good alternative to 30 degrees
- 60 degrees - Definite yield loss and set up problem

4.6.7 Crossing Wires

Crossing wires are another common mechanical error. Crossing wires are not allowed in single tier packages or packages that do not have vertical separation between tiers. For packages with two or more tiers that do have a vertical separation between tiers, then the following applies.

Let us take a look at the figure 4.6.26. The bond at pin 501 is acceptable because it is crossing outside the die attach cavity. The bond at pin 10 is crossing within the die attach cavity, and so crossing is not allowed. The bond editor in bonding machine program has the ability to detect and flag cross bond violations within the cavity. The possibility of the upper and lower wires crossing is greatest within the cavity region.

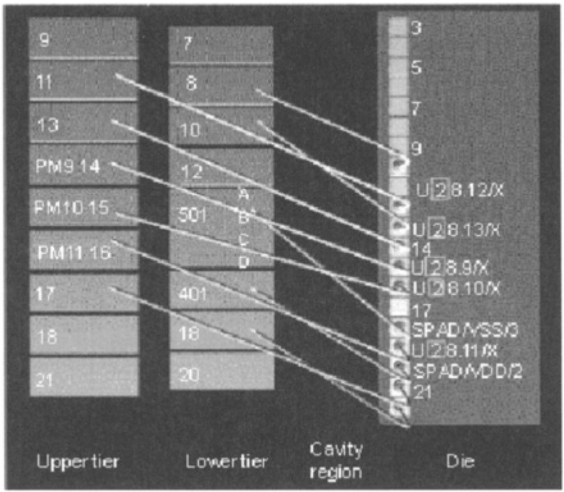


Figure 4.6.26 Crossing wire design rules [P-61]

Crossing wires should not be allowed in single tier packages. In packages with 2 or more tiers that have a vertical separation, crossing wires may be acceptable, if it is unavoidable. For example, here in figure 4.6.26, by moving the wire from pad 10 to pad 12, we can avoid crossing.

It is recommended that one should avoid cross bonds at all times, even outside the die attach cavity, as these can cause yield loss, when die attach is not centered or rotated slightly. Shorting caused by die shift is a frequently encountered problem during assembly of cavity down BGA packages. By quantifying the amount of tolerable die shift in your BGA wirebonding applications, you can determine whether process modifications will increase cavity-down BGA device yield.

4.6.8 Crossing Wires due to Die Shift

In cavity down BGA package with package shelves that are the same height and only separated by a narrow gap, all wires from the die pads to these shelves are also at approximately the same height. Wire length

typically ranges from 40 to 170 mils. During die attach, machine placement repeatability can shift the die as much as 5 mils (+ or - 2.5 mils). In the subsequent wire bonding operation, this results in shifting of the first wire bond to follow the pad movement.

An example of wire shorting due to die shift is shown in figure 4.6.27 and here we see that as the die shifts to the left, the bonded wires cross each other. And therefore in ultra fine pitch bonding, die placement accuracy and die shift due to die-attach epoxy instability must be controlled.

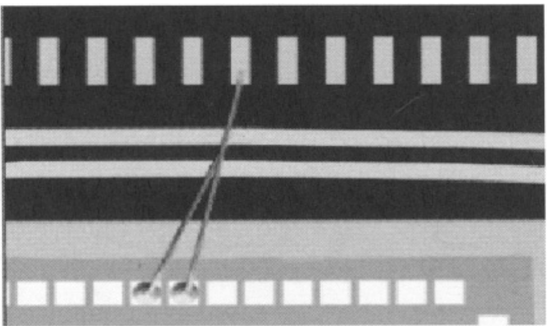


Figure 4.6.27 Die placement variation [P-62]

Figure 4.6.28 shows how wire length and die shift affect wire angle. Note, for example, that with 3 mil die shift (in either X or Y axis for a square/symmetric package), the change in angle is about 1 degree for 170 mil long wire and about 4.5 degree for 40 mil long wire. In a wire pair, if one wire has a length of 50 mils and the other has a length of 130 mils, and bond pad pitch is 4.0 mils, then the spacing between the wires is only 2.7 mils for a 1.3-mil diameter wire. Furthermore, if first and second bonds are perfectly centered for both wires and if the die is perfectly centered in the cavity, the two wires will be parallel at a fixed angle.

We can also see that when there is a die shift, the angle of the wire from the die to the lead finger changes. If the wire is short, the angular change is quite significant. For example, when the wire length is 40 mils, the angular change is about 5 degrees for a 3 mil die shift. Where as, when the die shift is 6 mils the angular change is almost 10 degrees. The change in angle is not

so significant when the wire length is long, say 160 mils. Here we see when the die shift is between 3 mils and 6 mils, the angular change is only 2 to 3 degrees.

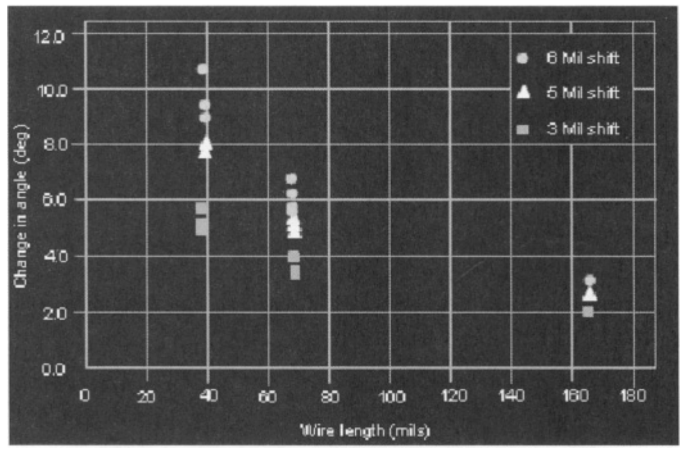


Figure 4.6.28 Change in wire angle due to die shift versus wire length [P-62]

When we have short wires and long wires in the same package, it will result in wire crossing due to die-shift. Figure 4.6.29 shows the data taken from visual inspection of 20 cavity-down EGA packages with 4.0-mil pitch die and wire length of 40 and 130 mils. For these packages, first die shift off center was measured in X and Y directions. Next the wire pairs that were physically touching (crossing each other) were counted through visual optical scope inspection. The total was plotted against the measured die shift per package [P-62].

It was observed for a combination of 40 mil short wire and 130 mil long wire, when the die shift was less than 3 mils there were negligible crossing wires, the yield was acceptable. Whereas, as the die shift increased, towards 6 mils as the number of crossing wires increased and this is unacceptable.

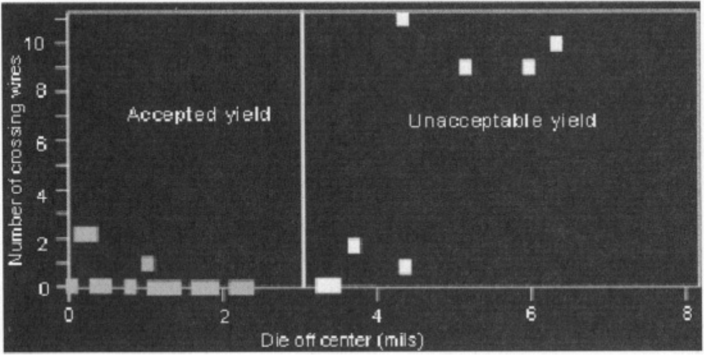


Figure 4.6.29 Wires crossing vs. die shift [P-62]

Most crossing wires can be eliminated early in the design phase prior to layout. It is important to adjust the bond wire placement to eliminate all crossing wires. Many crossing wires result from design switching from one cavity size to another in a two-tier package, such as PBGAs. This is due to scaling of package bond finger layout.

4.6.8.1 Minimum Distance between Wires and Adjacent Bond

The minimum distance is defined as the distance between paths of adjacent wires and between wires paths and lead finger. Two adjacent wires/pin (when not equipotential) must have a distance not less than 50 microns for standard plastic and hermetic, 25 microns for fine pitch packages and 200 microns for power package and metal can package with wire diameter greater than 38 microns.

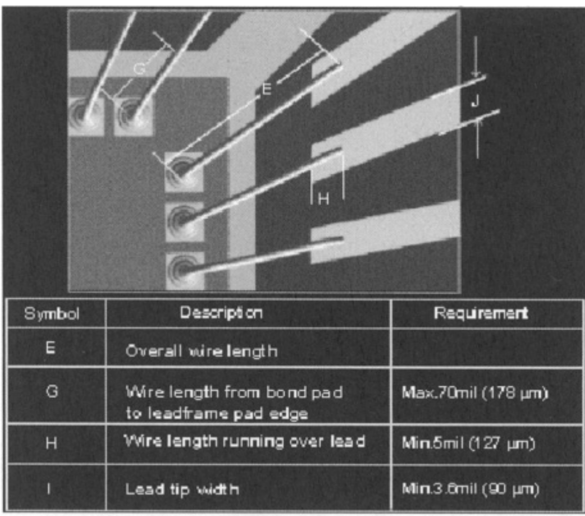
4.6.9 Wire Length Rules

The bond wires used in ceramic and plastic packages are different. In ceramic packages, the bond wire used is aluminum, while gold wires are used in plastic packages. Gold is used in plastic packages because of reliability issues with non-hermetic encapsulation. The maximum wire

length allowed is dependent on the package type and bonding technique used.

Length of bonding paths is the distance from bonding pad center to the stitch position. Length of bonding paths is a function of bonding wires diameter.

In designing the die and the package there are certain wire length rules that need to be followed such as, the overall wire length, wire length from bond pad to leadframe pad edge and wire length running over the lead and the lead tip flat width. Schematic representation of the different length rules are shown in figure 4.6.30.



Symbol	Description	Requirement
E	Overall wire length	
G	Wire length from bond pad to leadframe pad edge	Max.70mil (178 μm)
H	Wire length running over lead	Min.5mil (127 μm)
I	Lead tip width	Min.3.6mil (90 μm)

Figure 4.6..30 Wire length rules

Table 4.6.9 shows the over all wire length for a particular wire diameter for a specific package with bond pad pitch less than or greater than 4.5 mils.

The maximum wire length depends on the wire diameter as well as the type of wire that is used. Generally thinner the wire, shorter the wire length allowed. In table 4.6.10 we see that equipment manufacturers as well as the bonding wire manufacturers are making technological advances to allow

maximum wire length in a package. For example, a 25 micron wire today can have a loop length of 5 millimeters.

Table 4.6.9 Wire length for a particular wire diameter and package

Package	Wire DIA (MIL)	E: Overall wirelength			
		Minimum	Standard	Maximum BPP<=4.5 mil	Maximum BPP>4.5 mil
PDIP	1.0 1.3	35 35	70 80	110 120	120 130
PLCC BQFP	1.0 1.3	35 35	80 120	120 160	130 180
SOIC SSOP	1.0 1.3	35 35	70 80	110 120	120 130
TQFP	1.0 1.3	35 35	70 120	110 160	120 180
TSOP TSSOP	1.0 1.3	35 35	70 80	110 120	120 130
MQFP (>=28x28)	1.0 1.3	35 35	70 140	120 180	130 200
MQFP (<=32x32)	1.0 1.3	35 35	80 120	120 160	130 180
PBGA	1.3	35	140	180	200

(Unit conversion:1 mil=25.4 μm)

Table 4.6.10 Maximum wire length

Wire Diameter	1998	1999	2000
33 microns (1.3 mil)	5.08 (200)	**	**
30 microns (1.2 mil)	5.08 (200)	5.08 (200)	5.58 (220)
25 microns (1.0 mil)	4.57 (180)	4.57 (180)	5.08 (200)

The maximum wire length is also determined by the wire sweep limitation factor. During molding, the thinner wire has a greater tendency to sweep.

In figure 4.6.31, we see that the maximum wire length is not just limited by the bonding limit. The longer the wire, greater the propensity for wire sweep and therefore molding parameters as well as mold design have a significant impact on the maximum length of wire allowed in a package. Here in this example we see for a particular wire and machine configuration, the maximum wire length of a 25 micron wire, 4 millimeters. Whereas, the molding limit put the maximum wire length at 3.3 millimeters. Such experimental information needs to be generated in every factory order to optimize the package design.

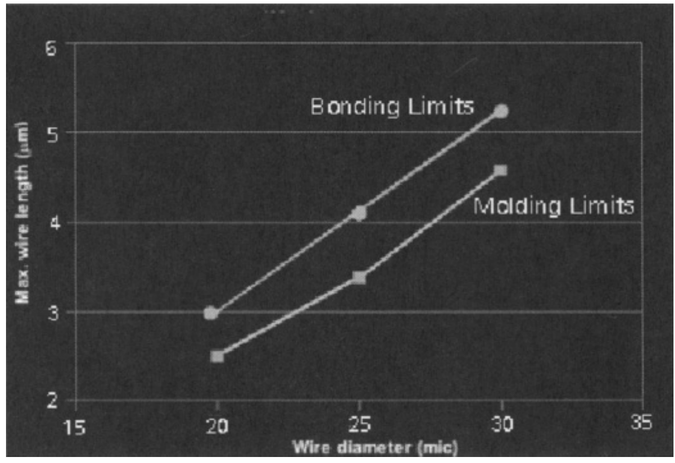


Figure 4.6.31 Wire length limitations as a function of wire diameter [P-11]

4.6.9.1 Loop Control

Ultra finepitch applications need the bonded wires to be as straight as possible. S-curves that exceed the target specification will cause shorts and defects after molding.

4.6.10 Bond Design and Package Compatibility

A package is considered compatible with another package when the same test hardware/software can be used, thus they are footprint compatible. Compatible packages can be interchanged for prototype/production builds assuming a successful bond editor has been through the final check. The successful bond editor is imperative to insure the die pinout for the alternate packages is viable.

In some designs, the I/O layout with a ceramic package passes the requirements but fails with the plastic equivalent package. It is important to understand that package compatibility does not imply design rule equivalence. Two packages are considered compatible when their package style and pin-to-pad interconnections are the same. By default, only one signal I/O bond is allowed per bondfinger. Multiple power and ground may be allowed to share the same bondfinger slot position, depending on the package bondfinger layout.

4.6.11 Bond Diameter Percent Off-Pad

This parameter is the allowance for the ball to extend off the bondpad. It is represented in percentage. For example, an entry of 10 means that 10% of the bond diameter extending beyond the bond pad boundary is acceptable. The effect of bond diameter percent off pad is that as the percentage increases, there is a reduction in the calculated minimal pad size. Misplaced bond is shown in figure 4.6.32.

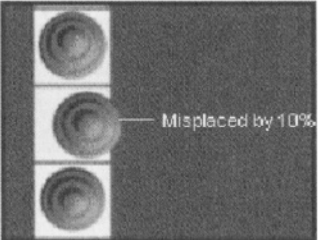


Figure 4.6.32 Misplaced ball

4.6.12 Lead Frame Design Considerations for Bonding

In many advanced packages many dedicated pins are specified for ground and power pins. And signal lead traces are kept away from the power pins to minimize cross talk. If the lead fingers are placed such that the wire is too long, it results in wires with high inductance.

The self-inductance value increases with increase in wire length, where as the mutual inductance value increases, as the wires get closer to each other.

Figure 4.6.33 shows the variation of self-inductance and mutual inductance of bond wire as a function of wire span. As the length of the wire increases, self inductance increases, and the mutual inductance between the wire and its first nearest neighbor, second nearest neighbor and third, fourth, and fifth nearest neighbors increases as the wire span increases.

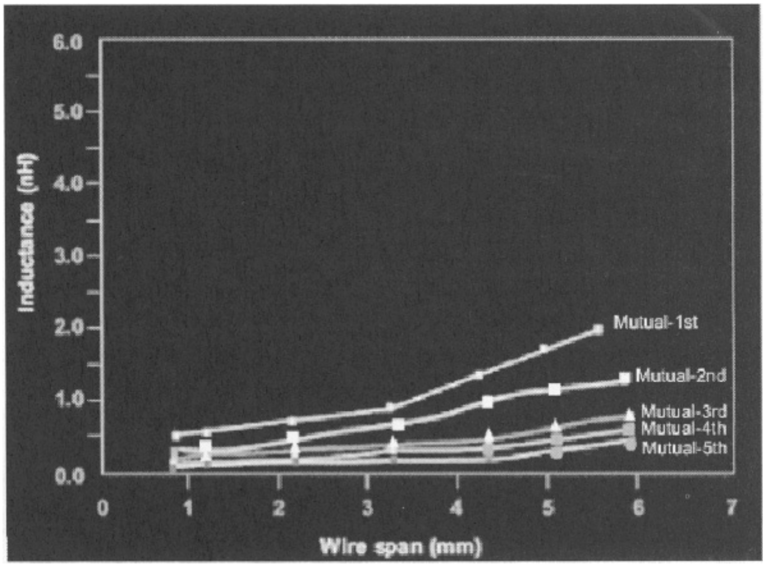


Figure 4.6.33 Variation of self inductance and mutual inductance of bond wire as a function of wire span [P-63]

In many advanced packages, dedicated power and ground pins are specified, and certain conventions are followed in numbering the VDD and VSS pins. Usually, VSS and VDD bond fingers with multiple bond positions are designed. This is to give the designer more flexibility in layout and design. Figure 4.6.34 shows an example of dedicated bond fingers.

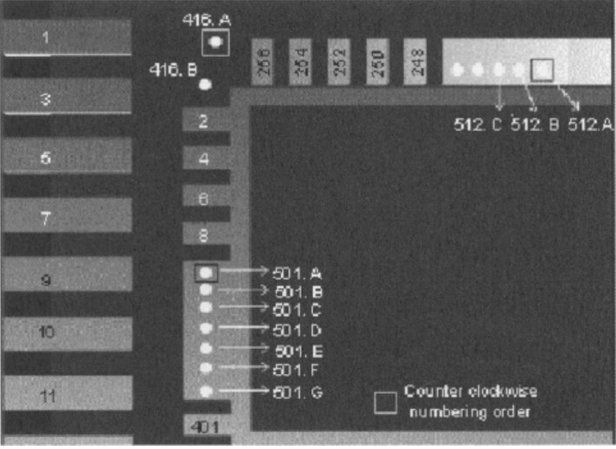


Figure 4.6.34 Dedicated bond fingers [P-61]

4.6.12.1 Cantilever Lead Frame Design

In certain special packages, the lead frame needs to be designed to meet the requirements of the bonding process. For example, in a molded package, the frequency resonance of the pin design must not be overlooked during the wire bond process. The brass pin embedded in the polyester block has special feature to increase the rigidity of the pin during the bonding. The distance of the "star" from the bonding area determines the resonance of the leadframe. The experimental set up of the wirebond resonance experiment is shown in figure 4.6.35.

When the product is wire bonded at a frequency of f = 60 kHz, theoretical length "L" at which a cantilever beam would resonate is given by:

$$L = (a_n/2 \Pi f)^{1/2} \ (EI/\mu)^{1/4}$$

where:

a_n : Constant for the fundamental mode

E : Modulus of elasticity of the material (Kilograms/meters^2)

I : Moment of Inertia (meters^4)

d : diameter of cylinder (meters)
μ : W/g mass per centimeter of length;
W : weight per meter of length (Kilograms/meter)
g : acceleration due to gravity (9.81 meters/sec^2)

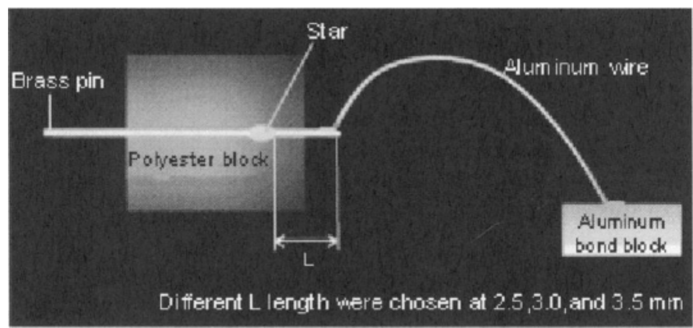


Figure 4.6.35 Experimental set-up of the wire bond resonance experiment [P-64]

With resonance calculations made, an experiment was conducted to determine if the theoretical cantilever distances calculated from the equation would hold with real time testing. Sample brass pins, with a star type retention feature on the pin was used for rigidity. The pins were positioned at different lengths from the plastic wall. The dimension "L" was 2.5, 3.0, and 3.5 mm respectively. Practice samples were bonded with 10 mil diameter aluminum wire from the pins to a strip of aluminum in order to establish the desired wire bond settings. We can observe from figure 4.6.36, ultrasonically bonded 10 mil aluminum wire showed higher pull strength value at shorter pad length.

The 2.5 mm pins performed well, while the 3.0 mm samples dropped slightly in pull strength with all bonds exhibiting lifts, indicating that non optimal bonding occurred. The 3.5 mm samples had multiple missed bonds. From the experiment, it was determined that the theoretical distance at which a natural frequency is reached (2.8 mm) is very close to the experimental evaluation of 3.0 mm. This shows that for optimal bonding process, package design is as important as die design.

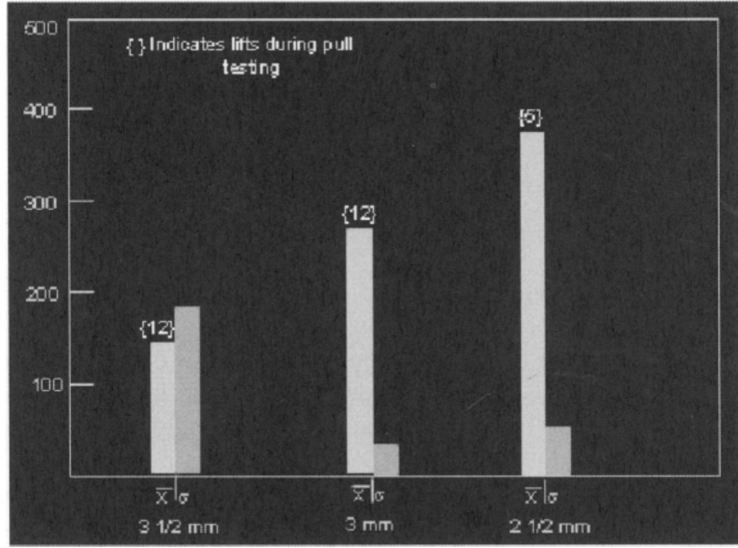


***Figure 4.6.36 Ultrasonic Wire bonding of 10 mil aluminum wire on cantilever lead fingers* [P-64]**

4.6.13 Package Design Software include Bonding Capability

Many IC design and package design software development companies have added a new wire bonding capability to their advanced package design software for designs using fine pitch and stacked packages. The stacked-die package is growing in popularity in cell phone, digital cameras and hand-held device designs, which require the faster turnaround, higher levels of integration and lower costs found in system-in-package (SiP) solutions.

But designing stacked-die packages has been a difficult process since it requires wire bonding the interconnect to the substrate. A single package design may also have hundreds of wires and multiple-bond patterns for various die combinations on a single substrate. The new wire bonding capability in the software's automates the design process and addresses reliability issues through advanced wire spacing and automated realignment features. Features include the ability to bond as many die as desired, use

different spacing rules for each die and quadrant, and create multiple bonding patterns so that one substrate can handle multiple-die combinations. The software package also provides the capability to combine flip-chip and wirebond die in same design [P-65].

4.7 Process Problems and Solutions

During the wire bonding process, we encounter many problems. Some of the frequent process problems that we come across are non stick on bond pad, non stick on lead finger, positioning of the ball on pad, positioning of wedge on lead finger, low loops, deformed balls, inconsistent balls, off centred ball (golf club balls), smashed balls, wire sagging, wire tailing, wire break, wire swaying, low loops/taut loops, cratering, metal squeeze out, and many others. We can classify the wire bonding process problems into process parameter issues, machine related issues, operator related issues and material issues. In this section we will discuss each problem from different perspectives and suggest probable solutions.

Example of materials related problems: Material supplier's limitations often dictate how well the wire bonder will perform. Incoming material deviations can halt production on the bonder. One must provide clear specifications to the materials supplier, and this will help to reduce random variations and downtime associated with incoming materials. The materials suppliers include wafer fab, lead frame supplier, package supplier, wire supplier and die attach materials supplier etc

Example of process related problems: Running the same device on different wire bonders often means that the devices are not processed the same. Variations from machine to machine are large enough that each machine must be treated as a separate process.

Example of operator related problems: An incorrectly taught bond recipe, or one that has faulty editing may cause machine down time by producing rejects.

Example of machine related problems: The machine's vision and x/y positioning mechanism may contribute to bond placement accuracy. When

100% of the ball is required on the bond pad, machine downtime will be higher, if the bond locations require constant editing.
Let us review some of the specific problems encountered during bonding.

4.7.1 Non Stick of Ball on Bondpad (Bond off)

Bond offs are usually seen in cases where the amount of energy applied between the ball bond and the pad is not sufficient. This insufficiency of energy could be due to low bonding parameters. Bond off can also occur if:

- die is not perfectly held on the heater block, in which the bonding temperature will be lower than what is indicated.
- the die is moving under the capillary, resulting in a great amount of ultrasonic energy loss because of improper ultrasonic transmission
- the capillary is not mounted properly, resulting in decreased transmission of the ultrasonic power
- aluminum pad is contaminated or is covered by passivating materials.

4.7.1.1 Corrective Actions for Bond offs

- increase the bonding parameters force, ultrasonic energy and time of the first bond.
- check the temperature of the heater block
- check and correct the lead frame clamping
- check Indexing
- reteach the base-bond level
- change capillary
- check wire path, change wire (wire could be contaminated)

4.7.2 Non Stick of Weld on Lead Finger (Weld off)

Weld off could occur from low bonding parameters. The other causes of weld off are:

Bad clamping of lead frame: In this case the lead will not reach the proper temperature because it is not in contact with the block-heater. When the leads are not properly clamped the ultrasonic coupling is not optimum and this leads to weld off.

Clamping is good but leads are mechanically damaged: In this case the contact surface between the wire and the leads is decreased. These types of leads will give a low pull test result and the device will have reliability problems.

Dirty capillary: Capillary that is clogged with contamination leads to incomplete ultrasonic coupling, and can be a source of weld off problem.

Old or damaged capillary: As the capillary gets old, it is worn out. This leads to improper ultrasonic coupling.

Incorrectly mounted capillary: If the capillary is incorrectly mounted the ultrasonic coupling is not transmitted properly to the lead finger.

Gold wire is contaminated: The bonding wire may be contaminated and this leads to weld off.

Lead contamination: In the case of lead contamination, gold wire will be in contact with a thin film of contaminating materials instead of silver.

Corrective Actions for Weld Off are:

- check and change capillary
- check clamping and adjust or clean if necessary
- increase second bond parameters such as force, ultrasonic energy and time.
- check the block heater temperature
- reteach the base bond level
- check indexing

4.7.2.1 Rebonding a Wedge Bond

When a wedge bond is lifted on the leadframe, one option is to rebond the wire by cutting the wire at the ball neck and rebonding. The technique of placing a second Gold ball bond on top of the original bond is adopted by

some companies for wire bond repair. The criteria governing the use of this technique are detailed in Mil-Std-883.

The major concern of ball-on-ball bonding is the formation of a crater under the bondpad. It has been found that the occurrence rate of crater shear mode failures is much higher for compound bonds, particularly when higher ultrasonic energy is used to form the compound bond. In some situations when the second bond has a non-stick problem, engineers on line tend to rebond by placing the second ball bond on already existing ball. Attainment of 100% alignment is not easy. More often, the engineers end up with 85% alignment or 75% alignment of the compound bond. Frequently, this compound bond results in cratering under the bond pad.

Figure 4.7.1 (a) shows the 100% alignment compound bond, (b) shows 75% alignment compound bond, (c) shows85% alignment compound bond, (d) Cratering due to compound bond.

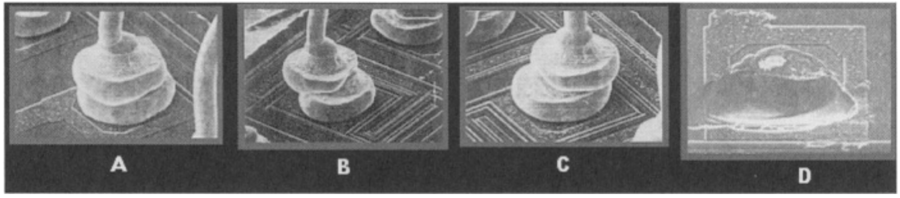


Figure 4.7.1 (a)100% Alignment compound bond (b) 75% (c) 85% (d) Cratering due to compound bonding [P-66]

This is caused by stress induced during the bonding process. The compound bonding process contributes additional stress. In some applications, when there is non stick problem on the lead finger, some companies use the ball on wedge technique to improve the reliability of the second bond. Figure 4.7.2 shows ball on wedge image.This method is preferred by some engineers over the removal and replacement of the original bond because the possibility of damaging these bonding pads on the die is precluded.

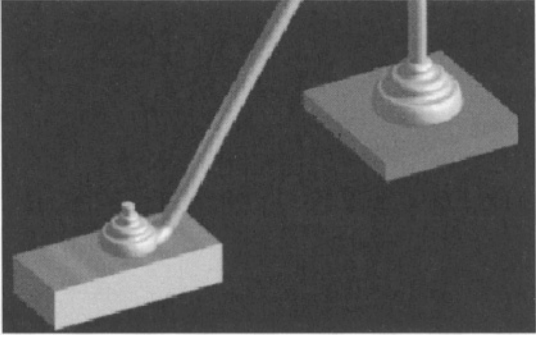


Figure 4.7.2 Schematic of ball on wedge re-bonding

4.7.2.2 Ball Bond Removal Tool

On a particular device if it is important to rebond the first bond, then the ball bond has to be removed. IBM has designed and patented a bond removal tool. In this technique, pulsating jets of air remove wires from a bonded chip in a controlled and repeatable process. Harmonic air provides a cost-effective and reliable repair process for devices on multichip modules or high-value substrates [P-67].

Harmonic pulsing of air jets fatigues the wires until failure. This system can remove aluminum and gold wires, wedge or ball bonded. Fatigue process is controlled and repeatable. 'Repeatability' capability increases control of wire bond rework processes.

4.7.3 Positioning of the Ball on Bondpad

As we go towards fine pitch bonding, positioning of the ball bond within the bondpad becomes a critical factor. The accuracy and consistency of ball positioning depends on the machine stability. It also depends on the leadframe transport system and the repeatability with which the transport system grabs and moves the leadframes. Another factor that impacts the ball

positioning consistency is the thermal expansion of the leadframe. This is particularly valid in case of BGA and COB substrates, because the PCB substrates have very high thermal expansion coefficients. Small variations in the heater block temperature will have variable expansion of the CSP or BGA leadframe and affect ball positioning accuracy.

4.7.4 Positioning of Wedge on Lead finger

According to package design guidelines, the second bond must be placed well within the lead finger. The weld positioning on the lead finger may not be accurate if the wires are too long. If the wire is long, it may sway during bonding (because of bond head motion) and this results in positioning of the weld away from the taught position.

The weld positioning will be inaccurate if the angle of approach, of the wire to the lead finger is greater than 30 degrees. Usually it is recommended during lead frame design that angle of approach, of the wire should be parallel to the lead finger, as shown in figure 4.7.3. It is also observed that, higher the loop height, greater is the problem of weld positioning inaccuracy.

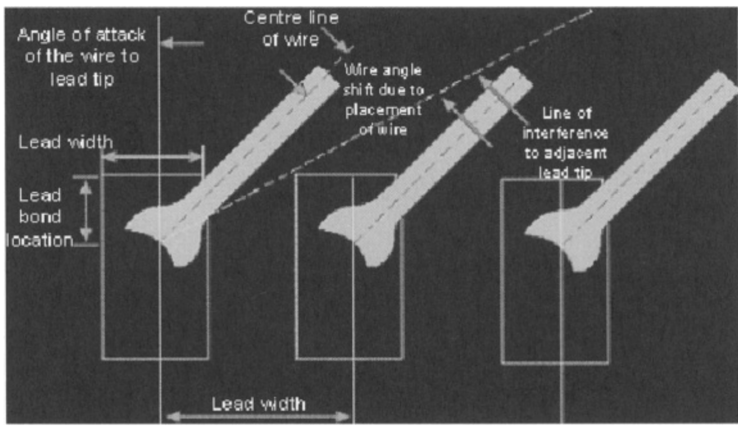


Figure 4.7.3 Angle of attack of the wire and its effect on weld positioning
[Courtesy: Kulicke & Soffa]

The material properties of the wire, such as elongation and yield strength also have an effect on weld positioning. Usually wire with higher elongation value, tend to sway more and this results in weld positioning problems.

4.7.5 Wire Sagging

Wire sagging problem is usually seen with gold wire bonded units, not as much with aluminum bonded devices. This is because gold is a high density metal, and it can sag under its own weight.

For comparison, the density of gold is 19 where as that of aluminum is 3.5. That means for the same length of wire, the gold wire is approximately six times heavier than the aluminum wire.

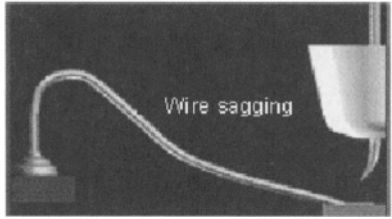


Figure 4.7.4 Wire sagging

Usually, sagging of the bonded wire can signify that the yield point of the wire has been exceeded during the bonding operation.

Figure 4.7.4 shows wire sagging problem. We can minimize wire sagging problem by:

- using a wire with a lower elongation and higher break strength
- the use of wire with optimum mechanical properties
- proper cam adjustment
- use of a larger diameter wire
- the reduction of the temperature of the substrate

4.7.6 Wire Tailing

Tailing is a problem usually seen with Au wire bonding. If the tailing problem occurs, then the length of wire remaining below the capillary after the second bond formation is not optimum. This can result in improper ball size formation. Figure 4.7.5 shows the bond tailing problem.

Tailing occurs if the elongation of the wire is too large. Usually, when the elongation of the wire is large, the wire is soft and therefore the tear is not "perfect". The tear is also "imperfect" if the amount of deformation during second bond is not sufficient. It is important to deform the wire enough so that when we tear the wire it breaks easily from the second bond.

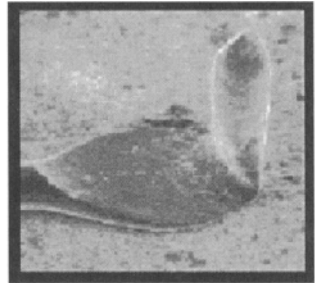


Figure 4.7.5 Bond tailing
[Adopted from product catalog : Gaiser Tool]

Tailing also occurs if the Inner Chamfer angle is too shallow or if the leadframe metallization is "soft". Ways to minimize tailing are:

- select wire with optimum elongation
- increase the second bond force to deform the wire for easy breakage and consistent breakage
- increase the inner chamfer angle

4.7.7 Wire Breakage during Bonding

The wire may break during bonding and usually this occurs more often with high speed bonders. Wire breakage can occur due to excessive drag between the bonding wire and the capillary. Wire may also break if the elongation is low and the UTS value is high. If the elongation is low, the wire does not have enough "give" and it tends to break during high speed low loop bonding. Wires may also break due inconsistent wire quality. Wire breakage can also be due to inconsistency of the x/y sliding plates which set the vector course of the wires between the bondpad and the lead finger. Some solutions to reduce wire break are:

- reduce the speed of bonding
- obtain wire with higher elongation

- minimize very low loop wires
- check the consistency of the wire under a microscope. Look for nicks or twists

4.7.8 Taut Loops

In high I/O, thin and fine pitch packages, we use low loops, and usually these high pin count packages also have long wires. During high speed bonding, if the machine does not stretch the wires uniformly after the first bond, just before the second bond, the loop formation becomes “taut”. Figure 4.7.6 shows taut loop versus high loop.

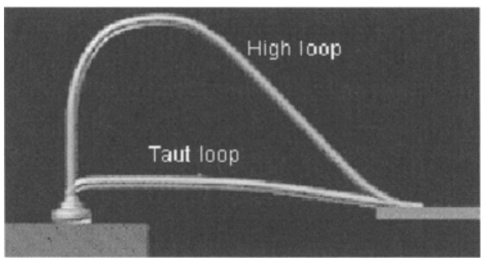


Figure 4.7.6 Taut loop versus high loop

4.7.9 Deformed Balls

Deformed ball formation occurs in gold ball bonding due to several reasons:

- if the bond force is insufficient on the bond tool, the ball wobbles during bonding and result in deformed ball
- if the free air ball is too small, it gets captured within the inside chamfer
- improper material properties of the wire which may lead to work hardening of the wire during ball formation

Solutions to minimize ball deformation are:

- increase the first bond force
- control the second bond force to minimize tailing
- make sure that the wire feed is uniform so that the FAB is uniform

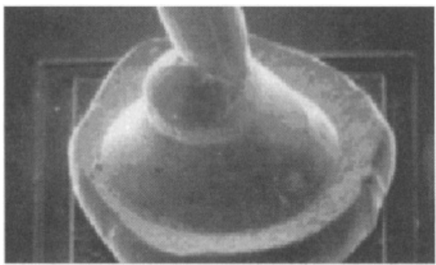


Figure 4.7.7 Deformed ball bond [Adopted from product catalog : Gaiser Tool]

4.7.10 Off Centered Ball (Golf Club Balls)

The off centered ball, also called "golf club ball" is shown in figure 4.7.8.

Some of the causes for the golf club ball formation are:

- inside chamfer is too small
- wire is too hard
- wire tension (or wire drag) is not tight enough
- the EFO gap is incorrect
- excessive tail length

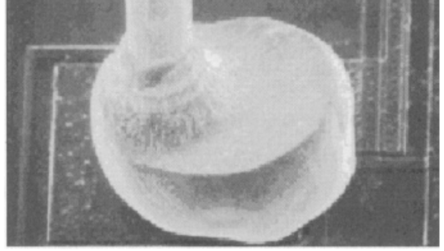


Figure 4.7.8 Golf club bond [Adopted from product catalog : Gaiser Tool]

4.7.11 Cratering

Cratering under the bondpad pad may occur during the bonding operation. The causes of cratering have been discussed in detail in reliability section. (For further detail about 'Cratering' refer Reliability chapter)

4.7.12 Metal Squeeze Out

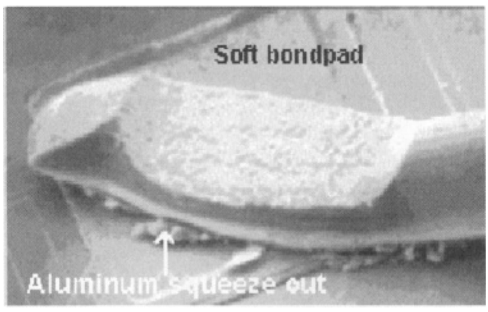


Figure 4.7.9 Metal squeeze out during bonding
[Adopted from product catalog : Gaiser Tool]

The problem of aluminum metallization squeeze out has been observed, particularly during ultrasonic aluminum wedge bonding. During wedge bonding if the bonding force is high the aluminum metal tends to squeeze out. In some cases it may result in electrical shorting particularly when bond pads are close to each other.

Some of the causes are:

- excessive force during bonding
- excessive ultrasonic power
- very soft metallization on the bondpad

In many power device applications, we use thick Al metallization, rather than thin Al-Si metallization. Usually thick metallization on the bondpad tend to be “soft”. Ultrasonic bonding at room temperature requires high force which may lead to metal squeeze out.

4.7.13 Wire Swaying

Wire swaying is a serious problem that one encounters in thin and long wire applications. It usually occurs when the wire is very long or when the speed of the bonder is very high. High speed bonding, results in very short time for loop formation, which impact the linearity of the wire between the bondpad and the lead finger. Some of the causes of wire sway are:

- wires less than 25 micron diameter
- wires longer than 4 mm
- excessive wire bond speed
- high loops coupled with long wires
- corner wires in a package
- angle of approach greater than 45 degrees.
- capillary hole too big for the wire
- wire elongation too large

4.7.14 Wire Clamp Problems

When the clamping mechanism clamps the wire, deep indentations are observed on the sides of the wire. It has been determined by SEM analysis that these marks are produced by the jaws of the clamping system through which the wire is fed from the spool to the bonding tool. The gap between the wire and the clamp, and the force exerted on the wire by the clamp have an impact on the wire loop trajectory. Figure 4.7.10 shows impact of gap between the wire and the clamp.

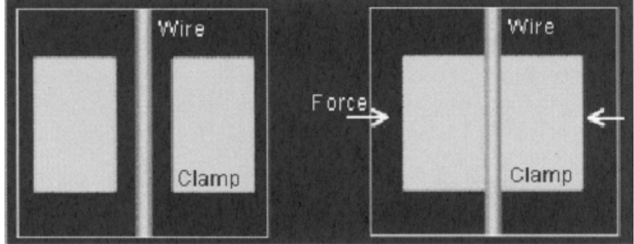


Figure 4.7.10 Impact of gap between the wire and the clamp

In addition to marring the surface finish, these imprints could work-harden the wire and thus affect bonding conditions. Occasionally the wire twists after passing through the clamping system and the indented portion then becomes a part of the actual bond interface. Of particular concern is the

possibility of contamination from the clamp becoming embedded in the wire and directly interfering with the bonding process.

One solution to this problem is to use large, 2 inch diameter, wire spools instead of small diameter spools. Wire from the large spools shows little tendency to twist. Also the wire clamps should be polished and the clamping force should be minimized. Incorrect adjustment of the wire clamp tension will allow excessive tail length from wire slippage resulting in inconsistent ball size and, in extreme cases, shorting of the wire across the wand producing a flame-off.

4.7.15 Low Frequency Motion and Bond Formation

Low-frequency differential-motion between the bonding tool and the bonding pad during ultrasonic bonding is a major cause of unreliable bonds. Such motion can originate from within the bonding machine, from various forms of operator movement or from external motion such as building vibration. Bonders installed on upper floors of buildings and/or close to heavy machinery may also exhibit vibration induced bonding problems. The operator should be cautioned about the detrimental effect that his/her own movements can have on bond formation. Bonding assembly lines should be located in a vibration free environment, preferably on a ground-level cement-slab floor.

4.7.16 Capillary Clogging

The capillary, used in gold wire ball bonding, is susceptible to contamination in its bore as well as gold buildup on its face due to the porosity of the material used. It is believed that capillary clogging is a primary reason for ball bond shear data on aluminum metallized substrates exhibiting a larger standard deviation than similar gold metallized substrates. Clogging usually occurs during the tail bonding process when the capillary tip is in contact with the substrate, where it can pick up surface contamination and metallic particle from the substrate. This accumulated

debris can result in an improper issuance of the gold wire through the capillary and thus cause a large variation in ball size, quality and ultimate shear strength.

It can be expensive and difficult to detect this contamination although such instruments as a scanning electron microscope with an Auger probe or a microscope with fluorescent illumination and a set of filters, usually recommended for detecting photoresist on the die, may be used.

4.7.16.1 Cleaning a Capillary or Wedge Tool

Even when contamination is detected through one of these methods, you can easily determine the composition of the contaminant, only whether it's organic or inorganic. Once discovered, the user can either adjust the wire bonding parameters to blow through the contamination or clean the capillary chemically in plasma cleaner using an Argon or CF4 plasma. Plasma cleaning, however, is a drastic step and should normally only be used in a worst case situation.

4.7.17 Capillary Unplugging

A few simple techniques can be used to unplug most capillaries. If it is done properly, we can save machine down time and also save capillaries. The preferred technique is to simply bond to unplug the capillary. Use a substrate or leadframe on which you have previously made a series of bonds. Bond down on one of the ball bonds. The ball will tend to extrude up the capillary bore and bond itself to any gold wire, thereby unplugging the capillary. If the above technique fails, then the use of a capillary unplugging probe is the next best technique. While the capillary is still in the bonder, the operator can introduce a capillary unplugging probe with tweezers, and gently raises and lowers the probe within the capillary. This action pushes most gold and debris out of the hole [P-68].

4.7.17.1 Other Unplugging Methods

The following are a variety of unplugging methods that have been used. Some may be of value, while others are marginal and may even damage the capillary.

Unplugging punch is one of the oldest methods. With this method, a steel unplugging punch is used in a special fixture to align the punch with the bore of the capillary. It is then punched through the gold in the capillary bore. There are several disadvantages with this method. First, the punch frequently punches through the gold, leaving gold in the inside chamfer of the capillary. Second, the punch pushes all the debris into the back area within the capillary which must be further removed. Third, punches often break off in the bore and the capillary must be thrown away [P-68].

4.7.17.2 Rotating Wire Method

Another method for unplugging capillaries is to rotate the capillary in a special lathe using tungsten wire to bore or drill the gold out. This procedure generally works well if one has the necessary equipment.

4.7.18 Chemical Methods of Bond Tool Cleaning

Prevention of gold buildup can normally be accomplished through the use of frequently scheduled aquaregia baths. Touching the capillary with hands and rough handling can damage the face or plug the tip. The proper use of tweezers and tool trays by well trained operators will go a long way toward improving bond tool life.

4.7.18.1 Cleaning with Aquaregia

Bonding tool cleaning and/or bonding pad material buildup removal can be accomplished by ultrasonic cleaning and use of aquaregia (See figure 4.7.11) to remove contamination and Gold bonding wire buildup. Care must be exercised to minimize the aquaregia exposure to two or three minutes.

Aquaregia may be used to batch unplug ceramic capillaries. However, this technique requires extreme care and caution. It should only be used by qualified personnel familiar with all chemical safety procedures. Aquaregia is three parts concentrated hydrochloric acid (HCL) and one part nitric acid (HNO_3). Mix only enough to cover the capillaries in a small beaker. Let stand for 20 minutes.

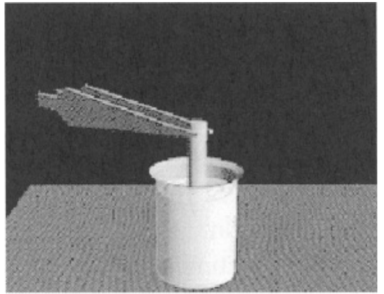


Figure 4.7.11 Schematic representation of capillary cleaning with Aquaregia

Empty the aquaregia and continually rinse the capillaries with running water. Retain some water in the beaker with the capillaries and place in ultrasonic cleaner for several minutes. Pour out the water and add new water. Place beaker back in ultrasonic cleaner. This must be done several times to make sure that the aquaregia is sufficiently removed from within the capillary. Blow out with clean air. This process is not normally recommended because of the potential safety hazard. It is also limited to batch processing.

4.7.18.2 Cleaning the Wedge Tool

The wedge in a wedge bonder is susceptible to the same types of problems as the capillary, including feedhole problems that might be displayed as sharp edges inside the feedhole. Some wedge bonders may also exhibit a problem with aluminum buildup on the foot. In this case, the wedge can be removed from the bonder and cleaned with Sodium Hydroxide.

Tools should be cleaned in a 20% solution of Sodium Hydroxide for 20 minutes at room temperature. Wash with water. Deionize by dipping 20% solution of hydrochloric acid. Wash again in water. Blow dry. Inspect tool tip at 60 to 100× magnification to ensure that any aluminum buildup on the tool has been removed. Inspect for wear. After cleaning approximately six times, the tool may show visible signs of wear and should then be replaced. Replace tool in vial for safekeeping.

4.7.18.3 Important Tips during Capillary Cleaning

When cleaning capillaries, never allow the capillaries to touch each other as they will become damaged and unusable. Use a hypodermic syringe to force water through the back of the capillary. A clean capillary will allow a straight stream of fluid to exit through the bore. A capillary which is dirty will not allow fluid to pass or if it does pass, it will tend to exit at an angle to the bore indicating a partial blockage. Blow out the capillary with clean high-pressure air. Make sure the air source is clean and free of oil and water by using an air line scrubber close to your capillary cleaning station. It is best to blow air through the tip of the capillary rather than through the back. Inspect the capillary optically using a 60× microscope with lighting directed from the tip up through the bore. A microscope can then be used to view down through the back large hole. Focus up and down into the back of the capillary. Residue and foreign matter can be detected within the back of the capillary in this manner.

