Using Simulation to Estimate MOSFET Junction Temperature in a Circuit Application

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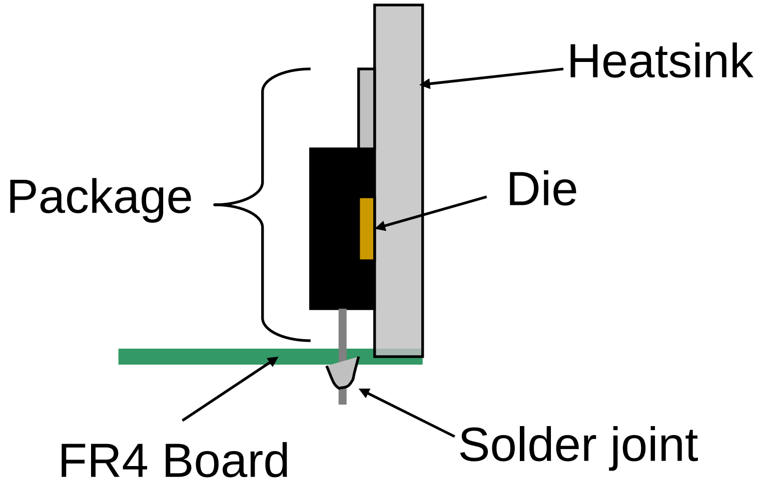
Agenda

- Definition of Electro-Thermal Simulation
- Simulation Tools and Methods
- Methods of Estimating Die Temperature
- Creating Quasi-Dynamic MOSFET Model
- Model Generation
- Example Application
- Conclusion

Electro-Thermal Simulation

- Purpose of Electro-Thermal Simulation is to predict MOSFET junction for a given application.



Electro-Thermal Simulation

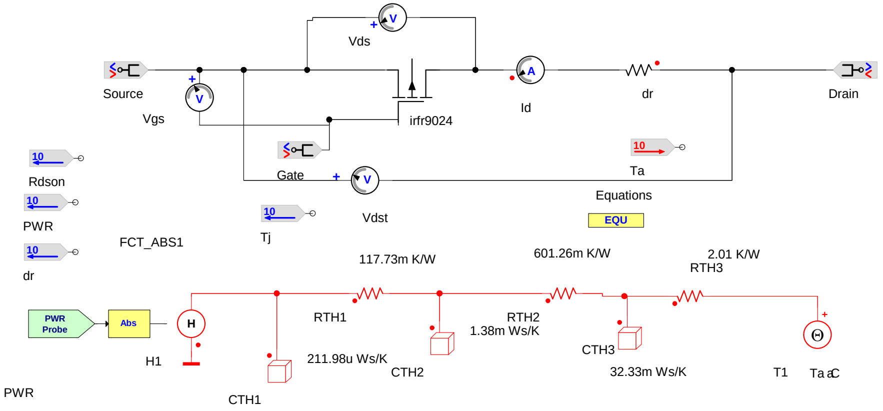
- Applications
  - Solenoid drivers
  - Motor drive
  - Lighting ballast
  - DC/DC converters
  - Switch model power supplies
  - Class D amplifiers

Simulation Tools and Methods

- Method
  - Implementing model in the hardware description language
  - Implementing model using equations and macro modeling

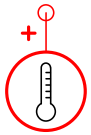
```
library ieee;  use ieee.std_logic_1164.all;
use ieee.electrical_systems.all;

entity comparator is
  port ( terminal a : electrical;
         signal d : out std_ulogic );
end entity comparator;

----------------------------------------------------------------

architecture ideal of comparator is
  constant ref_voltage : real := 5.0;
  quantity vin across a;
begin

  comparator_behavior : process is
  begin
    if vin > ref_voltage / 2.0 then
      d <= '1' after 5 ns;
    else
      d <= '0' after 5 ns;
    end if;
    wait on vin'above(ref_voltage / 2.0);
  end process comparator_behavior;

end architecture ideal;
```

vs.