4.7.19 Bond Pad and Leadframe Contamination

The contamination that hinders bonding on the bond pads include:

- passivation glass residues on bondpad
- fluorine or CF polymers after dry etch
- AlO, AlF compounds
- hydrocarbons/photoresist residues
- water spots (minerals)
- silicon dust (from sawing/dicing)
- no-metallization (during rebonding)
- discoloration (burnt aluminum over etching)
- multiple probe marks

On the substrates and Lead fingers, the materials or contaminations that hinder bonding include:

- variable thickness of metallization (too thin or too thick, both are bad)
- trapped organics from plating operation
- blisters and voids, uneven thickness
- oxidation/tarnish of the metallization
- porous thick film in hybrids
- exposed binder glass content in gold thick films

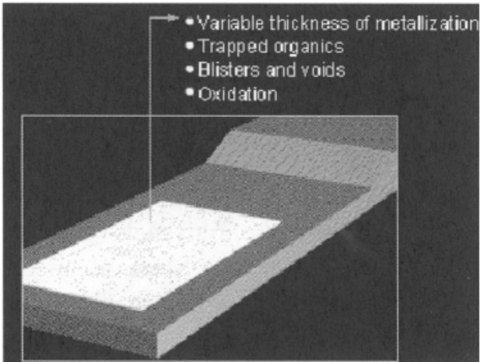


Figure 4.7.12 Material contamination that hinder bonding on the lead finger

4.7.20 Organic Contamination

Major cause of non-stick problems both on the chip and leadframe or package is due to organic contamination. Two types of contamination exist:

- thin film of photoresist is one of the most common organic residues encountered in both hybrid and semiconductor assembly.
- outgassing products of die attach epoxy resins during curing, may deposit on bond pads and lead fingers

Surface contamination, with photoresist, results in a significant reduction of shear strength of gold ball bonds for both gold and aluminum metallization. Die attach epoxy outgassing results in a less reproducible surface contamination and is highly dependent on metallization. In general,

bonds made to aluminum metallized substrates are more affected by epoxy outgassing contaminants, compared to gold.

4.7.20.1 Contamination Removal

Conventional methods, such as wet chemical cleaning or solvent decreasing have the drawback, that traces of the process chemicals are left on the treated surface. More advanced cleaning techniques such as plasma and uv-ozone cleaning are preformed. In the next sections we will study in detail the methods of cleaning used in assembly manufacturing, viz: plasma cleaning, UV ozone cleaning and other methods.

4.7.21 Plasma Cleaning

Cleaning is a very broad term and means different things to different people. In many cases, etching is a more descriptive term for plasma cleaning. Plasma cleaning/etching is an environmentally safe and effective technique for removing organic contaminants from a variety of materials and substrates. It is used for cleaning substrates in semiconductor assembly factories.

The plasma process offers several advantages over conventional chemical cleaning methods. Plasma process is a low temperature method using electrical energy to initiate chemical reactions instead of using thermal energy. Plasma cleaning is used for cleaning bondpad surfaces, leadframes, BGA substrates, COB substrates, MCMs and hybrids. Plasma cleaning of leadframes has become a major focus for improving the reliability of high density interconnections. Plasma is a simple process requiring little or no supervision.

Plasma treatment after die bonding and before wire bonding has a dramatic influence on both the bonding yield and the bonding strength. Plasma removes organic deposits that migrate to the bond pads during the curing process following the die attach. The metal surface becomes highly activated and a solid metallurgical bond is much more easily formed during the bonding process.

4.7.21.1 What is Plasma?

Plasma can be defined as a partially or wholly ionized gas with a roughly equal number of positively and negatively charged particles. Plasma is artificially generated using a high voltage, high temperature arc, which is the bases for the corona discharge process and for the plasma torch used to vaporize and redeposit metals. To ionize the gas stream, most plasma system manufacturers use energy fields whose frequencies (13.56 MHz or 2.45 GHz) are in either the radio or microwave segment of the frequency spectrum, respectively.

In plasma cleaning, the sample is placed in the process chamber and the chamber is evacuated using a vacuum pump. The plasma gas, usually argon or oxygen, is introduced throughout the gas inlet and the plasma is generated by applying a radio frequency voltage in the range of 13.5 MHz. Figure 4.7.13 shows the plasma process.

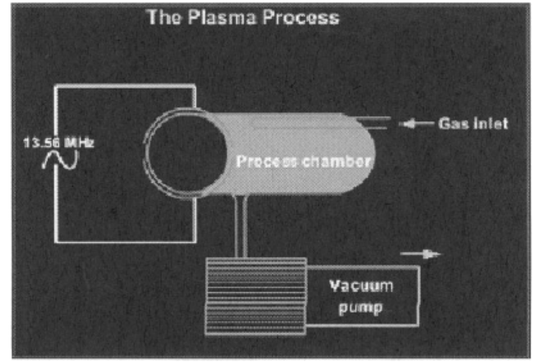


Figure 4.7.13 Plasma reaction chamber [P-69]

4.7.21.2 Generating a Plasma

Plasma discharge can be initiated by applying either a DC voltage or by radio frequency (RF) in the range of 1 KHz to 100 GHz. Most commercial systems utilize an RF voltage in the 13.56 MHz range. The plasma process is performed at pressures of 150 to 1500 millitorr. Efficient plasma etching will occur under following conditions:

- reactive species must be generated
- reactive species must diffuse to the sample surface

- gas plasma must absorb to the solid sample surface. It must penetrate the sample lattice and stick to surface
- there must be sufficient energy for the reaction to occur. If the reaction is
- not thermodynamically favorable, additional energy must be provided
- reaction must form a volatile compound that can be exhausted into the vacuum pump
- pump speed must be sufficient to remove volatile by-products and replenish reactive species

In a plasma reaction, the gas flows into the chamber, and the plasma discharge generates the etchant species. This etchant diffuses onto the surface of the sample, and gets adsorbed. Highly reactive etchant gas reacts with the surface film and the resultant gas is disorbed and diffuses into the bulk gas. Figure 4.7.14 shows plasma reaction.

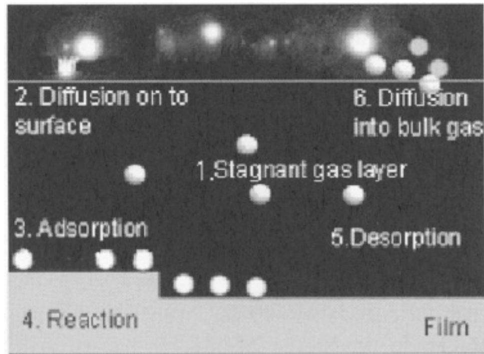


Figure 4.7.14 Plasma reaction [P-69] **[VIEW-IN-CDROM]**

4.7.22 Mechanism of Plasma

Plasma etch is also referred to as dry etch, since it utilizes gaseous chemicals, instead of liquid chemicals in a wet etch, to clean the drilled hole.

The gaseous chemicals, or process gas, is an electrically neutral mixture of charged and neutral particles, defined as a plasma gas. Some of these particles are reactive, which can break large organic molecules such as epoxy into small molecular segments. As the process gas flows through the hole it breaks the hydrocarbon contamination, washes away the small molecular segments, and hence makes the bondpad or leadfinger clean and ready for bonding.

When high energy electrons come in contact with gas molecules, the electron energy required for ionization of gas molecules is much greater than the energy required for dissociation. Very few electrons have the necessary energy to ionize gas molecules, yet many electrons have sufficient energy to dissociate them. When gas molecules are impacted with electrons, it dissociates and forms a free radical and roughly, for every 106 reactive gas molecules, 104 will form free radicals and only one will ionize [P-69].

4.7.22.1 Chemical Processes in Plasma Cleaning

Free radicals are neutral atoms or collections of atoms with incomplete bonding. Because they are neutral, they are not affected by the electric field induced in the reaction chamber and diffuse to the target surface in random directions. Radicals are highly reactive and are the most important species in plasma. They are responsible for the surface chemistry. Oxygen is an example of a gas which uses free radicals to chemically etch organics. The following equation shows the mechanism.

$$O_2 + e \rightarrow 2O + C_xH_y \rightarrow CO_2 + CO + H_2O \quad \text{[P-69]}$$

4.7.22.2 Physical Process of Plasma Cleaning

Ions do not react chemically, but some heavy ions, such as Argon can physically break weak organic bonds. Argon is a common ion used to dislodge organics. It is preferable to use oxygen over Argon whenever possible, because oxygen is a faster process for removing hydrocarbon contamination. However, the disadvantage of oxygen plasma is that the underlying metal may get oxidized, argon is inert, it will not oxidize metals.

Therefore, argon is preferred when cleaning hybrids where oxidation of the metal could change electrical properties.

4.7.23 Plasma Equipment

The instrumentation required for dry etching includes a reaction chamber, a power supply and a vacuum source. The sample is put into the chamber which is evacuated by the vacuum pump. Gas is introduced into the chamber and converted to reactive plasma by the power supply. The plasma reacts at the surface of the sample and volatile by-products are removed by the vacuum pump. Barrel systems are easy to design and manufacture, but lack etching uniformity.

A recent development in box style chamber with internally mounted shelves. This design is the most flexible. It has removable shelves and allows the user to configure the etcher for the most appropriate plasma method, directional (RIE), downstream direct plasma. This is accomplished by selecting and positioning shelves that are grounded, powered or at a floating potential.

The plasma chamber can have different configurations. As we can see in figure 4.7.15 in shielded plasma system, sample is placed on floating shelf outside the RF field. In direct plasma system, sample is placed inside the RF field. Whereas, in directional shelf system, sample is placed on powered electrodes.

Directional plasma also called as Reactive Ion Etching (RIE) is an aggressive form of plasma. It offers the benefit of fast etching rates and high uniformity. Downstream plasma is a mild process and is suitable for removing thin films of 10-50 angstroms [P-70].

4.7.23.1 The Plasma Chamber

The plasma chamber is typically made of quartz, aluminum or stainless steel. All three materials have excellent properties against most plasma gases. CF4 and other freon will form fluorine radicals that will etch quartz slowly, requiring periodic cleaning and replacement. Aluminum forms a thin oxide film on its surface and does not react significantly to any gas

plasma except chlorine. Stainless steel is also non-reactive to almost all gas plasmas and offers the added benefit of having very little porosity, making it easy to keep clean. The chamber should only consist of materials made of metal or ceramics. The use of teflon inside a chamber has been shown to cause bond degradation due to release of fluorine species. With any organic compounds, plasma can initiate a reaction that will form a polymer. Over a period of time, a portion of this polymer will deposit on the walls of the chamber and may redeposit on the sample. This problem of contamination can be minimized by not using any organic materials in the construction of the chamber [P-71].

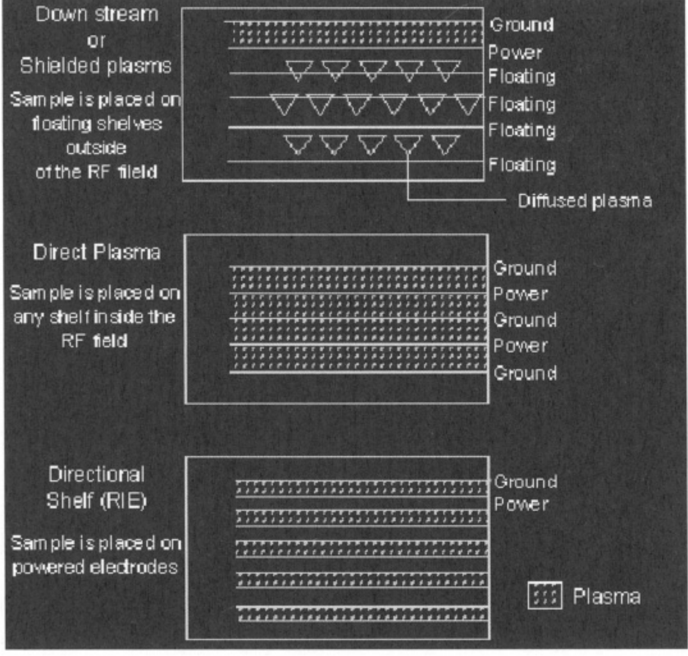


Figure 4.7.15 Side view of work shelves in plasma etcher showing configuration for various plasma modes [P-69]

4.7.23.2 The Plasma Power Supply

The power supply most commonly used to generate plasma is in the MHz region. Power supplies operating under 100kHz are less efficient and do not sustain a continuous plasma. Power in the GHz range is not generally used, because the microwaves can cause localized heating with materials having a dipole. Most applications operate between 50 and 1000 watts.

4.7.23.3 Plasma Cleaning in Magazines

In the earlier days of plasma cleaning, individual leadframe strips were processed. An automatic process using this technique is too slow and too expensive. Also a process based on transporting leadframes strip by strip and, in and out of a plasma chamber, is a process, manufacturing engineers feel uncomfortable with. Processing 30-40 leadframes within a magazine can be done five to twenty times faster. Today a complete magazine loaded with leadframes (or plastic laminates) is plasma cleaned in a batch process. During plasma cleaning of substrates within magazines, sufficient plasma penetration into magazines can only be achieved by designing proper magazines and keeping the magazines at a floating potential.

4.7.24 Plasma Process Parameters

4.7.24.1 Pressure/Flow Rate

Usually during plasma process, a process engineer keeps track of the flow rate of the gas. However, the reproducibility of a plasma process is primarily dependent on the pressure of the gas inside the plasma chamber. In any given system, the pressure (assuming no leaks) will be determined by the capacity of the pump. This is usually fixed and typically one pumps down to a predetermined pressure and backfills with the gas of choice. One can record the flow, but it is more important to monitor the pressure to reproduce the process consistently.

If the plasma process is based on Reactive Ion Etching (RIE) or ion bombardment with argon, then the chamber needs to be operated at the lowest pressures possible. At low pressures, ions are accelerated and the low mean free path between ions promotes action at the surface of the sample rather than collision between ions. Typical pressures are around 300-500 mtorr down to 10-50 mtorr.

Most plasma reactions are of a chemical nature, an active species like atomic oxygen reacts with hydrocarbons and forms H_2O and CO_2. This reaction is enhanced by high concentration of reactive species (high pressure) and fast removal of reaction by-products (greatest capacity pump). A practical limit exists in increasing the pressure in the plasma will not be sustained at too high pressure, usually more than 2,000 mtorr. Therefore, a typical pressure is around 500 - 1500 mtorr.

4.7.24.2 Power

In plasma cleaning process, generally, increased RF power gives faster etch rates. However, different chambers, electrodes and RF power designs can effect the efficiency. It must also be noted that, the greater the power the higher the temperature within the plasma chamber.

4.7.25 DC Hydrogen Plasma

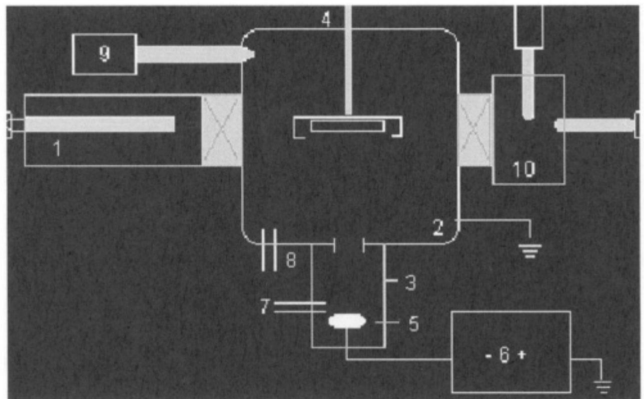
Plasma cleaning process techniques based on cleaning with reactive gases like O_2, HCl, SF_6 may have some disadvantages. Its use is environmentally problematic, traces of the working gas may be left on the treated surface or the cleaning process may be effective only for very specific contaminants. Ozone, for example, is chemically a highly reactive gas and thus very much suited for removing organic residues. It cannot be used to remove Oxide layers. In contrast, activated Hydrogen forms volatile by-products with nearly all type of contaminations. Hydrogen is therefore suited for cleaning of a large variety of substrate materials such as metals, glasses, plastics, etc. Recently DC hydrogen plasma chemical cleaning process, which differs

from conventional plasma cleaning, has been developed for the cleaning in IC-packaging before gold-bond wire bonding.

The process is based on a low energy argon-hydrogen discharge which allows very efficient cleaning by chemical reactions only and without sputtering of materials. With this process it is possible to plasma clean metallic and organic substrates that are used for wire bonding. Cleaning is done in low energy argon/hydrogen DC hot-filament discharge plasma.

4.7.25.1 Equipment Set-up

The DC hydrogen plasma cleaning module is schematically shown in figure 4.7.16. The DC hydrogen plasma process is based on a low energy argon-hydrogen discharge, and the cleaning process is predominantly by chemical reaction and not by physical sputtering of surface atoms.



1.Load lock , 2.Plasma chamber, 3. Plasma source, 4. Substrate loads 5. Heated filament, 6. Power source, , 7. Plasma source, 8. Cleaning chamber, 9. Process monitor system, 10. Auger spectrometer

Figure 4.7.16 Schematic drawing of the plasma cleaning module [Courtesy: ESEC Corp. and Balzers Corp.]

The substrate holder is mounted electrically insulated, but can be grounded or negatively biased with respect to the grounded chamber by a power

supply. The plasma source consists of the heated filament mounted in a separate cavity. An orifice connects the cavity to cleaning chamber. The dense Ar/H2 plasma discharge between the heated filament (cathode) and the chamber walls (anode) is established by applying a negative voltage to the filament.

It has been shown that for voltages as low as 25-30V, discharge currents up to 100A can be achieved. Argon is fed directly into the plasma source along with hydrogen [P-72].

4.7.25.2 Mechanism of DC Hydrogen Plasma

Exposing the substrates to the DC hydrogen plasma for 5-10 minutes guarantees a clean surface. Depending upon if the substrate is at floating, grounded or biased potential, cleaning proceeds very differently. For floating and grounded substrates the cleaning occurs by surface contaminations forming Hydrogen volatile compounds like CH_4, PH_3, OH with highly reactive radicals and low energetic ions.

When the substrate is biased, sputter cleaning or plasma physical cleaning occurs. When bias voltages larger than about 50V are applied to the substrate, cleaning is then caused by high energetic ions which remove all type of surface atoms by physical impact, in particular of species which do not form gas volatile with hydrogen [P-72].

4.7.26 Comparative Analysis of Chemical and Physical Cleaning

Plasma chemical cleaning can be used for cleaning leadframes and substrates in magazines where as plasma physical cleaning is not capable. Another serious drawback is that, a portion of the sputtered species, e.g., of the substrate material, is redeposited all over the process chamber. This effect might become problematic particularly when different types of substrate materials are processed in the same cleaning module. Plasma chemical cleaning is self-terminating where as sputter plasma cleaning is not self-terminating.

The temperature of the substrate is lowest for cleaning under floating conditions and is increased for cleaning under biased (150V) and grounded conditions. The substrate temperature depends upon the substrate material itself, but is not significantly different from that measured on the (metallic) substrate holder.

4.7.26.1 Impact of Plasma Cleaning on Bond Pull Strength

The bond pull force of a bond on a plasma cleaned surface is usually higher than the bond pull force of a bond on a non-plasma cleaned surface. But what is more important to observe is that the number of non-stick failures is greater in a non-plasma cleaned surface. In hybrid circuits, standard method of removing flux is by using organic solvents. Wire bonds bonded on such hybrids indicate high level of second bond non-stick failures. However, the same hybrids, after plasma cleaning, show no second bond failures. Figure 4.7.17 shows Wire bond test data on flux contaminated hybrids before plasma cleaning, after plasma cleaning

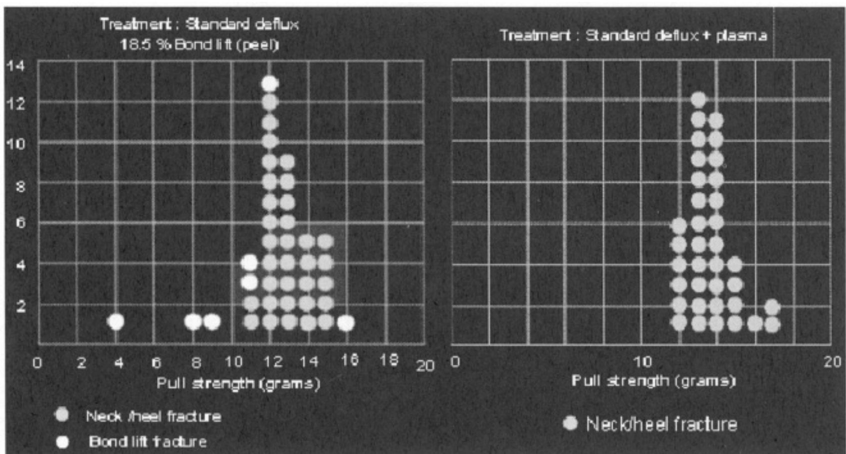


Figure 4.7.17 Wire bond test data on flux contaminated hybrids before plasma cleaning, after plasma cleaning [P-73]

When we perform gold wedge bonding on silver plated leadframes that are not plasma cleaned, the bonding temperature needs to be high and the bond strength increases with increasing temperature. However, when the leadframes have been plasma cleaned, the bond strength is high, even at low bonding temperature, and remains constant even when the temperature is increased. Figure 4.7.18 shows bond pull strength before and after plasma cleaning

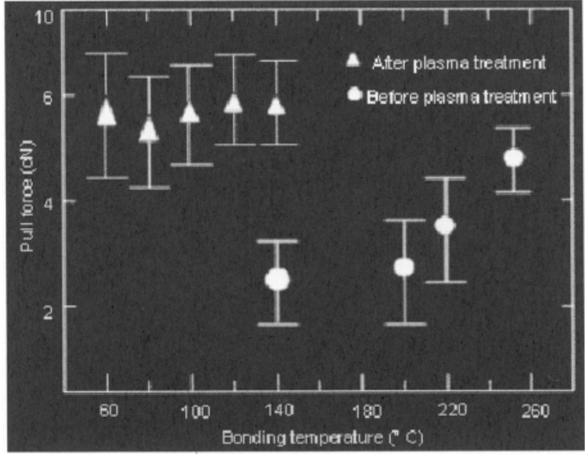


Figure 4.7.18 Bond pull strength before and after plasma cleaning [P-74]

4.7.26.2 Impact of Plasma Cleaning on Bond Shear Test

The plasma cleaning clearly increases the shear force values for all ultrasonic settings, indicating the potential of plasma cleaning to improve bond quality independent on bond process optimization. The shear force data (ball bond) measured on BGA substrates as a function of the ultrasonic power before and after plasma treatment of 6 minutes shows that for high reliability bonding, plasma cleaning is a critical necessity. Figure 4.7.19 shows shear force of a bond on a BGA substrate as a function of ultrasonic power. As we increase the ultrasonic power, the shear force increases. The plasma treated BGA substrate shows higher shear force compared to BGA

substrate without plasma treatment. Similarly, bond pull test of an MCM device shows high bond pull values after plasma treatment and very low bond pull values before plasma treatment.

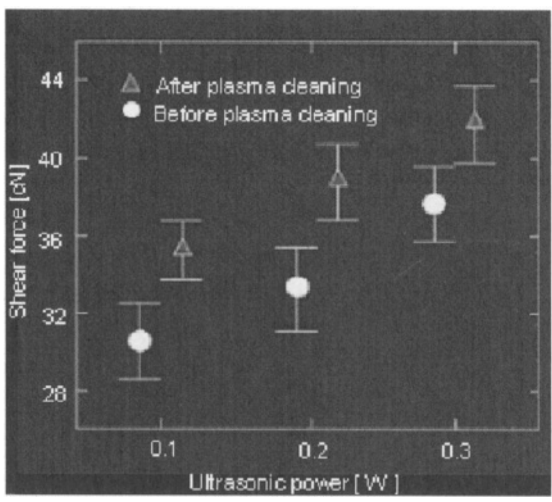


Figure 4.7.19 Impact of plasma cleaning on shear force [P-74]

4.7.26.3 Impact of Plasma Cleaning on Wettability

Any contaminated surface has low wettability which results in poor adhesion. Lower the wettability of the surface, poorer is the adhesion on that surface. Wettability is measured in terms of contact angle. Higher the contact angle of a droplet of water on a substrate, lower is the wettability. After plasma cleaning, and removal of contamination, the contact angle becomes low and this is an indication of better wettability and therefore better adhesion. Figure 4.7.20 shows contact angle on contaminated and clean surface. The wettability is improved because the hydrocarbon contamination on surfaces is removed. This can be seen by Auger analysis of surfaces before plasma cleaning and after plasma cleaning. Auger spectrometric analysis technique is used for identifying surface contamination on bond pads. Auger analysis of 'as-received' bond pads before cleaning shows

carbon, high level of oxygen, fluorine, and aluminum oxide as surface contaminants.

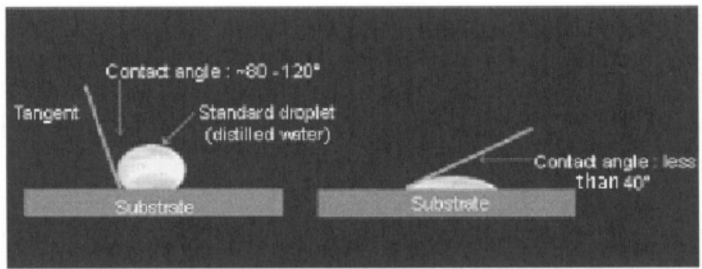


Figure 4.7.20 Contact Angle on contaminated and clean surface [P-69]

Figure 4.7.21 (a) shows bondpads on a component before plasma cleaning. After plasma cleaning, there is a dramatic decrease in carbon contamination, amount of fluorine, and aluminum oxide. Figure 4.7.21 (b) shows bondpad on a component after plasma cleaning.

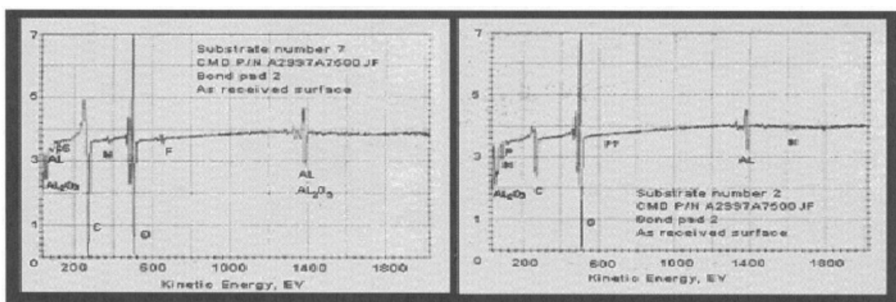


Figure 4.7.21 A scanning auger microanalysis of a bondpad (a) Before plasma cleaning (b) After plasma cleaning [P-75]

For the same amount of cleaning different surfaces show different contact angles. This is important to understand in deciding the plasma process

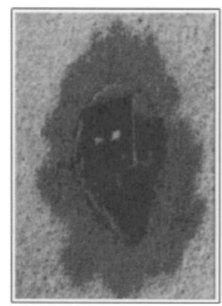
parameters and also in deciding whether a particular plasma treatment is useful for a surface.

4.7.27 Applications of Plasma Cleaning

Plasma cleaning is used for cleaning bondpad surfaces, leadframes, BGA substrates, COB substrates, MCMs and hybrids. For example, in a COB substrate, the wire bonding of the IC chip is done after the SMT components have been attached. There will be significant amount of flux contamination and water residue after the surface mount components have been attached and these needs to be removed for reliable wire bonding on the PCB substrate.

4.7.27.1 Hybrids

Hybrid circuits frequently fail due to poor wire bonding caused by organic contamination of the bonding surface. This contamination can be due to solvent residue on the device, residual photoresist on bonding pads, epoxy bleedout or other organic contaminants. Plasma cleaning is used for removing surface contamination. Figure 4.7.22 shows a SEM photographs of a transistor package surface before plasma cleaning and after plasma cleaning. Bondability on contaminated surface will be very poor compared to a plasma cleaned surface.



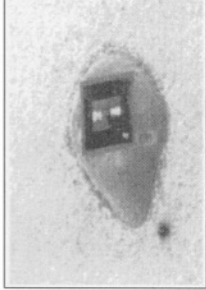


Figure 4.7.22 (a) Transistor before three minutes of plasma cleaning. (b) After three minutes of plasma cleaning. [P-76]

Argon plasma will effectively clean the organic contaminants without oxidizing the silver epoxy or the metal that could change the electrical properties. In addition to cleaning prior to wire bonding, plasma can be used to clean bare alumina substrates before metallization, before die attachment and before final sealing.

4.7.27.2 Low Temperature Bonding

Plasma cleaning today has become part of the assembly process. Beside the improvement of wire bond quality, a further potential of plasma cleaning is the possibility to process QFP and BGA substrates at temperatures considerably below the usual process temperatures. The bondability of freshly cleaned surfaces is very high and this can be an advantage if the plasma process is incorporated "in-line" system after die-attach and before wire bonding. This enhances throughput of a manufacturing line. Figure 4.7.23 shows the use of plasma cleaning in an "in-line" system.

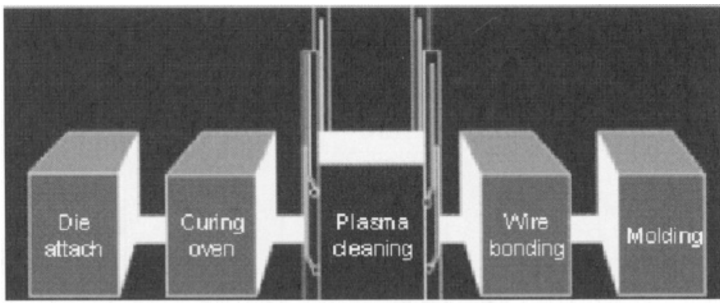


Figure 4.7.23 Use of plasma cleaning in an INLINE system [P-69]

4.7.28 Negative Effects of Plasma Cleaning

High energy particles, as created in the plasma during sputter cleaning, may lead to electron-hole pair formation in the device insulators (oxides and nitrides), causing possible changes of the electrical characteristics of the device. There is some concern that samples may be damaged in an RF field or in aggressive plasma. The evidence of damage is not conclusive and seems to occur only under very high RF power for repeated and extended periods of up to 60 to 120 minutes. Normally we do not encounter such conditions during short cleaning steps.

4.7.28.1 Argon vs. Oxygen Cleaning

The carbon contamination on bonding surfaces can be removed by using oxygen plasma or argon plasma. Argon plasma is somewhat slower, but it runs at lower temperature and does not oxidize metal surfaces or Silver filled epoxy. The oxygen cleaning is chemical, whereas argon cleaning is physical. Usually, for cleaning semiconductor devices, argon plasma is preferred. Table 4.7.1 shows oxygen versus argon cleaning.

Table 4.7.1 Oxygen vs Argon cleaning [P-76]

	Oxygen	Argon
Process	Chemical	Physical
Temperature	200°C	70 -100°C
Etch rate	800 - 1000 A°/min	500 A°/min
Pressure	1 torr	0.2 torr
Gas flow	5 cc/min	2 cc/min
Benefits	Faster	Less damage to device

4.7.29 UV/ Ozone Cleaning

4.7.29.1 What is UV/Ozone Cleaning?

There are two other processes that are used in the industry in addition to plasma cleaning. One involves the use of UV light and ozone, the other is a corona discharge. When UV light is generated at a wavelength below 180 nanometers, ozone is formed.

UV energy has the ability to break down organic compounds and in the presence of ozone, these organic compounds will form CO2 and can be removed. The ability of ultraviolet (UV) light to decompose organic molecules has been known for a long time and in the last few years UV cleaning of surfaces has been explored. Figure 4.7.24 shows UV/Ozone cleaning system.

Figure 4.7.24 UV/Ozone cleaning system
[Courtesy: FHR Anlagenbau Gmbh]

4.7.29.2 Advantages of UV/Ozone Cleaning

The major benefit of this process is that it does not require a vacuum. By storing clean surfaces under UV radiation it is possible to maintain the surface cleanliness indefinitely. UV/Ozone cleaning process provides a simple inexpensive, fast method of obtaining ultra-clean surfaces free of organic contaminants on most inorganic substances, such as quartz, silicon, gold, nickel, aluminum, gallium arsenide, alumina, etc. The process is ideal when thin film deposition with excellent adhesion to the substrate is required. Ultra-clean surfaces can easily be achieved by UV/Ozone processing in one to several minutes after the substrate has been cleaned by conventional techniques.

4.7.30 Mechanism of UV/Ozone

Since only the light which is absorbed can be effective in producing photochemical changes, the wavelengths emitted by the UV sources are important variables. The low pressure mercury discharge tubes generate two wavelengths of interest, 1849 A and 2537 A. The 1849A wavelength is important because it is absorbed by oxygen and it thus leads to the generation of Ozone. The 2537A radiation is not absorbed by oxygen,

therefore does not contribute to ozone generation. However, it is absorbed by most hydrocarbons and also by ozone. The absorption by ozone is principally responsible for the destruction of ozone in the UV box. Therefore, when both wavelengths are present, ozone is continuously being formed and destroyed. An intermediate product of both the formation and destruction processes is atomic oxygen, which is a very strong oxidizing agent.

Figure 4.7.25 shows a schematic representation of UV-ozone cleaning process. In UV/Ozone cleaning, the ultraviolet light of short wavelength is absorbed by the contaminant molecules and this result in ions, free radicals, excited molecules, and neutral molecules. Simultaneously, oxygen absorbs UV light and forms atomic oxygen and ozone.

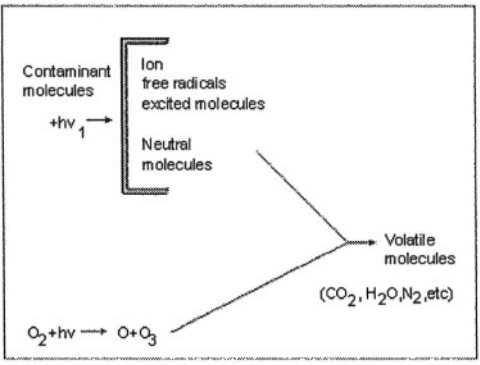


Figure 4.7.25 Simplified schematic representation of UV/ozone cleaning process. [P-77]

The atomic oxygen and ozone react with free radicals and excited molecules and form volatile molecules such as carbon dioxide, moisture and nitrogen, which can be removed from the chamber. The actual photochemical processes occurring during UV/Ozone cleaning are more complex. For example, the rate of production of ozone by 1849A photons is promoted by the presence of other molecules, such as N_2 and CO_2. The

combination of short wavelength UV light with ozone produced clean surfaces about 200 to 2,000 times faster than UV light alone or ozone alone.

4.7.31 UV/ Ozone Equipment

Oxygen is fed into the system from a gas cylinder and Ozone is generated internally. This internally generated ozone flows into the cleaning chamber which contains an ultraviolet lamp and heating coil. The most widely available sources of short-wave UV light are the mercury arc lamps. Low-pressure mercury lamps in pure fused quartz envelopes operate near room temperature, emit approximately 90% at 2537 A and generate sufficient ozone for effective surface cleaning. Approximately 5% of the output of these lamps is at 1849 A. Medium and high pressure UV lamps generally have a much higher output in the short-wave UV range. The mercury tubes can be fabricated in a variety of shapes to fit different applications. Other good sources of short wavelength UV such as xenon lamps and deuterium lamps are also available

4.7.31.1 Safety Considerations

In the construction of a UV cleaning facility, one should be aware of the safety hazard associated with short-wave UV light. Exposure to intense short-wave UV light can cause serious skin and eye injury within a short time. If the application demands that the UV lamps be used without being completely enclosed, then proper clothing and eye protection should be worn to prevent skin burns and eye injury. Another safety hazard is ozone, which is highly toxic. In setting up an UV cleaning facility, one must assure that the ozone levels to which people are exposed do not exceed 0.1 ppm. Usually safety is ensured by a Nitrogen purging system and by a safety switch on the cleaning chamber.

4.7.32 UV/Ozone Process Parameters

In setting up an UV cleaning facility, one should choose an UV source which will generate enough UV/Ozone to allow for rapid photosensitized oxidation of contaminants, however too high an output at the Ozone generating wavelengths can be counter productive because a high concentration of ozone will absorb most of the UV light before it reaches the samples. To maximize the intensity reaching the samples, the samples should be placed as close to the UV source as possible.

4.7.33 Effect of UV/Ozone

The effectiveness of the UV/Ozone cleaning is different for different types of contaminants, including: epoxy degassing residue, contamination absorbed during prolonged exposure to air, resin flux, mechanical vacuum pump oil, silicone diffusion pump oil, silicone vacuum grease, human skin oils. For the UV/Ozone cleaning procedure to work reliably, the surfaces must be precleaned first, to remove contaminants such as dust and salts which cannot be changed to volatile products by the oxidizing action of UV/Ozone.

4.7.33.1 Effect of UV Ozone on Wettability

The wettability of a surface is improved on cleaning using UV-Ozone. This is indicated by the decrease in contact angle as a function of UV exposure. Figure 4.7.26 shows UV ozone cleaning of a glass surface. The wettabilily of different surfaces after cleaning with UV-ozone are different. This is represented by the contact angle data.

4.7.33.2 Applications of UV Ozone Cleaning

- clean bondpads on dies, wafers
- strip photoresist, chrome masks
- treatment of surfaces for increased wettability

- removal of residual solvents
- clean metallization on CSP, BGA substrate and leadframe.

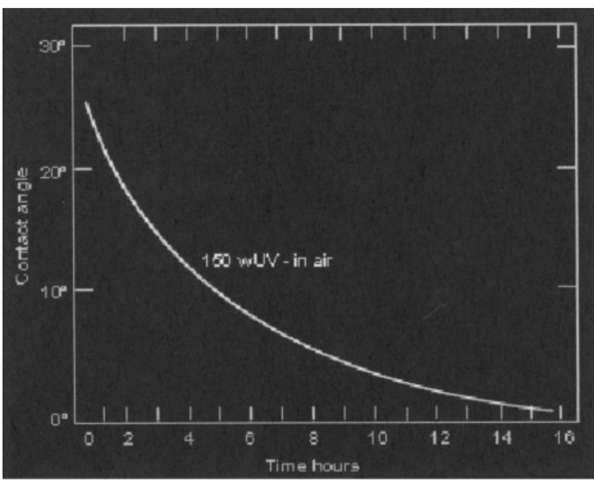


Figure 4.7.26 UV-Ozone of a glass surface **[P-77]**

4.7.34 Negative Effects of UV Ozone

The disadvantages of negative effect of UV Ozone are:

- the generation of toxic ozone
- surface damage due to high energy (temperature) of the electrons
- non-uniformity of treatment
- limited life of the activated surface

Prolonged exposure of oxide forming metals to UV light can produce rapid corrosion. Silver samples for example, turn black in UV box within 1 hour. Experiments with sheets of Kovar, stainless steel (type 302) gold, silver and copper showed that upon extended UV irradiation the Kovar, the stainless steel and the gold appeared unchanged, the silver and copper oxidized on

both sides, but the oxide layers were darker on the bottom sides than the top sides.

The major disadvantage of UV/Ozone process compared to plasma for bonding and surface adhesion applications, is the poorer quality of the resulting treatment. The low energy of the surface translates into a poorer quality bond. Because UV/ozone take place in an oxidizing atmosphere, metal oxides are formed which, on contact with moisture, will create a corrosive environment that can lead premature failure. The low temperature plasma process, in comparison, can be used with different gases, to provide both a reduction or an oxidation environment and the benefit of different active species such as argon, fluorine and hydrogen.

4.7.34.1 Disadvantages of UV/Ozone Cleaning

- the process is about twenty times slower than plasma.
- only an oxidizing environment can be generated, forming unwanted metal oxides.
- the surface modification in the case of polymers is not as thick as with plasma and the improved properties may not last as long.
- worker safety becomes an issue because ozone is toxic

4.7.34.2 Corona Discharge Cleaning

Corona discharge is also an atmospheric process. It involves generating an arc or spark, much like lightning. The discharge form will also generate ozone and the combination of the ozone and the relatively high temperature spark will modify a polymer surface and make it wettable. The benefit of this process is also that no vacuum chamber is required.

5

Quality

Today, most of the critical applications like high performance computers and industrial systems are controlled by microchips which have wire bond interconnections. The reliability of the IC chip during performance of its function in any application, be it in an automobile, space shuttle or a personal computer, is very much dependant on the quality of the wire bond interconnection. If the quality of the wire bond interconnection is poor and not consistent, it has a significant impact not only on the reliability and dependability of the device, but has a huge economic impact. Therefore, quality assurance of the wire bond is of utmost importance in the IC assembly work flow. The quality of a wire bond is determined by the strength of the interfaces between the bond wire and the bond pad as well as the bond wire and the lead finger. In addition, some of the other quality factors that one needs to check for during the wire bonding process are wire sweep, wire sway, wire sagging, heel cracking, bond deformation and many other defects. (for further details refer reliability chapter). The quality of the wire bond is controlled by using established methodologies such as bond pull test, bond shear test and visual inspection. We shall discuss each of the different quality inspection methodologies. In this chapter we shall also understand the applicability, advantages and limitations of each test.

5.1 Bond Pull Technology

5.1.1 The Bond Pull Test

The bond pull test was introduced in the 1960's and even today it is the most widely used technique for the evaluation and control of wire bond quality. This technique is also used for wirebonding process control and process optimization during assembly manufacturing. The bond pull test involves placing a hook under the wire and applying a normal upward force and the wire is pulled till it fails, as is shown in fig 5.1.1

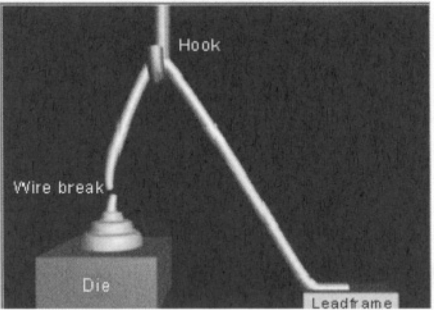


Figure 5.1.1 Bond pull test

Depending on the position of the hook between the ball bond on the chip and the wedge bond on the lead finger, the bond wire fails with different failure modes. The quality and the reliability of a bond is determined by the bond pull force at which the failure occurs. It is very important to recognize that higher bond pull force is a necessary criteria but not a sufficient requirement. The type of failure mode determines whether the bond is reliable or not. Two types of failures during the bond pull test, namely "ball lift" failure and "weld lift" failure are not acceptable.

During bond pull test, if a ball lift failure or weld lift failure occurs even at very high pull value, still it is unacceptable and the bond is considered of poor bond quality. In case of such failures the cause of the non-stick must be

analysed thoroughly and necessary remedial action needs to be taken. Examples of ball lift and weld lift failures are shown in fig 5.1.2.

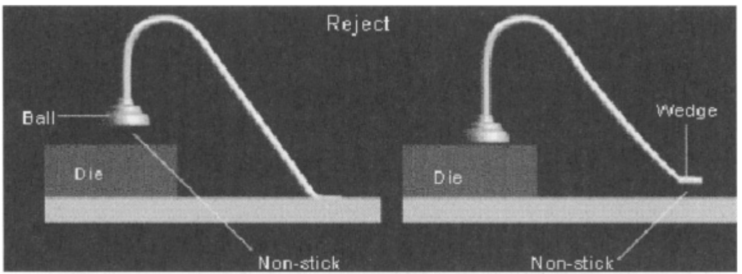


Figure 5.1.2 Ball lift and wedge (weld) lift failure

5.1.1.1 Different Modes of Pull Test Failures and their Interpretation

The major failure modes that one observes during a gold ball bond pull test are, ball lift (A type) ,ball neck break (B type), mid span break (C type) , heel break (D type) and weld lift (E type), as shown in figure 5.1.3. In special cases, the failure may also occur at other interfaces such as lift off of bond pad metallization, cratering under the bond pad and peel off of lead finger metallization. Let us review and discuss the five types of failure modes in detail.

5.1.1.2 Ball Lift Failure

The occurrence of ball lift failure indicates that the ball to bond pad interface is very weak. The ball lift failure indicates either the bond has not formed or the bond has become weak. Ball lift can be due to a variety of factors. Poor wirebonder set-up and bond pad surface contamination are primary causes of ball lifting. Poor set-up includes improper parameter settings, unstable workpiece holders, and worn-out tools. These result in poor initial welding and inadequate intermetallic formation between the bond pad and the ball.

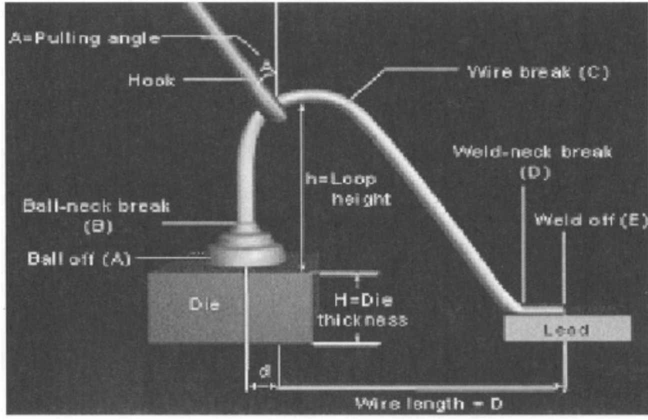


Figure 5.1.3 Pull test failure modes **[VIEW-IN-CDROM]**

Contaminants on the bond pad, which act as barriers between the ball and the bond pad are another cause for ball lift. Common contaminants that inhibit good bonding include unetched glass, unremoved photoresist, Si saw dust and resin bleed-out from the die attach material can also impede good bonding and result in ball lifting. Halides such as Cl on the bond pad can trigger corrosion, which is again another source of ball lifting. Silicon nodules on the surface of bond pads can also result in poor ball bonding. Lifted balls may also result from excessive interdiffusion between the bond pad and ball bond metals. Kirkendall voiding, which is the formation of voids underneath the ball bond due to excessive diffusion of Al from the bond pad to the Au ball bond to form purple plague, is an example of this mechanism.

The reflow of thermoplastic die attach material at the bonding temperature also results in ball lifting, because it allows movement of the die during the thermosonic bonding itself. Cratering, which is considered to be a different failure mechanism, can also manifest as a lifted ball, with the Si underneath the bond pad coming off with the bond. Similarly, bond pad peel-off from the barrier metal can result in ball lifting. Experience has likewise shown that excessive probing damage or deep probe marks on the bond pad can lead to ball lifting.

5.1.1.3 Actual Force on the Ball during Bond Pull Test

When we do bond pull test, the pull force F acts on the ball with a diameter d. The force per unit area on the ball is given by the equation shown in figure 5.1.4. Suppose the bond pull force value is 10 grams and the ball diameter is 3 mils, the force acting on the ball is only 1.4 grams per mil square. This is significantly lower than the 12.5 gms per mil square force experienced by the wire. If a ball lift failure occurs at a F value of 10 gms, it indicates a very weak ball-bond pad interface.

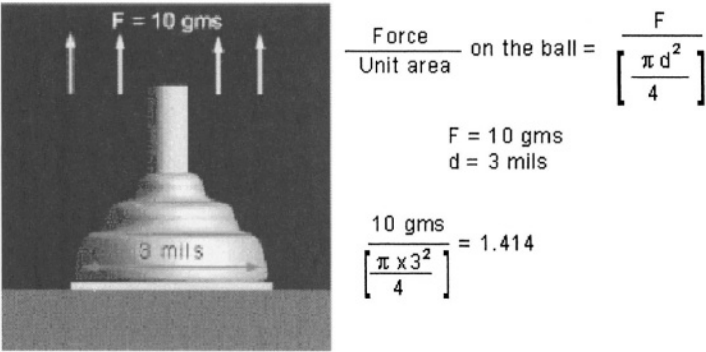


Figure 5.1.4 Force experienced at the ball - bond pad interface during pull testing

5.1.1.4 Ball Neck Failure

The failure of the wire just above the ball neck is shown in figure 5.1.5. This is the predominant failure mode that we observe during bond pull test. Neck breaking is the severing of the wire from its ball bond due to a fracture in the neck. The neck is the portion where the wire meets the ball bond. Neck breaking is commonly due to poor wirebonder set-up such as improper bonding parameter settings, bondhead movement settings, and worn-out or contaminated tools. Incorrect bonding parameters can deform the bond excessively, resulting in a thin, weak, or cracked neck which can easily fracture.

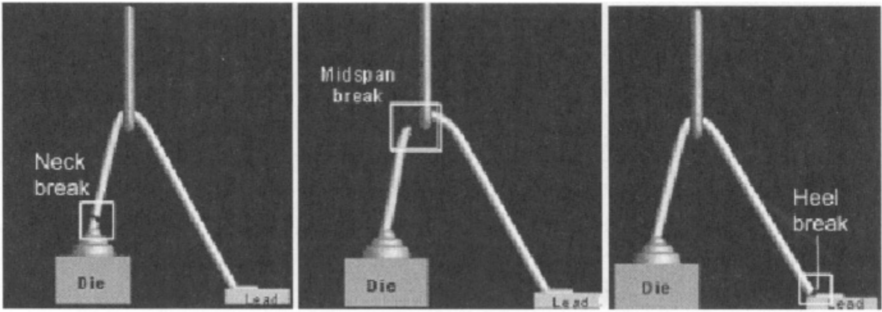


Figure 5.1.5 Shows neck break, midspan break and heel break

The wire is subjected to excessive stresses due to improper bondhead movements and low loop settings which inturn will result in awful neck cracks which may propagate to fracture. Crack propagation can also be caused by defects in the wires due to worn-out and contaminated tools.

5.1.1.5 Wire Break at Mid Span

Bond wire failure at the midspan is shown in figure 5.1.5. This failure mode indicates that the wire failed by plastic deformation and ductile fracture, rather than by brittle fracture at the heel or at the ball neck. Usually the failure at mid span gives the highest bond pull value, close to the ultimate tensile strength (UTS) of the wire.

5.1.1.6 Heel Break

Heel breaking is the severing of the wire from its wedge or crescent bond due to a fracture in the heel. The heel is the portion where the wire tapers off into the bond. When we perform bond pull test, the heel break failure may occur as shown in figure 5.1.5 and this usually indicates damaged heel area. Improper bondhead movements and low loop settings may subject the wires to excessive stresses that tend to pull them backward and away from the bonds, resulting in gross heel cracks which may propagate to fracture. The major cause of heel break is the presence of a micro crack at the heel (ref figure 5.1.6). This microcrack may be formed during bonding. The

causes of micro crack may be attributed to bonding parameters such as high bonding force and excessive ultrasonic energy. The other probable causes are damaged capillary, clogged capillary or over used capillary.

The amount of heel crack in a wedge bond depends on the back radius shape and size. The amount of heel crack allowed in a wedge bond depends on the wire diameter, the minimum pull strength requirement, and the type of package in which the bonding is done.

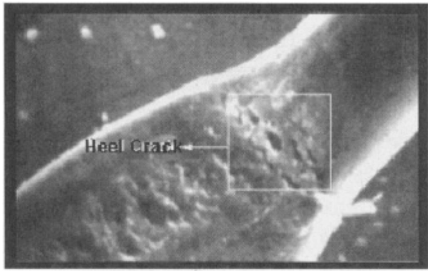


Photo 5.1.6 Heel crack in a wedge bond
[Courtesy: Gaiser Tool Company]

5.1.1.7 Weld Lift

Weld or wedge lifting is the detachment of a wedge bond from the bond pad or bonding post, or the crescent bond from the leadframe bonding finger as shown in figure 5.1.7. Weld lift during bond pull test, is an indication of improper process optimization. Similar to ball lift failure, weld lift failures, even at very high bond pull values is a mark of bad quality and therefore, should not be accepted. The weld lifting could be also caused due to low bond parameters, contamination on leadframe, hard metallization, or improper ultrasonic coupling between the capillary and the lead finger. The cause of this weak coupling between the capillary and the lead finger can be due to lead frame fragility or improper clamping during bonding.

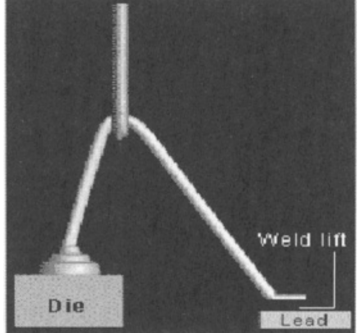
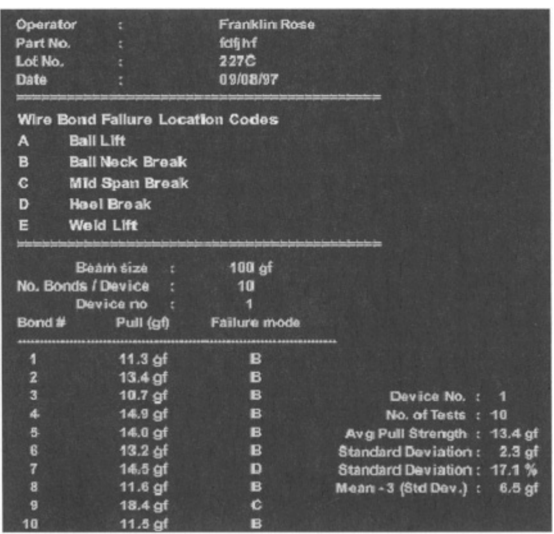


Figure 5.1.7 Weld lift

5.1.1.8 Bond Pull Data Specimen

The bond pull data after the test is performed is printed out or is available on the computer screen. Usually the data contains the pull strength value for each wire pulled and the corresponding failure mode. The bond pull test report also contains the lowest and highest pull values, the X-bar value and the standard deviation.

Here in figure 5.1.8 we can see that most of the failures are at ball neck (B type), one failure at midspan (C type), one failure of heel crack (D type). The data also shows the mean pull strength X Bar value of 13.4 and standard deviation of 2.3. The bond pull test is used as a quality assurance tool to pass a production lot to the next process. If the mean bond pull value X Bar, and the 3 sigma value are below the lower spec. limit (LSL), then the production lot is carefully scrutinized and necessary decisions are taken.



Operator : Franklin Rose
Part No. : fdfjhf
Lot No. : 227C
Date : 09/08/97

Wire Bond Failure Location Codes

A Ball Lift
B Ball Neck Break
C Mid Span Break
D Heel Break
E Weld Lift

Beam size : 100 gf
No. Bonds / Device : 10
Device no : 1

Bond #	Pull (gf)	Failure mode
1	11.3 gf	B
2	13.4 gf	B
3	10.7 gf	B
4	14.9 gf	B
5	14.0 gf	B
6	13.2 gf	B
7	14.5 gf	D
8	11.6 gf	B
9	18.4 gf	C
10	11.5 gf	B

Device No. : 1
No. of Tests : 10
Avg Pull Strength : 13.4 gf
Standard Deviation : 2.3 gf
Standard Deviation : 17.1 %
Mean - 3 (Std Dev.) : 6.5 gf

Figure 5.1.8 Typical pull test report

It is also important to recognise that even though the bond pull strength X-bar value is acceptable, if the bond pull test specimen showed any weld lift,

heel break or ball lift failures, then the production lot should not be accepted and it necessitates immediate attention.

5.1.1.9 Pareto Analysis of Bond Failures

When we perform bond pull tests as a process monitor or as a quality assurance test, it is important to monitor the failure modes and the corresponding X-bar values of pull force. Figure 5.1.9 shows an example of one company's bond pull data collected over 15,000 pull values. Analysis of approximately 15,000 bond wires that have been pull tested shows that more than 80% of the failure are in mid span and about 12% in ball neck and 1% in ball lift and stitch lift. The pareto chart indicates high levels of type A, type D and type E failures.

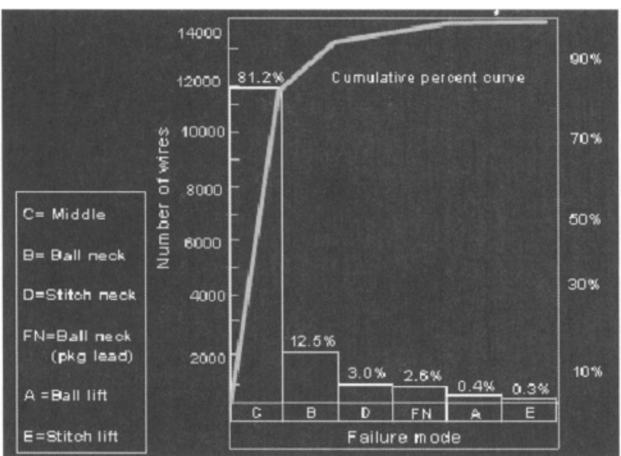


Figure 5.1.9 Chart of failure modes. Destructive wire pull test [Q-1] **[VIEW-IN-CDROM]**

When we look at the bond pull values, in figure 5.1.10 for individual failure types, ball lift (A type), stitch neck (D type) and stitch lift (E type), the X-bar values are low and the 3 sigma value is high, comparing the average pull force for different failure modes, one can see that for mid-span failure we have the highest mean value of 9 gms and the lowest pull value is

about 6 grams. However, when we compare the pull value of ball lift, the mean value is about 6 grams and the lowest pull value is close to 0 grams. Similarly for stitch lift problem, the lowest pull value is about 1 gram.

It has been observed that when A type, D type and E type failures occur during pull tests, there is direct correlation to increased field failures of the device.

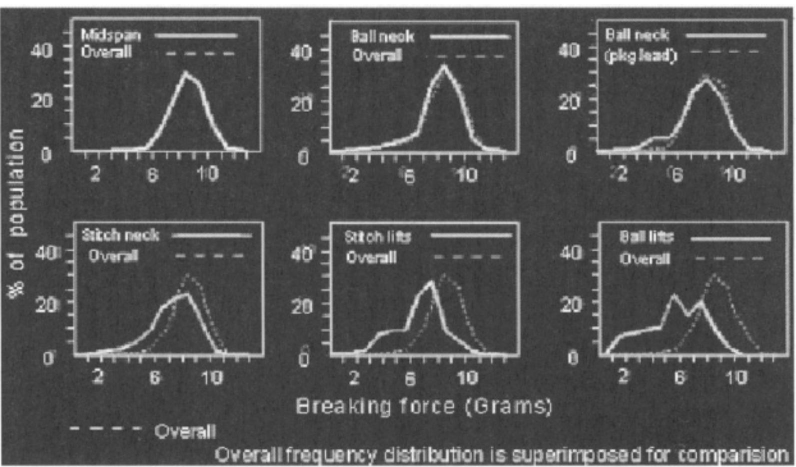


Figure 5.1.10 Frequency distribution of breaking force for various failure modes [Q-1]

5.1.1.10 Selection of Optimum Sample Size for Destructive Bond Pull Test

What is a good sample size for bond pull test? This question arises in every engineer's mind when he has to perform bond pull test on high lead count devices. If the sample size is too small, not enough information is available for the engineer to make a decision about the device quality or process consistency. On the other hand if the sample size is too large the bond pull test duration is too long and may unnecessarily be expensive. Therefore it is important to come up with an intelligent methodology to select the right sample size based on zero occurrences of certain failure modes.

Let us assume the speed of a bonder is 6 wires per second, which means in 2 hours we can bond approximately 43,200 bonds. In most of the assembly manufacturing factories wirebonding process is monitored by destructive bond pull test method on a small sample size, every two hours. The sample size could vary between 10 wires to 100 wires. Suppose we do pull test every two hours on 40 wires on one machine. If we obtain even one A, D or E type failure, out of 40 pulls it is an indication that the outgoing quality is poor and the process is not optimum. The device bonded in these two hours will have a high probability of field failures. Therefore it is imperative that the sample size must be as large as possible and the only acceptable criteria for bond pull testing must be no A-type, D-type and E-type failures. In case of an aluminum wedge bonding, the ideal failure mode is a heel break with the highest bond pull force value.

5.1.2 Effect of Hook Position on Failure Mode

The position of the hook during the bond pull test significantly affects the pull value as well as the failure mode. We must be aware that if the operators are not trained properly each operator may place the hook differently which gives rise to different pull values and different failure modes. The hook positions at the top of the loop or at the mid-span are shown in figure 5.1.11. The loop height, the wire length and the position of the hook impact the failure modes.

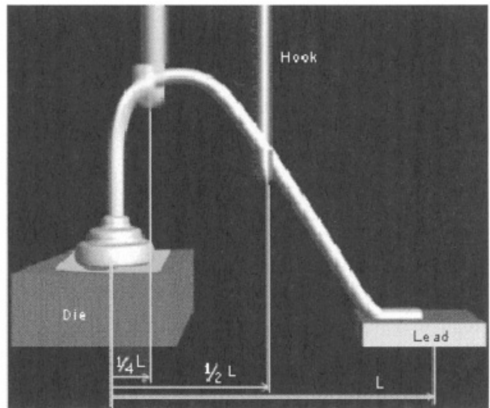


Figure 5.1.11 Hook position [Q-3]

The most popular method of pull is by placing the hook in the middle of the wire length. As shown in figure 5.1.12. In this configuration of hook positioning the majority of the wire failures occur at the ball neck.

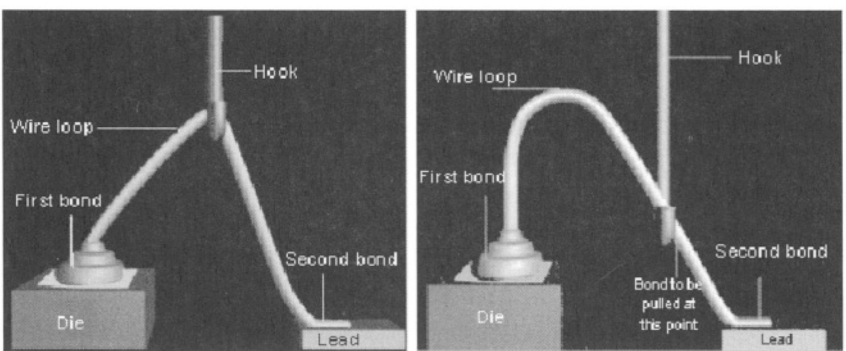


Figure 5.1.12 Hook in the middle *Figure 5.1.13 Hook close to the second bond*

When the hook is positioned close to the second bond, as shown in figure 5.1.13 the failure rate due to second bond failure will be higher. This can be attributed to greater stress on the second bond and a sharper angle of pull.

5.1.2.1 Force Distribution during Bond Pull Test

The bond pull force as a function of hook position has been calculated using the theoretical model shown in figure 5.1.14. It is found that as the hook is moved away from the first bond, the force on second bond, F/T1, increases. In this figure the values h1 and h2 indicate the loop height and chip thickness respectively. The force on the first and the second bond also varies with hook position, the chip thickness and the loop heights as shown in figure 5.1.15. As we position the hook away from the ball bond, the force experienced by the second bond increases and as we increase the loop height, the force on the second bond increases correspondingly.

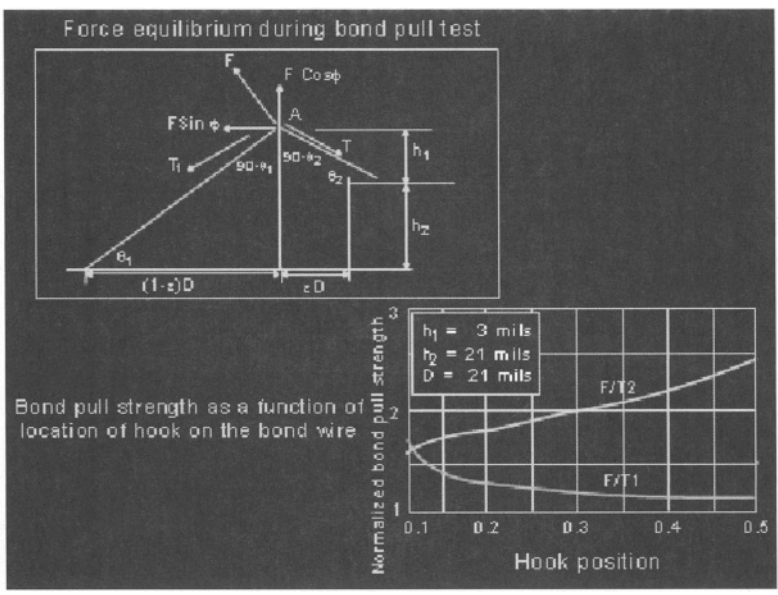


Figure 5.1.14 Force equilibrium during bond pull test [Q-2]

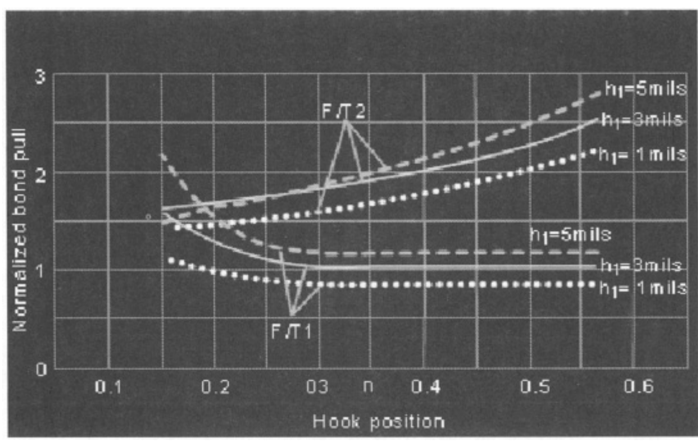


Figure 5.1.15 Normalized bond pull vs hook position [Q-2]

5.1.2.2 Pulling Speed during Pull Test

As shown in figure 5.1.16, depending on the position of the hook between the ball and the wedge, the pull strength values vary. For example, for a 25 micron wire of 2.5 millimetre length, the pull strength changes from 6.3 grams to 4.5 grams when the hook is positioned at the top of the first bond (ball) (¼ L position), midspan (½ L position), and close to the wedge (1L position) the pull strength value decreases. A few mils of change in hook location (operator differences) can put SPC data points outside of normal control limits.

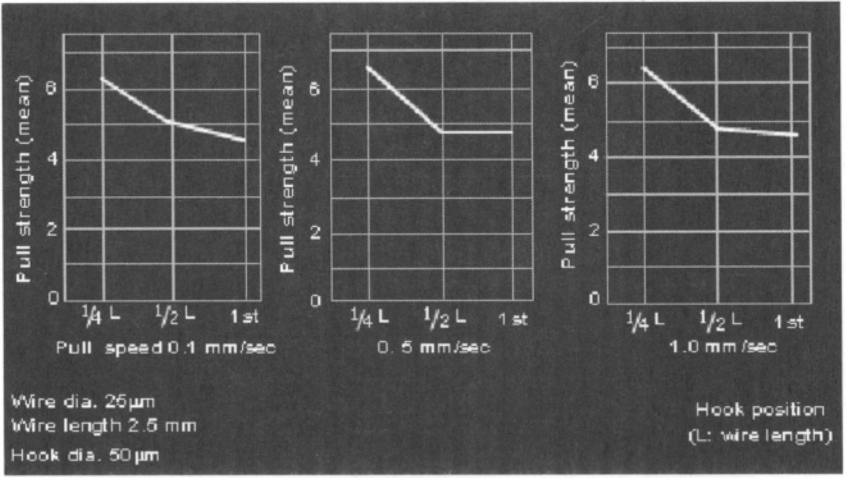


Figure 5.1.16 Hook position vs pull strength [Q-3]

5.1.3 Effect of Hook Diameter

A hook must be made of strong material to cut wire while testing. Usually the hooks are made of a hard material such as tungsten. The tungsten wire of a small diameter is fabricated into hook shape, (Usually L shape), and the ends are pointed for easy access during bond pull test. The recommended hook diameter for bond pull test depends on the wire diameter as evident from the table 5.1.1. Usually, it is recommended that, for less than 50

microns wire diameter, the hook diameter should be two times the diameter of the wire, whereas, for wire diameter greater than 5 mils or 125 microns, the hook diameter should be the same size as of the wire diameter.

Table 5.1.1 Recommended hook diameters [Adopted from product catalog: Dage Microtester]

Wire diameter	Hook diameter
Less than 50 μ	2.0 x
50 - 125 μ	1.5 x
More than 125 μ	1.0 x

Figure 5.1.17 shows the experimental data which reveals that small variation in hook diameter may not affect pull test values or pull test failure modes significantly. We see here, that, when the hook is positioned right above the ball, the pull value is high. The pull test data is shown for hook diameters of 25, 50 and 75 microns.

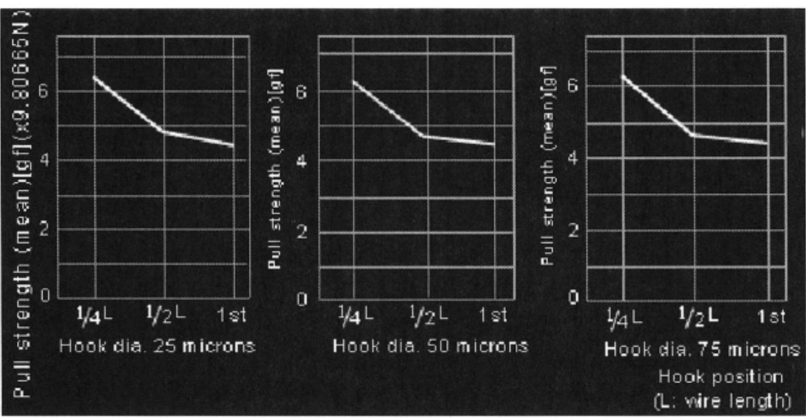


Figure 5.1.17 Hook position vs pull strength [Q-3]

It has been observed in certain factory environments, that the small diameter tungsten wire breaks easily (due to brittleness and operator mishandling) and therefore, the technician prefers to use a very thick wire. The table 5.1.2 shows three different bond pull test situations where the hook diameter is 215 microns to pull a 50 micron diameter wire. Bond pull test set up #1 with 215 micron hook does not show weld break type of failures and gives a false indication that the process is under control for all machines with X bar = 15 gms and s = 2.0. Bond pull test set up #2 with 215 micron hook, but a higher sample size shows that the process has different X bar values, ranging from 10 gms to 15 gms and standard deviation of 1.0 to 2.5. Bond pull set up #3 with 45 micron hook, however, shows that the process has a swing from machine to machine, X bar = 9.5 to 12.0 and s = 1.5 to 2.5 and set up #3 also shows Weld break failures.

This table also shows that the hook diameter significantly affects the pull values as well as failure modes. It also shows that the large diameter hook gives all failures which occur at ball neck, whereas smaller diameter hook results in both ball neck and weld failures. This indicates that the bond wire is not being pull tested optimally when the hook diameter is very large.

From the above discussion it is important to recognize that hook diameter plays a role in bond pull testing.

Table 5.1.2 Effect of hook diameter on failure mode [Q-4]

Set up		No. of wires	Mean x gms	Std. Dev	Failure mode
215 micron hook	SETUP 1	12wires/machine	15.0	2.0	All ball neck failures
215 micron hook	SETUP 2	40 wires/machine	10.0 to 15.0	1.0 to 2.5	All ball neck failures
45 micron hook	SETUP 3	40 wires/machine	9.5 to 12.0	1.5 to 2.5	Ball neck & weld failures

5.1.4 The Effect of Wire Elongation on Bond Pull Strength

Wire elongation is an important factor in bond pull strength. It is defined as the amount of strain at a particular stress level. Wire that has a high tensile strength, but low elongation value will break more easily than a wire with good elongation qualities. Power devices may use large wire diameter in the range 5 - 20 mil (0.13 - 0.5 mm) and elongation of up to 20%. Wires with a larger elongation have higher bond pull strength in spite of all other factors being equal.

The increase in the bond pull strength of high elongation wires is attributed to an increase in the final loop height. Figure 5.1.18 shows the loop height change vs. elongation for three different bond lengths, all starting with the same initial loop height. During pull test the final loop height is greater than the original loop height, the final loop height is directly proportional to the elongation of the wire and this will have significant impact on the final pull value. Loop height is an important factor in determining the bond pull strength. We see here that significant wire elongation during bond pull test changes the loop height and this affects the magnitude of the pull strength.

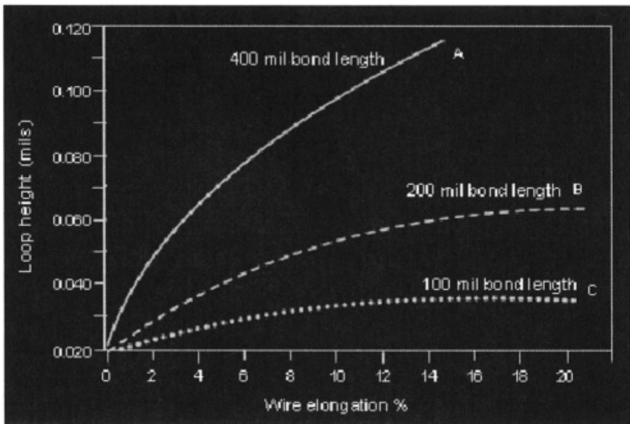


Figure 5.1.18 The effect of wire elongation on the loop height during pull test **[Q-5]**

5.1.4.1 Effect on Elongation during Packaging

IC devices assembled in CERDIP and ceramic packages are sealed at a temperature of approximately 320 - 480°C. This high temperature exposure of the wire results in annealing of the wire and the elongation increases dramatically, and this will have an impact on the bond pull value. The annealed bond pull value will be much lower than the pre-seal pull value. In many instances, the breaking strength of the resulting annealed wire may be less than one-third of its pre-seal value and the elongation typically increase by 8 to 10%. The bond pull strength is generally expected to be directly proportional to the reduced breaking strength of the wire. However, because of the elongation effect, the reduction in pull value (post seal) is much less than the reduction in breaking strength. It is apparent that the tendency of the bond pull strength to decrease with decreasing wire breaking strength will be partially or entirely offset by the increase in bond pull strength resulting from increased wire elongation. In practice, the properties of wire will vary from manufacturer to manufacturer or different lots from the same manufacturer. Therefore we should recognize that the bond pull strengths have no direct correlation with the wire breaking strength, particularly in case of wires with high elongation.

5.1.5 Effect of Wire Length on Bond Pull Strength

The bond pull strength decreases as we increase the length of the bond wire. The pull value is lower at lower loop heights. Figure 5.1.19 shows the theoretically calculated pull values for different loop heights and different wire lengths. The pull value is directly proportional to the loop height and inversely proportional to the wire length.

In order to avoid the wires from having different loop heights and wire lengths it is very important that one should follow proper bond rules. In such situations it is important to establish the lower and upper specifications limit for bond pull value for specific loop length and loop height. The effect of bond length on wirebond pull strength is shown in table 5.1.3. As the bond length increases, the pull value decreases. There is dramatic variation in pull values depending on diameter of the wire. Therefore, we must take extreme

care in establishing lower and upper specification limits for bond pull strength, for specific loop length and wire diameter.

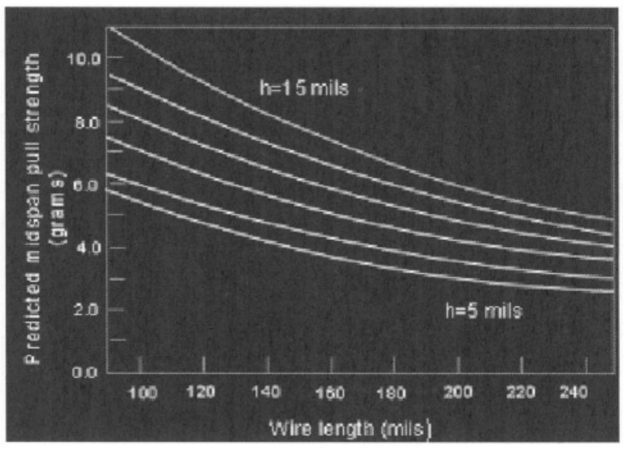


Figure 5.1.19 Pull strength vs wire height and length

Table 5.1.3 The effect of bond length on wire bond pull strength [Q-6]

Bonding wire diameter	25.4 µm (1-mil)		18 µm (0.7-mil)	
Bond length	Pull statistics[a]	Min-Max pulls[a]	Pull statistics[a]	Min-Max pulls[a]
0.51 mm (20-mils)	10.5 ± 0.8	8.8 - 11.8	4.5 ± 0.4	3.8 - 5.5
1.02 mm (40-mils)	9.2 ± 0.9	6.9 - 10.8	3.2 ± 0.5	2.4 - 4.3
1.52 mm (60-mils)	7.4 ± 1.0	5.7 - 9.1	2.3 ± 0.4	1.8 - 3.0
2.03 mm (80-mils)	6.6 ± 0.7	5.2 - 7.9	2.0 ± 0.3	1.4 - 2.3
2.54 mm (100-mils)	5.8 ± 0.5	4.8 - 6.6	1.8 ± 0.3	1.5 - 2.7

5.1.6 Effect of Loop Height on Bond Pull Strength

Effect of loop height plays a significant role in bond pull test. The bond pull strength value is a function of geometry of the wire loop. It has been observed that higher the loop height, higher is the bond pull value. If a wire has high elongation, during pull test the wire gets elongated to a higher loop height resulting in higher bond pull value. Therefore in many assembly factories, the engineers increase the loop height to meet customers demand for higher pull values. But this is not an indication that the process of bonding has been improved.

5.1.7 Effect of Loop Parameters

The loop height of a bond wire is controlled by two major parameters: reverse loop and kink height. As shown in figure 5.1.20, the loop profile depends on the kink height, reverse loop and the trajectory of the bond head. For every loop profile, there is a safe trajectory. Below this safe trajectory the wire has a tendency to buckle, whereas above this safe trajectory, the wire has a tendency to break.

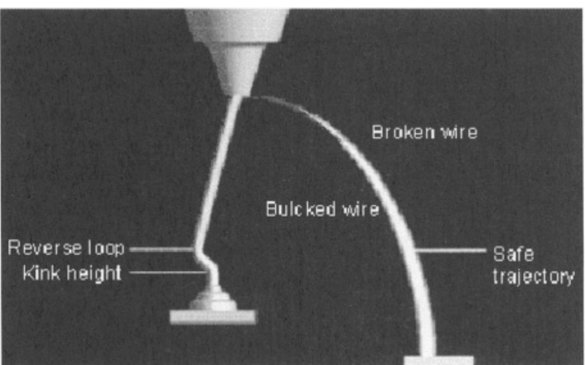


Figure 5.1.20 Schematic representation of reverse loop and kink height
[Courtesy: Kulicke & Soffa]

It has been found that, by controlling the reverse loop functions of the bonder, to obtain the same loop height, one could generate very low or high percentage of ball neck failures. The data shown in table 5.1.4 shows the increase in the weld failure and wire break as the reverse loop is decreased. As the number of ball neck failures decrease, the number of wedge failures increase along with an increase in midspan wire break failures

This indicates that the process engineer has to make the right loop height parameter selection, in order to guarantee minimum ball neck failures. A loop height variation of one mil from lot-to-lot could also put SPC pull charts out of control.

Table 5.1.4 Effect of loop characteristics on detectability of wedge failures [Q-7]

	Test 1	Test 2	Test 3	Test 4
Total No. Tested	62.0	62.0	62.0	62.0
X (g)	15.5	16.9	16.9	17.1
σ (g)	1.4	1.1	1.3	1.5
Ball neck failures	59.0	41.0	20.0	9.0
X (g)	15.4	16.8	16.8	17.1
σ (g)	1.4	1.1	0.5	0.8
Wire break failures	3.0	12.0	31.0	30.0
X (g)	17.2	17.6	17.7	17.7
σ (g)	0.2	0.7	0.5	0.8
Wedge failures	0.0	9.0	12.0	23.0
X (g)		16.2	16.7	16.7
σ (g)		1.2	0.9	1.8

5.1.8 Analysis of Force Distribution during Bond Pull

Now that we have looked at the impact of different parameters on the pull value, let us look at the distribution of force along the wire during pull testing. This is done using theoretical analysis of the bond wire structure. From simple static's it can be shown that the bond pull strength is a function of:

- location of the hook on the bond wire
- loop height

- die thickness
- length of the wire
- angle of pull and
- elongation of the wire

The equation that governs the force vectors along the chip side wire and the package side wire is given as:

$$F_{wt} = F\left[\frac{\{h^2 + \varepsilon^2 d^2\}^{1/2}\ \{(1-\varepsilon)\cos\phi + \frac{(h+H)}{d}\sin\phi\}}{h + \varepsilon H}\right]$$

$$F_{wd} = F\left[\frac{\{1 + \frac{(1-\varepsilon)^2 d^2}{(H+h)^2}\}^{1/2}\ (h+H)\ \{\varepsilon\cos\phi - \frac{h}{d}\sin\phi\}}{h + \varepsilon H}\right]$$

The bond pull strength increases as the hook position gets closer to either of the bonds. It can be observed from the equation, that the Fwt and Fwd changes depending on different values in the equation [Q-8, 9].

5.1.8.7 Simulation of Bond Pull Forces

In order to analyse the forces acting on the ball and the wedge, a simulated bond pull test was performed with strings and spring scales. This can be see in the figure 5.1.21.

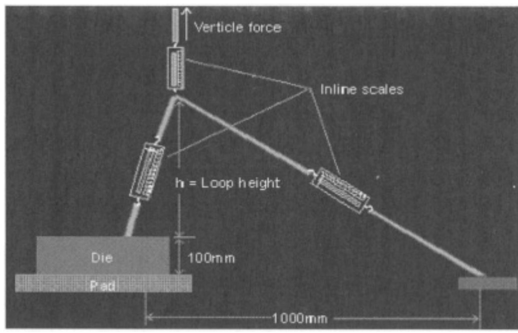


Figure 5.1.21 Simulated bond pull test [Q-7]

From the actual experiments it was found that, depending on the hook position either at the middle of the wire span or at the top of the loop, the force experienced by the ball and the wedge were different. Figure 5.1.22 shows the force experienced by the ball and the wedge depends on the position of the hook as well as the loop height. When the hook is positioned at the highest point, the loop height increases while the stress on the wedge decreases dramatically. For example, for a 600 mm loop height, and 5 kilogram vertical force, the stress on the wedge is only 0.9 kilograms while the stress on the ball is 4.2 kilograms [Q-7].

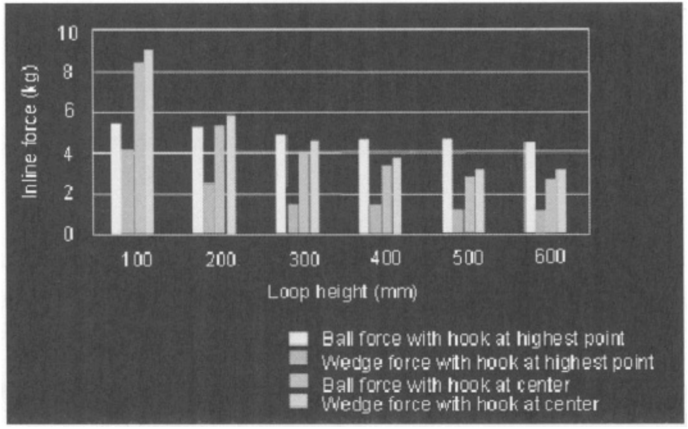


Figure 5.1.22 Force comparison during simulated bond pull test **[Q-7]**

5.1.9 Angle of Pull and Failure Modes

There are a number of important variables of the bond pull test that must be considered. For example, placement of the hook during testing. From the simulated bond pull test, it was found that when the hook is placed in the middle there were lot more ball neck failures. When the hook is placed in the middle of the wire during pulling, it will lead to micro damage at the ball neck.

During bond pull test the wire bends towards the hook. This bending motion generates a micro crack. When we apply force and pull the hook

upwards, the microcrack propagates and tears the neck of the ball. Figure 5.1.23 shows the ball neck deformation and microcrack of the bond.

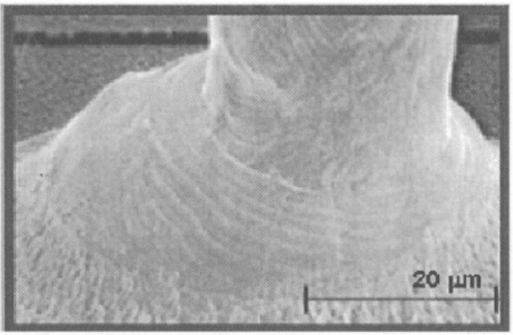


Figure 5.1.23 Ball neck showing deformation and microcrack [Q-7]

Let us take an example how tensile stress can accelerate crack propagation. Take an A4 size paper and hold the two ends and pull it as shown in figure 5.1.24(a). It takes a lot of stress to tear the paper. In this case, when we apply tensile stress, the crack initiates and propagates at a very high pull stress.

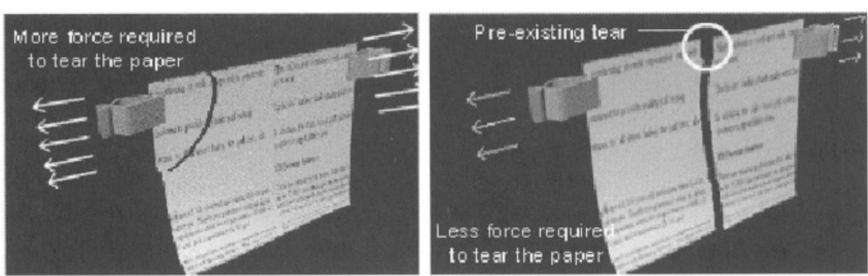


Figure 5.1.24(a) Paper pull test without pre-existing tear 5.1.24 (b) Paper pull test with pre-existing tear **[VIEW-IN-CDROM]**

If a small tear in the A4 paper already exists as shown in figure 5.1.24 (b), then less tensile strength is required to tear the paper. Similarly, when a

micro crack exists at the ball neck, the ball neck breaks due to accelerated crack propagation when bond pull force is applied.

Micro crack exists at the ball neck, due to the bonding of wire. When bond pull force is applied, the crack propagates at a much lower stress and results in ball neck failure. This is one of the reasons majority of bond pull data in the semiconductor industry shows only ball neck failures, and very rarely do we ever see weld failures. The ball neck failure masks the weld failures, even though the weld is weak.

If we can do the bond pull test such that we minimize the ball neck failures, then existing weak welds can be detected easily.

In a simulated experiment, second bonds were intentionally bonded with low parameters. As the number of ball neck failures decreased the number of wedge failures increased along with an increase in midspan wire break failures. (Ref table 5.1.4)

5.1.70 Suggested Pull Test Method

In an alternate pull test method, developed by S. Prasad., et-al., [Q-7] the wire is pulled at an angled such that the ball neck is not damaged. Here the force applied on the second bond is equal to the force applied on the first bond, but the first bond is not bent and stressed. Therefore if the second bond is weak, it will fail without being masked by the ball neck failure mode. Depending on the position of the hook between the ball bond on the chip and the wedge bond on the lead finger, the bond wire fails with different failure modes this is shown in figure 5.1.25. The hook position and the angle of pull also determine the direction of stress. The other factors that impact the stresses are loop height, and die thickness.

Using the above suggested pull technique, it has been found that if the second bond is good, then the wires will all break at the wire mid span. Wire break failures can be seen in the figure 5.1.26

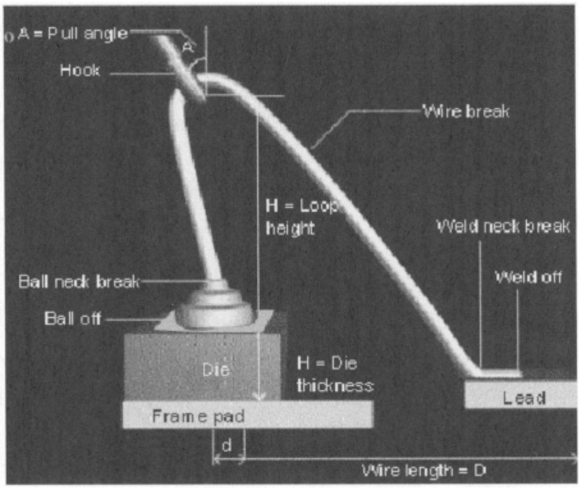


Figure 5.1.25 Hook position and angle of pull can significantly impact bond pull failure modes

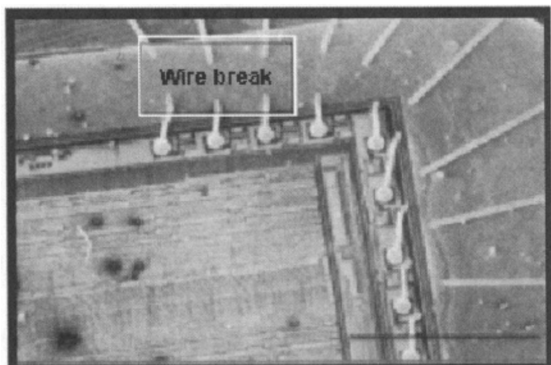


Figure 5.1.26 Wire break failure mode obtained with alternative bond pull test method [Q-7]

5.1.10.1 Advantages of New Pull Technique

Software has been developed for calculating the force on the wedge and the ball neck as a function of the position of the hook, the height of the wire loop, the thickness of the die, angle of pull and other parameters. The position of the hook can thus be optimized so that equal stress is exerted on the ball neck and the wedge during the pull test. The major feature of the alternate pull test is the work holder adaptable to all systems and capable of holding various packages and lead frames without wire deformation during the pull test. This system provides consistent pull test results, detects ball and wedge failures independent of the loop characteristics, and does not deform the ball neck before the pull test. When bonds are acceptable, end-of-test failure usually results in a wire break. Monitoring a bond process with the existing bond pull technique and the alternate method shows that the problem of weld lift was not identifiable by the existing bond pull technique, whereas weld problems were identified easily with the alternate bond pull method.

When we use the alternate pull test technique, the major failure mode is wire break. When we compare bond pull date from bonder B at 2pm we can see that samples pulled with standard pull technique showed X bar value of 11.8 grams and all the failures were ball neck breaks. When the same samples from bonder B at 2pm were bond pull tested with the alternate pull method the X bar value was 20.2 grams with 15 wire break failures, 7 ball neck failures and 18 wedge break failures. A comparative analysis of this date clearly indicates that the standard pull method gives rise to only ball neck failures, consequently masking the identification of weak wedge bonds.

Table 5.1.5 Comparison of pull data: Standard pull test vs Alternate pull test [Q-7]

Bonder	Time	X (g)	σ (g)	Wire Break (No)	Ball Neck Break (No.)	Wedge Break (No.)
A	8am	23.5	1.10	39	0	1
A	3pm	22.8	1,20	40	0	0
B	8am	21.5	1.34	30	9	1
B	2pm	20.2	2.42	15	7	18
B	2pm**	11.8	1.4	0	40	0
B	4pm	17.5	4.6	27	0	13

** Standard pull technique used.

5.1.11 Non-Destructive Pull Test

Non- destructive pull test (NDPT) is similar to destructive pull test but a fixed maximum pull force is applied which should be at the minimum required strength. The purpose of this test is to reveal weak or marginal bonds while avoiding damage to acceptable bonds. In other words Non destructive pull testing is used to check the validity of each wire bond by stressing the bond to a preset (non harmful) limit. The NDPT limit is based on the wire size, wire type and ultimate wire breaking strength. However the loop may get slightly deformed while testing, this can be seen in figure 5.1.27. Since this type of test is costly and time consuming process 100% non-destructive wire bond pull test is rarely used in commercial high volume processes. The NDP testing is generally applicable in case of wedge-wedge bonding or for evaluating the wedge bond in a ball-wedge system. Generalized guidelines are for NDP testing is described in the MIL Std 883, method 2023. [Q-10]

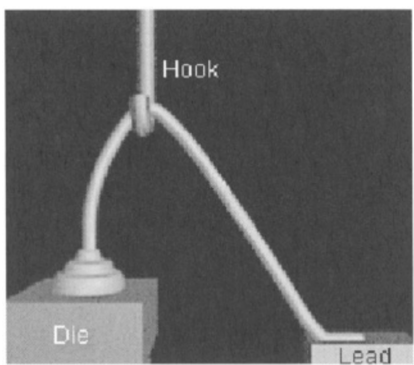


Figure 5.1.27 Non-destructive pull test

NDPT can be introduced into all areas like integrated circuit, hybrid, mutichip module and microelectronic application areas. The elements of this program may vary but should necessarily include:

- an operator training and testing program

- a controlled evaluation of NDPT procedures on representative circuits in the production line (to identify problem areas)
- the establishment of screening guidelines (determined by your equipment and operators) for all future circuits designs.

5.1.11.1 Precautions to be taken during NDPT

In destructive pull test, even if a wire gets damaged during testing, it is not of major consequence. However, during NDP testing it is important not to damage either the bond we are testing, or the neighbouring bond wires. During NDP testing the user have to take lot of precautions. The NDP test methodology is suitable only in case of devices which have enough space between bonds for pull test hook to be introduced. With skilled operators and the current semi-automated testers, minimum applicable wire spacing appears to be approximately 10 mils. Fully automated testers with pattern recognition system (PRS) may reduce this minimum spacing limit.

5.1.11.2 Determining the NDPT Force

There has been no systematic method of selecting the value of the NDP force. Nevertheless, this test has been used for a number of years in specialized high-reliability programs to weed out weak bonds. Usually NDPT pull force value is determined by the wire diameter and customers requirement. Companies currently manufacture specialized equipment for the NDPT of small wire bonded devices.

5.1.11.3 Is NDP Test a Reliable Test?

Now let us try to understand the reliability of the NDP test process. For many years there has been extensive discussion about the merits of NDPT. The fact that the pull value depends on many factors such as wire diameter, wire length, loop height, hook position, hook diameter and wire elongation, it is absolutely unscientific to perform NDPT and make major quality decisions based on the NDPT test data. The NDPT is valid only when the bonding process is totally out of control and one expects to encounter high level of non stick failures and heel break failures.

5.1.12 Testing Weld Strength using Bond Pull

The wedge bond on the lead finger cannot be easily tested by the normal pull method. Therefore, one may do special testing of the second bond by placing the hook close to the wedge and applying upward force on the wire. Due to greater stress and sharper angle of pulls, the failure rate of wedge will be higher. Though this test has been used, it is not a reliable test because the pull test data and the failure mode does not correlate with the actual mechanism of failure.

5.1.13 Bond Pull Equipment

There are many companies manufacturing equipment for bond pull testing. Different companies use different concepts for the application of pull force during the test. Few simple concepts are described here. One of them is the cantilever concept.

The cantilever with force-sensing system consists of a stainless-steel cantilever with four sensitive strain gauges attached. The pull hook is attached to a shaft that is suspended without friction by an air bearing. The force sensing system can detect movement in the thousandths-of-a-gram range. As shown in Figure 5.1.28(a) the wire-bond pull tester based on cantilever beam and the strain gauge is used to measure the force applied to pull the wire. The second concept is based on movable weight and air dashpot system. Figure 5.1.28(b) shows the manual wirebond pull tester. In this pull tester, a movable weight applies a tensile pull on the hook. The air dashpot is used to make the force application uniform and smooth.

Modern bond pull testers, contain sophisticated Optics, specific load cartridges, adapter plates and work holders to meet specific package requirements. Load cartridges are available with different load values to suit the anticipated breaking strength of the bonds to be tested.