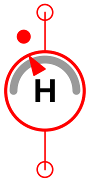


Simulation Tools and Methods

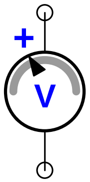
- Quasi-Dynamic MOSFET model implementation
  - Macro modeling with use of linking equations
  - Using a multi domain simulator that allows for Electro-Thermal simulation.
    - Volts and Amps
    - Heat flow (Watts) and temperature



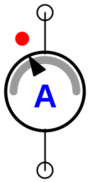
Thermometer



Heat



Voltmeter



Ammeter

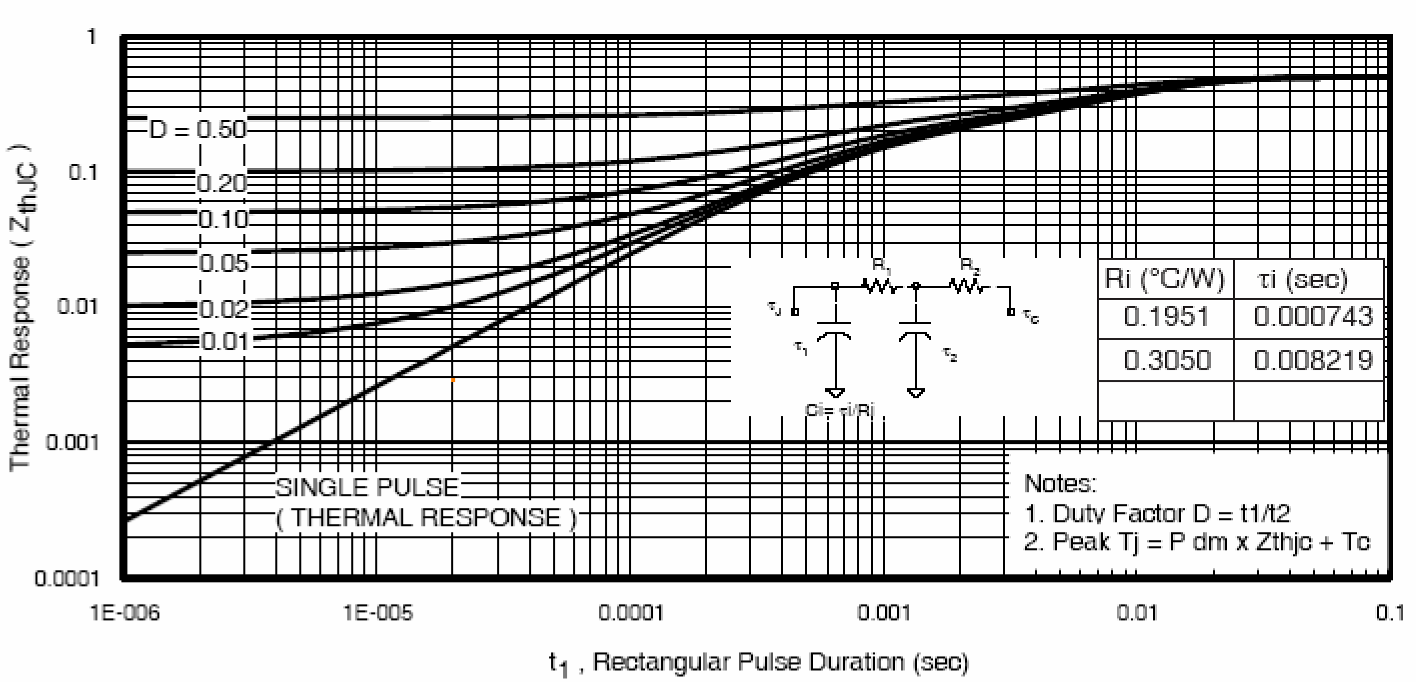
Methods of Estimating Die Temperature

- Methods of estimating MOSFET die junction temperature
  - Equation based + Thermal Impedance curve

$$P = I * V * D$$

Where:
I = average current during the conduction cycle
V = equivalent voltage across the device during the conduction cycle
D = duty cycle