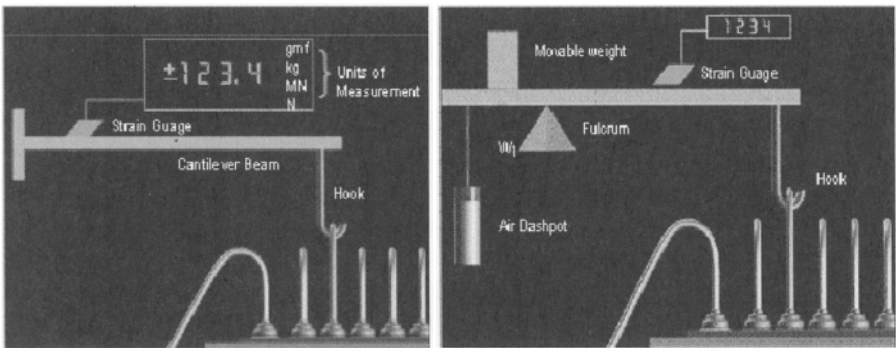


Figure 5.1.28 (a) Semiautomatic wire bond pull tester *Figure 5.1.28 (b) Manual wirebond pull tester.* **[Adopted from product catalog: Unitek Corporation] [VIEW-IN-CDROM]**

5.1.13.1 Hook Holders

The hook must have the freedom to move in any direction and also rotate in 360 degrees. This flexibility is necessary for accurate positioning of the hook, during bond pull test. A pendulum type hook holder is used to meet Mil.std. specifications. In some cases a semi rigid hook holder, which allows hook movement parallel to the beam but resists movement in any other plane, is also used. Beams are designed to move the hook vertically as the beam is raised or lowered.

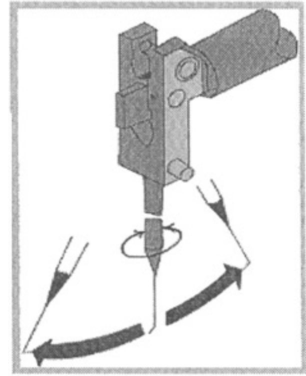


Figure 5.1.29 Semi rigid hook holder **[Adopted from product catalog: Unitek Corporation]**

Because of constraints imposed by MIL-STD-883B and 883C, the hook is allowed to pivot through a limited angular range in the front-to-back plane and is not allowed to pivot from side-to-side. In figure 5.1.29 we can see a semi rigid hook holder.

The MIL-STD also requires that the NDP should start with the hook positioned midway between the two bonds. Assuming single level bonds, the result is that the wire bond is reformed into an isosceles triangle wherein the pull force on each bond is equal. Beam design can vary from one application to another.

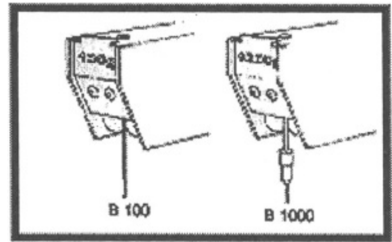


Figure 5.1.30 Beam design for different application. [Adopted from product catalog: Unitek Corporation]

We can see beam design used for different application in figure 5.1.30. Depending on the strength of the wire, beam design with 100gm and 1000 gm force application are used. It is also possible to have beam design which incorporates a rotatable hook can also be incorporated in the beam design.

5.1.14 Auto Bond Pull Test

The economic pressure of manufacturing have driven many companies to extensively automate assembly. Automatic wire bonders suggest the need for automatic wire pullers. The wire bonding is rapid in comparison to the labor-intensive manual inspection and wire-pull procedure. That has led to design and development of auto bond pull testers. The automation of this intricate task required the integration of several technologies. In the automatic bond pull method the operator only has to references the package or the hybrid on the work stage, after which the system locates and pull tests all wires on the module. Every wirebond connection must be verified for correct location and for a minimum pull-strength, particularly in space and military products. The design goals for an automatic wire-pull tester are:

- compatibility with existing manufacturing
- user friendly operation which requires minimum training time

- equipment capable of operating in a computer integrated manufacturing (CIM) environment.

For automatic wire pulling, a time efficient force-sensing system is necessary. As explained earlier one of the auto pull testers available in the market is the cantilever with force-sensing system which consists of a stainless-steel cantilever with four sensitive strain gauges attached. The pull hook is attached to a shaft that is suspended without friction by an air bearing. This shaft is roller bearing suspended from the cantilever. The force sensing system can detect movement in the thousandths-of-a-gram range. In addition, the auto bond pull system returns to all wires failing the pull test, allowing the operator to input failure data.

5.1.14.1 100 Percent Wire Bond Autotest

There are standard pull testers that offer high-speed 100 percent automatic wire-bond testing of up to 15,000 discrete points on any given substrate. These equipments are easily programmable using an alphanumeric keyboard with liquid-crystal display, these equipments meet the requirements of MIL-STD-883 speed (<2 seconds per wire), precision **(±5 μm)** and consistency **(± 10 μm).** These modern pull testers are fast, precise and consistent completely eliminating the test process inaccuracies resulting from operator fatigue. One such equipment is shown in figure 5.1.31

5.1.14.2 Pattern Recognition in Auto Testers

Pattern recognition furnishes the ability to perform automatic alignment of components. Compared to the time-consuming, fatiguing and error-prone process of manual alignment, pattern recognition represents a significant technological step forward in automating IC assembly and inspection. Touch sensitivity of 1 gram protects wires from damage. Automatic bias reposition control (ABRC) ensures that if anything is in the test-hook's path which is not expected to be there, it will not be damaged. If a wire is not placed where it is meant to be, the system looks in the most likely direction in order to find it [Q-11].

Bond pull testing with auto testers is a simple process. The program disk is simply loaded into the bond pull system. The operator has to initiate 'run'

mode. It is a simple task to 'teach' the system the wire position and the test points. The new testers have high accuracy and the test table can be positioned with 5 μm resolution. The accuracy of the applied load is better than ± 0.5%. These auto testers are capable of both destructive and non-destructive pull tests. The video pattern recognition option is used to compensate for manufacturing variations in die and package placement, thus allowing accurate determination of test point locations. Factory automation and control is possible by interfacing with mainframe and other computers. It allows downloading of test data for storage and further analysis by factory automation and statistical control systems. (Refer Bonding Equipment chapter for more detail)

Figure 5.1.31 Automatic bond pull equipment [Adopted from product catalog: Dage Corporation]

5.1.14.3 Multihead Operations

Bond pull test throughput can be enhanced by configuring the testers with multiheads. Here the pattern recognition system identifies the precise geography of the work which is then passed to separate pull stations for testing and analysis.

5.1.15 Bond Pull Test Specification

There are no defined industry standards for bond pull technique procedures. Presently, each semiconductor manufacturer has their own original test specifications and criteria. Below are some recommended steps in obtaining reliable and consistent data from bond pull testing.

5.1.15.1 Recommended Sampling

To monitor wire bond process, all wires from a device must be pulled for reliable SPC. However, in large pin count devices, this may mean more than 100 to 200 wires per device. Pull testing large number of wires is not a manufacturing worthy process. Therefore, the bond pull test must sample bonds from different parts of the device. It is suggested that one selects wires from all four sides of the device and preferably wires with different length and loop height. From each side of the device, selects the same number of wires randomly. Pull the same wires each time for SPC monitoring. For process control using bond pull testing in a high pin counted wires, it is recommended that we select corner wires, centre wires in both X and Y directions.

5.1.15.2 Bond Pull Tester Calibration and Standardization

Calibration of bond pull equipment should be done using official and traceable weights. The weights should be displayed to verify whether the results are within the equipment's accuracy. Measurement must be repeated using other weights to verify repeatability and linearity of the calibration. Calibration must be done at regular intervals, and the equipment must provide the ability to calibrate just before testing when necessary or specifically instructed.

5.1.15.3 Bond Pull Test Procedure

Listed below is the procedure for bond pull testing

- fix samples using a clamper or adhesive so that the sample will not float, without applying excessive stress to the wire
- set pull speed to 0.5mm/sec while measuring
- insert the hook under the bonded wire between the top of the first bonding and the centre of the loop
- select the proper hook position accordingly to package, wiring condition, and wire diameter
- place the hook perpendicular to the wiring direction, if there is no specific instruction
- do not measure damaged or deformed wire
- pull the hook perpendicular to die/substrate
- record the force that breaks the wire as the pull strength
- repeat the measurement on another wire
- do not change the position while testing the same samples

Report of the pull test must contain the following information: Pull strength, failure mode, hook position, rejection criteria (is the criterion of each semiconductor manufacturer to each product)

5.1.16 Limitations of Wire Bond Pull Test

The destructive wire bond pull test, however, has limitations in at least two significant areas. First, since the pull test by its very nature is destructive, it can provide information only on a lot sample basis or in a post-mortem fashion. Thus, it does not provide a measure of quality for each bond. Second, the destructive wire bond pull test provides very little information on the strength and overall quality of the first and second bonds themselves (i.e., the wire-bond pad interfaces). Obviously, only in cases of catastrophic bond failures, such as impurity-driven intermetallic growth, the destructive wire bond pull test yield information other than the relative breaking strength of the bonding wire.

These factors have. led to the development of a complementary wire bond tests namely ball shear test. The ball shear test can be used to investigate not only the integrity of the ball bond-bonding pad interface, but also the influence of both pre- and post-bond processing factors.

5.1.16.1 Wedge Bond Pull Test

As we studied about gold ball bond pull test, let us review little information about wedge bonding pull test and its failures. The major failure modes that one observes during an Al wedge-wedge bond pull test are:

A type: Wedge peel off / lift off from chip
B type: Heel break at first wedge
C type: Heel break at second wedge
D type: Wedge peel off / lift off from lead finger

As shown in the figure 5.1.32, in wedge bonding the major failures are bond lift on the chip, bond lift on the lead or heel break at the first bond or heel break at the second bond. Sometimes we also observe wire break at the mid span.

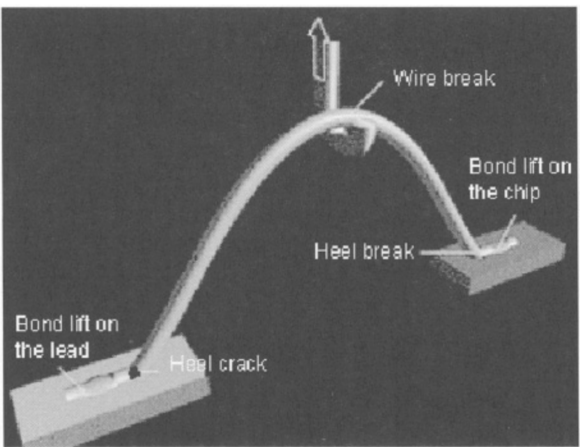


Figure 5.1.32 Wedge bonding pull test failure modes

Depending on the hook position between the first wedge bond on the chip and the second wedge bond on the lead finger, the bond wire fails with different failure modes during the pull testing. The wedge bonding pull test

data needs to be interpreted differently. Let us discuss each failure mode in detail.

5.1.16.2 The Wedge Peel Off

During the pull test, if the wedge peels off either from the bond pad or from lead finger, this indicates incomplete bonding. Even though the bond pull force may be high the failure mode is unacceptable.

5.1.16.3 The Heel Break

The major failure mode in wedge bonding is the heel break. During wedge bonding the wire transits from the loop to the bond pad and forms a heel. This transition is always weaker than the wire and the wedge. If excessive force and/or US energy is used during bonding, the heel area will have micro cracks. These micro cracks facilitate fracture during pull test. The ideal failure mode in case of a wedge bond is a heel break with highest bond pull force value.

5.2 Ball-Bond Shear Test

The destructive wire bond pull test has limitations, in that it provides very little information on the strength and overall quality of the first bond (i.e., ball-bondpad interface). A simple wire pull test does not fully explore the characteristics of a ball bond. A quality ball bond can withstand up to ten times the wire pull destruct force but a low quality bond will still take more force to pull off than a wire pull test will provide, i.e. a low quality ball bond may not fail under wire pull test conditions. Only in cases of catastrophic bond failures, such as impurity-driven intermetallic growth, will the destructive wire bond pull test yield information other than the relative breaking strength of the bonding wire. Thus pull tests fail in determining the true strength of ball bonds. This factor has led to the development of a complementary wire bond test methodology, the ball-bond shear test.

Ball shear testing is used to assess the integrity of the gold ball-to-bonding pad interface in the gold ball bonding process. It is also a destructive test. Ball shear data reflects the intermetallic formation and its coverage of bonds. It is measured by gram force over the area of the ball formation.

5.2.1 Description of the Test

A shear tool is used to perform this test. During testing this tool pushes the ball bond with a sufficient force. Positioning of the tool is very important during shear testing. The shear ram is positioned just above the bond pad such that the bottom of the shear tool is close to the centre of the ball. The shear tool moves parallel to the bonded surface and shears the ball bond. Figure 5.2.1 shows the placement of the shear tool.

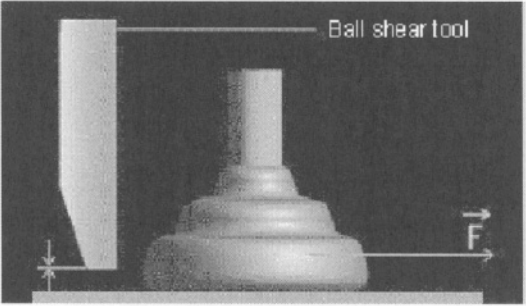


Figure 5.2.1 Ball shear test

The improper positioning of the tool is one of most common problem in shear test. During the ball shear test the shearing ram needs to be positioned exactly according to criteria described in the ball shear test specification. For a normally deformed ball, the tool should approach from 2.5 to 5 μm above the substrate and for large, high balls, it must be no higher than 13 μm. Otherwise the tool could drag on the substrate. Figure 5.2.2 shows the step by step movement of Shear Ram and the failure modes of the ball bond. Fig 5.2.2(a) shows the ball shearing at the neck, Fig 5.2.2(b) shows the ball shearing at mid way leaving the gold residue, Fig 5.2.2(c) shows the ball detaching from the aluminium pad due to incomplete intermetallic

formation, Fig 5.2.2(d) shows the aluminium metallization delaminating during shearing which may lead to formation of a crater.

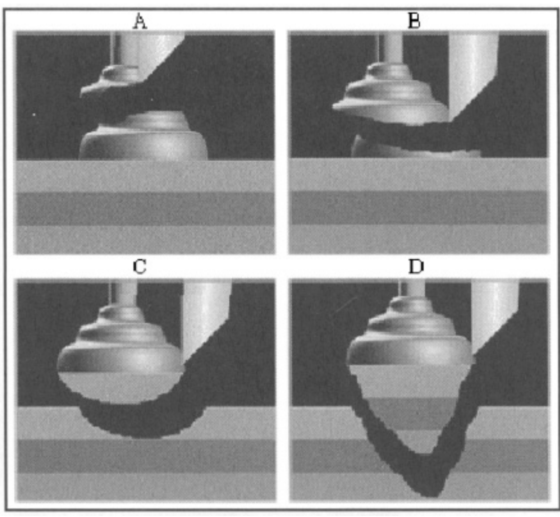


Figure 5.2.2 Shear test failure modes **[VIEW-IN-CDROM]**

The resultant failures can be visualised only by trained operator under a microscope. There are many interferences and measurement errors that can lead to improper analysis of shear data, and may result in misleading conclusions. So, it is important to determine whether the failures are legitimate or not. The failure modes generally observed during a ball shear test are: ball lift / partial metallization lift off, ball shear, bond pad lift and cratering. Let us review and discuss each of the above mentioned failure modes in further detail.

5.2.1.1 Ball lift / Partial Metallization Lift Off

A ball lift is defined as a separation at the bonding pad interface with little or no intermetallic formation present or remaining (area of intermetallic less than 25% of the bond deformation area). Figure 5.2.3(a) shows part of the Al

metallization sheared with the ball, leaving partial metallization on the bond pad during shear test.

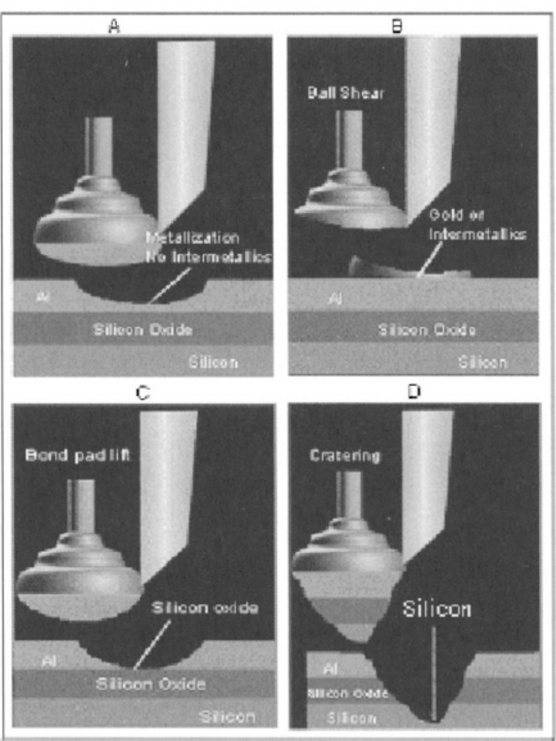


Figure 5.2.3(a) Ball lift, (b) Ball shear, (c) Bond pad lift, (d) Cratering

5.2.1.2 Ball Shear (Weld Interface Separation)

During ball shear test, if the intermetallic formation is pronounced, then the ram may shear the whole ball leaving gold or an intermetallic on the bond pad as shown in the figure 5.2.3(b)

5.2.1.3 Bond Pad Lift (Substrate Metallization Removal)

Another failure mode during shear test is bond pad lift. In this failure one can see the separation between the bond pad and the underlying substrate. The aluminum metallization is peeled off leaving SiO_2 exposed. This may occur due to improper adhesion of aluminum metallization. Here the interface between the ball bond and the residual pad attached to the ball remains intact as shown in the figure 5.2.3(c)

5.2.1.4 Cratering

Cratering is a general term used to describe one type of bonding failure that occurs as the result of mechanical damage to the bond pad or underlying material. This failure occurs on the underside of a wire bond during bond pull or shear test. Cratering occurs as a result of cracks generated under the bond pad during bonding. Figure 5.2.3(d) shows cratering effect during ball shear test.

5.2.2 Ball Shear Equipment

The ball shear test and equipment were introduced in the late seventies. However, it took almost a decade for this test to become popular. One of the main reasons was lack of standards and the lack of availability of precision equipment that was easy to use. But today, there are many companies that have ball shear equipment.

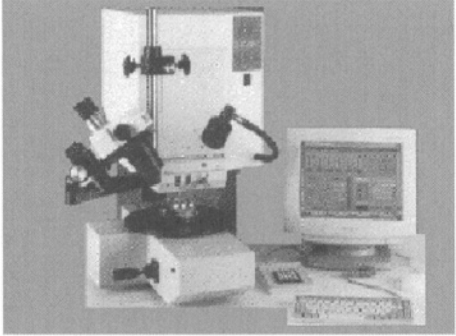


Figure 5.2.4 A ball shear test equipment [Adopted from product catalog: Dage Corporation]

The advanced machines such as one shown in figure 5.2.4, have automatic vertical position finder, which can record shear force and failure modes and can be interfaced with computers for data analysis. Table 5.2.1 describes some of the details of bond shear test equipment. Some critical parameters to look for are shear tool size, accuracy of tool positioning, tool landing force and load cartridge accuracy.

Table 5.2.1 Typical specification for shear equipment [Adopted from product catalog: Dage Corporation]

Size (W X L X H)	500 X 660 X 420mm (20 X 26 X 16 1/2 in)
X-axis travel	2.0mm (0.08in)
Shear tool size	0.15mm (0.006in) tip width
Z-axis travel	20mm (0.8in) - stepper motor driven
Intelligent 'Z' tool positioning	0.005 ± 0.0025mm (0.0002 ± 0.0001 in)
Tool landing force	3 to 7g (0.107 to 0.25 ozf)
Load cartridge accuracy	± 0.4% max rating
Load beam deflection	0.5 mm (0.02in) full scale

5.2.2.1 *Shear Ram Size and Selection*

The most critical part of a shear tester is the shear tool also know as shear ram. The shear ram is designed in different configurations. Usually the thickness is between 150 to 200 microns and the foot print is about 0.025 millimetre square. The shearing ram is shown in Figure 5.2.5.

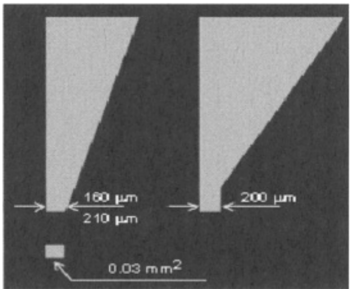


Figure 5.2.5 Ball shear ram

Many varieties of shear ram are used in ball shear test. Apart from the vertical shearing ram, one can also use horizontal shearing ram. However, the most commonly used is the vertical shear ram. Fig 5.2.6 shows both the horizontal and vertical shearing ram.

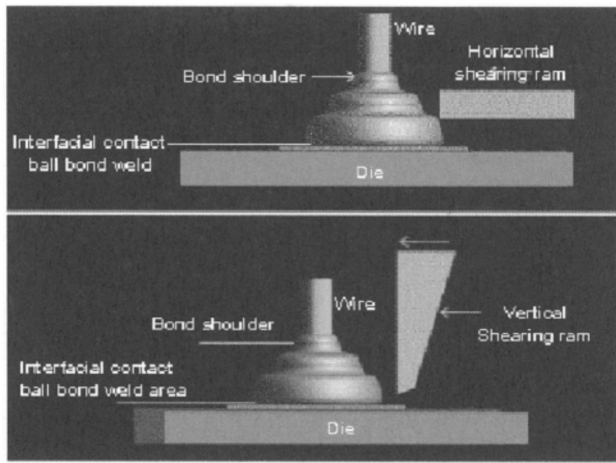


Figure 5.2.6 Horizontal and vertical shear ram [Q-11]

5.2.2.2 *Size of the Shear Ram*

The selection of the shearing ram size depends on the ball diameter which in turn depends on the wire diameter. The ideal shear ram size will be the diameter of the ball. However, we use shear rams of 100 microns to 200 micron in size. For smaller wire size, we use shearing ram of size 120 microns, and for larger wires the ram size is approximately 200 microns. Figure 5.2.7 shows the shearing ram size range for different wire diameter.

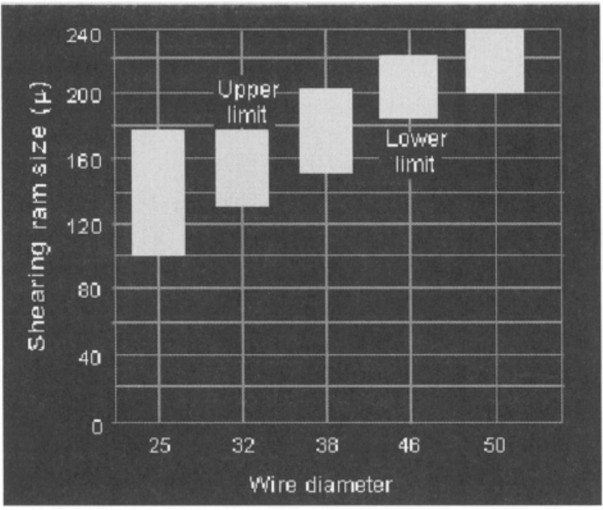


Figure 5.2.7 Shearing ram size range for different wire diameter [Q-12]

5.2.2.3 Cleanliness and Wear of Shear Ram

When a shear ram is being used continuously, it will pick up micro bits of aluminum metallization, passivation or gold metal. This may prevent proper vertical positioning leading to inconsistent shear test. This problem is more prevalent in fine pitch bonding and particularly with gold bonds which are flatter. Shear tools must be monitored and replaced with the same urgency as bonding tools. Shear tools used for fine pitch balls ($\leq$ 80 µm bonded diameter) require more frequent monitoring than tools used for coarser pitch.

5.2.3 Ball Shear Test Process

When ball shear test was first introduced, the biggest concern was positioning the shear ram accurately next to the ball. And positioning the shear ram consistently at the same height and same distance from the ball required tremendous patience and an experienced operator. Some of the

problems while doing shear test include: Not maintaining correct height between the ball and the shear ram- Figure 5.2.8

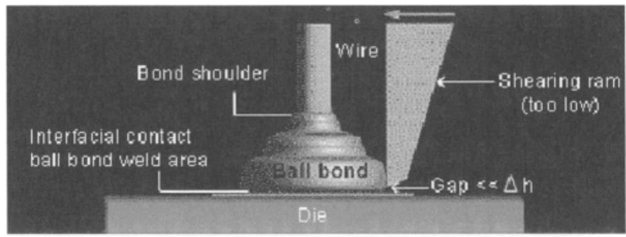


Figure 5.2.8 Shearing ram position too low [Q-11]

- Shear ram is too high and having complete and consistent contact with ball – Figure 5.2.9

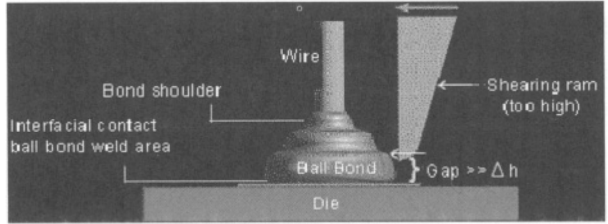


Figure 5.2.9 Shearing ram position too high [Q-11]

- Shear ram is tilted either towards the ball or away from the ball - Figure 5.2.10

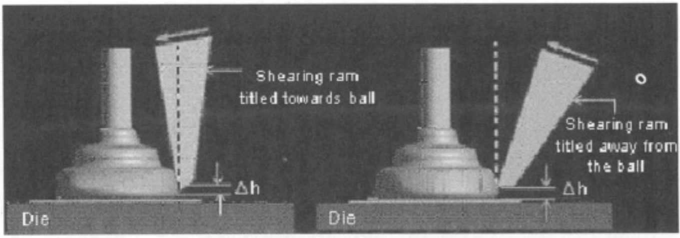


Figure 5.2.10 Shearing ram tilted [Q-11]

In each of these cases the force at which the shear failure takes place and the mode of shear failure will be different from normal.

In today's ball shear testers, the equipment comes with intelligent shear ram positioning features that eliminate inconsistencies. With the new shear testers the shear ram comes down and senses the chip surface and then moves back to a predetermined height. When the motor drives the shear tool horizontally, the tool pushes the ball and completes the test. The schematic representation of the complete procedure of the tester is shown in figure 5.2.11.

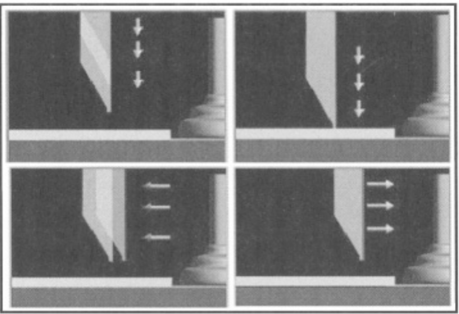


Figure 5.2.11 Sequence of shear test **[Adopted from product catalog: Dage Corporation]**

5.2.4 *Shear Test Variables*

The shear test variables that influence shear force value are: operator technique, shear tool geometry and bonding temperature. Let us review each one in detail.

5.2.4.1 Operator Technique

Alignment of the shear tool with respect to the ball is an operator related source of error. Due to the inherent curvature of the ball bond, any variation in the point of cleavage will result in differing shear strengths. When a shear tool pushes the ball, the shear force exerted on the ball depends on the contact area of the shear tool with the ball. If the ball has a perfect spherical

shape, the tool has a large surface area of contact whereas if the ball is slightly oblong, the shear tool has a smaller surface area of contact. Figure 5.2.12 shows tool contact with round and oblong ball

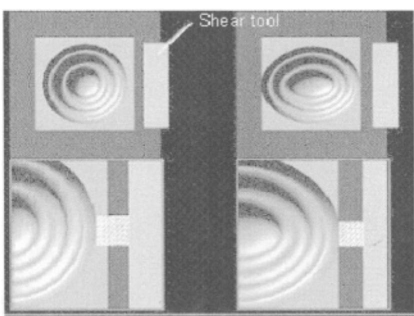


Figure 5.2.12 Tool contact with round and oblong ball

5.2.4.2 Shear Tool Geometry

Tool size also plays an important role. If the tool is too large and if there is some camber in the substrate, portions of the substrate metallization may be contacted along with the ball, thus increasing the recorded shear strength. An ideal shear tool would have a shearing face width equivalent to the ball diameter (typically 75 microns) with perhaps a slight curvature to capture the ball. Ball shape can also influence the ability to properly shear a ball bond. When the shear tool is positioned such that the tip is at half the height of the ball, it shears the ball smoothly. If during bonding, the ball becomes flat, then the shear tool rides up the ball and shears the wire instead, as shown in figure 5.2.13.

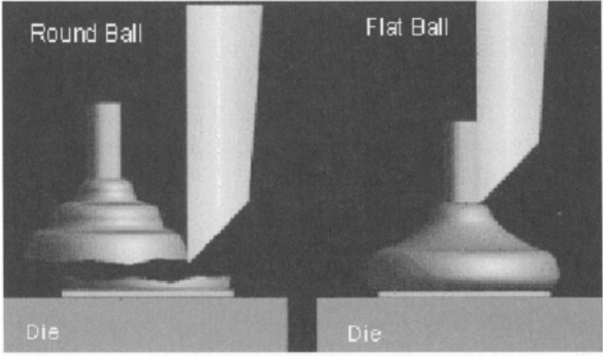


Figure 5.2.13 Shear tool rides up when ball is flat

A "three-quarter sphere" ball is found to be the most desirable shape for shearing. This results in better contact between the shearing ram and the ball.

5.2.4.3 Bonding Temperature

If the device is exposed for long time at high bonding temperature, then the first bond will have higher intermetallic compared to the last ball that was bonded on the device. And this impacts shear value. This may be due to high bonding temperature which is found particularly in very high pin count devices. Some additional variables which can influence the out come of the shear-test are: surface topography, fluctuation or drift in bonding machine parameters, operator fatigue, machine operation, external parameters. Some of the other variables that affect the shear test are:

Shear Tester **:** Accuracy and repeatability of the shear tester impacts the shear force value.

Shear Testing Process **:** Direction of application of the shear force has been found to have an effect on the shear force value.

Chip Design **:** The bond pad periphery has a passivation window. When the ball bond covers the whole bond pad, the shear ram will land on the

passivation. If there is any variation in passivation layer this will cause the shear ram to "scuff" and result in higher shear force value.

Bond Shape **:** It is always assumed that the ball is perfectly round and therefore the ball presents a uniform surface to the shear tool. But this is not always true. Depending on the Free Air Ball shape and the capillary configuration, the ball may have an "oblong" shape. This will impact the way the shear tool makes surface contact with the ball.

For Statistical Process Control (SPC) using shear test, one clear objective should be to minimize the inhomogeneity of the shear test sample population. We can achieve this by randomizing both the bonding and shearing patterns. This way we can minimize the effects of errors, which are not clearly understood or which cannot be controlled. For example, during the bonding procedure the ball size after flame-off may differ. This results in a variation of the cross-sectional area of the ball, which directly influences the indicated shear strength.

5.2.5 Shear Test Interferences and Measurements Errors

There are many interferences and measurement errors that can lead to improper analysis of shear data, and may result in misleading conclusions. So one has to maintain the proper position of the shear ram during the ball shear testing to obtain consistent results. The measurement errors are mostly caused by improper positioning of the ram. We generally observe two types of failures when the shear ram is not properly positioned, namely wire shear and Shear ram drag.

5.2.5.1 Wire Shear

Here the ball is sheared too high or off-line. When the shear test is done, only a minor fragment of the ball remains on the pad which is attached to the wire. The major portion of the ball remains on the pad with the bond pad weld interface region intact. Rams that are too high or angled upward result in lower than normal shear strength values. Rams that are angled downward or positioned too low, will strike the bonding pad and the substrate, or both,

(chip) and cause inordinately high shear strength as well as potentially damage the shearing ram.

If there is excessive intermetallic growth formed around the ball bond, the shearing ram may contact the intermetallic rather than the ball bond. This may lead to invalid shear readings.

5.2.5.2 *Shear Ram Drag*

As we go to finer pitch balls, the ball heights are getting thinner (15 microns). In this case the tool must be positioned about 6 microns from the bottom of the ball so that it makes perfect contact during the test. If the tool is not positioned properly on the substrate the tool may "drag". The ram experiences friction and gives rise to higher shear force values. Figure 5.2.14 shows ram friction

If the shearing Ram is placed away from the ball and touching the passivation layer during ball shear test, the passivation layer gets damaged during shearing this is termed as 'Scuffing'. Figure 5.2.15 shows the damaged passivation layer.

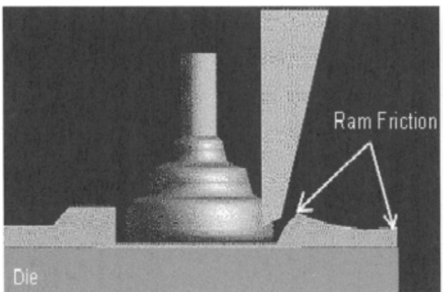


Figure 5.2.14 Ram friction

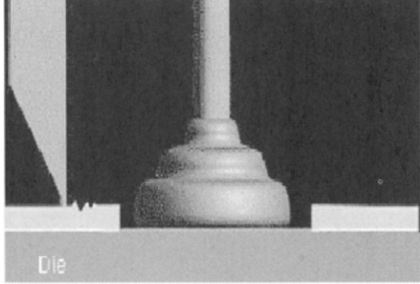


Figure 5.2.15 Scuffing [Adopted from product catalog: Dage Corporation]

5.2.6 *Shear Strength on Different Metallization*

The shear value varies from one metallization to another. For example when gold wire is ball bonded on gold metallization, the mean shear value is much higher than gold ball on aluminum metallization.

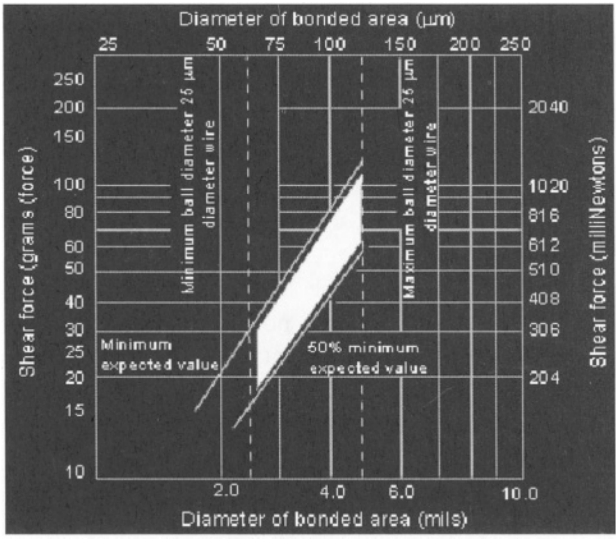


Figure 5.2.16 Ball bond shear strength window [Q-11]

For a particular wire diameter the ball bond shear strength depends on the diameter of the bonded area. Based on a large number of evaluations ASTM has proposed a shear strength window for a 25.4 µm diameter gold wire bonded to aluminium metallization. The shaded area shown in figure 5.2.16 represents the ball bond shear strength window. Similarly a window has been proposed for gold wire bonded to gold thin film metallization. One can see for gold to gold bonding, the window is much narrow.

Windows for other diameter wires (d) can be obtained by multiplying the reading by d^2/do^2 where $do = 25.4$ µm. The ball shear strength of a ball is actually dependent on the effective weld area under the ball. Ball shear strength as a function of bond diameter with effective weld area as a parameter is shown in figure 5.2.17. Here we can see that for high quality gold-gold bond, the effective weld area should be about 90% whereas for gold-aluminum bonds, this is reduced to 75%.

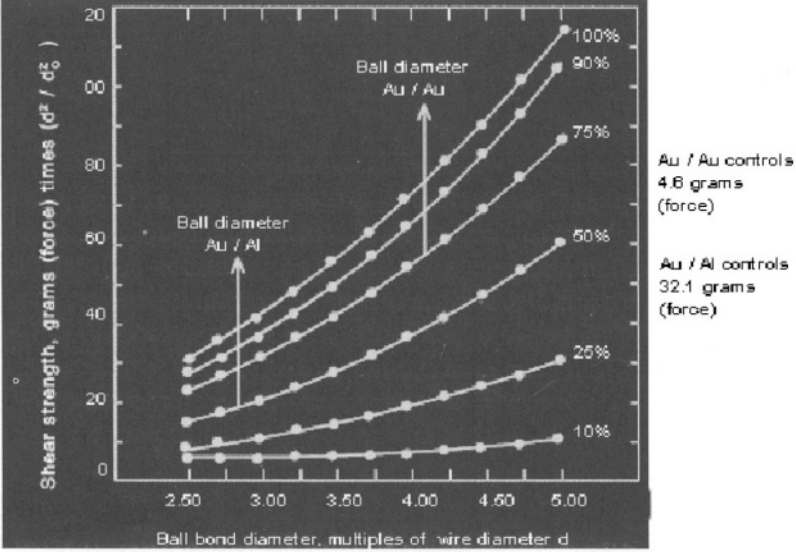


Figure 5.2.17 Ball bond shear strength vs ball bond diameter for gold wire [Q-12]

5.2.6 *Shear Test of Bonds on Uncontaminated Pads*

Evaluations were done with a series of test chips that have been gold bonded immediately after argon ion etching treatment. The gold bonds were annealed for 1.5 hours, 7 hours and 102 hours at 300°C in N_2. When these bonds are shear tested and fracture faces analysed, three different types of fracture mechanisms were observed [Q-13]. Figure 5.2.18 shows a SEM photograph of fracture faces after the shear test. Type 1 shows the samples without an annealing treatment are separated by plastic deformation of the aluminium pad. The shear forces measured show a rather narrow distribution at 0.8 ± 0.07 N. Type 2 shows after short annealing, about one hour at 300°C. The aluminium of the pad under the ball is consumed by the growth of compound layers and a ductile fracture occurs in the gold ball. The shear force is increased to 1.1 ± 0.09 N. Type 3 shows after longer annealing time a ring of brittle compounds (Al_3Au_8) is formed under and around the ball and brittle fracture is observed with a large scatter of the shear forces measured.

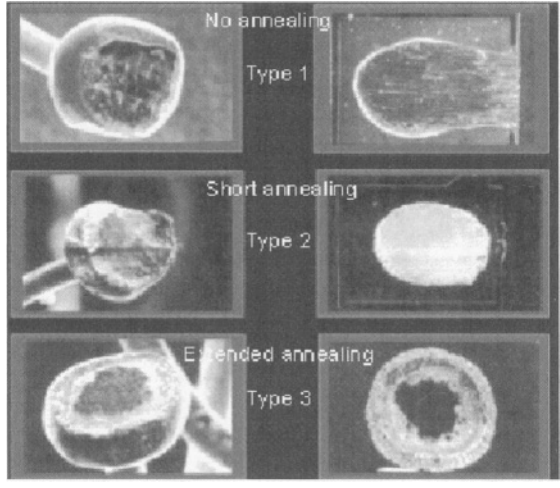


Figure 5.2.18 Micrographs of fracture faces after the shear test [Q-13]

5.2.7.1 Shear Ram Speed

The speed of the shearing ram during shear testing has an impact on the failure mode. As the speed of the shear ram is increased, greater is the tendency for brittle fracture at the bond pad interface. For example from figure 5.2.19 we observe that partially annealed (Type 2) wire bonds have less amount of intermetallic resulting in higher shear strength and a ductile fracture mode, whereas bonds that have been annealed for a longer time (Type 3) have excessive intermetallic resulting in lower shear force and a brittle fracture behaviour.

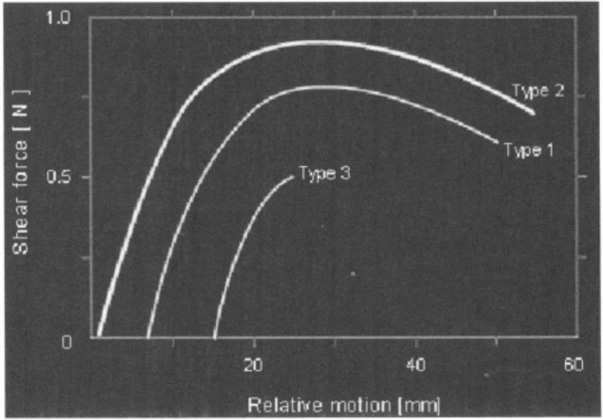


Figure 5.2.19 Shear force vs. motion of the shear ram [Q-13]

5.2.8 Shear Test on Thick Films

When we perform ball shear test on thick films, the shear tool can lift of the thick film metallization or drag the film giving rise to higher value of shear force. This can particularly happen in case of thick films with poor adhesion. Figure 5.2.20 shows the shear test for bond on thick film.

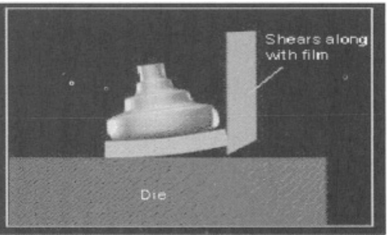


Figure 5.2.20 Shear test for bond on thick film

5.2.9 *Shear Force and Shear Strength*

When shear test began to be used as a quality test methodology, the industry was measuring the shear force of the ball and the 3 sigma value. And if the measurements met the specification limits, the product was deemed of good quality.

As the industry moves towards finer pitch bonding, the ball size is becoming smaller. And if the ball interface does not have a minimum

strength, it may result in reliability failures. A larger ball size will have higher shear force, and a smaller ball size will have smaller shear force. But the strength of the interface in both cases should be high. This can be checked by calculating the shear strength per unit area. For facilitating easy comparison between different ball diameters and wire sizes, the industry has accepted to use the normalized shear test values. This is the shear strength. The shear strength is calculated by dividing the shear force by the area of the ball.

Shear Strength = (Shear force) / Area of the Ball **(π d^2)/4,** where d is the apparent ball diameter. The apparent ball diameter d is shown in figure 5.2.21.

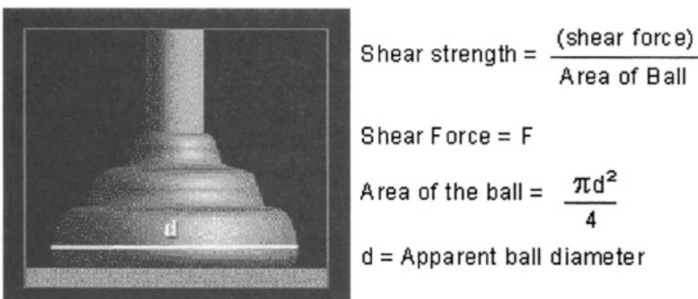


Figure 5.2.21 Apparent ball diameter

To calculate the shear strength more accurately, we can also use the actual welded area. Shear Strength = (Shear force) / Actual weld area. Figure 5.2.22 shows the actual ball diameter. If the actual welded area is 'a' then the shear strength value is calculated as force divided by **(π a^2)/4,** where 'a' is the actual ball diameter.

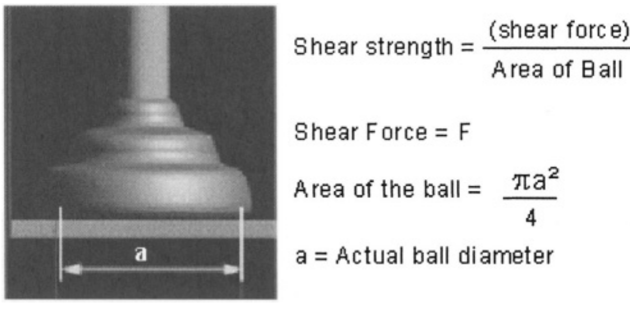


Figure 5.2.22 Actual ball diameter

The actual weld area or contact area will be significantly less than the apparent ball area. But this can not be easily determined. However it is possible to do experimental analysis and determine the average contact area for a particular set of process parameters and wire diameter.

5.2.9.1 Calculation of Lower Spec. Limit (LSL)

The shear force is a function of the ball diameter. The LSL value should be specified based on the ball diameter used in a particular device. The larger the bond diameter, higher is the shear strength and therefore as we increase the ball size, we must specify the lower acceptable specification limit to a higher shear strength value as shown in figure 5.2.23.

It is possible to decide on the lower spec limit value by deciding on the Cpk value. The process capability, Cpk is given by the equation:

$$Cpk = (X - LSL)/3\sigma$$

Where: X = the mean value of shear force
LSL = Lower Spec. limit
σ = Standard Deviation

The LSL value can be calculated using equation.

$$LSL = X - 3\sigma\, Cpk$$

at a specified Cpk = 1.67, therefore

$$LSL = (X - 1.67 \times 3\sigma) = X - 5\sigma$$

By generating X and σ values from the process data we can establish the LSL value.

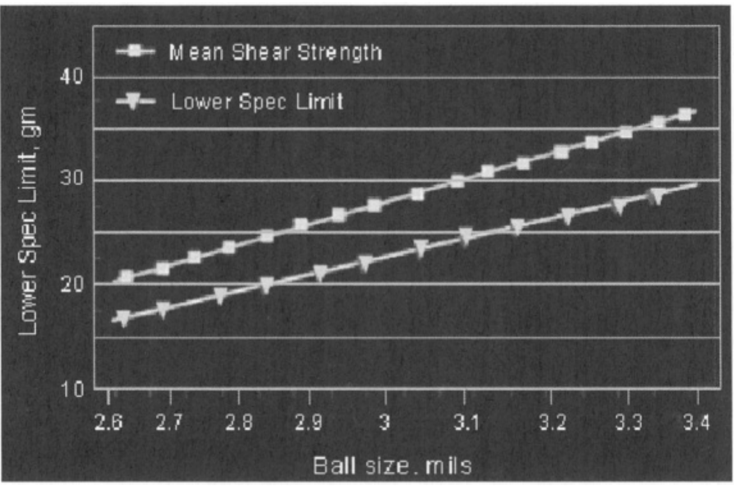


Figure 5.2.23 Variation of lower spec limit with ball size

5.2.10 Shear Test Specification

By establishing and following a standard shear test procedure, it is possible to achieve consistent quality in the wire bonding process. For the convenience of the reader we provide below a sample specification for performing shear test on a wire bonded device.

- Purpose:
  - to define a ball shear test procedure
- Scope
  - this specification covers tests to determine the shear strength of a series of ball bond made by conventional thermosonic techniques. It

covers ball bonds made with wire diameter from 25 to 50 microns currently used in integrated circuits.
- this method is destructive and appropriate for use in process control or quality insurance with a proper sampling plan.
- a non destructive procedure is possible but not recommended as it provides lack of information on the bonding quality

- ASTM Standards
    - destructive shear testing of ball bond: ASTM Std F 1269-89
    - assembly design rule spec: 001xxx
    - wire bonding acceptance spec: 001yyy
    - final optical of IC before sealing spec: 001zzz

- Definitions
  - Failure mode definitions.
    - ball lift - A ball lift is defined as a separation at the bonding pad interface with little or no intermetallic formation present or remaining (area of intermetallic less than 25% of the bond deformation area)
    - Note 1 - Intermetallic refers to the aluminum gold alloy formed at the ball bondpad metallization interfacial area where a gold ball bond is attached to an aluminum pad metal.
    - ball shear (Weld interface separation) - Appreciable intermetallic remains on the bonding pad (area of the remaining metal or intermetallic greater than 25% of the bond deformation area.)
    - bondpad lift (substrate metallization removal) - Separation between the bondpad and the underlying substrate. The interface between the ball bond and the residual pad attached to the ball remains intact.
    - cratering - Bonding pad lifts taking a portion of the underlying substrate material with it. Residual pad and substrate material attached to the ball.
    - Note 2 - It should be noted that cratering can be caused by several factors including the ball bonding operation, the post bonding processing occurs, chemically etch off (NaOH 10g/100cc 90° C) the ball bond and bondpads of untested units are microscopically

checked for cratering. Cratering caused prior to the shear test is unacceptable.

- measurements errors - Most of them are caused by improper positioning of the ram during the ball shear operation. Rams that are too high or angled upward result in lower than normal shear strength values. Rams or the substrate and cause inordinately high shear strength as well as potentially damage the shear ram.
  - wire shear - The ball is sheared too high or off-line. Only a minor fragment of the ball remains on the pad which is attached to the wire. The major portion of the ball remains on the pad with the bond - pad weld interface region intact.
  - ram friction to substrate - The ball is sheared too low and the ram rubs the substrate resulting in too high shear strength value.

- General
  - Apparatus
    - ball bond shearing machine that can work either on horizontal test configuration (DAJE BT 23, KTC shear tester) or vertical test system (DAJE BT22) with the following components or equipment.
    - shearing Ram - The minimum shear edge dimension must be equal to one ball diameter. The ASTM standard F1269-89 specifies one to two ball size diameter. The maximum shearing edge dimension should be chosen in order to prevent from touching the ball
    - 160 μm for 25μm ,33μm, and 38 μm. Wire diameter, 210 μm for 46μm and 50 μm. wire diameter.
    - shearing and gauging mechanism - The ram speed must be between the range of 0.25 to 3.0 mm/s. In no case, should the ram speed exceed 3.0 mm/s. Some bond shearing machine are equipped with a proximity detector that allow automatic height position of the ram from the substrate. A transducer with a maximum load of 200g is necessary to cover the shear test value of wire diameter from 25 to 50 μm. The maximum of scale reading must be within the same range.
    - microscope and light source - The minimum magnification shall be 60x.
  - device holder - A clamping mechanism for rigidly holding the device under test in either vertical or horizontal position. The shear test holder

must be able to position to tolerances better than +/- 10 µm. in the X and Y direction (plane of bonding pad) and +/- 5 µm, in the Z- direction. The shearing rams over travel should be limited to 2 ball diameters.
- metallographic microscope with magnification 50X to observe the bondpads after ball shear.

- Sampling.
  - since the shear test method is destructive, it shall be performed on a sampling basis. The size of the sample should be as large as practical (not less than 20 bonds) to ensure the proper statistical inferences from quantities such as the mean shear force and its Std deviation
  - sampling must be 5 bonds per by die side (20 bonds) /device / machine

- Calibration
  - calibrate the ball bond shearing machine once a week.
  - for multi function test machines (i.e. Dage BT22), set up the test machine in the proper configuration for the ball bond shear test.
  - calibrate the shearing and gauging mechanism.
  - for mechanism which incorporates a calibration mode, calibrate the mechanism according to the manufacturer's instructions.
  - for mechanism without a built-in calibration mode, attach a selected calibration mass (nominally 200g) to the shearing and gauging mechanism in such a manner as to lead the shearing ram in a direction normal to the ball shearing force. Observe and record the measured force in grams and plot as a function of the force by the masse. A calibration curve should be constructed using a least-square fitting technique and used to interpret readings in term of actual force loading.

- Safety Requirements - N/A

- Procedures
  - operating procedures
    - place the device having the ball bond to be tested in the device holder so that the plane of the device is horizontal or vertical according to the mechanism configuration of the tester.
    - position the microscope and light source and focus the microscope so that the ball bond to be tested is clearly seen in the microscope field.

Note : Only ball bonds which are visually acceptable should be tested.

- position the device hold so that the ball bond to be tested is located adjacent to the shear ram.
- while viewing the ball bond and the shearing ram through the microscope, move the shearing ram in line with the ball bond and lower the shearing tool tip in contact with the substrate, then back off the shearing tool to a distance of approximately 10 microns as determined by micrometer setting of the x,y,z stage. Shearing mechanism with proximity detector on the shearing ram, the distance of the ram from the substrate should have been pre-set to 10 microns.
- activate the shearing mechanism while observing the ball bond and the shearing ram through the microscope. If the ram is observed to slip to the side of the ball or up over the top and/or strike the substrate as the force is applied, then the recorded shear value should be discounted and an error mode indicated. Similarly care should be exercised to avoid condition of friction rewelding and/or advanced intermetallic growth. If the ram strikes another object prior to shearing, test should be repeated.
- measure and record the force required for shearing the ball bond
- examine the remaining part of the ball bond, attached to the wire and the pad, to determine the nature of the failure
- record the ball bond failure as being one of the following:

Mode No.	Mode Description
1.	Ball Lift
2.	Ball Shear
3.	Bondpad Lift
4.	Cratering
5.	Wire Shear
6.	Error Mode

- Report
  - the report shall contain the following information
    - name of the person performing the test
    - date of the test
    - identification of the ball shear test system
    - identification of the wire bonder system and wire size
    - device type and pad structure

- identification of the assembly lot
- all individual shear strength values, average x bar, range R, and standard deviation.

- a control chart will be built from above data

- Specifications
  - the nominal values showed are shear strength values to achieve for optimized ball bonding. Data outside the lower spec limit will reject the lot
  - wire Size, Nominal values, Lower spec. Limit

    25 micron, 65g, 30g
    33 micron, 75g, 40g
    38 micron, 90g, 50g
    50 micron, 105g, 60g

5.2.11 Non Destructive Shear Test

Non-destructive ball shear testing has also been investigated, but the difficulty of its implementation as 100% test in most integrated circuit, hybrid, and multichip module geometries has limited its use.

5.3 *Visual Inspection of Bond Quality*

Inspection of wire bonding had traditionally been done visually, because the human ability to discern faults had been much better than the available machines. This technique is used to ensure the proper ball and wedge bonds. Signs of cracked heels, tearing at the wedge, misplaced wires, inconsistent wire placement, "golf-clubbing" at the gold ball, excessive neck down etc. are visual indications that the wire bonding process is not in control. Visual inspection also verifies whether the bonds are properly placed with respect to the bond pads and bond fingers of the leadframe/substrate. Beside that the visual inspection also screens possible bond defects that may results in open or short, based on a specified defined criteria of wire clearance and close proximity of each bond to the other.

As discussed earlier, bond pull and bond shear test check the quality of bonded interfaces, both on the chip and on the lead finger. However, there are many other failure modes that can only be detected by visual inspection, for example deformed bond, s-ing of wire and probe marks to name a few. Therefore visual inspection is very much essential in today's wire bonding process. Visual inspection of bond quality includes both "Pre-Bonding Inspection" and "Post Bonding Inspection". Pre-Bonding Inspection is necessary for assuring process consistency and reliability. Post Bonding Inspection is necessary to assure package reliability.

5.3.1 Pre Bonding Inspection

One of the final steps in the manufacture of integrated circuits is the inspection of the probe marks on bonding pads caused during electrical testing of the integrated circuit wafers. Prebonding inspection is useful in isolating potential problem areas caused when:

- the probe mark extends beyond the pad boundary,
- the mark is too large in size, or
- extraneous scratch marks have been introduced during electrical testing

Inspection of the bond pads is facilitated by evaluating parameters which can be used to quantify these defects.
These include:

- size of the pad
- location of the pad centre
- size of marks on the pad and percentage coverage of pad
- location and size of the largest mark

Other problems on the bonding area that have an impact on the quality of the bond are: discoloration of bond pad (due to corrosion) and photo resist residue. These can be visually inspected and problems resolved. Photoresist residue is not visible under normal lighting. However using polarized UV

lighting under a microscope it is possible to identify passivation and photoresist residue problems.

5.3.2 Post Bonding Inspection.

The following list gives a range of problems that one may encounter after the bonding process, and these problems can only be identified visually. The post bonding inspection includes bond quality problems such as:

- smashed bonds
- skinny bonds
- misplaced and deformed bonds and
- wire conditions such as loop height etc

The visual inspection can be done manually with the assistance of an operator, or with automatic visual inspection systems.

5.3.3 Visual Inspection Criteria

After wire bonding operation, when one performs visual inspection of the bonded device, the following are the possible defects one can look for. These defects are cause for rejection of the device.

- device wire bonds not connected to correct locations in accordance with the device build specification bond layout diagram
- missing, or broken wires
- wires touching, or a gap of less than two wire diameters between other wires, leadfingers, not unpassivated die areas are not acceptable unless the wires are common
- nicks, crimps, scores or neck down which reduces wire diameter to less than 75% of its original are not acceptable
- wires which cross when viewed from above are not acceptable, unless they are either, common wires, or wires bonded to different heights with a minimum separation of two wire diameters

- wires showing no loop along their length from die pad to lead finger are not acceptable
- ground bonds from either a finger to the pad or the die to the pad which have no looping are not acceptable
- loop height must not exceed 10 mils (or a pre specified value) above the level of the die surface
- for this criteria, measure the loop height of four corner wires on the first device in a lot and on the first device in each subsequent magazine of frames in the lot. Use a hisomet z check for this measurement with x200 magnification
- any evidence of fracturing, or tearing at the bond to wire interface, which is visible with a 3rd optical microscope is not acceptable
- any evidence of peeling bonds visible with a 3rd optical microscope is not acceptable
- any metal that is displaced from the bond pad as a result of bonding (shooting material) must leave a visible gap between the shooting metal and unpassivated operating metal, scribe line, or an uncommon bond pad
- the ball diameter must be between 2 and 5 times the wire diameter
- the stitch bond length must be between 0.5 and 3 times the wire diameter
- the stitch bond width must be between 1.2 and 5 times the wire diameter
- when viewed from above the exit of the wire from the ball must be greater than 1/4 wire diameter away from the perimeter of the ball (golf club bonds)
- Adjacent common bonds may overlap by up to 25% of their width
- balls that have more than 33% of the bond area off the target bond pad are not acceptable
- ball with more than 50% of the bond area on foreign material, or where the visible foreign material covers more than 25% of the ball perimeter is not acceptable
- bonds on leads must have the entire bond within the boundary of the lead metallization
- bonds must not touch any die attach material
- stitch bonds must not have tails present

- the angle between the stitch bond impression and the existing wire at the heel must not exceed 30 degrees
- there must be a line of visible separation between ball bonds and other balls, uncommon passivated and unpassivated operating metal and scribe lines
- reject a device if a bond is missing more than a quarter of the bond impression compared with the normal shape of bonds in that device
- reject if tool mark cannot be seen round all 360 degrees of the ball bond, or across the entire width of a stitch bond

5.3.4 Automated Visual Inspection

A significant problem in increasing reliability in the manufacture of integrated circuit devices is that of inspection of these bonds. Frequently, in many factories such inspection and quality control is done off-line and on a sample basis by human operators. In addition to being expensive and time consuming, the results of such testing are also some what subjective due to factors such as fatigue and limitations of human visual consistency. An automated system, on the other hand, leads to increased consistency and reliability of the inspection process. Further, the continuing increase in packing density of VLSI circuits requires that the inspection process be completely automated. For such a scheme to be feasible, the algorithms and techniques used in the inspection process must be implementable on workstations at reasonable cost.

Systems have been developed which use image processing and pattern recognition techniques in an automated system for inspection of different wire and bond defects. For example inspection of the bonding process consists of the following steps.

Pre-bonding inspection to:

- find the shape and size of the pad
- locate the centre of pad
- analyze the probe and scratch marks on the bond pad

Post-bonding inspection to:

- compute the shape, size, and location of the bond
- analyze orientation of pig-tails in wedge bonds
- determine the 3-D profile on the wire connecting the pads and the pins

The algorithms available today combined with advanced computing power allow in-line optical post-bonding inspection. Inspection determine ball and wedge shape and position and 's'-ing of the wire. The optical evaluation can be used to extend the functionality of the bond process analysis as well as for statistics.

Automated inspection and measuring systems also offer an alternative solution to handling problems. These systems allow "hands-free" loop height inspection and eliminate defects from operator handling and operator measurement error. While both ball and wedge bonds have several features in common, wedge bonds, in many cases, have a fairly long pig tail. Further, with wedge bonds, the nature of the bonding process used may cause reflections from the bond surface, which may not be totally eliminated even by controlling the lighting conditions. Thus automated visual inspection analysis of wedge bonds is somewhat more difficult than ball bonds.

5.3.4.1 Automated Visual Inspection Requirements

The inspection machine used in this particular application should incorporate a new set of optical systems that enable two-dimensional (2D) and three-dimensional (3D) inspection of these devices. It is necessary to have 3D capability if manufacturers are interested in defects such as lifted ball/wedge and height or sagginess of the wires along the path.

5.3.4.2 Inspection System

The inspection system should consist of a precision variable X-Y stage with optional lifting/rotating mechanism, either integrated in-line (on bonder) or standalone. The inspection system must be configured at low or high magnification or both. The low magnification station, where only the

wires are inspected, should consist of up to three cameras as stereo pairs and a programmable directional light pattern (structured light). The high magnification station requires an entirely different lighting set-up than the low magnification station. At this station, only the physics of the bond should be inspected. In order to accurately recognize the defect types involved in bonding, a magnification of 20 to 50X is required. It is desirable to select a field of view for the optical set-ups, so the entire length of wire(s) in low magnification and bonded pad/wedge in high magnification are within the image. This will reduce the complexity of the inspection procedures, which in turn speeds up the inspection time.

5.3.4.3 Before Inspection

Once the part is properly positioned for inspection, it should be viewed from two different angles, vertical and angled. The angle of view is a function of the loop of the wires. The higher the loops, the smaller the angle with respect to the vertical camera. Determining this angle is critical in preventing overlapping of the wires in the image. Using the vertical view, the system searches for fiducial marks on both the frame and the die to register the part. This search is within a window provided by the data base. Once these fiducial marks are found, the translation both in X and Y and rotation angle θ are calculated. This information is used to correct the data base which holds pin and die pad centers. Completion of this procedure initiates the inspection routines.

5.3.4.4 System Performance

When it comes to performance, the expectations are different. Some may prefer accuracy over speed, or vice versa, and some may want to have both. Basically, a vision system's performance depends on its hardware configuration, resolution of the input devices, and the complexity of the inspection area. It is desirable to inspect semiconductor devices at speeds comparable to the wire bonder. The speed of wire bonders may vary but bonding of about 10 wires per second is typical. Keeping in mind the number of defects that a vision system must detect gives an idea of the speeds involved.

5.3.5 Visual Inspection Equipment Capabilities

In modern wire bonders many of the visual inspection equipment features and capabilities are incorporated into the wire bonder itself. Thus the post bond inspection can be done on a sample basis on the bonding machine itself.

Today inspection systems are available which can be used at low magnification and vertical view to identify defects such as:

- missing Wires
- multiple Wires
- bent Wires
- broken Wires
- lost Reference

When we use an inspection system at low magnification and angled view we can identify defects such as:

- multiple Wires
- lifted Ball/Wedge
- wire Path (High, Low)

When we use an inspection system at high magnification and vertical view we can identify defects such as:

- bond Position
- ball shape (Diameter, Too Flat, Golf Club)
- ball/Wedge Size
- capillary Marks
- foreign Material
- tails

With currently available automated visual inspection systems, we can perform wire bond inspection to the following accuracies or better.

- Bond geometry detection:
  - ball Size (Au-wire) $\pm 5\ \mu m$

- wedge Size (Al-wire) ± 5 μm
- Bond position detection
  - ball/wedge off pad position ± 10 μm
  - wedge off lead position ± 10 μm
  - ball/wedge bridging metal ± 10 μm
- Internal wiring detection
  - Actual loop height ± 25 μm
  - loop out of position ± 10 μm
  - wire sagging Yes/No decision
  - wire shorts Yes/No decision
  - wire missing Yes/No decision
  - correct bonding diagram Yes/No decision

Many of these inspection systems can be integrated into the production line or used for quality control as a stand-alone machine. Some auto systems have two inspection heads programmable in x and y - direction, for parallel processing and high accuracy. Both stations may operate on different resolution for individual inspection tasks. Each head has a CCD camera with a multiple switchable lighting system, allowing three dimensional inspection. Typical inspection time for one complete bond (including ball size, ball placement, loop height, wire tracing, die position) is in the range of 400-500ms with multiple wire devices.

5.3.6 Loop Height Measurement

With the introduction of thin and fine pitch packaging technologies, loop height, loop profile and wire length have become critical parameters. If the loop height is not tightly controlled and monitored, it may cause yield problems. Typically for a TQFP or BGA package, the loop heights are 5 mils ± 1 mil. Usually loop height measurements are made with a microscope equipped with a z-axis (vertical) micrometer. The microscope must be capable of accurately distinguishing very small height differences. Microscope gauge capability studies are critical to process reliability.

Here is a step-by-step approach to measure the loop height with a z-axis microscope

- focus the microscope on the bond pad, near the ball
- reset the microscope
- focus the microscope on top-of-loop
- read the difference in height

To make accurate measurements, the key requirements for microscope include the following:

5.3.6.1 Depth-of-Field

Depth-of-field is a function of numerical aperture, total microscope magnification, and the wavelength of the light source; it typically decreases along with numerical aperture as magnification increases. To accurately measure the loop height, depth-of-field should be less than 1 μm, which requires a minimum magnification of 400x. Using lower magnification results in larger measurement errors because of their increased depth-of-field.

5.3.6.2 Single-Wave Length Light Source

For loop height measurement, a single-wave length light source is preferred because white light has a larger depth-of-field than single wavelength light. Thus, measurement error is higher for a white light source than for a single-wavelength light source. Monochromatic (525-nm) green light is recommended.

5.3.6.3 Split-Prism Focusing Aid

Microscopes with a split-prism focusing aid are preferred because, during fine focusing, alignment of the images formed by the split prism results in the optimum focus.

5.3.6.4 Micrometer Encoder Pitch

The z-axis micrometer must have sufficient encoder resolution. Microscope manufacturers offer a variety of micrometers with different

gradations. It is important to select a microscope with an encoder resolution of **1μm** or less.

5.3.7 Scanning Electron Microscopy for Wire Defect Analysis

In Au ball bonding as well as in Al wedge bonding, there are micro cracks formed either at the ball neck or at the heel of the wedge. These can only be seen under high magnification of a scanning electron microscope. Similarly, the heat-affected zone (HAZ) above the ball is the weakest segment of the wirebond and the most sensitive to damage during loop formation and subsequent handling. Scanning electron microscopy (SEM) is used to detect damage in the HAZ.

5.3.8 Third Optical Inspection Specification

Third optical inspection is a crucial step in an assembly manufacturing floor after the wire bonding operation. We provide below an example of a third optical inspection specification. It is strongly recommended that every assembly factory must develop and write there own specification based on the device and packaging requirements.

Example of final optical acceptance of IC devices before encapsulation or sealing (3rd optical specification)

- Purpose
    - The purpose of this specification is to define the visual criteria for bonded dice before sealing, to ensure the quality

- Scope
    - This specification has to be applied before sealing

- Materials
    - 30X and 60X Binocular/Stereomicroscope
    - 75X to 150X Metallographic Microscope with micrometric lens
    - Nitrogen blower (.2um/.008 mil filtered)

- Tweezers
- Fingercots / Gloves
- Antistatic equipment
- X-ray equipment with image analyzer or equivalent

- Preliminary Controls
  - check that previous operations are correctly mentioned on traveller card
  - check that the relevant mounting bonding diagram is in front of the inspection work area
  - check that sampling plans are according to requirement
  - check that working area is clean
  - check that lens or eyepieces are clean
  - check that equipment is in good working order
  - check whether the antistatic system is correct; the operator must
  - absolutely be connected to ground with 1 (one) mega ohm cable
  - devices must be handled only with clean and not damaged finger cots / gloves
  - 30X and 60X inspection must be done with a binocular or stereoscopic microscope
  - the adapted angle for reading is between 0 degree (i.e. at right
  - angle with the top surface of die) and 30 degrees
  - the observed area must be correctly illuminated with white diffuse light
  - check that all devices are made with the same mask set

- Inspection Criteria and Codifications
  Main defect criteria described in this specification concern the following elements:
  - bond control
  - wiring control
  - foreign material control
  - lead frame control

- Bond Criteria for Acceptance (as presented in 5.3.3)

5.4 *Special Test for Quality*

The industry uses a variety of techniques for measuring the quality and of bonds. The most frequently used techniques are:

- visual inspection
- bond Pull
- bond shear test
- bond etching
- electrical testing
- bake test
- thermal cycle/thermal shock testing
- electro magnetic resonance
- acoustic emission
- surface analysis

Some of these tests are usable as production monitoring techniques, where as some tests can only be used in the laboratory for evaluation and development of wire bond technology. We have already discussed the three major techniques namely bond pull, bond shear and visual inspection. Let us briefly discuss the other techniques.

5.4.1 *Bond Etching*

Bond etching measures the condition of layers under the bond pads after bonding. With this technique, the ball (wire) and pad metallization is removed, and the condition of underlayer materials is examined for defects. Wet etching method not only allows detection of subsurface damage caused by equipment parameters, but can also serve as a tool for optimization of the bonding parameters. Typically, NaOH, $HCl+HNO_3$ or KOH are the chemical solutions of choice used to remove the interconnection material and expose the underlying structure. For example to check if cratering has occurred under the bond pad, we remove the bond pad metallization using potassium hydroxide (KOH) solution.

5.4.2 *Electrical Testing*

Electrical testing measures the quality of the bond. A non-sticking bond will result in an electrical open, while two adjacent bonds in contact will result in an electrical short. There are special techniques such as "Four Point Probe Testing" to measure the electrical resistance of the Au ball-Al bond pad interface. The resistance increases as the amount of intermetallic compound increases. And an open circuit failure is an indication of extensive voiding at the interface.

5.4.3 *Bake Test*

Bake test measures the degree of intermetallic compound formation of gold-aluminum (Au/Al). Over diffusion of aluminum atoms into gold can lead to Kirkendall voiding at Au/Al interface resulting in bond lifting. By baking the bonded devices at high temperature (175°, 240° or 300°) for different lengths of time, one can determine the long term reliability of the bond.

5.4.4 *Surface Analysis*

Surface analysis techniques such as energy-dispersive X-ray analysis (EDX), wave-length dispersive X-ray analysis (WDX), auger, and scanning electron microscopy (SEM) are the failure analysis tools one can use to identify the presence of contamination, extent of intermetallic compound formation, and bond irregularities.

5.4.5 *Acoustic Emission*

When we apply a force on the wire during bond pull test the micro welds that are formed under the ball begin to crack. And with continued application of force the crack propagates and the interface fails. The initiation of the crack gives rise to "acoustic emission". By placing sensitive micro phones near the bond pad during bond pull test it is possible to hear the acoustic

noise. By measuring the force at which a certain intensity of acoustic emission occurs it is possible to know the "goodness" of a bond. When we apply force during bond pull testing, a micro crack is generated at the ball bond interface.

If the force is high and if the intermetallic compounds are weak, the crack will become bigger and propagate. When the crack is initiated, there is acoustic emission. While listening to the acoustic emission using a sensitive microphone, it is possible to determine at exactly what force value the interface starts to fail. Figure 5.4.1 shows a schematic representation of acoustic emission test. However, this test is a laboratory technique and cannot be used for process control on the production floor. [Q-14]

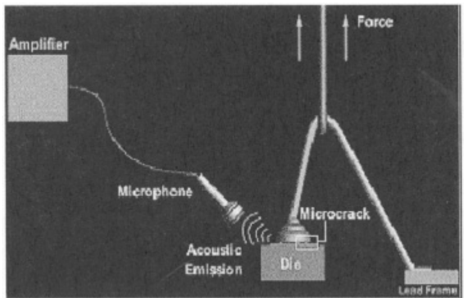


Figure 5.4.1 Acoustic emission

6

Reliability

Reliability of the bonded interface as well as the bonding wire is of utmost importance. It has been seen that more than 30% to 40% of the field reliability failures are due to wirebond failures, which means device reliability and system reliability are significantly affected by wirebond reliability. In this chapter we shall discuss some of the major reliability failures such as purple plague, spiking, cratering, wire sweep, corrosion and heel crack. Apart from these we shall also discuss other reliability failures such as die attach pad shift failures, over current failures, grain growth failures, Al bond failures on Ag plated leadframes, aluminum silver corrosion and gold silver problems.

6.1 Purple Plague

6.1.1 Purple Plague or Intermetallic Compounds

Purple plague or intermetallic compound is an important reliability issue in wire bonding. The term purple plague in Au-Al wire bonding systems stems from the characteristic coloration of the Au-Al alloy's aluminum-rich intermetallic compound - the purple phase - $AuAl_2$. However, nowadays we use the term intermetallics, which describes the natural physical event.

The term "plague" was coined in late 60's when the Au-Al bonded systems used to have massive and catastrophic processing problems due to the formation of the intermetallic, and the detailed metallurgical analysis had not been made. The only visual criteria for the failure were the purple phase of Au-Al alloy. When gold and aluminium react at high temperature purple plague or intermetallics are formed.

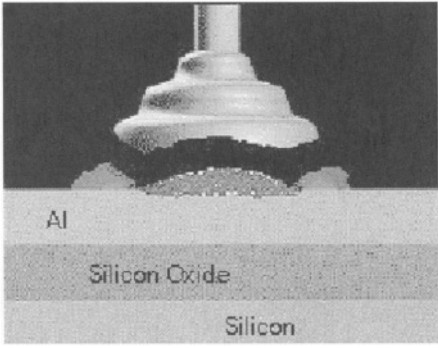


Figure 6.1.1 Bond failure due to formation of purple plague **[VIEW-IN-CDROM]**

This formation of intermetallic results in wire bond failure. Figure 6.1.1 shows the formation of purple plague.

In today's devices, since the failure mode does not occur in great frequency, it is not considered a "plague". However, the problem is of critical importance, particularly in case of high speed and high power devices. The term intermetallic formation - rather than purple plague - more accurately describes the situation for IC manufacturers today.

6.1.2 Formation of Intermetallics

An intermetallic phase is composed of two or more metallic elements. When gold ball is bonded on aluminum metallization, the two elements react and form an intermetallic compound. This intermetallic compound formation is necessary for good interfacial adhesion of the Au and Al. The type of intermetallic compound formed at the interface depends on the temperature of exposure and length of time of exposure. During the thermosonic bonding process, usually, Au_5Al_2 is the phase that is formed. However, during thermal annealing, many different phases are formed depending on concentration of Al and Au. As the amount of Au in Al increases, different intermetallic compounds are formed, such as $AuAl_2$, Au_5Al_2 and Au_4Al. These are determined from the phase diagram of Au and Al. The phase diagram shown in figure 6.1.2 can tell us which phase will be the

predominant equilibrium phase at a particular composition of Au and Al. Depending on the concentration of Au and Al, we can predict which intermetallic compound exists at room temperature.

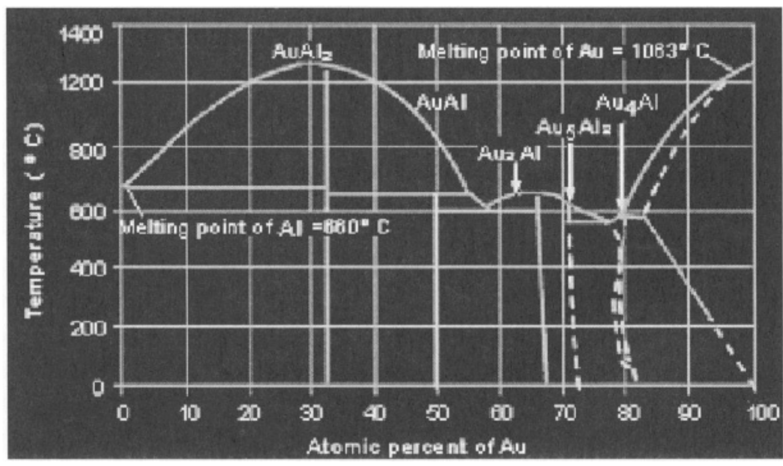


Figure 6.1.2 Gold-Aluminum phase diagram [R-1]

From the phase diagram we can see that Au and Al have almost no solubility in each other and there are many intermetallic phases. The five major intermetallic compounds are: Au_5Al, Au_4Al, $AuAl_2$, Au_2Al and AuAl. These compounds and other intermetallic compounds, have characteristic colors, with $AuAl_2$ being purple and the rest being tan or white. Each phase has its own composition, its own crystal structure and unique physical properties.

When gold and aluminium react to form intermetallic compound the electrical resistance, the thermal expansion co-efficient and the hardness properties of the intermetallic are dramatically different from either aluminium or gold. As previously shown in table 4.5.1, hardness of Al is between 20 to 50, whereas that of Au_4Al is 334 and similarly, the specific resistance of Al is 2.3, whereas that of Au_4Al is 37.5.

6.1.2.1 How do Intermetallics Affect Reliability?

The intermetallic compounds formed at the interface can affect the reliability in two different ways, namely Kirkendall voids causing high resistance or open circuit and intermetallic compounds causing brittle fracture. Let us discuss each of these in greater detail.

6.1.3 Kirkendall Voids Causing High Resistance or Open Circuit

When gold and aluminum interdiffuse into each other. They form compounds depending on the concentration of each element at that site. However, if one of the atomic species diffuses faster than the other, then it leaves vacancies behind. These vacancies may cluster together and form a void. These are called Kirkendall voids named after the famous metallurgist professor Kirkendall. This typically occurs with gold wire-bonded to thin aluminum (1 micron thick) metallization when voids form around the bond periphery limiting the available electrical conduction paths. These voids coalesce and result in open failure. Figure 6.1.3 shows the interdiffusion and Kirkendall void formation. The presence of Kirkendall voids makes the interface mechanically weak and electrically non-conductive. Now let us take a look at what happens in real situation of a Au wire bond on Al metallization.

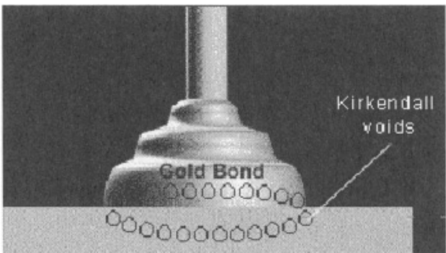


Figure 6.1.3 Interdiffusion and Kirkendall void formation

When gold ball is bonded thermsonically on Al bondpad, the two metals react at the bonding temperature and usually Au_2Al intermetallic compound is formed. This provides the adhesion strength to the ball bond. After bonding, if the package is exposed to burn-in operation at 125°C for long

period of time, the intermetallic compound formation increases. Further exposure of Au ball bond to higher temperature of 300° C and above results in formation of Kirkendall voids and other intermetallic compounds. Figure 6.1.4 shows void formation due to preferential diffusion of Au, thru Au-Al intermetallic compounds.

The voids appear at the interface because, the diffusion rate of Au through Au intermetallics is much greater than the diffusion of Al through Al intermetallics. Many studies have been reported that in the aluminum-gold binary system the growth rate of the gold-rich [R-2, 3, 4] intermetallic phase is approximately 10 times as large as the growth rate of the aluminum rich intermetallic phase, and the formation of Kirkendall voids is observed at the interface of the gold-rich intermetallic phase and Gold. If there is excessive void, it results in bond breaking and this causes open electrical circuit failure.

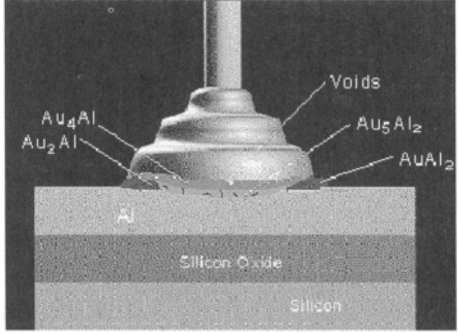


Figure 6.1.4 Voids appear at wire bond interface on heating

6.1.4 Intermetallic Compounds Causing Brittle Fracture

Gold-aluminum intermetallic compounds are stronger than the pure metals however, they are also more brittle. Thus, if a wire-bond system contains intermetallic, that system is far more susceptible to brittle fracture during thermal-cycle-induced flexure than gold or aluminum wires alone. When a micro defect exists in the intermetallic during thermal cycling, the crack

propagates at a high speed and causes brittle fracture of the intermetallic compound. Figure 6.1.5 shows the brittle fracture. Some of the intermetallics have a larger volume than the parent Au and Al metals. This increased volume at the interface causes tremendous stress. This stress causes microcrack and eventual bond lift failure.

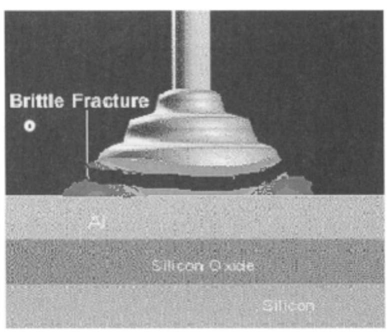


Figure 6.1.5 Brittle fracture of the intermetallic compound

6.1.4.1 Growth of Intermetallic

The failure rate of the bond wire is directly proportional to the growth rate of the intermetallic compounds. The growth rate in turn is dependant on the diffusion co-efficient. Observations suggest that the initial growth rate of the intermetallic alloys usually follow a parabolic relationship:

$$x = (Dt)^{1/2}$$

where x is the intermetallic layer thickness, t is the time, and D is the diffusion co-efficient, which is given by:

$$A.\exp[-E/kT]$$

where
A: is a constant,
E :is the activation energy for layer growth (in electron volts),
k :is the Boltzmann constant, and
T: is the absolute temperature (in Kelvin) [R-5]

The value of D changes for each intermetallic phase. If we know the value of D, we can calculate the diffusion length of a species at a particular temperature and duration of time, and eventually derive the acceleration factor for failure, as shown in the equation in figure 6.1.6.

$$A_t = e^{\frac{-E_A}{K}\left(\frac{1}{T_S} - \frac{1}{T_O}\right)}$$

A_t - Acceleration Factor

T_S - Stress Temperature

T_O - Operating Temperature

Figure 6.1.6 Calculation of acceleration factor at a specific temperature

For an atom to diffuse from one position to the other, it has to overcome a barrier, namely, the energy hill. This energy hill is different under different conditions. For example, suppose for a gold atom to diffuse through pure Al the height of the energy hill may be 1 eV. The same gold atom may diffuse through Au_4Al alloy much easily, because the energy barrier is only 0.7 eV. That means the activation energy required for Au diffusion through Au_4Al is much less than the activation energy required for Au diffusion through pure Al.

For the atom to climb the energy hill it needs thermal energy. Higher the temperature, faster the climb, whereas, lower the temperature slower the climb. Therefore for the same activation energy, at higher temperature the reactions are much faster. Similarly, at same temperature, lower the activation energy faster the reaction. Figure 6.1.7 shows the atomic diffusion as a function of activation energy and temperature.

Usually, diffusion along grain boundaries and surfaces is much faster compared to diffusion through the crystal lattice. This is because of the lattice at the grain boundary has more open structures, have many vacancies and can speed up diffusion rates by orders of magnitude compared to diffusion in the bulk.

When we see published activation energy for “Purple Plague” or for intermetallic failure, the activation energy is a generic activation energy (E) (one that combines the effects of all five compounds). And also the

activation energy has been measured by different methodologies and thus it is very difficult to judge which is the correct one.

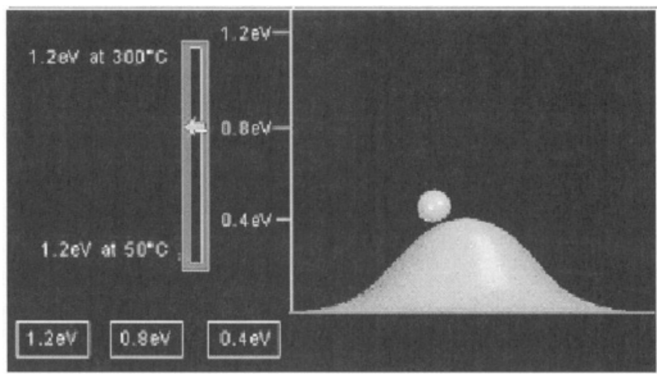


Figure 6.1.7 Atomic diffusion as a function of activation energy and temperature **[VIEW-IN-CDROM]**

However, from all the studies that have been performed so far we can estimate that the activation energy for Kirkendall void failure is approximately in the range of 0.9 to 1.0 eV. Kirkendall voids form typically during bake times greater than an hour at temperatures greater than 300°C to occur on the gold-rich side (Au_5Al_2), or greater than 400°C on the aluminum-rich side ($AuAl_2$) [R-6].

6:1.4.2 Kirkendall Void Formation in Aluminum Bond on Gold Film

When Al wire is wedge bonded onto gold film, the metals interact at high temperatures and form intermetallic and eventually Kirkendall voids. The width of the Al wedge bond and the thickness of the gold film have an impact on the Kirkendall voids formed. The Kirkendall voids are formed at the interface between the gold intermetallic compound and the plated gold film as shown in figure 6.1.8. The depth of intermetallic phase and the radius of the Kirkendall voids determine if the Kirkendall voids will form a continuous chain and induce an open circuit. This in turn determines the width of the Al wedge bond with respect to the thickness of the gold film [R-7].

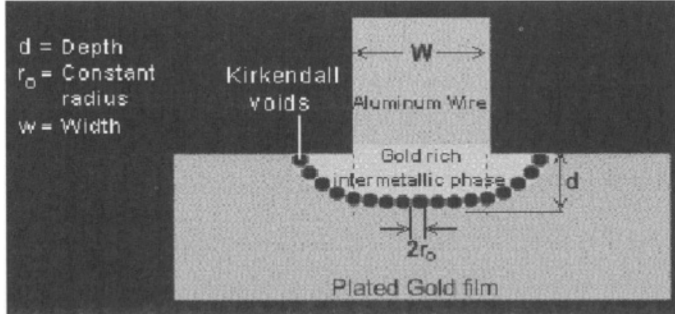


Figure 6.1.8 Schematic representation of the degradation of bonding strength [R-7]

Analysis has shown that the aluminum wire width to gold plating thickness ratio should be at least four. As the Al wire width gets narrower, the critical depth gets shallower, and the failure occurs faster. It is imperative that we maintain a certain wire width to film thickness ratio.

The above analysis gives us some idea of how to use reliability data for designing a package with proper gold metallization thickness and the minimum wire deformation that could be allowed for a particular wire diameter.

6.1.5 The Arrhenius Equation

To predict chemical reactions, failure rates and diffusion rates, we use the Arrhenius equation. This equation is particularly useful for situations where temperature is used as an acceleration factor. We can use the equation to predict Mean Time To Fail (MTTF) of a Au-Al bond system. If we know the failure rate at a particular high temperature, we can use the Arrhenius equation to calculate the failure rate at other operating temperature of the device. The acceleration factor of a reaction is given by the equation in figure 6.1.6 . The demo model of the equation is given in the CD.

6.1.5.1 Impurity Accelerated Gold-Aluminum Bond Failures

In real wire bond situations there are other external factors that accelerate intermetallic formation. For example, studies have shown that presence of nickel, iron, cobalt and boron in gold plated films may accelerate intermetallic formation [R-8, 9, 10].

6.1.5.2 Effect of Bromine on the Gold-Aluminum Bond System

When bromine is present in the plastic molding compound as a flame retardant additive, the plastic does not catch fire (even if the device gets over heated). There has been considerable study of bromine flame-retardant molding compounds for the plastic encapsulation of devices. In plastic encapsulated packages, rapid Au-Al bond failure occurs in the presence of brominated resins and elevated temperature [R-11].

When the device gets hot during device operation, bromine from the plastic encapsulant is slowly liberated and this bromine attacks the Au-Al bond system. Bromine accelerates the formation of Au-Al intermetallic compounds and Kirkendall voiding and leads to faster bond failures. In the absence of bromine atoms the rate of intermetallic formation at the gold aluminum interface is slow. The higher the percentage of bromine in a molding compound, greater is the failure rate. The failure rate is measured in terms of increase in electrical resistivity of the Au-Al interface. We can observe from figure 6.1.9 molding compounds with 2.35 % bromine show very rapid increase in resistance when exposed to high temperature for 400 to 600 hours whereas molding compound with 0.4 % bromine show a very slow rate of resistance increase even after exposure to more than 1400 hours. This clearly indicates that bromine content has a direct impact on the rate of formation of intermetallic compound [R-12].

We can also look at failure rate as the time it takes to reach 20 milli ohms resistivity. It has been shown that as the bromine content in a molding compound increases, the time taken to reach resistivity of 20 milli ohm decreases.

We can observe from figure 6.1.10. when the gold-aluminum bonds are annealed at 175° C, for compound X, time to reach 20 milli ohm resistivity is 3100 hours at 0.4% bromine and approximately 2000 hours at 2.8% bromine. As the bromine content increase the failure rate increases.

However, this is not true in all situations. Depending on the type of molding compound, the effect of bromine release is different. For the same bromine content, molding compound X will show a different failure rate compared to compound Y.

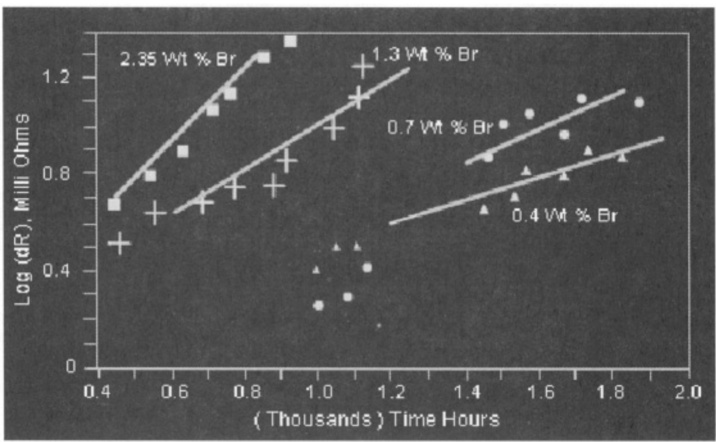


Figure 6.1.9 Effect of bromine content on resistivity [R-12] **[VIEW-IN-CDROM]**

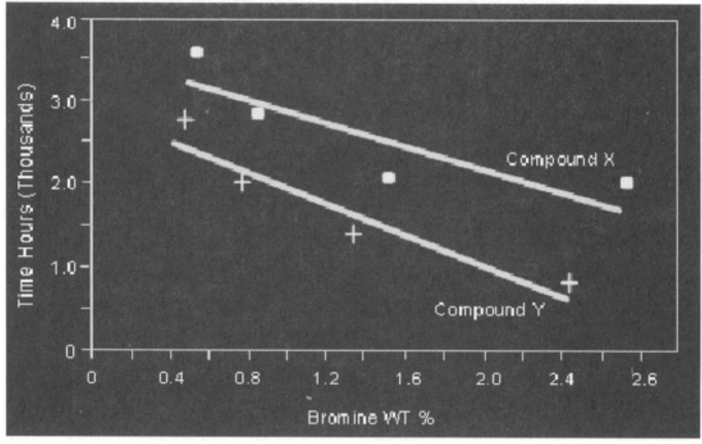


Figure 6.1.10 Mean time to 20 milli ohm at 175°C [R-12]

We can observe from figure 6.1.11. The resistivity of the gold-aluminum bonds increases as we increase the bromine content. To reach a resistance value of 20 milli ohms at 0.4 % bromine content, it takes about 130 hours and to reach the same value for a bromine concentration of 2.4%, it takes only 80 hours. In addition, we can also see that, even if bromine concentration is the same two different molding compounds behave in two different ways.

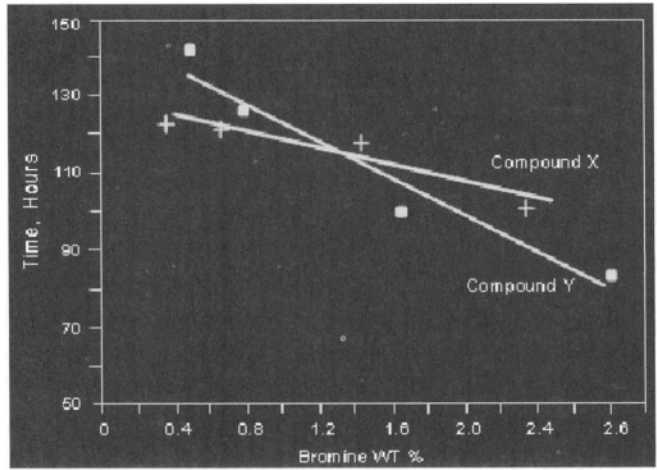


Figure 6.1.11 Mean time to 20 milli ohm at 200°C [R-12]

When we calculate the activation energy for the gold-aluminum reaction, we can see that for compound Y, the activation energy drops from 2 electron volts for 0.4 weight % bromine to 0.8 electron volts at 2.8 % bromine, whereas for compound X, the activation energy remains constant. This is attributed to the ease with which bromine can be released from the epoxy molding compound at a particular temperature. Figure 6.1.12 shows the dependence of activation energy on bromine concentration.

The activation energy for mechanical bond failure due to brominated epoxies has been found to be around 0.8 eV. However, activation energies for resistive bond failures have been found to be in the range of 0.2 to 0.5 eV.

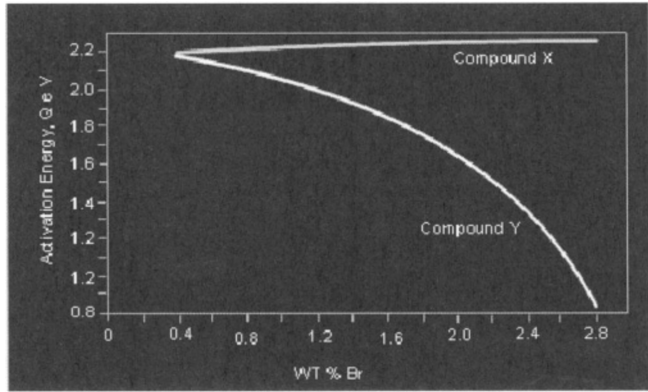


Figure 6.1.12 Dependence of activation energy on bromine concentration [R-12]

6.1.5.3 Effect of Temperature on Molding Compound

Bonds in one molding compound "A" degrade faster than those in molding compound "B". The faster degradation at bake temperature of 160°C or higher is triggered by thermally outgassed components from the flame retardant compounds. However the failure rate does not follow the straight line trend based on data from 200, 175, and 160°C bakes. Instead a lower failure rate occurs at 150°C bake temperature [R-12]. This behaviour suggests that the failure mechanism of bond degradation is changing at about 150°C.

6.1.6 Methods of Analysis of Intermetallic Formation

The intermetallic compounds are formed below the ball bond, at the interface between the ball and the Al bondpad. To analyse the intermetallic formation different methods are used which are: metallurgical cross section and visual inspection, silicon etch from backside, infra red microscope inspection and electrical resistivity measurement.

6.1.6.1 Metallurgical Cross Section and Inspection

The intermetallic compound formed at the interface can be analyzed by cross sectioning the ball bond. Both parallel and perpendicular cross section of the bond can be done. The whole circuit is cast in epoxy and after hardening, the samples are cut and polished with standard microstructural cross sectional analysis.

6.1.6.2 Infra Red Microscope Analysis

To observe the bonds from the bottom, the silicon of the chip is first removed from the bottom of the bond by etching the chip from the backside with a mixture of five parts HNO_3 (65%), three parts H_2SO_4 (95%) and two parts HF (40%). If the SiO_2 layer between chip and pad is undamaged the etching process stops there and the bottom of the bond is visible through this layer. Silicon is opaque to normal visible light. However, infrared radiation can pass through thin silicon layer.