Methods of Estimating Die Temperature



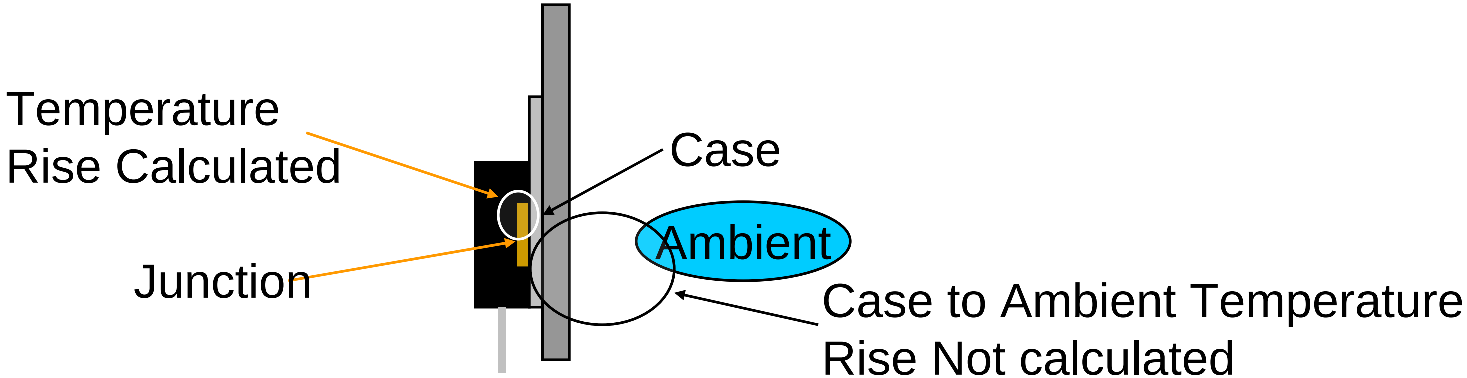
Ri (°C/W)	τi (sec)
0.1951	0.000743
0.3050	0.008219

Notes:
1. Duty Factor D = t1/t2
2. Peak Tj = P dm x Zthjc + Tc

- Use Power calculated with P=I*V*D
- Use pulse width and duty cycle to determine Zth (thermal impedance) from device thermal impedance curve
- Temperature rise (ΔTjunction)= Zth * P

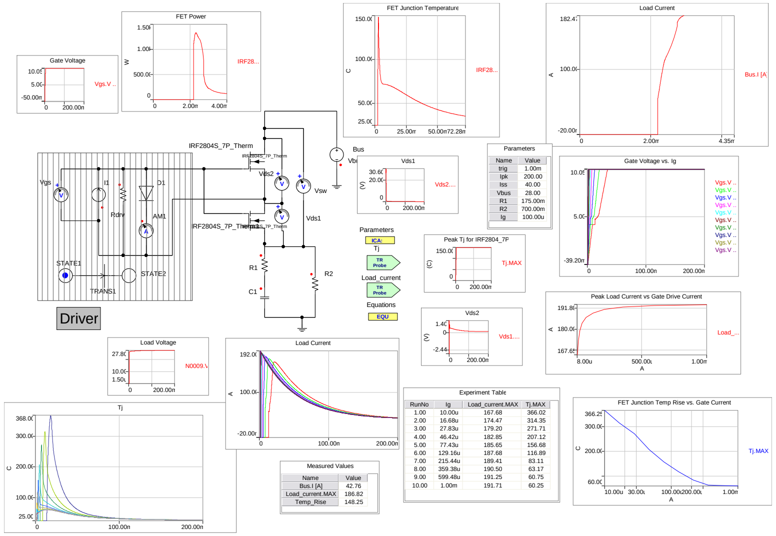
Methods of Estimating Die Temperature

- Limitations of the equation based junction temperature estimate
  - Only temperature rise from junction to case is taken into account. Neglects case to ambient temperature rise.
  - Assumes the power pulse is an ideal square edged pulse train.
  - It does not allow for transient thermal response.



Methods of Estimating Die Temperature

- **Simulator based MOSFET junction temperature estimate**
  - **Uses circuit simulation to calculate junction temperature in an application**
  - **The circuit can be arbitrary**
  - **Transient thermal response is calculated**
  - **Component parameters change with temperature**



Parameters

Name	Value
trig	1.00m
Ipk	200.00
Iss	40.00
Vbus	28.00
R1	175.00m
R2	700.00m
Ig	100.00u

Experiment Table

RunNo	Ig	Load_current.MAX	Tj.MAX
1.00	10.00u	167.68	366.02
2.00	16.68u	174.47	314.35
3.00	27.83u	179.20	271.71
4.00	46.42u	182.85	207.12
5.00	77.43u	185.65	156.68
6.00	129.16u	187.68	116.89
7.00	215.44u	189.41	83.11
8.00	359.38u	190.50	63.17
9.00	599.48u	191.25	60.75
10.00	1.00m	191.71	60.25