We can use the IR microscope to see through the silicon and observe the intermetallic compounds and voids at the bond interface. Using IR microscope, we can look at bond formation from the back of the die, and we can also calculate the area of intermetallic coverage. Figure 6.1.13 shows the intermetallic compounds seen through silicon using infra red rays [R-13].

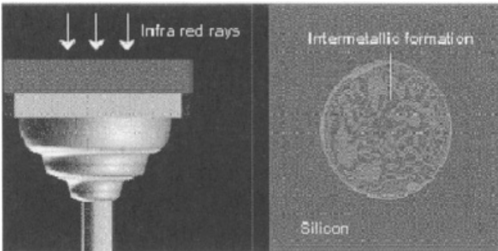


Figure 6.1.13 Intermetallic compound seen through silicon using infra red

6.1.7 Electrical Resistivity Measurements

The intermetallic compounds have much higher resistivity compared to pure Al and Au. Intermetallic compound formation and bond degradation

can be measured non-destructively using a special test chip, by measuring variations in Kelvin resistance of bonds as a function of temperature and time.

6.1.7.1 Four Point Method

The contact resistance of bonds on the test chip can be measured by a technique based on the four point method with a constant low voltage. Changes of the resistivity of the metallization and of the electrical contact at the pad/ball interface are monitored. Figure 6.1.14 shows the module to measure the resistance of Au-Al bond

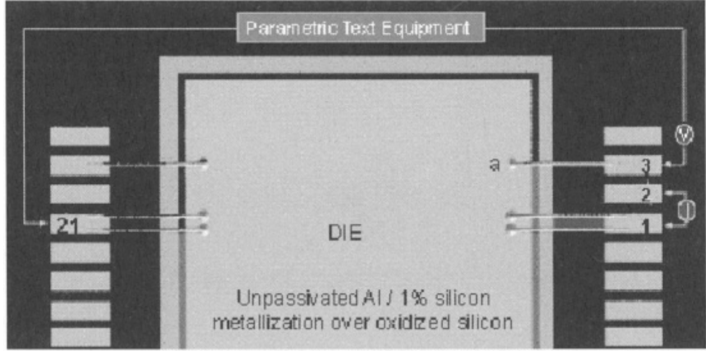


Figure 6.1.14 Module to measure resistance of gold-aluminum bond **[R-12] [VIEW-IN-CDROM]**

The special test chips are prepared with unpassivated Al-1% Si metallization over oxidized silicon. These dice are attached to 40-lead leadframes. These leadframes have gold-plated lead fingers for Au wire bonding. The dice are wire bonded with 1.3 mil Au wire. The bonding scheme produced four wire Kelvin measurement modules capable of measuring the resistance of one wire in series with the resistances of the Au-Al interface at the chip end of the wire and the Au-Au interface at the leadfinger end. As only the Au-Al interface degrades appreciably due to thermal ageing, therefore, changes in the measured resistance are taken as a measure of degradation of Au-Al interface. [R-12]

When we heat gold - aluminum bonds, the formation of gold - aluminum intermetallic compound increases the resistance. However, when gold is bonded to gold, there is no intermetallic formation, and therefore no increase in resistance. Figure 6.1.15 shows Kelvin resistance measurement using test chips.

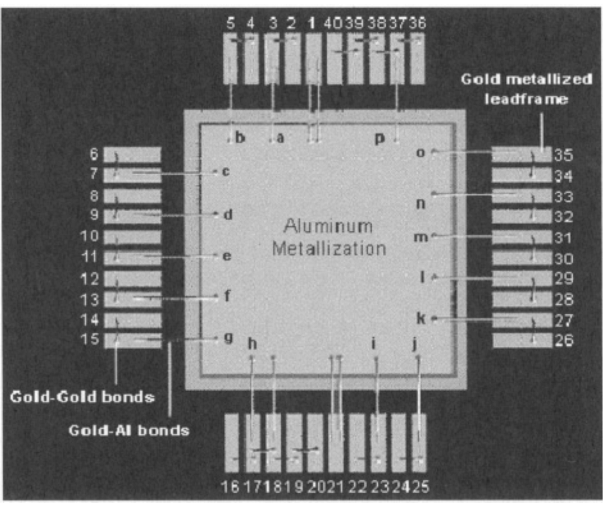


Figure 6.1.15 Kelvin resistance measurement using test chips [R-12]

By comparing resistances of gold - gold bonds and the gold -aluminum bonds as a function of temperature, we can study the rate of formation of Kirkindall voids in gold-aluminum system. In this arrangement, resistance of a bond is obtained by dividing electrical potential by the forced current. A minimum value of current is chosen in such a way that the resistance repeatability falls in the range of ±0.1 milli ohm or less. Some observations during Kelvin resistance measurement are given below:

- 0-4 meg ohm increases follow no clear pattern and probably correspond to initial annealing but not bond degradation
- 4-20 meg ohm increases correspond to bond degradation

- increases of 20 meg ohm or more correspond to catastrophic failures

6.1.7.2 Effect of Annealing Temperature on Resistivity

When gold and aluminum bonds are annealed at different temperatures between 175°C and 300°C, we see that at lower temperatures, the increase in rate of resistivity is very slow; where as at higher temperatures, the rate of resistivity increase is exponential. This can be observed in figure 6.1.16.

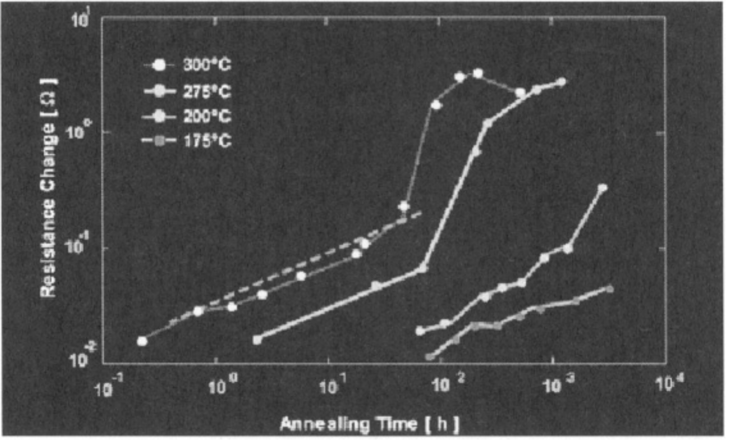


Figure 6.1.16 Change of the resistivity of bonds during annealing at various temperatures [R-12]

We can also study the effect of contamination on intermetallic formation using the resistivity methods.

6.1.7.3 Resistivity Change Due to Molding Compound

Two flame retardant molding compounds, X and Y, were used for encapsulation of these Kelvin test chip devices. The compounds are formulated with four different concentrations of bromine: approximately 2.5, 1.35, 0.8 and 0.45 percent by weight. The devices were baked at 200°C and 175°C. Resistance measurements were taken at various time

intervals for each temperature to track their behavior over time [R-12]. The result showed that with increasing bromine content the resistivity also increases.

6.1.7.4 Controlling Purple Plague in Thick Films

Aluminum bonds bonded to thick gold film metallization have shown more failures than Al bonds bonded to thin Au films. This is attributed to more grain boundaries, vacancies and impurities in the thick films which give rise to higher diffusion rate of Au and Al to form the intermetallics. Palladium is added to gold thick films for use in aluminum ultrasonic bonding. This slows both the Au and Al diffusion and lengthens the life of the aluminum wire bonds. Many applications requiring Al wire bonding currently employ such palladium-doped gold thick films.

6.2 Spiking

6.2.1 Aluminum-Silicon Alloy

Although aluminum metallization is still the dominant metallization scheme used by most integrated circuit manufacturers, it has one significant problem. Silicon is soluble in aluminum and during post-deposition (physical vapor deposition or sputtering) heat treatment or alloying, at an annealing temperature exceeding 300°C, silicon atoms at silicon surface diffuse into aluminum layer. Silicon diffuses into the aluminum, leaving holes or voids in the Silicon which are filled by aluminum metallization to form “spikes” [R-14]. Pure aluminum on silicon oxide when heated reacts and forms aluminum oxide and silicon. The silicon atoms because of their solubility in aluminum diffuse into silicon. At the end of this process, we have silicon precipitate in aluminum metal and aluminum has spiked into silicon, creating an electrical failure. This aluminum spiking problem can be solved by adding approximately 1% silicon to aluminum and thereby avoiding silicon diffusion. The chain of reactions during aluminum spiking is schematically shown in Figure 6.2.1.

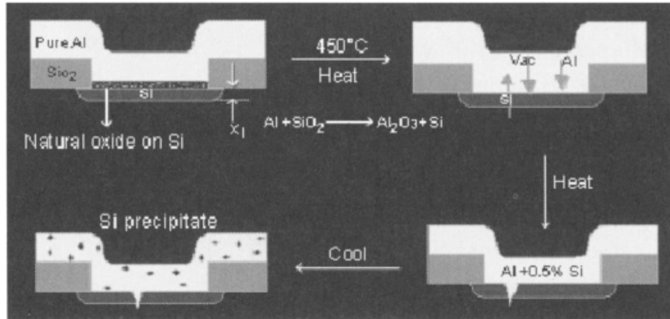


Figure 6.2.1 Aluminum spiking [R-14] **[VIEW-IN-CDROM]**

Spikes can be minimized by reducing processing times and rapidly increasing temperatures. As device junctions become shallower due to the rapid shrinkage in device size, the aluminum spikes go deep enough to cause junction shorting. Silicon is used as an alloying element in sluminum to minimize the probability of failure by junction spiking. Al-1% Si is a widely used composition. Although the addition of Silicon suppresses spiking, new problems can arise. One of them is re-precipitation of silicon. This occurs when the additional silicon at high temperatures comes out of solution on cooling. More information on spiking can be obtained in reference [R-14].

6.3 Cratering

6.3.1 Bond Pad Cratering

Cratering is a general term used to describe one type of bonding failure that occurs as the result of mechanical damage to the bond pad or underlying material.

Cratering is generally revealed as a small odd shaped pit out of which a small amount of Silicon is gouged out or just a disturbance in the Silicon single crystal. Occasionally large pits comparable to the size of the bonding pad are seen. Cratering can't be detected reliably at final test. Therefore, it usually appears during reliability testing or in the field. Figure 6.3.1 shows a SEM photographic image of a typical crater formed on a silicon chip during gold wire bonding.

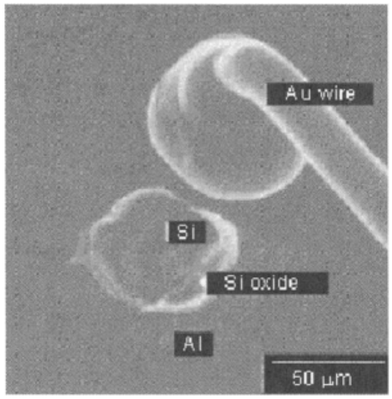


Figure 6.3.1 Crater on bondpad

Crater occurs in different sizes to different depths in the silicon chips depending on the kind of stress and the amount of stress exerted during bonding. Figure 6.3.2 shows small, medium and large craters.

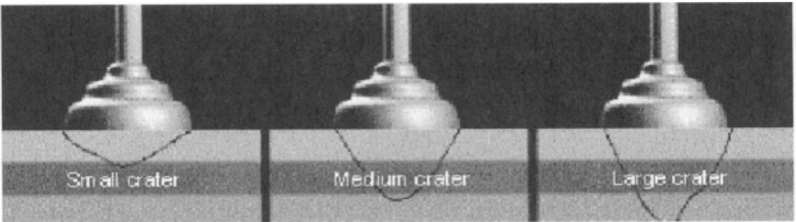


Figure 6.3.2 Different types of cratering

Cratering of semiconductor bonding pads is an important problem. Cratering can often be serious because there is no visual indication of the presence of such craters when they occur, because they occur below the Al bond pad metallization. There are potentially many causes of cratering. Wire hardness, bond pad thickness, bonder set up parameters in particular high ultrasonic energies, have all been identified as causes or contributing factors to the cratering problem. Some underlying materials such as polysilicon are more susceptible to cratering.

6.3.1.1 Causes of Cratering

Cratering can be caused due to many reasons:

- bond wire materials related
- bonding Process parameters related
- wafer related

Though many papers have been published discussing cratering and its many causes, there are few detailed and controlled experiments made to pin point the mechanism of cratering under these conditions. For example, it has been observed and reported that there is cratering when the bond force is low; but the mechanism to explain this, "chattering effect, hammering effect or ploughing effect" are all "kind of hypothetical" [R-15, 16, 17].

If we need to repeat the experiment and get similar results, it may be quite difficult, because we are not sure under what other conditions the problem was observed. It is important to recognize this variance and shortcoming when we encounter a cratering problem on the production floor.

Out of the many causes of cratering, some of the well understood ones are bonding force, bonding ultrasonic energy, presence of silicon nodules, bond pad metallization thickness, intermetallic formation, tool impact velocity and impact force, underlying dielectric layers, type of bonding tool, wire hardness, type of power supply, bond squash factor, length of bonding tool, type of bonding chuck, probing of the dice, operator associated variables. We shall discuss some of them in detail.

6.3.2 Effect of Bonding Force

Cratering has been observed in both Al ultrasonic and Au thermosonic bonding at high bonding forces. High bonding force coupled with ultrasonic energy may cause craters in the silicon, particularly if there is any localized stress concentration. In some cases, particularly in Al wedge bonding, even low bond forces seem to cause cratering. The explanations given are that there is a "hammer effect" (or a chattering effect) due to inefficient transfer of ultrasonic power.

Not many detailed and controlled studies have been made to really understand the effects of bond force. One study shows that in Al wedge bonding, the cratering is high both at low bond force and at high bond force, but no satisfactory explanation has been given to explain the phenomena. Experiments done with ultrasonic aluminium bonds have shown that at low bond force, there is more cratering. As we increase the bond force, cratering reduces to zero and continues to increase as the bond force increases. We must optimize the bond force for minimum cratering during process setup. Figure 6.3.3 shows the incidence of cratering versus bond force for the ultrasonic bonding [R-15].

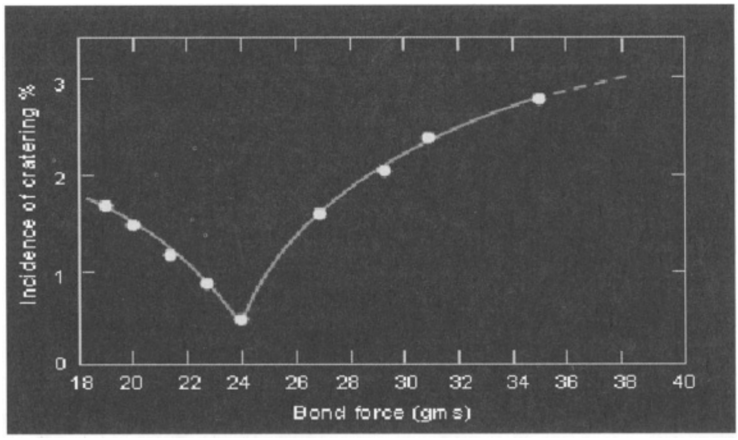


Figure 6.3.3 The incidence of cratering vs bond force for ultrasonic bonding [R-15] **[VIEW-IN-CDROM]**

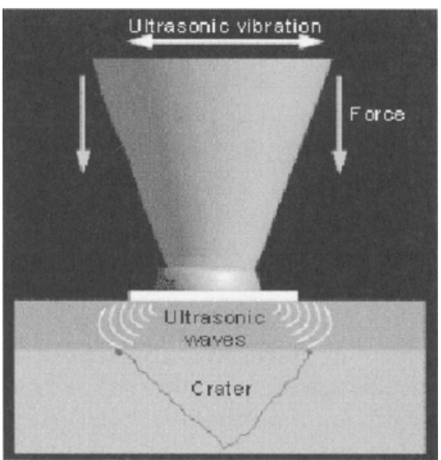
6.3.3 Effect of Ultrasonic Energy

It is found that apart from bonding force and bonding temperature, ultrasonic energy is also a major cause for cratering. For example during thermocompression bonding it has been observed that even application of very high stress and high temperature does not cause excessive cratering. To add more credence to this theory, it has also been showed that force alone, without ultrasonic energy, would not cause the form of cratering resulting from silicon nodules in the metallization [R-17].

6.3.3.1 Probable Mechanism of Cratering with Ultrasonic Energy

During ultrasonic and thermosonic bonding, when the bonding tool presses the wire on the bond pad, there are few localized points that are in actual physical contact. If there is a small defect in the silicon under the bond pad, the application of ultrasonic energy coupled with localized high stress could propagate through the micro crack. Figure 6.3.4 shows the effect of ultrasonic energy on cratering.

The ultrasonic energy during bonding generates stress that causes stacking faults and other material damage in the Silicon, and this has been confirmed by observations of etch pits marginal cratering along the perimeter of the bond. Steam oxidation studies have revealed ultrasonic bonding induced stacking faults in silicon. Though ultrasonic energy may not initiate cracks in a single-crystal, if the stress of an electrical probe or other mechanical damage has produced a micro crack in the position of the bond perimeter, that crack can easily propagate under the influence of ultrasonic energy [R-18].



6.3.4 Effect of ultrasonic energy on cratering **[VIEW-IN-CDROM]**

6.3.3.2 Cratering in Fine Pitch Devices

In fine pitch bonding one tries to maximize the area of interfacial reaction at the Au ball and Al bond interface to maximize shear strength. And in case of high speed bonding this is done in very short time of approximately 10 to 15 ms of bond time. This is achievable only with higher bond force per unit area and higher ultrasonic energy per unit area. Both these requirements may pose a serious concern in terms of higher cratering propensity of fine pitch bond pad.

6.3.3.3 Cratering in GaAs Devices

Since GaAs is a compound semiconductor and is mechanically weak, it has a greater propensity for cratering, particularly in presence of ultrasonic energy. Therefore it is much preferred to use thermocompression bonding. If ultrasonic energy is used during GaAs bonding, one has to optimize the process carefully and establish a reliable process control [R-19].

6.3.3.4 Cratering of Contaminated Bond Pads

When a bond pad is contaminated with hydrocarbons or with residual photoresist, it requires higher ultrasonic energy to break through the contamination and create a bond with high shear strength. This increases the propensity for cratering in contaminated bond pads.

6.3.4 *Silicon Nodule-Induced Cratering*

We have already discussed that silicon is often added to aluminum metallization in order to prevent aluminum spiking. If the Al-Si metallization is not processed uniformly, then micrometer-size silicon nodules precipitate on aluminum bond pads. These silicon nodules can act as stress raisers and crack the underlying silicon during thermosonic gold ball bonding.

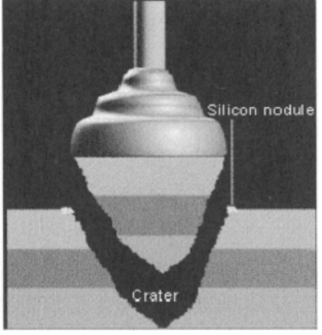


Figure 6.3.5 Effect of silicon nodules on cratering

When silicon nodules are present, a crater is formed much more easily even under low ultrasonic energy and low bond force condition. Figure 6.3.5 shows the effect of silicon nodules on cratering [R-20].

Cratering can be minimized when the stress concentration at the Si-modules is not allowed to cause any cracks on the brittle oxide layer. One can use the alternative pad structure with titanium : tungsten below Al-Si (1%) and this acts as the buffer to the stresses exerted on the pad and

protects the oxide from being cracked due to these induced stresses. Figure 6.3.6 shows effect of bondpad structure on cratering.

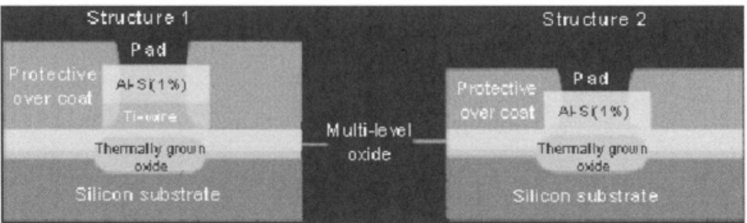


Figure 6.3.6 Effect of bondpad structure on cratering [R-21]

6.3.5 Effect of Wire Hardness

There are no clear experimental studies that have been done to show that higher the hardness of the wire, higher is the cratering. But generally it has been observed that during copper ball bonding there is greater cratering. Since copper is harder than Au it is expected that the cause of cratering is higher. Higher the hardness greater is the bonding force and ultrasonic energy required for bonding; and this leads to cratering. However, when we use soft wire, the force required for deformation is low and thus the propensity for cratering is also very low. But studies have shown that the hardness of Au ball at touchdown also contributes to the stress exerted on the bond pad [R-22, 23]. The hardness of the Au ball at touchdown depends on:

- the temperature of Au ball at touchdown
- the impurity content in Au wire

When the wire is melted with the EFO, it melts to form the ball. The cooling of the ball depends on the time it takes for the ball to reach the bond pad (touch down time). When ball takes a long time to touch down, it hardens during the travel time and therefore it does not deform easily when bond force is applied. The bond force is transmitted through the hard ball and this generates craters. On the other hand, if the touch down time is fast, the molten ball has no time to cool down and remains soft. When bond force is applied, it is squashed and dissipates force causing minimum cratering.

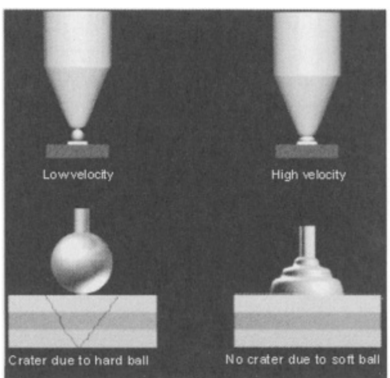


Figure 6.3.7 Effect of impact velocity on cratering **[VIEW-IN-CDROM]**

Figure 6.3.7 shows the effect of impact velocity on cratering. As we increase the touchdown time, the number of bond pad cracks tends to increase. Table 6.3.1 shows the touchdown time versus cratering propensity.

Cratering is affected significantly by the bonding parameters. Table 6.3.2 shows a comparison of combination of parameters that have been used to study their impact on cratering. When a cratering experiment is done with two sets of parameters, parameter A and parameter B, we can see that the parameter A conditions result in less cratering compared to parameter B. We can recognize that, to minimize cratering, one must use consistent force, high bonding temperature and uniform ultrasonic vibration.

Table 6.3.1 Touchdown time vs cratering propensity [R-24]

Time taken from ball formation to touchdown (milliseconds)	27	34	55	62
Bond pull test (# bond pad crack / sample size)	0/97	5/98	6/99	8/100
Defect PPM (bond pad crack)	0	51020	60606	80000

Table 6.3.2 Optimization of parameters to minimize cratering [R-24]

Parameter A	Parameter B
More consistent bonding force using closed loop control	Less consistent bonding force with open loop control
Low impact force at touchdown	High impact force at touchdown
Higher bonding temperature	Lower bonding temperature
More uniform ultrasonic vibration	Less consistent ultrasonic vibration

6.3.6 *Effect of Metallization Thickness*

It has been observed from experiments that as the metallization thickness increases there is a significant reduction in cratering failure mode during ball shear test. It has also been experimentally studied that thinner metallization has higher tendency for cratering and thicker metal has less tendency for cratering. This has been attributed to the "cushioning effect' of the thicker metal. And technically speaking, a damping of the stresses due to plastic deformation of the metal [R-16].

6.3.7 *Moisture Absorption in Plastic Package*

Plastic encapsulated SMT devices show particularly high level of cratering after board assembly. This has been attributed to moisture absorption. It has been found that most of the plastic molding compounds absorb moisture and the absorbed moisture gets released during high temperature soldering operation. During surface mount reflow soldering, due to the rapid heating of the component, the thermally expanding SMT plastic package exerts shear stresses on the ball bonds, resulting in bond pad cratering. This failure mode is enhanced if the plastic package has absorbed moisture. In plastic encapsulated ICs, the corner of a chip experiences shear force during thermal excursion. And this shear force tends to cause cratering of corner bond pads. Figure 6.3.8 shows the cratering of corner bonds due to shear force [R-16].

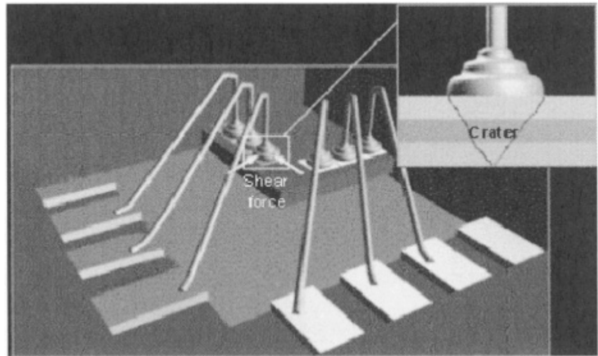


Figure 6.3.8 Cratering of corner bonds due to shear force

6.3.8 Effect of Intermetallic Compound

When Au wire is bonded on aluminum bond pad, the interface reacts and forms intermetallic compound. The type of intermetallic compound depends on the reaction time, reaction temperature and whether it is Au rich or Aluminum rich intermetallic. Different types of intermetallic compounds have different volumes and they exert variable stresses at the interface. It was discovered by Clatterbaugh et.al in their shear test experiments that when Au-Al bond was annealed for four hours at 250° C, more than 20% of shear test failures were cratering failures. The same Au-Al bonds after annealing for 35 hours at 250° C, the cratering failures after shear test was less than 4%. This phenomenon was attributed to stress at the interface of Au-Al bond due to the varying volumes of the intermetallic. At 250° C and four hours, the Au_2Al is formed with high volume and greater stress. And the same compound may anneal or give rise to a different intermetallic compound with smaller volume, thus reducing the cratering [R-25]. This intermetallic volume-induced strain is referred to as the Clatterbaugh effect. It is important to understand that this Clatterbaugh effect can occur due to any post bond high temperature operation such as:

- molding and post mold cure operation
- curing of epoxy or silicone glob tops

- curing of other plastic encapsulants
- burn in or stabilization bakes

One should be aware that cratering usually does not occur because of one single reason but usually it is a combination of effects described above. For example, cratering can occur due to a combination of effects such as silicon nodule with thin film metallization, high ultrasonic energy coupled with probe damage on bond pad and so on.

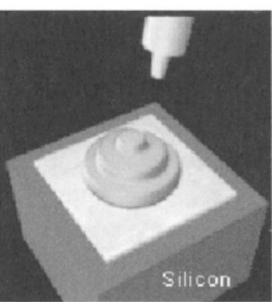
6.3.8.1 How to Minimize Bond Crater Problem

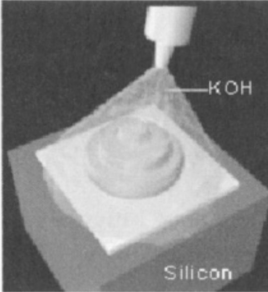
Some of the remedial measures to minimize cratering are:

- use short time from flame off to touch down
- use Al+Si+Cu to minimize Si nodules
- use wedge bonding tools with a concave foot
- use bonding tool without broken off corners
- use softer wire
- use thicker bond pad
- reduce silicon nodules
- design bond pad on poly Si, Ti:W or other material
- use low ultrasonic energy
- use negative electronic-flame-off for ball bonding
- use conditions which allow best bond formation

6.3.8.2 Diagnosis of a Crater

The crater under the bond pad can only be visualized by removing the bond pad metallization and lifting the bond. Usually this is accomplished by dissolving the Al metallization using hot potassium hydroxide (KOH) and lift the bond gently and that results the crater underneath. Figure 6.3.9 shows dissolving of Al metallization using hot KOH.





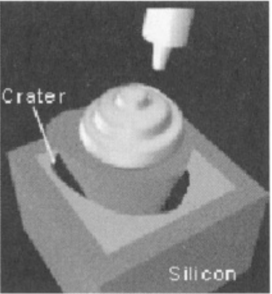


Figure 6.3.9 Dissolving Al metallization with KOH **[VIEW-IN-CDROM]**

6.4 Wire sweep

Wire sweep is wirebond deformation that occurs during molding of IC packages. Wire sweep usually denotes visible wire deformation, typically a lateral movement in the direction of the compound flow through the cavity. Reliability concerns with sweep include device shorting and current leakage. Shorting can be from wire to wire, from wire to lead finger, or from wire to die edge. Failure can be immediate or may not show up until the package experiences stress excursions. Wire sweep can occur from any one of a number of causes: high resin viscosity, high flow velocity, unbalanced flows in the cavities, void transport, late packing, and filler collision.

The gold wirebonds between the bond pad and the leadfinger, deflect under the action of molding compound flow during cavity filling. If the wire deformation is elastic, the wirebonds will tend to spring back to their premold positions before the mold compound melt cures. If the deformation is plastic, the wirebonds will undergo significant permanent displacements. These permanent displacements are defined as “wire sweep”.

Mold wire sweep is common to all plastic IC packages, but becomes more critical in thin and fine pitch packages. Wire sweep can cause wire crossover and shorting of the device. Mold sweep is an important criterion for acceptance of new mold designs from vendors. It is equally important to control it in production because of its effect on yields and its reliability implications.

In order to establish acceptance rejection criteria, one has to understand the amount of wire sweep. Figure 6.4.1 shows, low wire sweep, medium wire weep and high wire sweep situation in a plastic package.

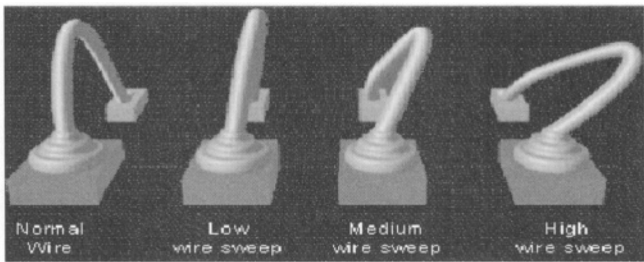


Figure 6.4.1 Schematic representation of low level and high level of wire sweep. The low level wire sweep can be elastic, whereas the high level is plastic

Wire sweep is defined as the ratio of displacement of the wire from its normal position to the overall length of the wire 'L'. Figure 6.4.2 shows the definition of wire sweep

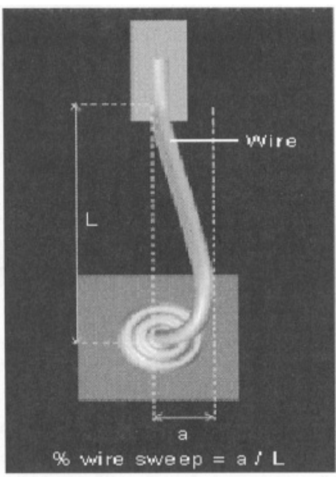


Figure 6.4.2 Measurement of wire sweep

6.4.1 Different Causes of Wire Sweep

Wire sweep is a complex subject. There is no universal standard to evaluate wire sweep in IC packaging. The wire sweep criterion depends on the package design, the bond condition and quality requirement. There are many factors that influence wire sweep, including: bonding wire, IC package design, bonding precision, mold design, molding process, encapsulant material. Let us review each one in detail

6.4.2 Effect of Bonding Wire

Wire sweep depends on many wire parameters such as: wire length, wire diameter, wire material properties (stiffness,Young's modulus, yield strength, thermal stability) and wire profile (loop length, loop height and loop shape). Let us discuss each of them in greater detail.

6.4.2.1 Effect of Wire Length

As the length of the wire gets longer, the structure becomes inherently unstable. For same loop height and wire diameter, the longer the wire length greater is the wire sweep. Figure 6.4.3 shows the variation in amount of wire sweep for different wire lengths. As the viscosity of the molding compound goes up, the maximum length of wire that can withstand wire sweep decreases.

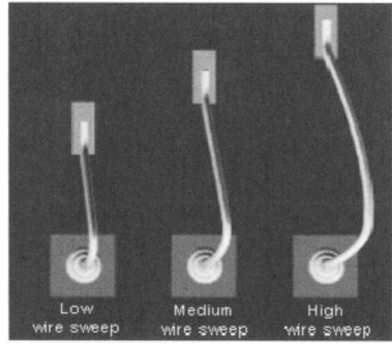


Figure 6.4.3 Variation in amount of wire sweep for different wire lengths

For example, studies have shown that inside a cavity with a volume of 0.9 cc, as the flow momentum is raised to Reynold's number of, Re=0.001, the critical length before wire sweep is approximately 3.6 mm. When the

Reynolds number is increased to Re=0.01, the maximum allowable wire length is lowered by another 30%, to 2.5 mm [R-26].

6.4.2.2 Effect of Bond Height

The effect of the bond height, with in-plane flow load, has been extensively studied. It has been shown that the maximum displacements increase as bond height increases for a 1 mil (0.025 mm) gold wire exposed to the melt flow at different flow Re (Reynold's number). The results confirm again that the bond height has a great effect on the wirebond deformation, even in the case of an in-plane flow load. This means that bond height should be kept as low as possible. Figure 6.4.4 shows the effect of bond height on wire deformation under flow load [R-26].

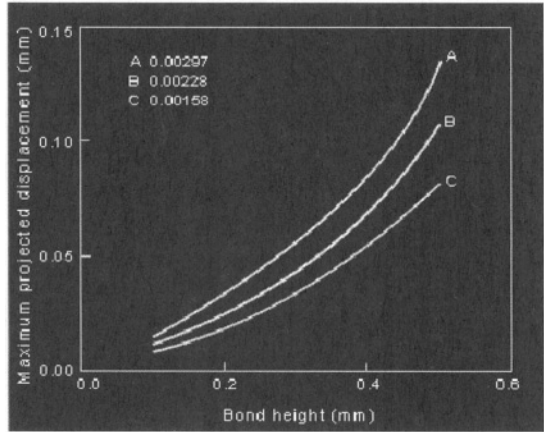


Figure 6.4.4 Effect of bond height on wire deformation under flow load **[R-26]**

6.4.2.3 Effect of Bond-Wire Diameter

The wire behaviour also depends on the wire rigidity, which is a function of wire modulus and wire diameter. For the same gold material used, the wire modulus is constant. Hence, the wire deflection is directly dependant on the wire diameter. The effect of the wire diameter on the wire behaviour

at different Re (Reynold's number) is shown in figure 6.4.5. Here we can observe that, as the wire diameter increases the maximum displacement due to wire sweep decreases. At the same time as we decrease Reynold's number from 0.015 to 0.001 the amount of displacement decreases dramatically.

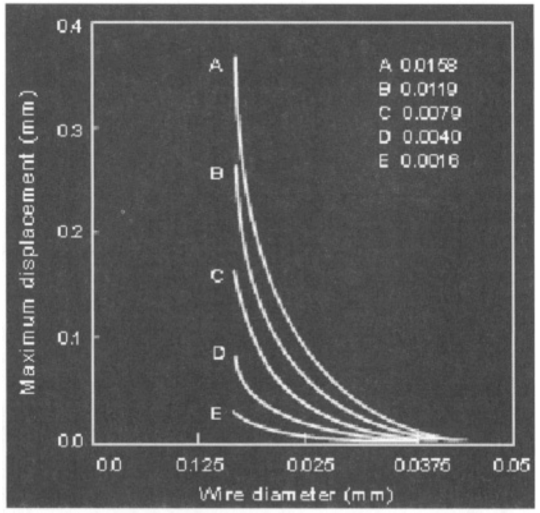


Figure 6.4.5 Effect of wire diameter on wire sweep [R-26]

It has been found that when the wire diameter, d, is greater than 1.25 mil, the wire sweep seems insensitive to the diameter, even at high Re values. When the wire diameter, d, is less than 1 mil the wire sweep becomes very sensitive to both diameter and Re. For example, at d=0.6 mil and Re=0.01198, the maximum displacement is 0.2654 mm, which is about nine times that for d = 1.0 mil.

6.4.2.4 Effect of Loop Trajectory and Package Type

Looping trajectory optimization is also critical because it reduces the total amount of wire in the loop, and therefore, minimizes wire sweep. The BGA package is more susceptible to wire sweep because of the package construction. In a TQFP package, the wires and the lead tips have some

degree of freedom of movement as the mold material encapsulates the device. In a BGA package, the leads are fixed, and only the wire is free to move. Reducing the amount of wire in the loop ensures that the wire cannot move very far, and therefore, minimizes wire shorts after mold.

6.4.2.5 Effect of Young's Modulus

Gold is used almost universally as the bond-wire material. The addition of trace amounts of beryllium gives a larger elastic region before yield. The stress strain curve in figure 6.4.6 is a typical curve of gold wire with 1 mil (0.025 mm) diameter at room temperature (20°C) and at a high temperature (250°C). This wire is used for wire bonding TSOP's in industry. It contains a very small quantity of additive elements. The purity of gold is maintained at a level of more than 99.99%. Temperature has a great effect on the mechanical properties of the wire. Yield strength decreases as temperature increases. In figure 6.4.6, we can see the stress strain curve for a gold wire. Here at 20°C, the yield strength is very high, whereas at 250°C, the yield strength drops dramatically.

During molding operation, the wire is exposed to high temperature, thus there is reduction in yield strength, and this gives rise to easy wire deformation displacement. With a modulus approximately 10% lower than that of gold, aluminum wires deflect more by the same amount, regardless of the cross-sectional profiles. Therefore we must consider the effect of temperature on the mechanical properties on bond-wire, before choosing the wire for a particular packaging application.

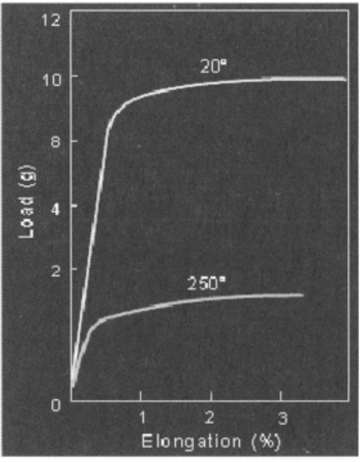


Figure 6.4.6 Effect of temperature on yield strength [R-26]

6.4.3 IC package design

When molten molding compound enters the cavity, drag forces act on the wires. As along as the drag force does not exceed the elastic strength of the individual wire, wire sweep does not occur. Although there will be some deformation, spring back may actually happen to a certain extent before the material gels completely. However, if the drag force is higher than the elastic limit of the wire, then wire sweep occurs. Some of the contributing factors are:

- gate design and runner design in a mold tool
- viscosity and spiral flow of a molding compound
- transfer time, transfer pressure and molding temperature

6.4.3.1 Effect of Mold Design

The design of the mold gate and the runners affects the flow characteristics (thixotropy) of the molding compound inside the mold cavity. This affects the wire sweep.

6.4.3.2 Effect of Mold Process

During molding process, wire sweep can occur due to slow filling of the mold cavity. This happens when the transfer speed is slow, and thus the molding compound is in an advanced state of cure, and has high viscosity. Using FEM, we can calculate the lateral displacement of the wire bonds. In figure 6.4.7 we can see the increase in lateral displacement, as the viscosity of the molding compound indicated increases. The viscosity of the molding compound is indicated by the Reynold's number.

On the other hand, if the ram transfer speed is high, the high flow momentum also may induce wire sweep. Usually, wire sweep in end cavities is due to slow transfer speeds. However, wire sweeping occurs in cavities closest to the pot when excessive ram speeds are used. Therefore filling speed needs to be optimized for a particular mold design and specific molding compound.

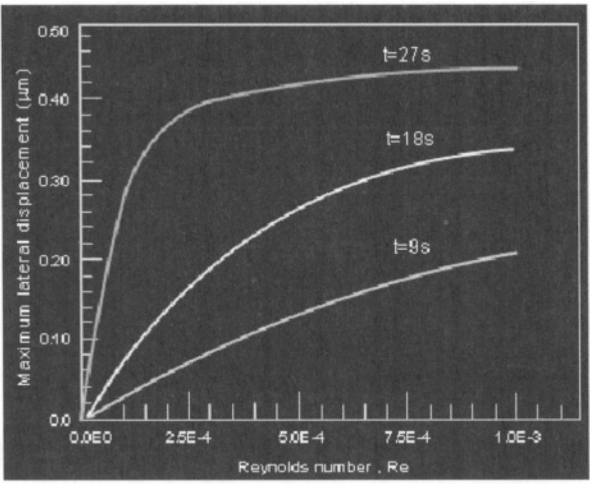


Figure 6.4.7 Maximum lateral displacement of wirebond **[R-27]**

6.4.3.3 Effect of Mold Temperature

The viscosity of the molten molding compound is directly related to the temperature. Higher the temperature faster is the cure, resulting in rapid changes in viscosity. This affects the wire sweep. The lateral displacement increases as we increase the curing temperature of the molding compound. In figure 6.4.8 we can observe that in case of wires that are perpendicular to the flow direction. The wire bond deformation is very sensitive to the molding temperature especially, for longer transfer time. This is because, higher the molding temperature, faster the curing and this leads to higher viscosity.

However bonds which are parallel to the mold front usually have low wire deformation. We can observe from figure 6.4.9, bond wires that are close to the gate and also parallel to the flow of direction experience less lateral displacement at low temperatures. At high temperature the displacement increases. This is due to cured state of the molding compound which has higher viscosity. Therefore controlling mold process parameters is of utmost importance in minimizing wire sweep.

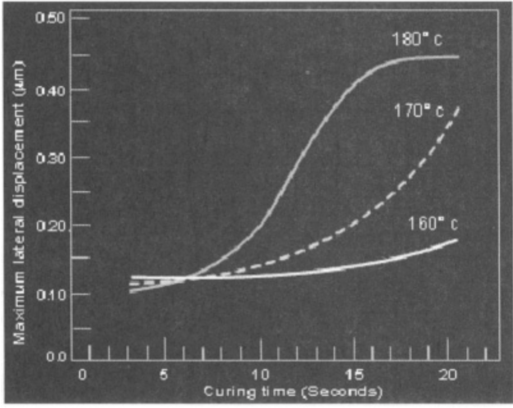


Figure 6.4.8 Maximum lateral displacement of bond wire perpendicular to flow direction [R-27]

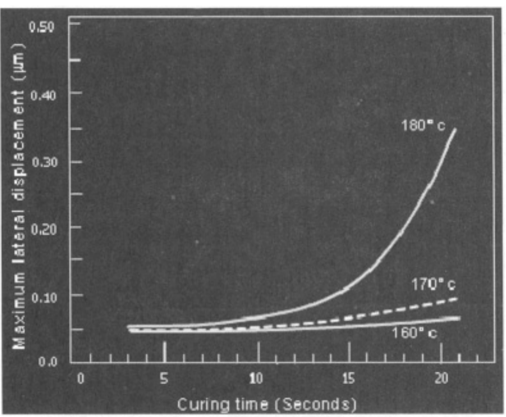


Figure 6.4.9 Maximum lateral displacement of bond wire parallel to flow direction [R-27]

6.4.4 Effect of Molding Compound

There is a strong relationship between the compound viscosity and the level of wire sweep. In turn, the compound viscosity is influenced by filler

shape, filler size, filler content, resin chemistry, hardener type and thixotropy level.

The chief property that impacts wire sweep is the molding compound viscosity, which is given in terms of TORQUE value. From figure 6.4.10 we see, as the torque value of the molding compound increases, the percent wire sweep also increases.

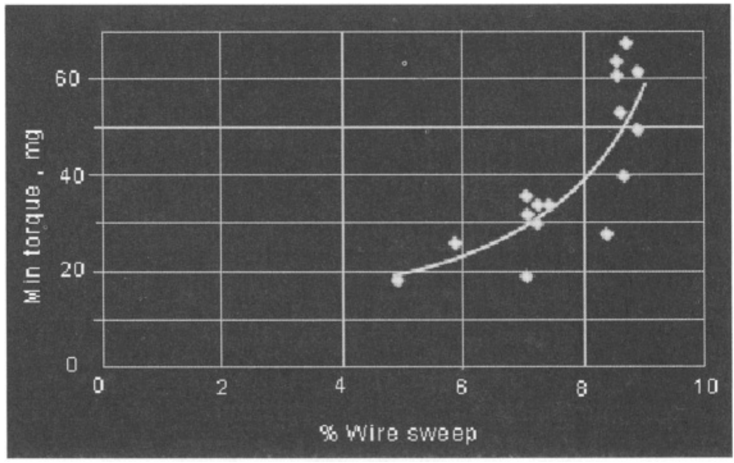


Figure 6.4.10 Molding compounds with high torque value lead to higher wire sweep [Courtesy: National Semiconductor]

When we compare different molding compounds and their effect on wire sweep, we see that compounds with high torque results in higher wire sweep. Figure 6.4.11 clearly shows the close correlation between torque and wire sweep for different compound evaluations. The viscosity of a molding compound is expressed in different forms, namely, spiral flow and gel time. But it has been shown that the amount of wire sweep is not co-relatable with the values of spiral flow or gel time. Only the torque value, which actually measures the thixotropic property of the molding compound, has direct correlation with the amount of wire sweep.

From table 6.4.1. we can see compounds with different formulation, different particle shape and filler contents shows that the amount of wire sweep has close correlation with torque. Though we use spiral flow and gel

time as indicators of viscosity of the molding compound, there is no clear correlation between the amount of wire sweep and these two parameters.

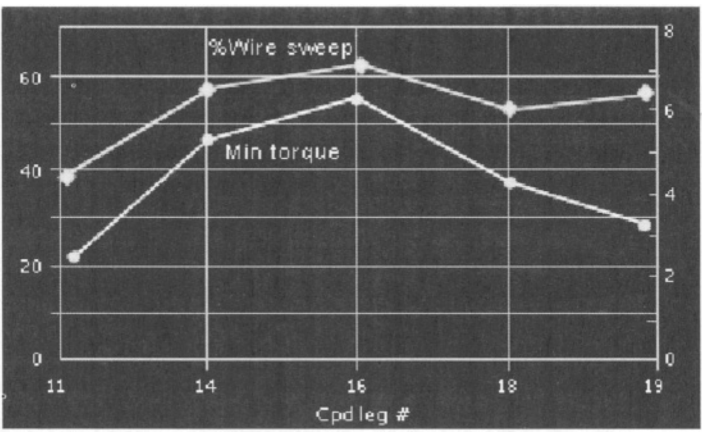


Figure 6.4.11 Shows close correlation between molding compound torque value of wire sweep in different compounds [Courtesy: National Semiconductor]

Table 6.4.1Comparision of wire sweep with respect to torque value, spiral flow value and gel time value [Courtesy: National Semiconductor]

Cpd #	Formulation	% Wire sweep	Min.Torque	Spiral flow	In Gel time secs
11	Bi-phenyl. 76%filler ragged/spherical	5.87	25	50	33.5
14	Bi-phenyl. 80%filler ragged/spherical	8.56	64	36	32.5
16	TRIS, 80% Filler ragged/spherical	8.61	53.5	29	29.5
18	ECN, 76% filler ragged/spherical	7.07	35.5	32	23.5
19	ECN, 76% filler ragged	7.18	34.5	37	29.5

6.4.5 Effect of Wire Orientation with Respect to Mold Front

If the wires are in the direction of mold flow, i.e., in-plane flow stress, no wire sweep is observed but, the wires are deformed in vertical direction and causes deflection of the wire either downwards or upwards as shown in figure 6.4.12.

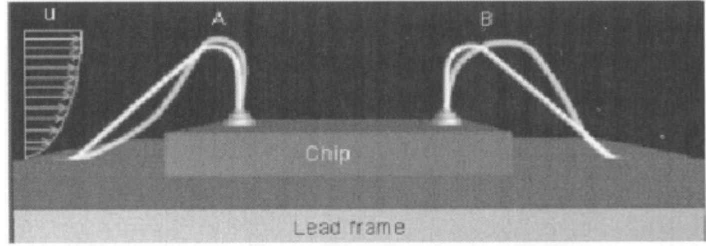


Figure 6.4.12 Deflection of curved wirebonds under inplane flow load [R-26]

If the wire is exposed to the mold front "perpendicularly", then we observe higher level of lateral wire deformation. When the molding compound enters the cavity through the mold gate shown in figure 6.4.13 wires that are oriented parallel to the mold front experience less wire sweep, whereas, wires that are oriented perpendicular to the mold front experience higher level of wire deformation.