Measured Values

Name	Value
Bus.I [A]	42.76
Load_current.MAX	186.82
Temp_Rise	148.25

Methods of Estimating Die Temperature

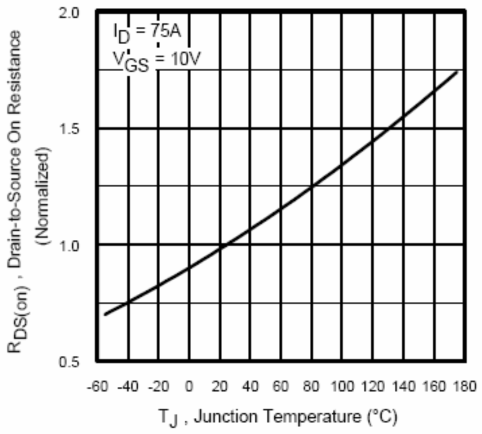
- Assumptions made for junction temperature estimates using simulation
  - No other source of heat considered (Temperature rise due to self heating only)
  - Only MOSFET Rdson and threshold voltage changes with temperature
  - Since simulation solves Ordinary Differential the junction is assumed to be a point source of heat.

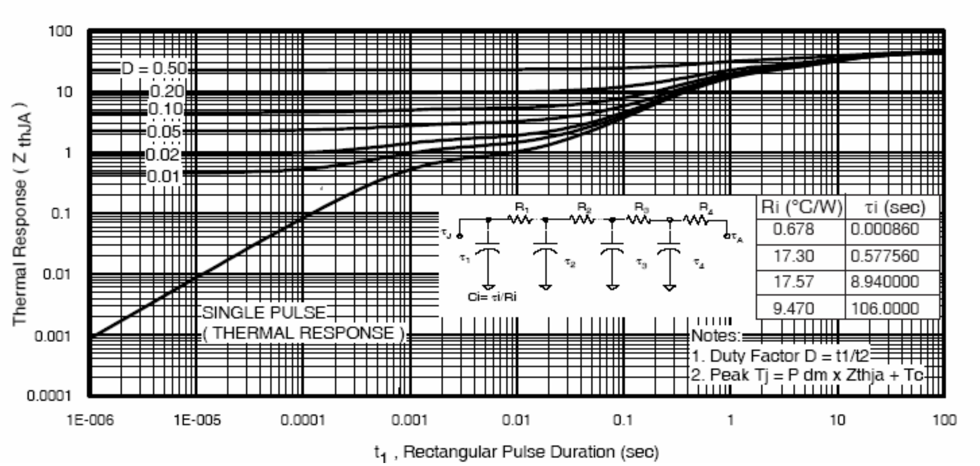
Creating Quasi-Dynamic Thermal MOSFET Model

- Gathering information:
  - 25C Spice Model of MOSFET
  - Datasheet information
    - Rdson vs. Temperature curve
    - Thermal Impedance Curve with thermal RC ladder network

```
.SUBCKT irf1404 1 2 3 * SPICE3 MODEL WITH
THERMAL RC NETWORK
*************************************** * Model Generated
by MODPEX * *Copyright(c) Symmetry Design
Systems* * All Rights Reserved * * UNPUBLISHED
LICENSED SOFTWARE * * Contains Proprietary
Information * * Which is The Property of * *
SYMMETRY OR ITS LICENSORS * *Commercial Use
or Resale Restricted * * by Symmetry License
Agreement * *************************************** * Model
generated on April 2, 01 * MODEL FORMAT: SPICE3
* Symmetry POWER MOS Model (Version 1.0) *
External Node Designations * Node 1 -> Drain * Node
2 -> Gate * Node 3 -> Source M1 9 7 8 8 MM L=100u
W=100u .MODEL MM NMOS LEVEL=1 IS=1e-32
+VTO=3.74183 LAMBDA=0.00250986 KP=514.947
+CGSO=7.17952e-05 CGDO=1.60578e-08 RS 8 3
0.00282867 D1 3 1 MD .MODEL MD D IS=1.89845e-
10 RS=0.00218742 N=1.20398 BV=40 +IBV=0.00025
EG=1.2 XTI=1.85712 TT=2.00014e-05
```

```
FC=0.1
.16781
S=0
3e-09
MD2 *
0 TT=0
IS=1e-
VFI2 4
I1 7 9
*
0 TT=0
MD3 D
```





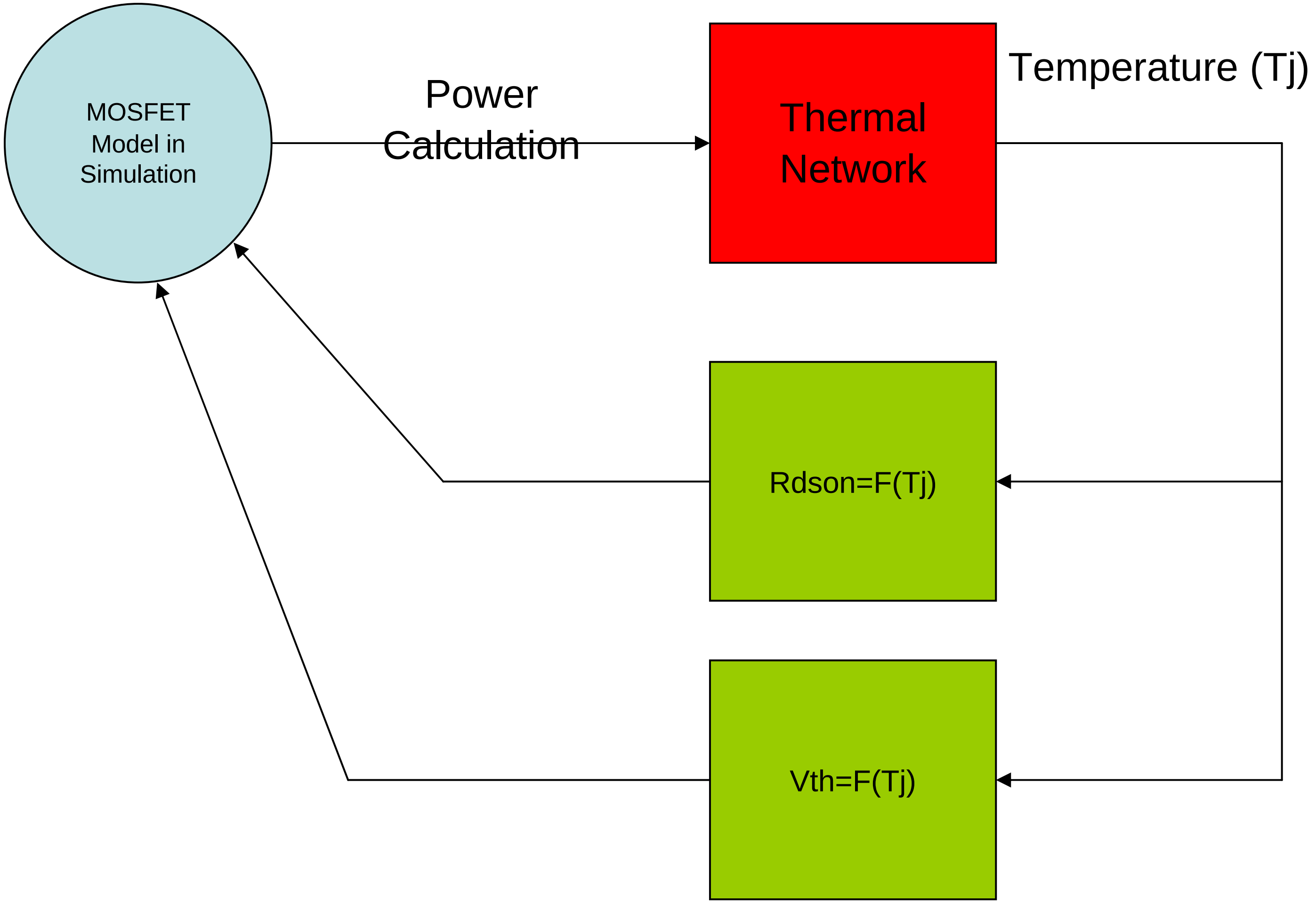
Ri (°C/W)	τi (sec)
0.678	0.000860
17.30	0.577560
17.57	8.940000
9.470	106.0000