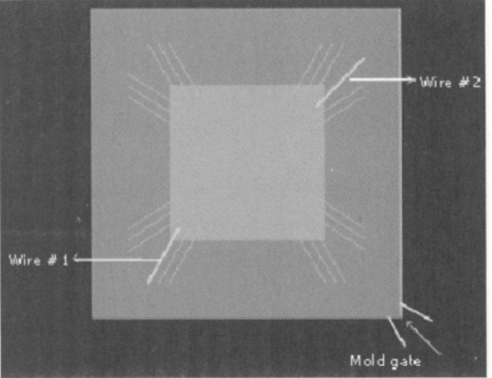


Figure 6.4.13 Orientation of wire and its effect on wire sweep [Courtesy: National Semiconductor]

When the position of the mold gate is in the corner as shown in the figure, it has been experimentally observed that the degree of wire sweep is more per dominant at wire number 1 and wire number 2 corners. This is also

confirmed with the high electrical rejects caused by wire shorting in the corners.

A highly viscous melt rushing out of a gate onto a row of wirebonds all angled at 90° will cause much more damage than in configurations where the wire is exposed at less than 90°. Thus, positioning the wirebonds within the mold cavity can have a significant influence on their structural and electrical integrity.

Computer Software has been developed to predict wire sweep in high pin count IC packaging. Figure 6.4.14 shows an example of a predicted wire bond deformation during molding. We can see here that the wire bonds deflect in the direction of the compound flow and shorting of the wires happens in a region where the flow fronts, meet at the end of the cavity.

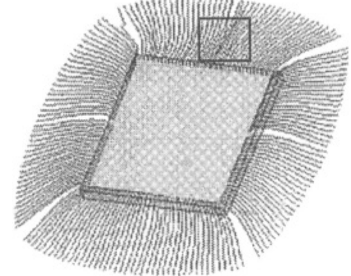


Figure 6.4.14 Wirebond deformation during molding [Adopted from: IME News Links Bulletin]

6.4.6 FEM of Wire Sweep

Using the advanced computer software numerical investigations on the effects of different design factors can now be performed to determine the optimal combination of molding compound, mold design, device layout and process conditions without recourse to expensive tooling fabrication. This will reduce the design-evaluation cycle from initial design to the final optimized package. Based on finite element modelling, of the 173 wirebonds between the silicon chip and gold plated leads on the substrate, the wirebond deformation during molding can be predicted. It can be seen that wirebonds deflect in the direction of compound flow and the wire-short happens in the region where the flow fronts meet at the cavity end. This simulation result is well correlated with the experimental result.

6.4.6.1 Prediction of Flow Induced Forces

High pin count finepitch plastic package are prone to wire sweep problem. Therefore softwares have been developed to stimulate the wire behaviour during molding and predict the probability of wire sweep. This is an extremely complex technology and we will briefly addressed some salient points in this section.

When the molten mold compound flows over the wirebond, viscous forces act on the wirebond, causing it to deform. These forces depend on the mold compound properties, local velocity at the wirebond and the wirebond diameter. When molten molding compound flows over a wire, this flow can be divided into two parts:

- the cross-flow that flows across the wire segment with the velocity component $\mathbf{V_n}$ and
- the broadside-flow that flows along the wire segment with the velocity component $\mathbf{V_t}$.

The model of the flow induced force is shown in figure 6.4.15.

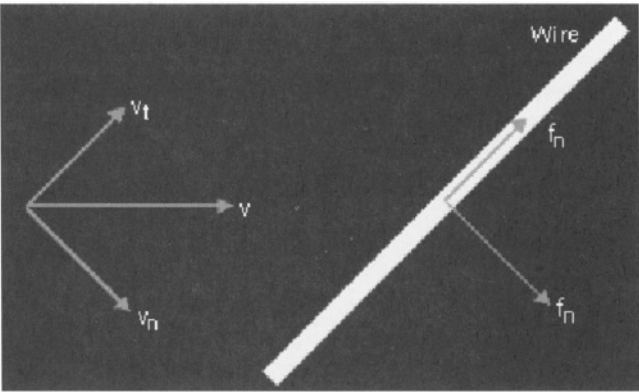


Figure 6.4.15 Model of flow-induced force [R-26]

The wire segment can be considered a finite slender cylinder because its diameter is quite small, compared to its length. For the finite slender

cylinder, the forces acting on the wire segment induced by the cross-flow and the broadside-flow can be described by the equations. Thus, a distributed flow load related to the cavity flow velocity field and the wirebond position can be obtained. By calculating the forces acting on the bond wires and by knowing the actual materials properties of the wire, it is possible to predict if the wire is going to deform or not. For example, if the force acting on the wire is higher than the yield strength of the wire, then the wire deforms [R-26].

$$f_n = \frac{8\pi\eta V_n}{2\ln\varepsilon+1} \qquad f_t = \frac{4\pi\eta V_t}{2\ln\varepsilon-1}$$

Where

f_n is the normal component of the force acting on unit length of the wire segment

f_t: is the tangential component of the force acting on unit length of the wire segment

ε: is the ratio of the wire length S of the wire diameter d

If the force is below the yield strength, the wire springs back without deformation. While many of the FEM analysis are done on a straight wirebond, the straight-wire geometry is not typical of a wirebond. A more realistic geometry is where the wire rises to a significant height above the die and the lead frame. This structure is much weaker than the straight wirebond in resisting lateral flow loads. Lateral wire deformation and hence wire sweep is much more serious in this case.

6.5 Corrosion

In this section we discuss corrosion issue, mechanism of corrosion and its effect on the wire bond as well as on bondpads. When we discuss corrosion issues, we should know about two different kinds of corrosion, which are:

- pre bonding corrosion, affecting bonding process
- post bonding corrosion due to contamination and moisture on the bondpad, affecting bond reliability

6.5.1 *Corrosion of Al-Cu Bondpad Metallization*

Copper is added to aluminum to enhance the electro migration resistance of aluminum and to suppress hillock growth, an essential requirement for multilevel metallization. Copper atoms in the grain boundary not only act as diffusion barrier, but they also attract aluminum atoms to form $CuAl_2$ precipitate. This preferential $CuAl_2$ intermetallic compound reduces the mass diffusion of Al from one end to the other, and in this manner, minimize electromigration failure.

However, from wire bonding point of view there are some concerns. Assembly studies have revealed a unique problem associated with Al-Cu metallized chips. SEM examination revealed presence of small pits (1-2 μ diameter) in the metal, with a particle centered inside the pits. Analysis showed that the particles are $CuAl_2$ intermetallic compound. When copper is used as an alloying element with Al, small precipitates of $AlCu_2$ are formed. In presence of moisture, these small intermetallic phases slowly corrode and form pitting corrosion sites along with a very thin film of aluminum hydroxide. This could be a major cause of non sticking of wire bonds. Figure 6.5.1 shows an SEM Photographic image of pitting corrosion [R-28].

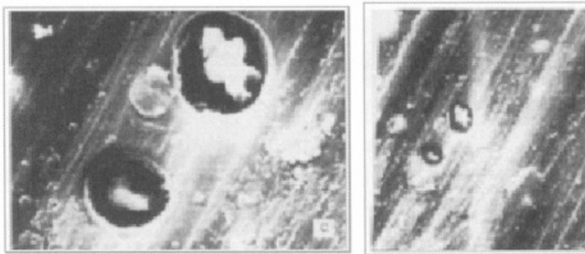


Figure 6.5.1 Scanning electron micrographs of bondpads of Al-1.5% Cu metallization showing pitting in the probe marks [R-28]

6.5.1.1 *Mechanism of Pitting Corrosion*

When the wafer goes through the sawing operation, the thin film of water on the bondpad acts as an electrolyte and sets up a galvanic cell between the $CuAl_2$ intermetallic and the surrounding aluminum.

Figure 6.5.2 shows galvanic corrosion. This happens when an intermetallic compound such as $CuAl_2$ is present and if there is a residual water stain, then a galvanic cell is set up between the aluminum metallization and $CuAl_2$ intermetallic compound.

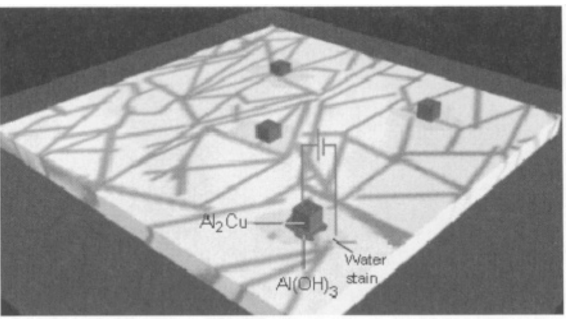


Figure 6.5.2 Galvanic corrosion

This galvanic reaction results in micro corrosion of aluminum and results in formation of a thin layer of aluminum hydroxide on the bondpad. The anodic aluminum surrounding exposed cathodic $CuAl_2$ particles is corroded to form hydrated aluminum hydroxide. Pitting continues until the $CuAl_2$ particle is isolated electrically and physically from the aluminum matrix. The presence of residue of aluminum hydroxide, causes non sticking problem during bonding. Pitting corrosion was found to occur more due to improper drying following sawing, as opposed to occurring during sawing. By correcting the drying process, the problem was eliminated allowing assembly to proceed normally. The pit density was generally higher in the mechanical probe mark on the pad as compared with the surrounding pad area [R-28].

6.5.2 Chlorine Induced Corrosion

Halogen induced bondpad corrosion has been studied extensively [R-29, 30, 31]. Chlorine induced corrosion plays a major role in plastic encapsulated devices. Here the Aluminum bondpad corrodes particularly in presence of chlorine ions. This chlorine may enter the bondpad area as external contamination, along with the leadframe and bond wire; or it may get

released from the molding compound. Chlorine reacts with aluminum and dissolves the aluminum metallization as shown in figure 6.5.3. This results in an electrical open failure.

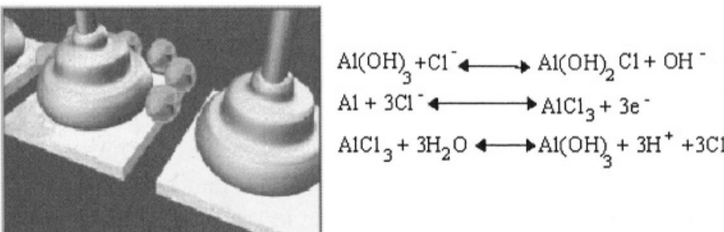


Figure 6.5.3 Chlorine induced corrosion [R-31] **[VIEW-IN-CDROM]**

The initiation of the corrosion process is dependent on Cl concentration, aluminum oxide thickness, temperature and the presence of an electrolyte. It has been proposed that the Cl- reacts with aluminum hydroxide, which is present in the aluminum oxide layer and then proceeds to attack the underlying aluminum. Aluminum hydroxide is the corrosion product. The corrosion mechanism starts with the dissolution of $Al(OH)_3$ in the Oxide layer.

$$Al(OH)_3 + Cl^- \leftrightarrow Al(OH)_2\,Cl + OH^-$$

When the oxide layer has been reacted sufficiently to expose base aluminum, the reaction becomes

$$Al + 3Cl^- \leftrightarrow AlCl_3 + 3e^-$$

the $AlCl_3$ then reacts with water

$$AlCl_3 + 3H_2O \leftrightarrow Al(OH)_3 + 3H^+ + 3Cl^-$$

As we can see from the above reaction equations the free Cl^- is regenerated and it continues to react with Al and due to this catalytic action, Cl^- even in PPM concentrations in the presence of water will generate continuous corrosion. The presence of Au ball on the bondpad forms the galvanic cell because of the wide difference in the EMF of Au and Al and this is the

driving force for the reaction. The presence of chlorine catalyzes the dissolution of aluminum. From these reactions, we also see that chlorine is regenerated and used again in the original reaction.

6.5.2.1 Reliability Effects of Fluorine Contamination

The SiN passivation on the bondpad is opened using dry etching with fluorine based plasma. During the dry plasma etch process, flourine atoms may get embedded in the bondpad. In presence of high temperature, electrical bias and moisture, it has been observed that the ball-bond interface may corrode, due to the presence of fluorine in the bondpad [R-32, 33].

6.6 Heel crack

One of the more subtle problems in ultrasonic wire bonding is controlling cracking in the wire at the heel of the bond. The problem of heel cracks is more common with aluminum wire than with gold. Heel cracks are also more frequent with 30° wire feed angle bonding than with steeper wire feed angles. This is due to the wire being worked more during looping. The wire starts out at a 30° angle, is flexed to 90° during the beginning of the loop and then is returned to about 30° after the lead bond is made [R-34].

6.6.1 Thermal and Power Cycling Induced Heel Failures

A broken internal bond wire can result from one of several stresses:

- electrical (over current) overload
- mechanical failure due to tensile overload
- mechanical overload of a cyclic nature (high-cycle fatigue) or
- thermal / power cycling

Both Au and Al wire fail for each of these stresses. Some superficial cracking is nearly always evident under SEM (scanning electron microscope) examination, and this probably does not degrade bond integrity. As shown in

figure 6.6.1(a) deep cracks, may contribute to premature failure even though the initial loop pull strengths may be satisfactory.

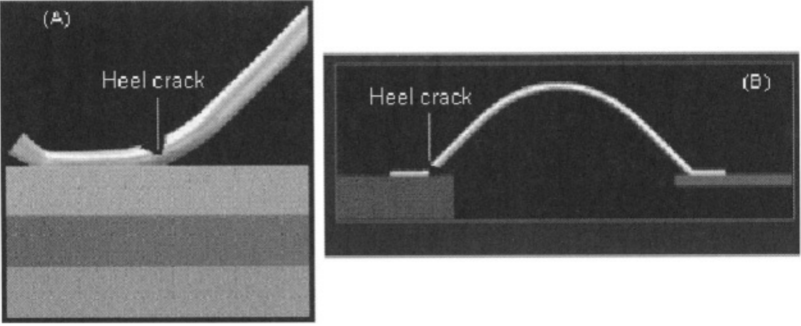


Figure 6.6.1(a) Heel crack (b) Power cycling fatigue

Presence of heel cracks affects bond wire reliability. During thermal cycling or power cycling, the wire expands and contracts. This induces mechanical fatigue as shown in figure 6.6.1 (b). When power is applied to the device, the device gets heated and in turn, the wire gets heated and the wire expands. When the power is removed, the chip cools and the wire contracts. If a micro crack is present in the heel, it propagates due to tensile stresses during power cycling, and the heel on the first bond cracks. If there are micro defects on the first bond and the second bond, when the package goes through thermal cycling, the microcrack propagates and may cause heel crack either on the chip side or on the lead finger. Cyclic application of stress causes a wire to fail due to fatigue. Fatigue failure is accelerated if a micro crack is present in the wire. If there is no heel crack the wire may withstand 10,000 cycles or more. A micro crack may reduce the fatigue life to 500 cycles and a large heel crack may fail the wire within 100 cycles [R-35].

In wedge bonding, the failure rate depends on the size of the microcrack present at the heel of the wedge bond. Deeper the crack, higher the failure rate. The same micro crack will fail faster depending on the wire diameter, wire strength, geometry of the wire, the magnitude of cyclic stress and the amount of power applied.

6.6.2 Power Cycling and its Impact

When power is applied to a device, the junction temperature of the device goes up. The heated chip expands. When the power is turned off, the chip cools down and contracts. The wire in turn undergoes flexure when chip undergoes power cycling. Higher the power higher is the flexure.

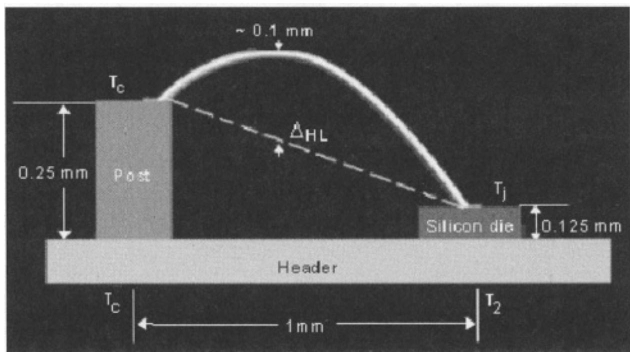


Figure 6.6.2 Calculation of wirebond flexure [R-36]

To understand the wire bond flexure, we can use the following schematic diagram. The figure 6.6.2 represents the wire bond structure used in the calculation of wire bond flexure. The wire bond flexure, ΔH_L, depends on the loop height. It has been found that lower the loop height, greater the ΔH_L value; and higher the loop height smaller the ΔH_L value [R-36].

6.6.2.1 Use of Al Wire vs Au Wire

High loop heights are problematic in many package applications. An alternative solution to using Al- Si wire with large loop heights is to use gold bonding wire with moderate loop heights. The basis of the above flexure calculations is the differential coefficient of expansion between the wire and the iron-nickel-cobalt alloy header. This differential is significantly smaller for gold than for aluminium wire. The use of gold wire with the same loop height as aluminium reduces the wire flexing in the device by about one half

for the same power dissipation. In addition, gold has a higher metallurgical resistance to flexure fatigue.

6.6.2.2 Effect of Power Dissipated on ΔH_L

The ΔH_L value also depends on the power dissipated. As the power increases the ΔH_L value increase. When bond wires are subjected to power cycling, they fail by fatigue. The failure rate depends on wire bond flexure ΔH_L. The ΔH_L increases as we increase the input power to the device. The rate of change of delta H_L is linear irrespective of the loop height; this is depicted in the figure 6.6.3.

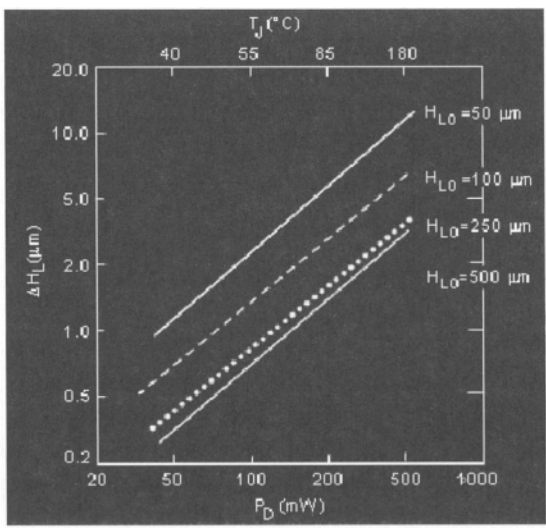


Figure 6.6.3 Rate of change of ΔH_L *as a function of input power* [R-36]

Since wire flexing is reduced as the loop height is increased, failures due to wire flexing are minimized if a large loop height is used. Whenever a wire exhibits higher ΔH_L value, it indicates that the wire is going to expand and contract significantly. This expansion and contraction causes the wire to undergo flexural fatigue. A fatigue failure always propagates from a defect

site in the material. If the heel of the wire has a micro crack, it acts as the initiation site for crack propagation and results in fatigue failure.

6.6.2.3 Temperature Cycling and its Impact on Bond Reliability

The purpose of thermal cycling is to determine the electrical performance of wirebond interconnects to exposure to the temperatures alternatively changed. The failure mechanisms addressed by the test include flexure failure of the wire at the heel, bond pad-substrate shear failure and wire-substrate shear failure. Susceptibility to these failure mechanisms may be actuated by excessive neck down at the heel or excessive embrittlement of the wire during bonding, or poor bond shear strength resulting from surface roughness and the presence of contaminants. During the thermal cycle test, the units are subjected to alternating temperatures with a given ramp rate and dwell time at low and high temperature extremes. The heel crack can also occur under temperature cycling due to repeated wire flexing resulting from different coefficients of thermal expansion between the bonded wire and the header as the device heated up and cooled down.

When a package (plastic or hermetic) is subjected to thermal cycling, the mismatch in TCE will induce the wire to break due to thermal fatigue. The failure initiation will be at the heel of the bond.

6.6.3 Causes of Heel Cracks

As discussed earlier heel cracks have been a cause of concern to device users for many years. Listed below are the factors that significantly contribute to heel cracking:

- excessive bond force
- high ultrasonic energy
- contaminated bonding tool
- worn out bonding tool
- hardness of the wire
- angle of approach of the wire
- loop height

- bond tool design
- trim and form operation
- clamping of the package during bonding

Let's discuss each of the above factors in brief.

6.6.3.1 Excessive Bond Force

Bonding parameters are extremely important because they control the bonding yield and reliability directly, bond force is one such key variable bond force is required during bonding. But excessive force can result in greater plastic strain, and lead to micro cracks at the heel. Usually a production engineer increases the bond force when the wire shows non-sticking problem, and he may do it without realizing the repercussions of increased force.

6.6.3.2 Contaminated and Worn Out Bonding Tool

The capillary, used in gold wire ball bonding, is susceptible to contamination in its bore as well as gold build up on its face due to the porosity of the material used. When the wedge tool or the capillary is contaminated, the contamination particle can exert high localized stress at the heel, resulting in heel crack. Similarly, a worn out capillary has a rough surface and will generate heel cracks. Refer figure 6.6.4

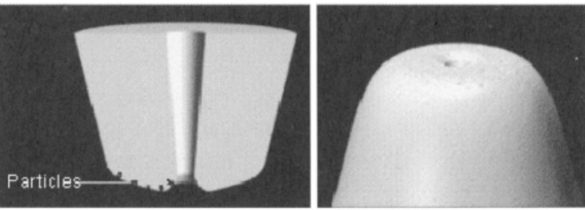


Figure 6.6.4 Worn out capillary

6.6.3.3 Hardness of the Wire

Usually, high tensile strength is associated with high hardness of the wire. Very hard wire is not suitable for bonding soft aluminum. Harder the wire the more resistance to plastic deformation. Therefore harder wires have a greater tendency to have heel cracks. By increasing the elongation of the wire, the heel crack can be reduced.

6.6.3.4 Silicon Precipitates at the Heel

In case of Al-Si wires, if the silicon particles are not uniformly distributed, they may cluster to form large precipitates. If these large precipitates exist in the wire at the transition region, they give rise to heel cracks. For example, exposure to elevated temperature, as in the lid sealing of a hermetic ceramic package, causes significant modification of the Si dispersion. The wire undergoes recrystallization resulting in grain growth. And secondly, there is marked second phase precipitation. Excessive Si precipitation, particularly at the heel of the first U/S bond, degrades the fatigue resistance of the wire. It is important to minimize high-temperature exposure of the wire bonds if maximum reliability is to be assured.

6.6.3.5 Loop Height and Angle of Approach of the Wire

If the wires have a high loop height, during second bond, the wire approaches the lead finger at a high angle. Thus the transition from the wire to the wedge or heel is sharp. This leads to heel crack.

6.6.3.6 Bond Tool Design

The face angle and the outer radius have a significant impact on the heel damage in Au bonding. Similarly the back radius dimension in a wedge has a big impact on the heel damage.

6.6.3.7 Trim and Form Operation

In plastic lead frame packages and in cerdip packages, the package undergoes the “trim and form” operation. During this process the lead frame is punched with high force, and the lead frame experiences very high shear

stress. This pulls the lead frame in the direction away from the die. This stress may cause micro crack at the heel. When the package goes through the trim and form operation, the leadframe experiences excessive stress and the force acts in the direction away from the package. When the package is subjected to temperature cycle stress, this heel crack will fail by fatigue. Listed below are some of the precautions that help to alleviate heel crack problem:

- minimize the wire loop height,
- minimize the first-bond wire deformation,
- maximize the radius at the back of the bonding tool heel,
- assure that the device to be bonded is held very firmly and,
- if all else fails, revise the bonding schedule so that the wire with higher elongation may be used.

6.6.4 Characterization of the Fatigue Properties of Bonding Wires

In fine pitch packages, thermal stress induced wire fatigue failure is a concern of package reliability performance. Increasing pin counts per package mean that each device is dependent on an increasing length of wire and an increasing number of wire-bonded joints for proper operation. At the same time, new reliability specifications ("six-sigma, 0.1 FIT") demand greater reliability from packaging features independent of the pin count. One needs to understand the fatigue behaviour of the thin wires. One of the techniques used is the wire fatigue machine.

The critical region for mechanical properties of a wire bond is the heel joint. This critical region is about 25 microns in length. In order to conduct fatigue test on very long (say 1 meter) lengths (which can be viewed to contain a large number of 25 μ segments) a new method of testing fatigue has been developed. The schematic representation of wire fatigue machine is shown in figure 6.6.5.

Here the wire is strained in bending; a specific strain is developed in the wire by bending it around a mandrel. Two mandrels are used in the configuration to produce tension/compression cycles. [R-27] Even high

temperature fatigue properties of the bond wire can be measured by heating the mandrels.

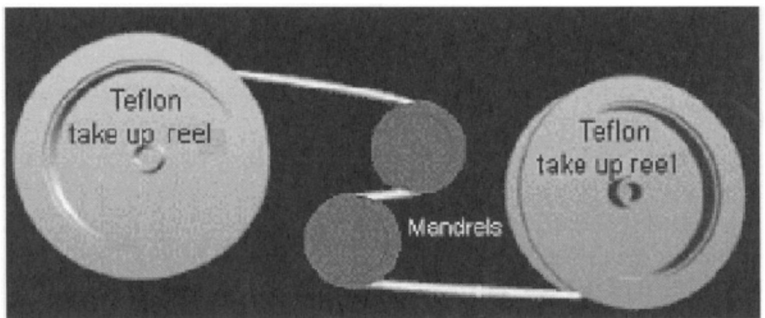


Figure 6.6.5 Schematic representation of wire fatigue machine [R-27]

6.6.5 *Can we Screen Heel Cracks by Visual Inspection?*

Heel cracks can be micro cracks or macro cracks. The reliability implication of a particular heel crack can not be quantified and it is not easy to come up with a go-no-go specification. In other words we can not develop easy acceptance criteria for heel cracks. This is because, visual screening for heal cracking poses two problems:

- firstly, routine bond inspection under a binocular microscope does not reveal heel cracks; (high-magnification of 200X or more optical or SEM examination is required)
- secondly, it is difficult to discern surface cracks from deep flaws which might accelerate field bond failures.

In estimating the probable long-term harm likely to arise from observed cracks, it is probably better to err on the side of excessive caution, and not accept any heel cracks.

6.7 Other Reliability Problems

Vibration Induced Failures: Vibration forces are seldom severe enough to cause metallurgical fatigue or other bond damage. However in cavity packages such as ceramic package, cerdip package and MQUAD package, bond wire failures have been observed, that are vibration induced. Failure analysis of failed packages indicates broken wires near the second bond (bond to the leadframe lead tips). In certain MQUAD packages the failures were observed on leads with the longest lead cantilever and longest bond wire combination. These failures usually appear after PCB mounting and cleaning operation [R-37].

In cavity packages, such as MQUAD, one can see failures such as broken wires near the second bond. These failures are particularly seen on long cantilevered leads. The cause of failure is due to PC board vibration during depaneling process and the vibration gets transmitted to the internal cantilever packaged leads.

Analysis of the MQUAD wire failure showed that the failure is due to severe vibration of PCB panels during the routing operation. The external vibration of the PCB was transmitted to the internal lead frame and the lead frame resonance caused the second bond failure. In this particular case it was found that the lead frame cantilevered too far from the inside edge of the package. This long cantilever beam resonated with the external vibration and caused high cycle fatigue of the second bond heel and resulted in the failure. By reducing the length of the cantilever extension, the problem was resolved.

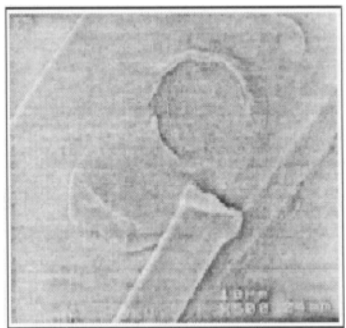
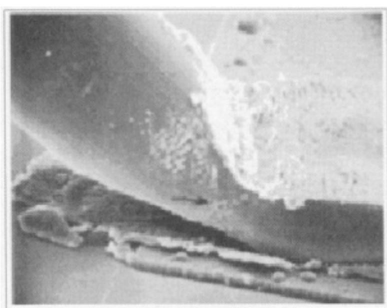


Figure 6.7.1 SEM photograph of a typical broken wire [R-37]

Ultrasonic Induced Failures: Ultrasonic vibration has been known to cause wire bond failures, particularly heel cracking both in Au and Al bonding due to high cycle fatigue. [R-38] Figure 6.7.2(a) shows an SEM of 25 μm (1 mil) Al wire exposed to ultrasonic cleaning stress.



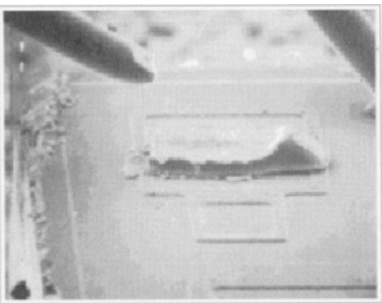


Figure 6.7.2 (a) SEM of 25mm (1 mil) Al wire exposed to ultrasonic cleaning stress.
Figure 6.7.2 (b) SEM of wire failure due to high-cycle fatigue (ultrasonic cleaning) [R-39]

Improper bonding parameters, such as very high bonding force can induce micro cracks at the heel of the wedge bond. This micro crack can act as a damage initiation site. During ultrasonic cleaning, or during thermal or power cycling, the wire experiences fatigue and fails by crack propagation and fracture as shown in Figure 6.7.2 (b)

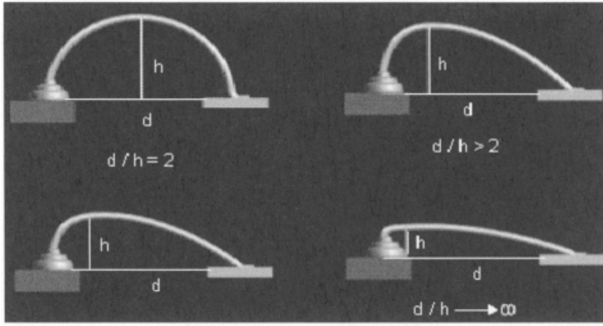


Figure 6.7.3 Ratio of length (d) over height (h) [R-40]

When the wire resonates with the applied frequency, it is postulated that the wire undergoes intense flexing, with the two wire ends acting as hinge points. The resonant frequency depends on the d/h value. As depicted in Figure 6.7.3, when the wire loop shape is semi circular, ‘d’ over ‘h’ ratio is 2. As the‘d’ increases and ‘h’ decreases, the ‘d’ over ‘h’ value becomes higher and when ‘h’ is very small, the value tends towards infinity.

The figure 6.7.4 shows how the wire bond resonant frequency changes as the length of the wire increases. For example, for a gold wire with d over h ratio of 5, and a length of 1 millimeter, the resonant frequency is about 10 KHz. Presently, most of our ultrasonic cleaners operates at high frequency of greater than 100 KHz. And therefore, it’s unlikely that any vibration induced wire failure occurs in normal cavity packages with wire lengths of 1 to 4 millimeters.

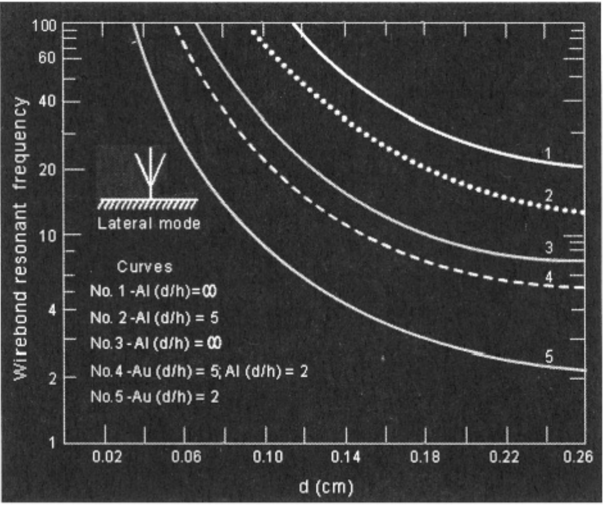


Figure 6.7.4 Dependence of the resonant frequency on bond separation [R-40]

Different d/h values have different resonant frequencies. Only when the wire is of “right” length, the failure occurs and usually where there is already a micro defect, say at the heel of the bond. However, there has been no “conclusive” study to prove or disprove this notion or to specify under what

conditions the failure will occur. Because of this vagueness, though ultrasonic cleaning has long been recognized as an efficient method for cleaning printed circuit board assemblies, in military circles its use has either been forbidden, or strongly discouraged. It is feared that exposing boards loaded with electronic components to ultrasonic vibration would produce irreversible damage to the components and/or compromise long-term reliability.

6.7.1 Die Attach Pad Shift Failures

In high pin count thin and fine pitch plastic packages, the lead frames are getting very thin. When these lead frames are molded the pressure exerted by the molten molding compound in the mold cavity pushes the lead frame, upwards. In particular the die attach pad is displaced more due to the large surface area it has in contrast to lead fingers.

As shown in the figure 6.7.5 The die attach pad shift close to the mold gate is much less compared to die attach pad shift opposite to the mold gate.

This shift will affect the wire bond reliability. When the die pad shifts up, it pushes the fragile wire bonds and causes second bond failures as well as wire deformation. The die pad shift has been observed usually in the region away from the mold gate. The pad shift has also been found to be dependant on the molding compound properties. Compounds which show higher torque value, induce higher die attach pad shift.

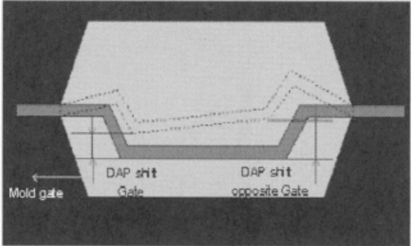
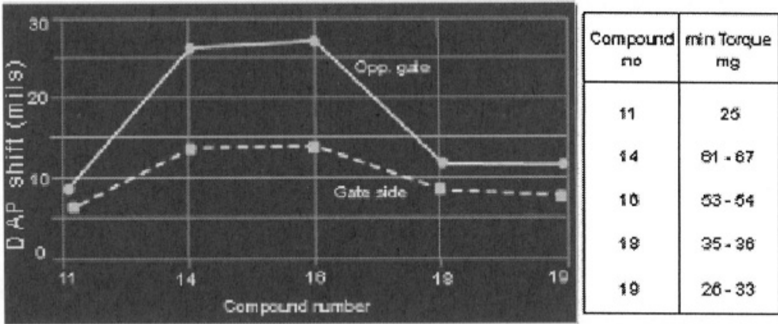


Figure 6.7.5 Die attach pad shift
[Courtesy: National Semiconductor]



Compound no	min Torque mg
11	26
14	61 - 67
16	53 - 54
18	35 - 36
19	26 - 33

Figure 6.7.6 Compound DAP shift comparison [Courtesy: National Semiconductor]

As depicted in figure 6.7.6 the die attach pad shift is also directly affected by the torque value of the molding compound. For different compound legs, we can see that the die pad shift both near the mold gate and opposite the mold gate, change according to torque values.

6.7.2 *Over Current Failures*

In power devices which carry high current, the current density increases in regions where the wire has less cross sectional area. For example, in the heel region of a wedge bond the cross-sectional area is less than the main wire. If due to power cycling the heel becomes more crack prone, current density goes up and eventually results in wire melting.

Small micro cracks in the heel can reduce the effective diameter of the bond wire resulting in increased resistance.

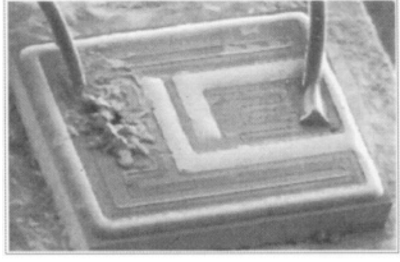


Figure 6.7.7 Example of an electrically overstressed darlington transistor having punch and melt through damage and a fused bond wire 50x [R-39]

When excessive current passes through a wire, the wire melts near the heel of the wedge as shown in the figure 6.7.7.

6.7.3 Grain Growth Failures

There are some peculiar reliability failures observed in the industry. One of them is the creep failure of Au wire during thermal cycling. The wire creep failure is characterized by a break along slip planes or a fracture at grain boundaries.

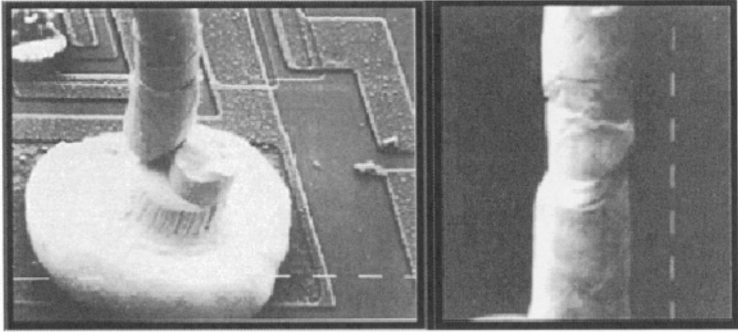


Figure 6.7.8 Typical grain growth 'Wire creep' failure [R-41]

When gold wire is thermocompression bonded, the region above the ball has large grain size. Very large grain size wires under constant stress and high temperature fail by 'creep failure' mechanism as shown in figure 6.7.8.

The wire creep, grain growth failure has been attributed to thallium-contaminated lead frame. The lead frame is Au plated and thallium is one of the impurity additives. Thallium diffuses from lead frame to the gold wire after stitch bond contact; highly mobile thallium forms a gold-thallium eutectic at the grain boundary. The Au-Ti eutectic has a low melting point of approximately 130°C and this induces weakened grain boundaries, which fail catastrophically during thermal cycling.

6.7.4 Al Bond Failures on Silver Plated Lead Frames

The aluminum wire bonded to a conventional gold metallized leadframe and cavity in cerdip packages has been a well known reliability hazard due to 'Purple Plague' or Kirkendall voiding. As we have observed earlier, when Kirkendall voiding occurs, the bond system shows high electrical resistance or an open circuit, and at the same time the bond pull value tends to be zero. (See purple plague section for greater detail). However, it was discovered that when Al is bonded to Ag metallization in a cerdip package, the Ag-Al substrate bond system shows a 'high resistance'. This thermally activated process, which causes the resistance of Al-Ag bond to change from negligible (~ 0.1Ω) greater than 15k Ω should result in a completely open bond. However it was observed that inspite of the high resistance, the bond pull strength showed no degradation. In order to study the kinetics of such a failure and to determine the failure mechanism, differential resistance analysis technique was developed to measure the continuous change in resistance with time under isothermal conditions. The Al-Ag bond showed very high electrical resistance, when exposed to about 240 hours at 299° C. in dry ambient as shown in figure 6.7.9.

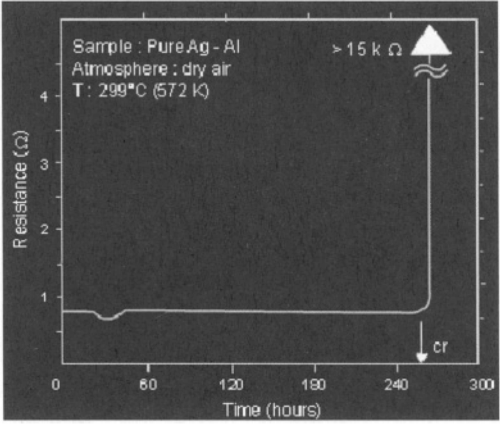


Figure 6.7.9 Bond resistance vs. time for pure Ag –Al junction [R-42]

However, the bond pull value is not degraded. On a more realistic situation when aluminium wedge bonded cerdip package, was sealed at a temperature of 435° C the resistance increased dramatically within 4 hours, as shown in figure 6.7.10. This is attributed to the accelerated reaction of silver-aluminum in presence of moisture released by the cerdip glass. Failure analysis showed that Kirkendall voiding is not present, which implies that the Ag-Al system failure is very different in nature compared to Au-Al system, which is known to fail due to Kirkendall voiding at the diffusion front.

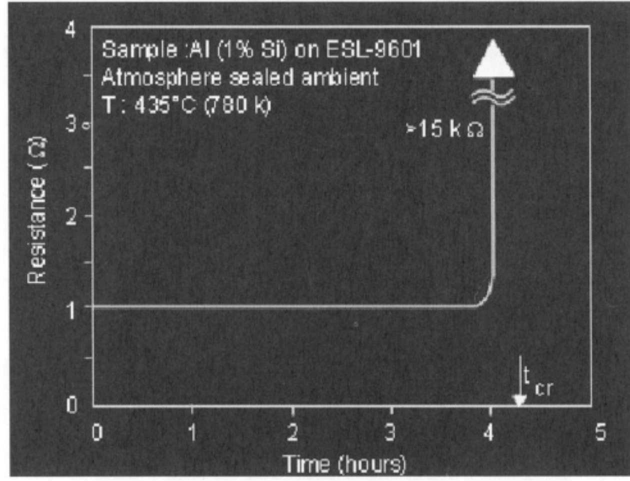


Figure 6.7.10 Bond resistance vs. time for CERDIP substrate bond system [R-42]

The Al-Ag failures are attributed to a selective oxidation (external) of the Ag-Al intermetallic zone which results in an insulating layer of oxide at the diffusion front. These micrographs show oxygen enrichment at the diffusion front in the 'failed' bonds, implying an oxide layer is present at the interface. This result clearly indicates that the high resistance in the Ag-Al bond occurs due to oxidation of the Ag-Al alloy, resulting in a thin, insulating oxide layer which completely envelopes the alloyed zone. The susceptibility of the Ag-Al intermetallic to oxidation was further confirmed by Auger map for

oxygen of a cross-section of the substrate bond region. Extensive oxygen concentration in the alloyed zone is seen in this micrograph.

In aluminium - silver bond that is conductive, the -ray dispersive analysis for oxygen shown in figure 6.7.11 shows no oxygen concentration. However, when the oxygen scan is performed on failed bonds which have high resistivity, there is a clear indication of large concentration of oxygen along the boundary of the aluminum bond. This clearly indicates that oxidation of aluminum in presence of silver causes high resistivity and thus an open circuit.

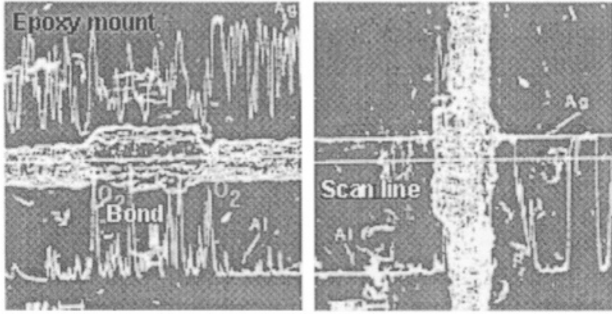


Figure 6.7.11 X-ray wavelength dispersive line scans for oxygen **[R-42]**

The failure rates have been found to be catastrophic in a humid environment (0.3 eV activation energy). The source of humidity in a cerdip package is the serdip sealing glass which liberates moisture at about 435 deg -C. Failures do occur in dry air but these failures are of lesser concern as the activation energy is high (1.4ev). This problem is inherent to cerdip packages which have moisture at or above 1500 ppmv.

6.7.5 Aluminum Silver Corrosion

6.7.5.1 Corrosion of Al Wire Bonds on Ag Plated Surfaces

When Al wire bonded to plated Ag surface was exposed to 85-85 testing, significant corrosion failures were observed. Storage of aluminum ultrasonic

wire bonds to silver plating at 85/85 (no bias) resulted in significant bond strength degradation and a shift in the primary failure mode from wire breaks to bond lifts. Similar test on Al bonded to evaporated Ag, did not show any failures. It was found that plated Ag has inherent chlorine and sulphur contamination which induce Al to corrode on Ag metallization in presence of moisture [R-43].

6.7.6 Bond Failures Due to Centrifuge Test

Devices bonded in cavity packages such as ceramic or cerdip package are subjected to centrifuge test to meet the military criteria. The packages are subjected to 30,000 g force during the test (Mil Std. 883D). If the bonds are weak, they fail by bond lift or wedge lift failure modes.

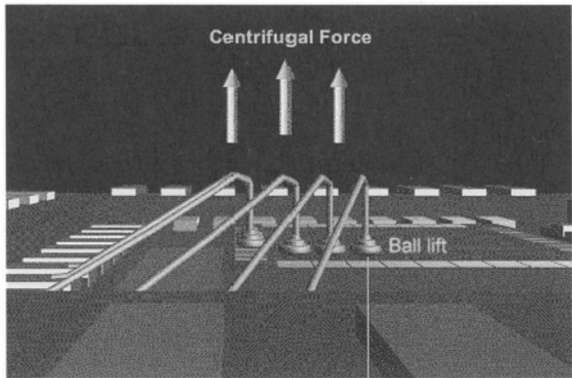


Figure 6.7.12 Stress on bond wire during centrifuge test resulting in bond lift

6.7.6.1 Failures Due To TCE Mismatch

In many applications the IC chip is coated with a glob top layer, usually silicone gel, epoxy or polyamide coating. The chip is later encapsulated with plastic molding compound or a hermetic package after this glob top process. When such a package is subjected to temperature cycling, the thermal

expansion mismatch between the glob top material and the encapsulant can stress the wire at the point where it exits the glob top. When the package is subjected to thermal cycling, the thermal expansion coefficient mismatch between the die-coat, and the bond wire imparts cyclic tensile stresses on the bond wires. This results in fatigue failures of the wire at the wire-die coat interface, this is shown in figure 6.7.13.

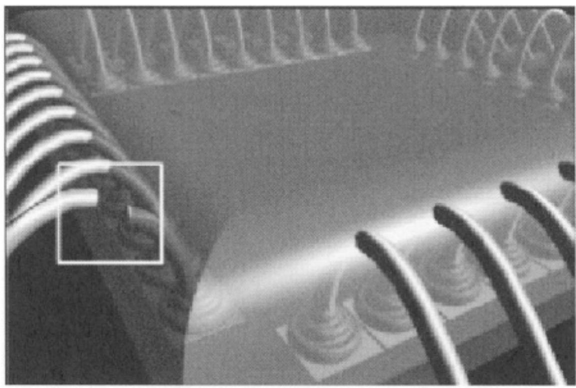


Figure 6.7.13 Thermal fatigue due to diecoat

6.8 Electrical Performance Degradation due to Wire Sweep

As we move towards high I/O, high frequency IC chips, that make use of ultra fine pitch wirebonding, the effect of bondwire electrical parameters on the functionality of the chip becomes very significant. Inductance and resistance values controlled early in the design stage can save costly manufacturing expenses later and ensure the functional integrity of the chip. The current generation of wire bonders can operate at BPPs of 60 microns or less. In high pin count and ultra fine pitch bonding the thinness of the wire, long wire loops and many neighbouring bonds that are too close to each other, affects electrical resistance (Rdc), self inductance (Ls), mutual inductance (M) and loop inductance (L) of the bondwires.

The self inductance of the wire is determined by the total length of the wire, whereas the mutual inductance is dependent both on the length of the wire as well as spacing, and the loop inductance is a combination of self

and mutual inductance, The figure 6.8.1 diagrammatically represents the three different inductances. In high frequency devices we would like to keep the inductance value as low as possible. As the wirebonds get closer they cause signal integrity problems, cross talk and propagation delays. Therefore, for optimum operation of the devices, the wire parameters such as wire length and spacing between the wires must be consistent, and must not change after wire bond process.