Notes:
1. Duty Factor D = t1/t2
2. Peak Tj = P dm x Zthja + Tc

Creating Quasi-Dynamic Thermal MOSFET Model

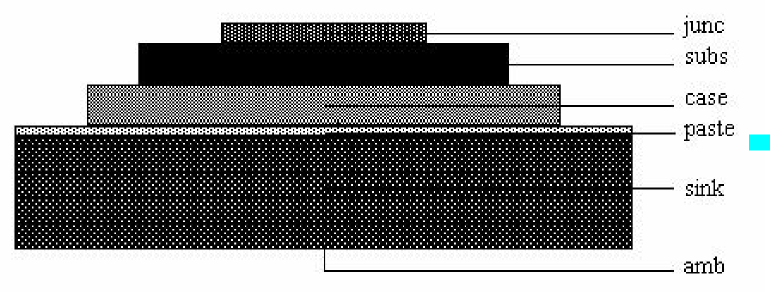
- 25C Spice Model
  - Characterized to the datasheet
  - Does not change performance characteristics as power is calculated
  - Used as base model for Quasi-Dynamic MOSFET model

Creating Quasi-Dynamic Thermal MOSFET Model

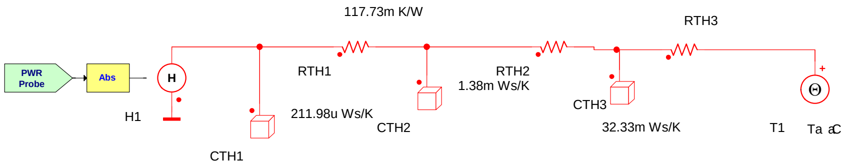


Model Generation

- Ladder Network
  - A thermal RC network used to model the dynamic thermal behavior of the package + mounting system.



Package + Mounting



Equivalent RC Ladder Network

The ladder network can be synthesized from the thermal impedance curve or is given by the MOSFET manufacturer

Model Generation

- Tying the thermal model to the 25C Spice model
  - Create the equation that represents Rdson vs. temperature

$$Rdson(Tj) = Rdson(25C) * [a * Tj^2 + b * Tj + c]$$

$$\Downarrow$$

$$\frac{dRdson(Tj)}{dTj} = Rdson(25C) * (2 * a * Tj + b)$$

$$\Downarrow$$

$$dRdson = Rdson(25C) * (2 * a * Tj + b) * (Tj - 25) \longleftarrow$$

This expression gets implemented in the model

Note: a, b and c are calculated via a curve fitting routine.
The Rdson vs Temperature curve is assumed to be quadratic.

Model Generation

- Create the voltage source that represents the temperature dependence of Vth (threshold voltage)

$$Vth(Tj) = -0.007 * (Tj - 25) \longrightarrow$$ Expression used in model.

The voltage source is in series with the MOSFETs gate.

Model Generation

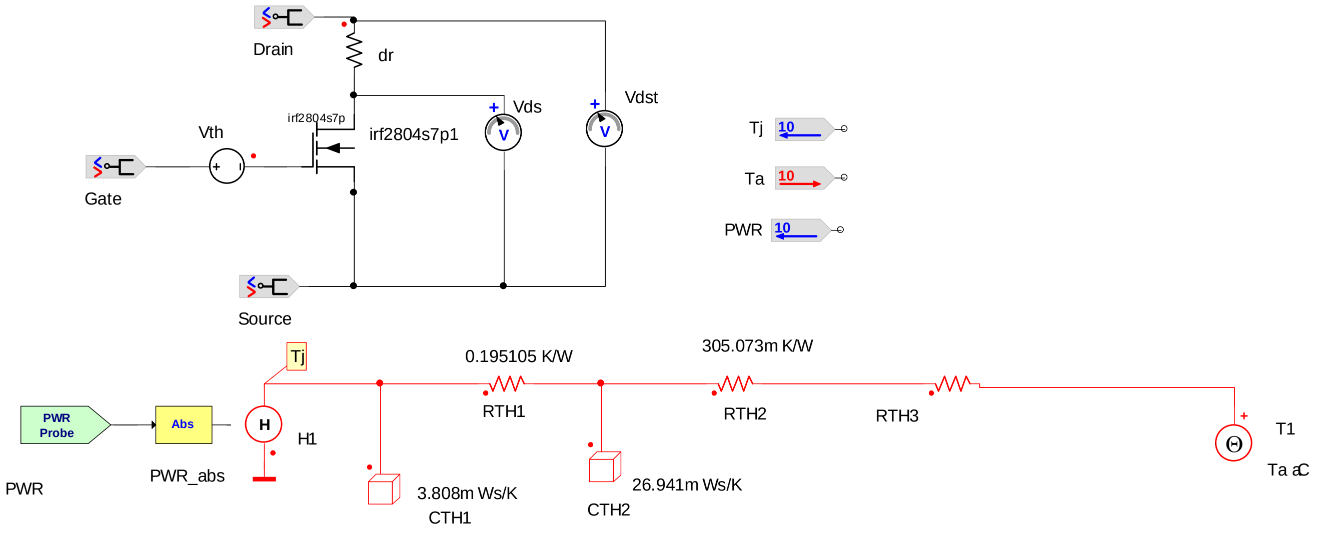
- Calculating the power in the MOSFET for use in the thermal network.

$$P = Id * Vds$$

This calculated power is the source for the thermal network.