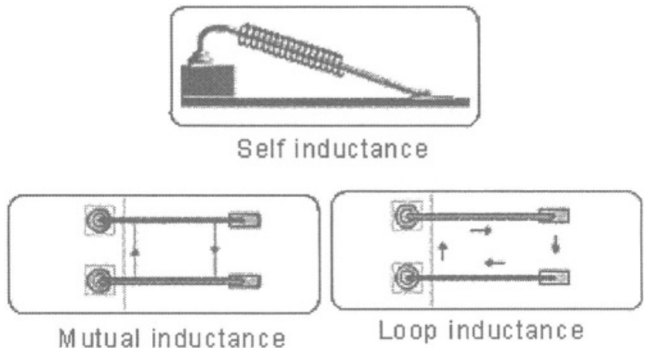


Figure 6.8.1 Schematic representation of different types of inductances

The bond wire resistance and Inductance value depends on wire diameter, wire spacing, loop shape and many other parameters. In packaging a device in a package such as TSSOP, TQFP, CSP or BGA, one uses different types of loop lengths and loop profiles in different packages. When we have a variety of loop shapes like: CSP loop, fiat loop, standard loop, smart loop etc., the resistance and inductance values change with each loop shape.

As shown in the figure 6.8.2, we see that the total length of the wire is not just a function of the value ‘D’. Instead the height of the chip, the loop height, the flat of the loop, as well as the angle, contribute to the total length of the wire, which in turn determines the total inductance value.

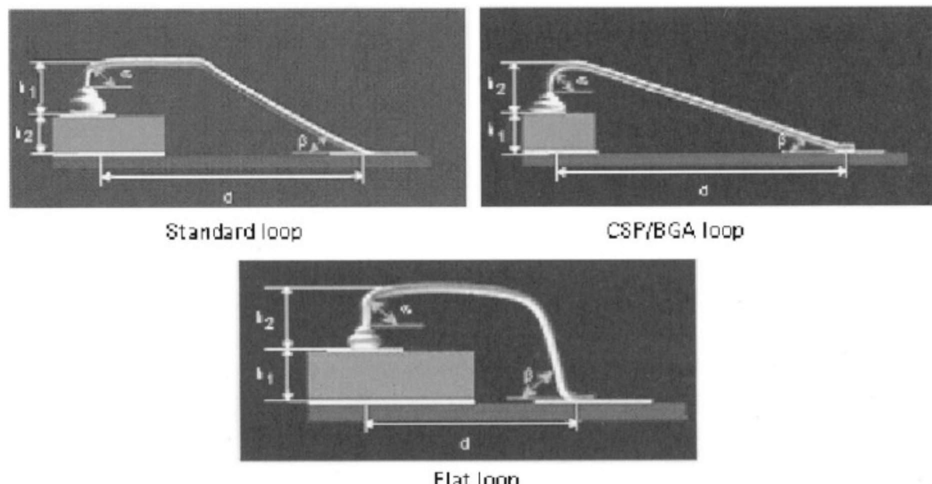


Figure 6.8.2 Different types of loop shapes

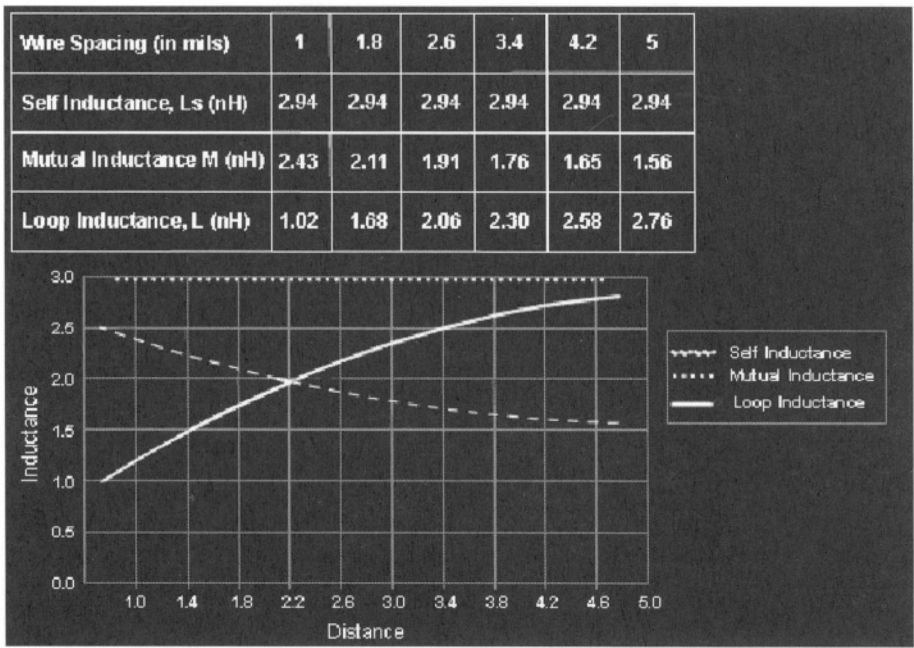
6.8.1 Effect of Wire Span on Inductance Values

Let us now take a closer look at how the problems such as wire sweep, and wire deformation due to S-ing and resultant spacing between the wires affect the inductance values. In the case study shown below, we consider a Flat loop with chip height = 10 mils loop height = 6 mils wire span = 100 mils Alpha = 89°, Beta = 30°, wire diameter = 1 mil wire spacing = 2 mils and height over ground plane = 2 mils. When we increase the spacing between the wires from 1mil to 5 mil , the mutual inductance decreases while the loop inductance increases. The self inductance remains unchanged.

In the table 6.8.1 we can see that as the wire spacing decreases from 5mil to 1mil, the mutual inductance value increases and this will affect cross talk between the signals. Measurement of these inductance values of different loop profiles in different package systems is a complicated process involving sophisticated fixturing and de-embedding processes. Besides, accurate prediction of inductance values through simulation is very

complicated involving 3D modelling of wire loops and complex analysis. For many applications, a first order estimation of bond wire electrical values is suffice and would provide a significant performance optimization capability.

Table 6.8.1 Effect of wire spacing on inductance value [Courtesy: inkroma wire bond modelling software]



Wire Spacing (in mils)	1	1.8	2.6	3.4	4.2	5
Self Inductance, Ls (nH)	2.94	2.94	2.94	2.94	2.94	2.94
Mutual Inductance M (nH)	2.43	2.11	1.91	1.76	1.65	1.56
Loop Inductance, L (nH)	1.02	1.68	2.06	2.30	2.58	2.76

7

New Technologies and New Applications for Wire Bonding

We have in the previous chapters discussed the issues related to design, materials, equipment, quality and reliability issues of gold wire bonding and aluminum wire bonding. We have looked at the many options that are available in technology, material, equipment and design domains. Now let us take a look at some of the recent applications, such as opto-electronics and stacked die packaging where wire bonding has been used. By understanding the demands made by these new packaging applications, one can appreciate the criticality of understanding the wire bonding technology and its importance in the "food chain" of micro chip manufacturing and more importantly in the electronics vertical.

We will also explore new technologies such as low temperature bonding and copper wire bonding that are gaining relevance and importance in the IC assembly industry in the past few years.

7.1 Wire Bonding in Opto-Electronics

Even today, choosing and designing a packaging technology for a device is often undertaken late in the game and without appreciation of its difficulty and its potential effects on the final product performance and reliability. However, in optoelectronic applications, packaging accounts for roughly 60 to 90 percent of the cost, and much of the cost is related to low yields in

manufacturing. Therefore, significant amount of stress is given to the packaging issues both from design and manufacturing perspectives.

A typical opto component consists of substrates, sub mounts, heat spreaders, optical components, amplifier ICs, detectors and most importantly the optical fibre, as shown in Figure 7.1.1. The precise placement and alignment of the optical components are the most technically challenging. The other key technology in optoelectronic manufacturing or photonic component manufacturing is wire bonding. Here the challenge lies in bonding to multiple surface metallization within the same package, large bonding height differential and low bonding temperature. Let us review some of the challenges from wire bonding perspective.

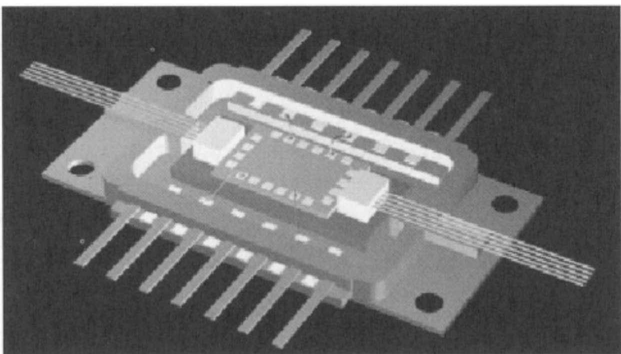


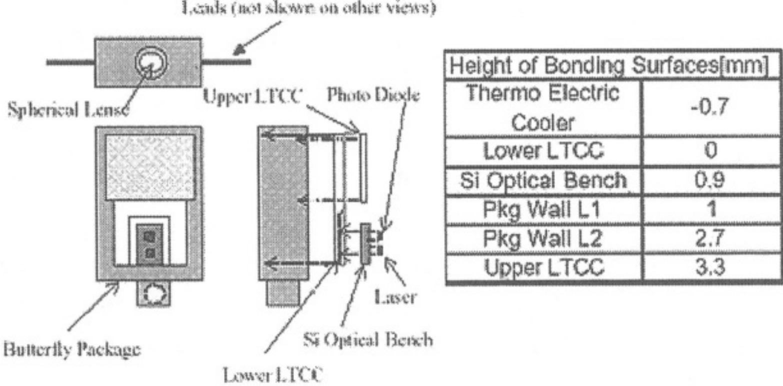
Figure 7.1.1. Optoelectronic component

7.1.1 Design Challenges

There are many types of opto packages including LTCC packages (Low Temperature Cofired Ceramic), Photo Patterned Thick film package, and plated copper on ceramic, direct bonded copper and thin film substrate packages. Each of these packaging technologies have different kinds of metallization which necessitates choosing the either ultrasonic Al wire bonding or thermosonic Au ball bonding, and optimizing the wire bonding technology for each package.

One of the greatest challenges in wire bonding an opto package is the height differential between different components in the package. As can be

seen in figure 7.1.2, the wire bonding height can vary from -0.7mm for LTCC to Thermoelectric cooler to 3.3 mm for lower LTCC to upper LTCC.



Height of Bonding Surfaces[mm]	
Thermo Electric Cooler	-0.7
Lower LTCC	0
Si Optical Bench	0.9
Pkg Wall L1	1
Pkg Wall L2	2.7
Upper LTCC	3.3

Figure 7.1.2 Butterfly package with height of bonding surfaces **[N-1]**

7.1.2 Material Challenges

The bonding surfaces in an opto package can vary from soft thick films on LTCC to hard surfaces on HTCC packages. The wire material hardness must be controlled to minimize metal squeezing and forming a reliable second bond. At the same time, to control loop characteristics the wire should have enough toughness. Since the opto packages are not fine pitch packages, the wire diameter can be large to obtain a large bonded area.

7.1.3 Process Issues

The process variables that one encounters during opto wire bonding include many of the variables that we have discussed in chapter 4.1, but more important variable is the different metallizations. One has to design experiments very carefully to optimize the wire bonding process taking into consideration different process parameters required for different metallizations in the same package.

In normal IC assembly factory, the wire bonding process optimization is done on a large sample size and the process is used for wire bonding large volumes of a particular type of device. But opto packaging being in small lot sizes and short runs, the process optimization process has to be done with minimum number of samples due to the high cost of components. The fractional factorial DOE using Taguchi methods are very useful in finding the optimum bonding process parameters which will facilitate high yield assembly.

One of the other issues that one encounters in opto packaging is the loop profile. Because there are many shapes, heights and lengths of the wire loop in one single package, there are no established looping algorithms that one can utilize consistently. Each type of package needs separate establishment of the bond recipe and teaching the auto bonder. For example, setting up a loop profile with a height of 3.3 mm and using the same bonder to do the next bond with a height of -0.7 mm is an extremely difficult task. And to do this consistently with precision is almost impossible.

Achieving reliable second bonds or wedge bonds on the lead frames is yet another critical challenge. Usually the second bond is formed on lead fingers that are extending beyond the wall of the package. This cantilever beam configuration results in resonant vibration of the lead finger when the capillary applies ultrasonic energy during wedge bond formation. This resonance can be detrimental to second bond formation. This issue has been addressed in chapter on reliability in greater detail.

When the cantilever is long the resultant resonant vibration will give low bond strength. On the other hand, if the cantilever beam lead finger is short and stubby, the bond strength will be high, but bond placement will be difficult. If one tries to place a ball bond on the short cantilever beam lead, the capillary shank will touch the package wall. So in such situations, it is recommended to use deep access wedge bonding tool and perform reverse bonding.

Another constraint in opto wire bonding is the necessity to use low temperature bonding due to the use of low melting point solders for die attach. These die attach solders may melt and cause slight displacement of the die during bonding if high temperatures are used. The die displacement result in misalignment of the optical beam.

To achieve reliable bonding at low temperature we have seen earlier that one has to use high frequency ultrasonic energy which demands clean surfaces for bonding. Therefore plasma cleaning the opto packages before wire bonding is essential.

7.1.4 Process Problems in Opto Wire Bonding

The fragile nature of the opto devices requires that the bonding parameters such as bonding force and ultrasonic energy are kept as low as possible. This low value parameters give rise to bond non stick problems, both during the process as well as in the field. This is a concern. If one enhances the bonding parameters to yield higher bond adhesion, it may result in bond pad cratering and in some cases even die cracking. This problem is exaggerated in opto devices because of the brittle nature of the compound semiconductors.

The bond pad metallization on the compound semiconductor devices is generally gold. The adhesion of gold to the wafer surface is not so good and this results in metallization peeling during bonding, if the ultrasonic energy is high..

7.1.5 Bonding Tools for Opto Wire Bonding

Special bonding tools are necessary for wire bonding opto packages due to the different heights of the bonding area that one encounters in an opto package. A typical ball bond capillary will not be able access the bond finger along the wall of the package. In many situations the interference may come form the ultrasonic transducer, the wire clamps and the bond tool shank. Specially designing capillary or wedge tools with thin shanks is an alternative but with uncertain process capability. Therefore it is recommended that the package be designed for manufacturability with standard bonding in mind, with reverse bonding as an option only in case of extreme necessity.

7.1.6 Equipment Requirements

Wire bond equipment for opto package bonding must meet requirements such as variable height bonding and variable loop profiles. Wire bonder manufacturers need to develop easily controlled and programmed loop shapes as they have done for standard packages. In most of the IC packages the second bond is at a lower level below the die surface, and therefore the bond descends, where as in an opto package the majority of bonds ascend and this needs to be taken into consideration in designing the bonder for opto applications.

The PRS system on the bonder must have good resolution to differentiate between a gold plated capacitor and the gold plated substrate on which it is mounted. If the PRS resolution is not sufficient to differentiate between the two components, it results in low yield as well as low productivity. Such situations also demand design rules and design ideas such as contrasting fiducial marks to increase the accuracy of PRS. In order to locate accurately and consistently bonding areas whose surfaces are at different heights the PRS must have programmable focal height capability.

Some of the wires in the opto package carry high frequency signals and such wires demand accurate loop height and loop length. The equipment must be capable of maintaining consistency in loop parameters under the constraint that the loop heights can change between -0.5 to 3mm.

High frequency applications also require, some times, ribbon bonding. Ribbon bonds show lower inductance values compared to their round wire counterparts. Ribbon bonds also have the advantage of requiring low bonding force and bonding power during bonding. This is a better option for bonding fragile opto devices made of Gallium Arsenide, Indium phosphide and Lithium Niobate etc. However, ribbon bonding demands bonding equipment that can perform ribbon bonding with special wedge tools.

In conclusion, we can say that wire bonding opto electronic packages is a major challenge faced by the industry today and new developments need to be made in designing and building wire bonders that meet the flexibility, speed and consistency required by optoelectronic industry.

7.2 Wire Bonding in Stacked Die Packages

As the industry moves into thin and light weight devices with high functionality, the need for packaging multiple dice in a single package is becoming increasingly important. One of the growing trends is the use of stacked die in a package. To achieve the thinness required by current applications the package assembly manufacturers have to decrease the die thickness, the substrate thickness, spacer thickness, bond line thickness and most importantly the bond wire loop height.

Today, it is possible to achieve low loop height by using different technologies, namely forward and reverse ball bonding, as well as wedge bonding. Ultrasonic wedge bonding, though a slower bonding process, has the advantage of extreme low loop capability (zero loop height capability) and bonability at low temperatures. Let us discuss below some of the technology issues associated with wire bonding a stacked die.

We can see in figure 7.2.1 examples of stacked die BGA packages with 2 dice and 3 dice stacked one above the other. One of the biggest challenges in 3D stacked packages is meeting the total package height requirement. The typical height of a 2 die stack package is 1.2 mm max and a 3 die stack package is 1.4 mm max.

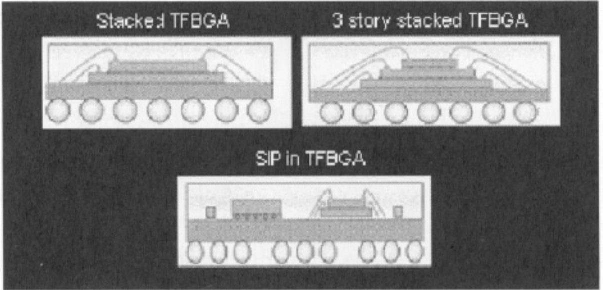


Figure 7.2.1 Stacked die packages

The total budget height of a stacked package consists of the following:

- the ball height after reflow

- the substrate thickness
- the bond line thickness of die attach 1
- die thickness of die 1
- the interposer thickness between the two dice
- die thickness of die 2
- the wire bond loop height
- the encapsulant thickness

These components are schematically shown in figure 7.2.2. To meet the total height budget, each of the above components must be as thin as possible.

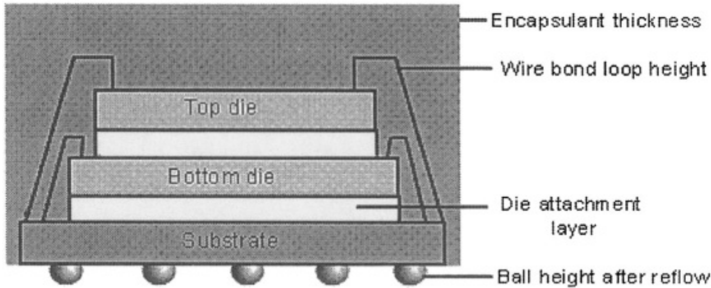


Figure 7.2.2 Stacked die package height budget

The challenge in assembling the 3D stacked die packages involve thinning wafers to less than 50 microns, handling thin dice, attaching these dice with non bleeding die attach material, wire bonding the dice with 100% yield and molding the package without wire sweep.

In wire bonding the stacked die, the main concern is the looping process. Low and consistent looping is absolutely essential. Minimizing wire sweep and maintaining the gap between the upper and lower tier wires are also critical to avoid electrical leakage current, cross talk and shorting. The complexity of looping is much greater in stacked die packages due to the above requirements.

Many of the IC assembly manufacturers are mostly using gold ball bonding in stacked die packaging. However ball bonding has certain

minimum loop height limitations. For example, today's ball bond technology can consistently produce 100 micron loop heights, and anything below that, the consistency is not reliable. Under such conditions one has to follow certain design guidelines as to the loop heights, loop length, bond flat length, distance between the die edge and lead finger, die attach bleed out and the angle of attack of bonds. These design rules are in turn dependant on the die thickness as well as the type of package, BGA or LQFP. Figure 7.2.3 show examples of cross-sections of a stacked die BGA and stacked die LQFP.

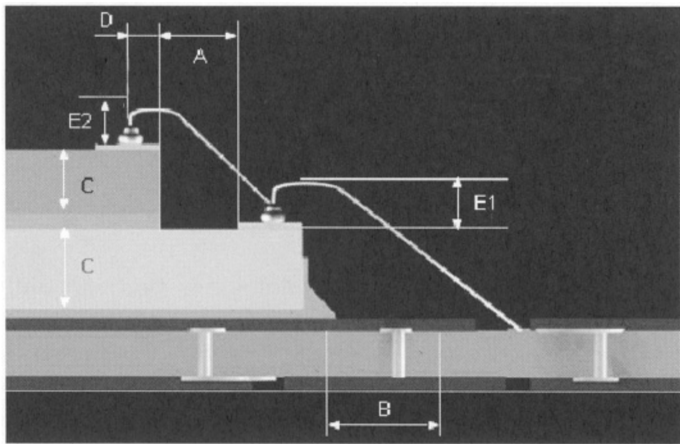


Figure 7.2.3 (a) Stacked die BGA (cross section) [N-2]

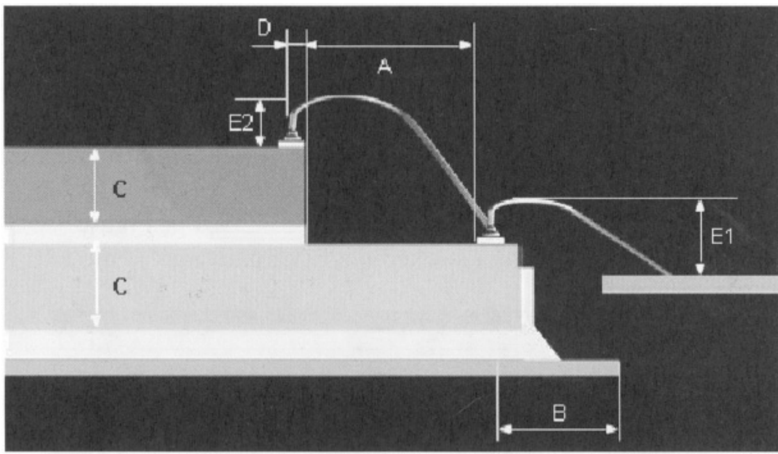


Fig 7.2.3 (b) Stacked die LQFP (Cross section) [N-2]

Standard fine pitch ball bonding technology is predominantly used in today's stacked die packaging technology, In ball bonding there are options of using reverse ball bonding which will give loop heights below 50 microns, however, this adds much more complexity in the wire bonding process and requires larger ball size. A comparison of standard low loop and reverse ball bonding is shown in figure 7.2.4.

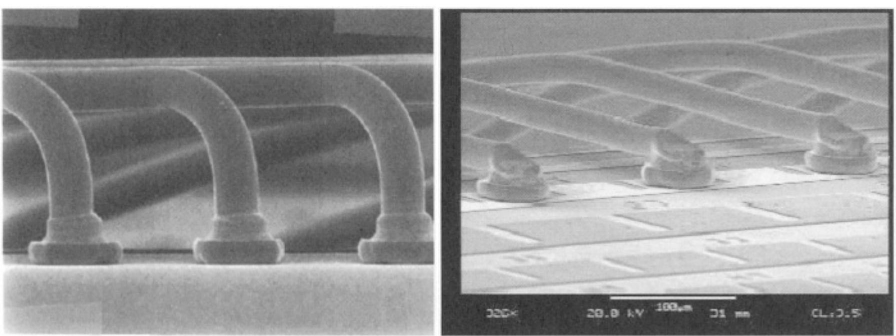


Fig 7.2.4 (a) Normal ball bonding low loop bonding [N-2]

Figure 7.2.4 (b) Stand-off (reverse) ball

7.2.1 Zero Loop Wedge Bonding

Although ultrasonic wedge bonding is slower than ball bonding, wedge bonding offers many advantages for use in a stacked die packaging application. Some of the benefits include:

- less than 50 micron loop height capability
- straight loops and negligible wire sway
- low temperature bonding
- finer pitch (50 microns) bonding capability

Let us examine the above in detail.

7.2.2 Low Loop Height

In ball bonding, there is formation of a heat affected zone, and the height of the loop is controlled by the HAZ length. In case of wedge bonding, due to the way the bonding wedge tool moves and due to the lack of the HAZ, the wedge bonder can achieve lower loops than the ball bonder. For a ball bonding loop, the loop take off angle from the bonded ball is always 90 degrees, and to avoid neck damage the ball bonder loop height is taken to about 150 microns above the die surface. Only after reaching that height the loop trajectory is changed towards the lead finger. The wedge bonder, on the other hand, can take off at angles of about 45 degrees and achieve loop heights less than 100 microns. If there is no active circuitry near the edge of the die, the wedge bonder can achieve loops with extremely low angle and even with zero die clearance. Figure 7.2.5 illustrates this loop profile.

In ball bonding the neck region above the ball is the weakest section of the loop. Therefore during loop formation of long wires, the wire has a tendency to sway, leading to “S-ing”. Such problems are not encountered in case of wedge bonding, and even long wires maintain straightness. The lack of a neck region in case of wedge bonding also minimizes wire sweep problems. One can use thicker wires in wedge bonding, which also reduces wire sweep vulnerability.

Traditionally wedge bonding has been done at room temperature and the reliability of the bond has been well established. In case of stacked die package low temperature bonding is preferred because it causes less device

warpage. Studies have been done to show that wedge bonding gives the same bond strength and meets the same reliability criteria as would a ball bonded package. [N-2]

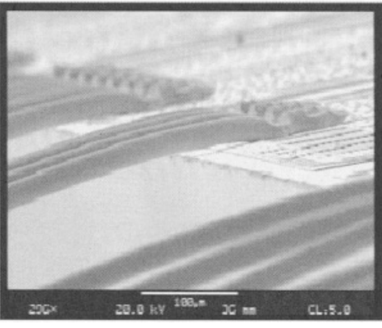


Figure 7.2.5 (a) Wedge bonding low loop

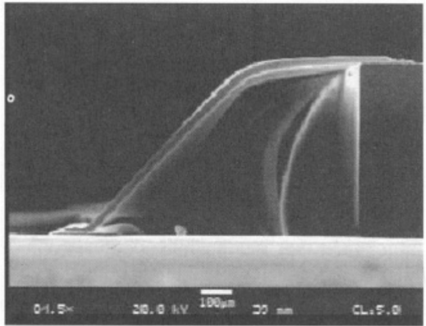


Figure 7.2.5 (b) Wedge bonding "Zero loop height" loop [N-2]

7.3 Low Temperature Bonding with New Ultrasonic Transducer

In both ultra fine pitch Au ball bonding and in copper bonding the stability of the ultrasonic vibrations must be extremely good. BGA, CSP and Stacked die packaging require low temperature bonding and therefore demand higher bonding frequencies. These require stable high frequency converters. The demand for high UPH and greater placement accuracies necessitates new requirements in the dynamic mechanical behaviour of the transducer horn. New bonding technologies like copper wire bonding requires stable, robust and optimal vibration frequencies compared to the conventional transducers horns. To meet this demand, a new transducer has been developed with special design to meet the above requirements. [N-3]

Conventional transducer horns were made of steel and aluminum. The new system is made of Titanium. Titanium is chosen because of its lightness, high mechanical quality factor, high tensile strength, low thermal expansion

coefficient and high elastic limit. The relative values of the above properties are compared for Ti, Steel and Al in Table 7.3.1.

	Unit	Al	Ti	Steel
ρ*	$10^3 kg/m^3$	2.79	4.42	7.85
$\Delta l/(l\Delta T)$*	$10^{-6}/K$	23	8	15
Q_m*		50,000	24,000	1400
T_f*	MPa	190	720	550
S_f*	10^{-3}	2.57	6.8	2.52

*ρ = density; $\Delta l/(l\Delta T)$ = thermal expansion coefficient;
Q_m = mechanical quality factor;
T_f = tensile strength; S_f = elastic limit

The new transducer design has a "unibody" design which is expected to minimize ultrasonic loss. The new design, the dimensional stability and the low TCE all contribute improved placement accuracy even at high bonding speed.

Some of the comparative studies done with the new transducer design versus the conventional design show significant improvement in touchdown robustness, the bond quality and overall superiority of the new titanium transducer. This is shown in Tables 7.3.2, 7.3.3 and 7.3.4.

Table 7.3.2 Some improved properties of the new transducer [Courtesy: ESEC]

Ultrasonics	Conventional horn	New horn
Maximum amplitude (μm)	3.8	5.3
Frequency (KHz)	107	125
Total decoupling (horn to wire bonder)	Not present	Present
Stability of capillary vibrations	Average	Very good
Transverse mode components (vertical)	6%	0%
Transverse mode components (horizontal)	11%	2%
Power conversion factor ($\mu m / \sqrt{W}$)	1.45	2.26
Mechanics		
Weight (g)	33	24
Touch-down robustness	Average	30% better
Coefficient of thermal expansion ($10^{-6}/K$)	13	9

Table 7.3.3 Touch-down disturbance and level, and impact compared [Courtesy: ESEC]

	New transducer*	**Conventional transducer***	**New transducers Suggested parameters for 50μm-pitch process**
Touch-down disturbance for the ball bond (mN)	45	150	<40
Touch-down disturbance for the wedge bond (mN)	60	150	<60
Touch-down level for the ball bond (mN)	100	180	80
Touch-down level for the wedge bond (mN)	150	200	100
Impact for the ball bond (mN)	160	400	160
Impact for the wedge bond (mN)	190	600	320
*for 70μm-pitch bonding on a BGA			

Table 7.3.4 Bonding process outcome for the 70μm process [Courtesy: ESEC]

	Target for 70μm- pitch process	**Conventional transducer****	**New transducer****
Wedge pull strength (g)	>3	5.5	7.9
C_{pK}	>2	1	2.9
Ball diameter (μm)	45 ± 5	49.3	45.7
C_{pK}	>2	0.18	1.37
Ball height (μm)	12 ± 2	9.7	12.5
C_{pK}	>2	-0.04	0.3
*on a BGA after optimization; **measured values on BGA, 70μm-pitch process			

The higher frequency of the Titanium transducer is expected to be beneficial for low temperature and copper bonding applications, where the lower temperature and stiffer material properties can be compensated for by the higher energy contribution from the transducer horn. Similarly, reduction in touch down disturbances on the wire bonder both on the ball side and on the wedge side, allows one set lower touch down levels. This achieves lower impact values resulting in smaller ball and wedge bonds.

7.4 Copper Bonding Technology

Copper wire and ribbon have been used in manufacturing discrete and high power devices, but more recently copper wire has been explored for ultra fine pitch wire bonding application. One of the main driving forces for evaluating copper for fine pitch wire bonding is because of the emergence of copper metallization on wafers.

The need for increased speed and functionality of IC devices has forced the wafer fab people to look at metallizations other than aluminum. With shrinking wafer line geometries, aluminum is prone to electro migration. Copper metallization reduces electromigration and in addition it provides higher conductivity and less heat generation of the device. The industry

required a robust and stable wire bonding process capable of making reliable interconnections to the copper metallization bond pad. Copper metallized dice bonded with copper wire provide a low cost, high speed, and more importantly a mono-metallic system at the bond pad interface. Long term reliability of mono-metallic system are much better than intermetallic systems.

In high pin count devices, the wire lengths are extremely long, sometime as much as 5 mms. Au wire being of low yield strength has a tendency to deform when subjected to molding. Copper wire which has much higher mechanical strength can withstand molding stresses and therefore result in less wire sweep.

Yet another reason why copper is being considered as alternative wire bond material to gold is cost. Fine pitch packages with greater than 500 leads approach wire lengths of 5 mms. The gold value of the wire for a 500 lead package exceeds $0.25 (at today's prices) and the potential savings by using copper is significant. Copper being about 3 to 10 times lower in cost can significantly impact the final package cost.

But some of the challenges in copper bonding include materials, equipment, capillary, process development and finally reliability. Let us review each of these briefly.

7.4.1 Copper Bonding Wire Materials Technology

High purity copper wire (99.999% and 99.9999%) is generally used for wire bonding application. The tempered and annealed copper wire exhibits UTS and elongation characteristics equal to or better than Au alloy wires. Copper being a very ductile material, can be drawn to very fine wires of upto 10 micron diameter. In addition copper possesses excellent electrical properties and in many cases better than Au wire. In copper ball bonding, copper wire displays excellent ball neck strength and thus high degree of loop stability during the molding operation. However, the harder, stiffer copper wire which can provide looping and molding benefits, has a downside to it. Harder and stiffer wire properties can result in bond defects such as bond pad cratering and bond failure at both first bond and second bond. Today efforts are being made by both wire producers as well as equipment

manufacturers to develop new approaches to wire manufacturing and wire bonding processes to reduce the modulus and improve bond quality without demanding 6N purity copper material. Copper wires that are insensitive to oxidation are under development and soon should be commercially available.

7.4.2 Equipment Issues and Challenges

Copper wire oxidizes easily under normal ambient conditions. Therefore ball bonding with copper wire definitely needs an inert or reducing ambient. The EFO design for copper bonding includes gas flow to provide a reducing atmosphere during ball formation. But gas flow always causes turbulence and gives rise to deformed balls and in some cases oxidized balls. Generally oxidized balls are harder than pure copper balls, resulting in non bonding. There are new designs being developed by equipment suppliers that has special tubes that capture the gas in a laminar flow and without turbulence, ensuring that the ball spericity and surface characteristics are defect free. Besides these new designs do not require a reducing atmosphere, but can operate under normal nitrogen ambience. Use of nitrogen instead of a reducing gas also lowers cost of process gas.

The copper pads on the die will also require adequate gas shielding to prevent oxidation. Copper has much less tolerance for environmental contaminants compared to gold, and as such translates into greater emphasis on clean room air quality.

Process windows are also expected to be smaller, thereby increasing the need for machine capability to be enhanced (higher resolution, better control).

Another challenge is the second bond (wedge) formation. A reliable wedge formation on silver-plated lead frames is impossible under standard bond conditions (temp. of ~220°). Therefore, fine-pitch copper bond technology will probably apply only to BGA (ball grid array) substrates. In the future we may see copper wire bonded on bare copper fingers, but for now the challenge lies in forming a reliable connection between the harder copper wire on the softer gold-plated finger.

7.4.2.1 Inert Gas Requirement for Copper Bonding

The oxidation behaviour of copper demands that the wire bonding equipment include:

- installation of a modified electronic flame-off (EFO) electrode that is capable of supplying forming gas during the free air ball (FAB) formation
- utilization of special heater plate that supplies a shielding gas to the bond area

7.4.2.2 Closed Loop Force Control

Previously it was mentioned that the tighter tolerances for fine pitch copper bonding would necessarily mean that machine capability needs to be enhanced. The new closed loop force control (COFO) feature incorporated in bonding machines, utilizes real-time force regulation (closed loop controlled) for ball and wedge bonds. With this new feature the bond force for ball/wedge is constantly monitored during the bonding process, providing better control and maintaining an average precision of ±10 mN.

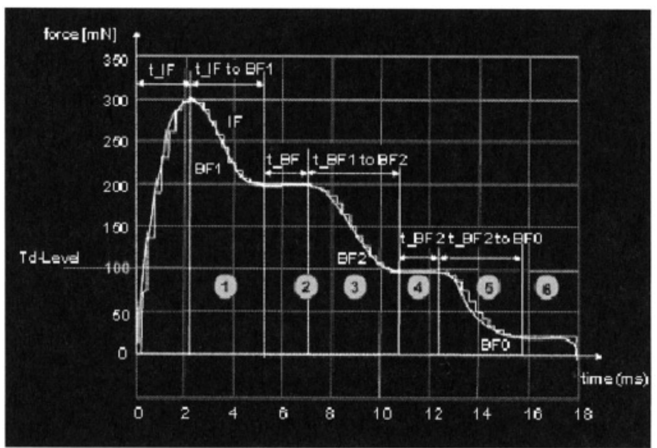


Figure 7.4.1 Force profile with force controlled bond force with two programmed force segments. [N-4]

In relation to copper bonding, the potential benefits of the close loop force control feature is better control of impact and force to yield more consistent results. Results comparing wire-pull values for 0.9 mil Cu wire with and without the close loop force control feature are presented in table 7.4.1.

Table 7.4.1 Pull value of 0.9 mil Cu wire [N-4]

	Without	With
Pull force (at wedge) [cN]	6.76	7.25
Max [cN]	9.39	9.23
Min [cN]	3.31	5.27
Std dev	1.61	1.2

7.4.2.3 Second Bond Considerations in Copper Bonding

In relation to second bond considerations, the following three factors are found to be significant for a 60 microns copper wire bonding process:

- material variation
- capillary design
- ultrasonic control

Factors relating to material variation include:

- contamination on the lead fingers
- the wire spool left exposed to air room temperature yields noticeable differences in pull values after approximately four days
- shielding the wire spool (with nitrogen) prolongs its life span

7.4.3 Capillary Selection

Capillary design considerations for bonding copper wire to aluminum or copper metallization are not entirely the same as for standard gold ball bonding to aluminum metallization. Because the copper wire is harder and the plastic flow characteristics of copper FAB will be different, one has to design the capillary for the particular application. Critical capillary dimensions can be specified based on the size constraints of the bond pad and lead finger.

The capillary may require optimized surface coatings and ceramic materials to meet life expectancy requirements of the capillary, because of the greater hardness of the copper wire as well as greater tendency of copper wire to adhere to capillary tip surface. Special tool geometries are also be required to improve the second bond and reduce short tail defects. In general, the effect is more noticeable when using an 80 microns tip diameter capillary (60 microns process) than with a 110 microns tip diameter capillary (90 microns process).

For capillary considerations affecting the second bond, 11 ° face angle capillaries yield the best results. However, to finer pitches, smaller chamfer diameters make the formation of strong tail bonds more difficult. This is truer for the harder copper wire, which tends to become brittle upon deformation.

Currently, industry is looking into a number of possibilities in improving the capillary design for 60 microns ultra fine pitch applicable copper wire. Higher face angles and larger chamfer diameter may help stabilize the tail bond process and allow the utilization of bond parameters for better pull values.

7.4.3.1 Ultrasonic Wedge Bonding of Copper Wire

For ultrasonic wedge bonding of copper wire, it is generally recommended that one uses tungsten – carbide bonding wedge tool with a linear cross-groove tip with a very small back radius. Small back radius facilitates proper wire termination. The effect of cross groove is to increase coupling between the ultrasonic transducer and the wire, and the effect is shown in Figure 7.4.4.

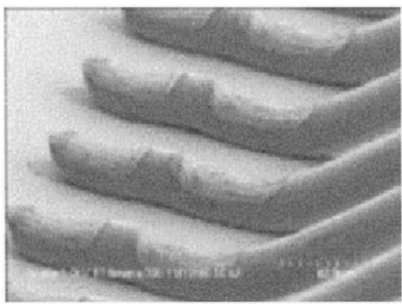


Figure 7.4.4 Wedge bonded copper wires [N-4]

7.4.3.2 Reliability of Copper Bonding

Two major areas of reliability concern in copper bonding are, the intermetallic formation between copper and aluminum bond pad and secondly, the copper corrosion due to flame retardant in the molding compound. Intermetallic growth of copper –aluminum alloy is significantly lower compared to the intermetallic growth of Au-Al alloys. Kirkendall voiding and the resultant reliability failure does not seem to be a real concern in Cu-Al bonding, when compared to Au-Al bonding system. Many studies have been done in this area [N-5]. Figure 7.4.5 (a) shows that the rate of intermetallic growth between Cu-Al interface is about 2.5X slower compared to that of Au-Al interface.

Further evidence of this is shown in Figure 7.4.5(b) where the electrical resistance of the Cu-Al and Cu-AlSi interface appears to stabilize after aging for 100 hours; where as the Au-Al interface resistance continues to increase. The difference in the level of intermetallic formation in a copper wire bond versus a gold wire bond is apparent when the underside of the squashed ball, is examined. This is shown as SEM pictures in Figure 7.4.6. One can clearly see that the intermetallic penetration in copper is much less compared to that in gold [N-5].

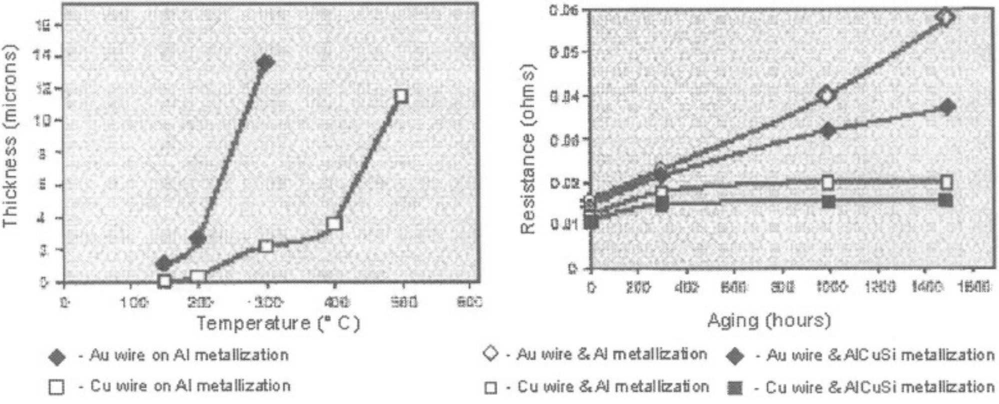


Figure 7.4.5(a) Intermetallic thickness vs temperature (b) *Effect of wire material and substrate metallization* on resistance [N-5]

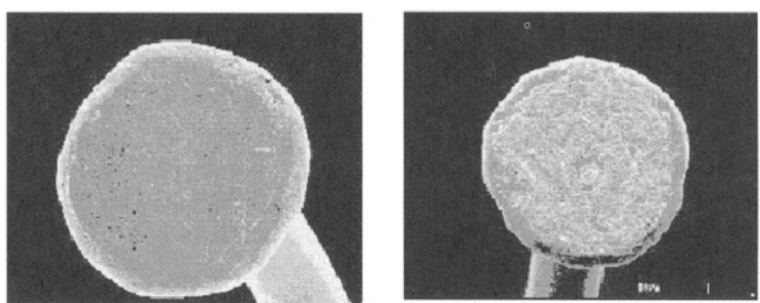


Figure 7.4.6 (a) Intermetallic penetration –Cu wire ball (b) Intermetallic penetration- Au wire ball [N-5]

7.5 MicroBGA Lead Bonding Process

MicroBGA is chip scale package developed and licensed by Tessera Corp. in USA. This package uses a wire bonding equipment to interconnect the chip and the package substrate. However, the wire bonding equipment does not use Au or Al wire for bonding, instead bonds a thin lead to both chip and the package.

The main processing steps in the MicroBGA packaging flow are: die attach, lead bonding, edge sealing, ball attach, and device singulation. Lead Bonding has a major impact on the reliability of the entire MicroBGA package. Due to the different thermal expansion coefficients of the die and circuit panel, leads must flex along the lead direction during power and heat cycling of the device without failure [N-6]. The lead has to be shaped in such a manner, that no fatigue effects are provoked in the lead. In addition, a high performance long-term stable electrical interconnection is established between the bond pad and the signal trace on the MicroBGA flex material.

7.5.1 Differences between Lead and Wire Bonding

The lead bonding process in MicroBGA package differs in many points from the well known ball wedge wire bonding. Standard wire bonding equipment has therefore to be adapted to meet all the requirements for lead bonding.

Common characteristics of both processes are material handling, use of thermosonic bonding principles and an extremely accurate, high speed motion of the bondhead.

The main differences are determined by the different materials and geometry which apply in wire and lead bonding. The Au wire is replaced by the lead which is an integral part of the tape material. For lead material, a compound of Au plated Cu or pure Au is used. The ceramic wire bonding capillary is replaced by a non-symmetrical bonding tool made of a different composition. This has a strong impact on the ultrasonic coupling during the bonding process. The chip itself is mounted below the package substrate material, and a rigid material is no longer used for the package substrate.

7.5.2 Lead Bonding Process Overview

The lead bonding process in MicroBGA can be roughly divided into three steps as shown schematically in Figure 7.5.1.

- the bondhead moves vertically towards the chip surface until the lead is broken. The break point on the lead is defined by a notch in the lead

- the lead is guided with the tool towards the bond pad B. During this movement, the lead is bent to achieve the desired shape
- ultrasonic energy is applied to establish an intermetallic bond formation between the lead and the underlying bond pad.

The bonding scheme is finished with a simple complementary process wherein the bondhead moves to the starting point of the next lead cycle. The first two phases differ completely from wire bonding and have to be specially designed for lead bonding. In contrast to wire bonding, the electrode flame-off and the entire wire handling are obsolete.

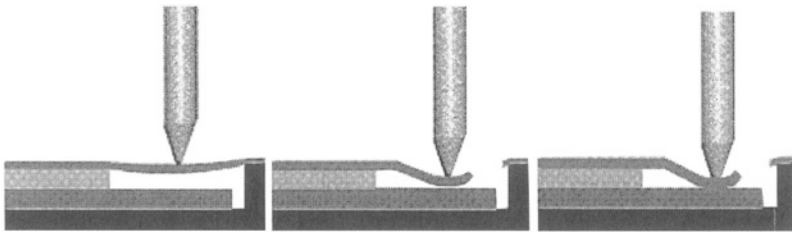


Figure 7.5.1 Schematic representation of lead bonding process steps: Cut lead, shape lead and bond formation [N-6]

In MicroBGA lead bonding, linear travel distances of the bond head are ten to a hundred times smaller than for wire bonding. The trajectories have therefore to be very accurately executed. Especially in Z direction, high precision motion and position control is required to achieve precise bond placement. These requirements are satisfied by using a sophisticated wire bonder platform [N-7] as a base for a lead bonder.

Conclusion

We have attempted to review some of the major application areas where new wire bonding technologies are being developed. However, the reader is forewarned that we have not been able to incorporate all the new developed technologies that are taking place in the industry.

The semiconductor and microelectronics industry is extremely diverse and many companies develop customized solutions technologies to meet the

requirement of the device, application and specific requirements of manufacturing, and such information is not available in public domain.

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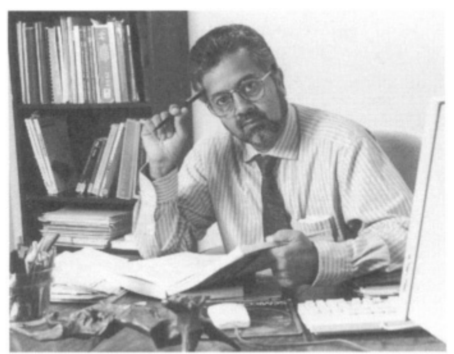
About the Author



Dr. Shankara Prasad obtained his Masters degree in Materials Science from Indian Institute of Technology, Kanpur, India and his Ph.D. in Materials Engineering from State University of New York, Stony Brook, New York.

Dr. Prasad has spent more than 20 years working in the area pf VLSI packaging and microelectronics manufacturing. He has worked for major Semiconductor companies including Intel, California, as Reliability Project Leader, Cypress Semiconductor, as Assembly Tehcnology Development Manager, Robert Bosch, Germany as Packaging Technology Manager & International Operations Manager, and most recently as Director of Engineering & Technology Development at CS2 Belgium.

Dr. Prasad has consulted with more than 30 companies in 17 countries worldwide including IBM, Digital, Siemens, Fairchild, ST-Microelectronics and Xilinx. His consulting assignments include technology development, manufacturing optimization, supply chain integration, failure analysis and reliability engineering.

Since 1983, Dr. Prasad has developed and taught 12 packaging technology courses to more than 3000 technicians, engineers and managers worldwide. His company INKROMA (formerly APT Interactive) has developed many e-learning CDROMs and Decision Support softwares relevant to the VLSI Packaging domain.

Dr. Prasad was awarded the 1998 IEEE award for “Major Educational Innovation” for innovation in the delivery methods of VLSI packaging education. He was adjunct professor at California State University, San Jose and Advisor to Center for Electronics Development & Technology, Indian Institute of Science, Bangalore.

Dr. Prasad has served on many SEMI task forces, IMAPS & IEEE conference committees and also as an expert evaluator to many European Commission projects on electronics packaging. Presently, he is the CEO of Inkroma E-Business Solutions, in Bangalore, India and the company focuses on Rosettanet enabled ERP/SCM and KM solutions to electronics companies.