Model Generation

- Putting it together



Equations

EQU

```
dt:=Tj.T-Ta
Tj:=Tj.T-273.15
if(Vds.V<0.1) {Rdson25:=abs(Vds.V/dr.I)} else {dr:=1m
if(Vds.V<0.1) {dr:=(7.41u*Tj+3.519m)*dt*Rdson25} else {dr:=1u}
PWR:=PWR_abs.VAL
Vth:=-7m*(Tj-25)
```

Model Generation

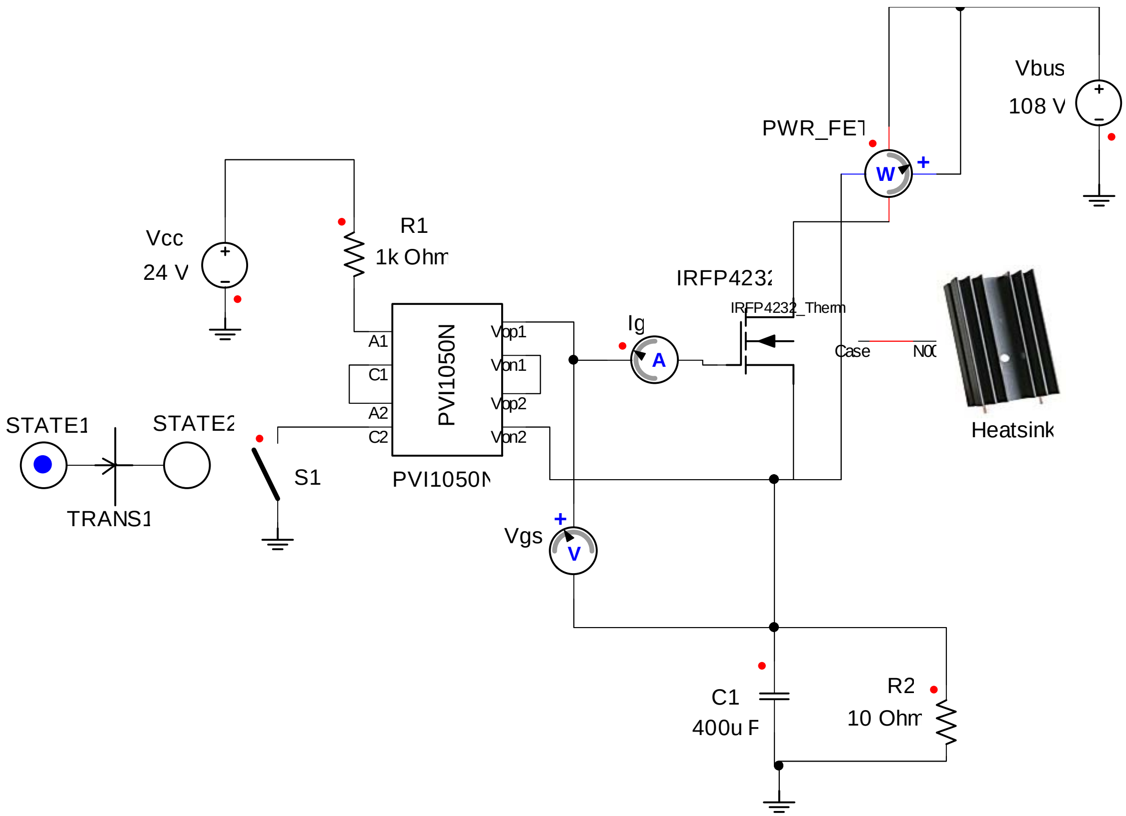
- Final model
  - 25C Spice model
  - Added voltage source Vth in gate implements Vth(Tj)
  - dr implements $dRdson = Rdson(25C) * (2 * a * Tj + b) * (Tj - 25)$
  - Vds and the current in dr are used to calculate Rdson25C
  - Vdst and the current in dr is used to calculate the total power
  - PWR_abs is used to insure that the thermal network is driven with positive power.

Example Application

- High side switch
- MOSFET being driven by a opto isolated drive
  - Very low drive current capability
- Load is capacitive
- Issue: How does driving this load effect the junction temperature of the MOSFET

Example Application

- Simulation Schematic

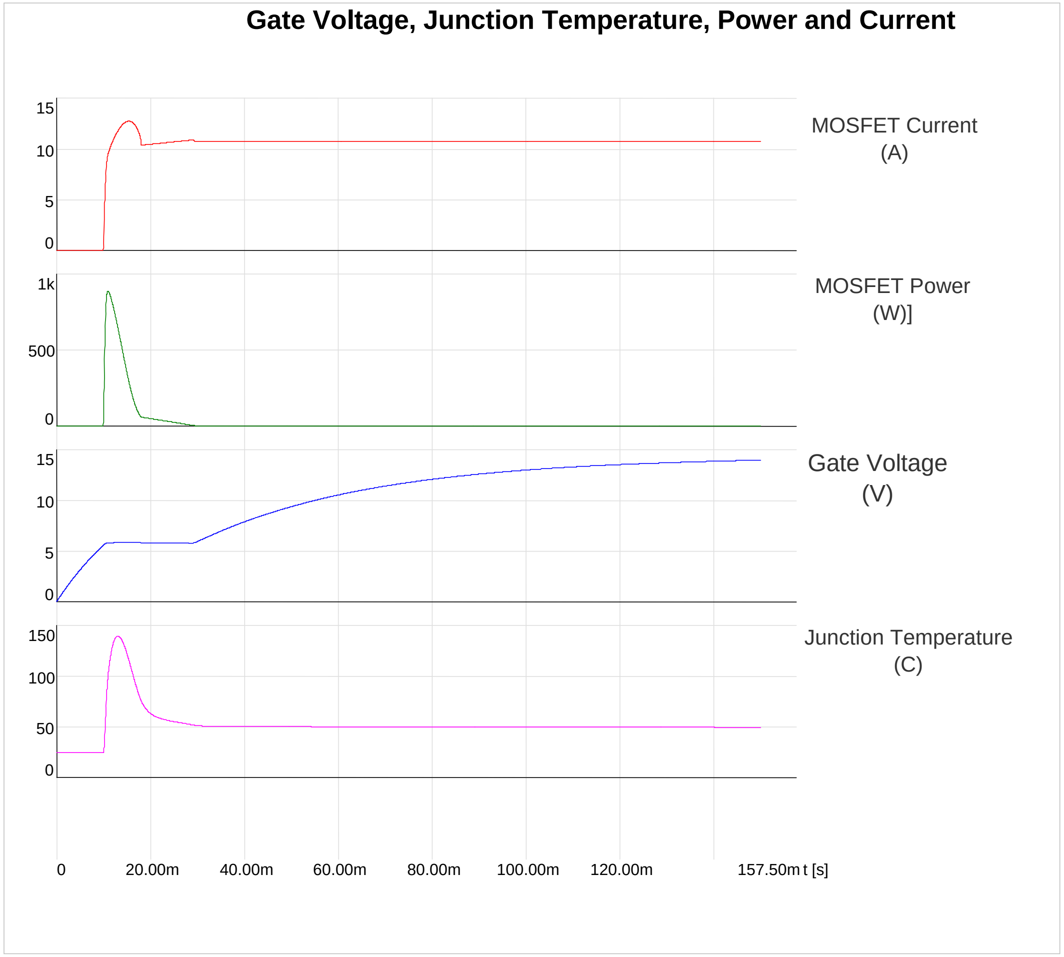


Example Application

- Assumptions
  - Tambient=25C
  - Heak sink is modeled as just a thermal resistor
  - C1 & R2 represent a load system i.e. power supply
  - Ig, Vgs, PWR_FET, States 1 & 2, Trans1 and S1 are measurements, input stimulus and ideal switch

Example Application

- Results



Conclusion

- Electro-Thermal simulation allows for analysis in both electrical and thermal domains
- Quasi-Dynamic Thermal MOSFET model allows for self-heating to alter Rdson and Vth during simulation as a function of temperature
- Quasi-Dynamic Thermal MOSFET Model generation is a data gathering task
- The example shows why it is difficult to switch a capacitive load with an opto-driver and a MOSFET due to the excessive junction temperature spike during turn-on.