Bandgap reference

The schematic diagram of the bandgap voltage reference is shown in Figure 1.
The bandgap reference has largely independent of temperature and the supply rails and is therefore used as the controlling current source for mirroring throughout a circuit eg an op-amp.

As shown in the diagram there are two voltage sources, one generated across a diode junction ie V_{BE} (eg the base-emitter junction on a bipolar transistor) and the other a thermal voltage Vt.

V_{BE} = -2.2mV/°C and
Vt = +0.085mV/°C

Thus if multiply Vt by a constant K and combine with V_{BE} it is possible to cancel the temperature effects of each voltage source to leave a stable reference voltage V_{REF} ie

$V_{REF} = V_{BE} + K.Vt$

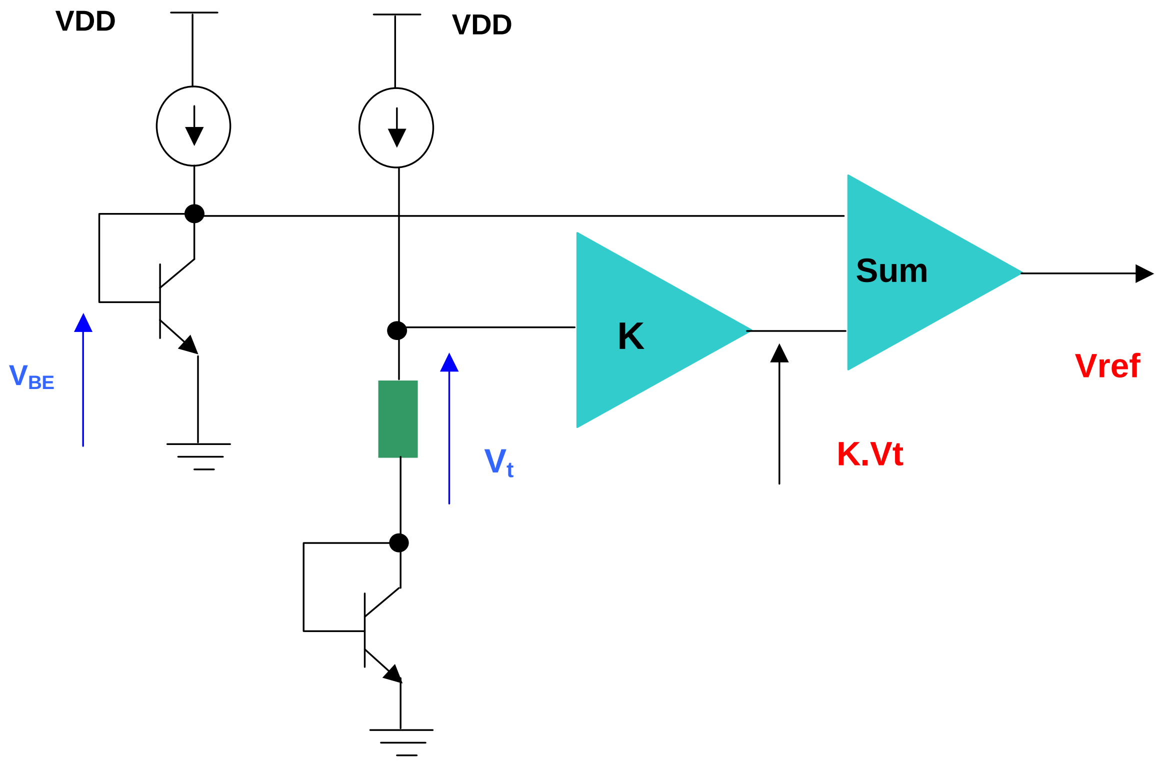


Figure 1 Schematic diagram of a bandgap reference. Vref = K.Vt +V_{BE}.

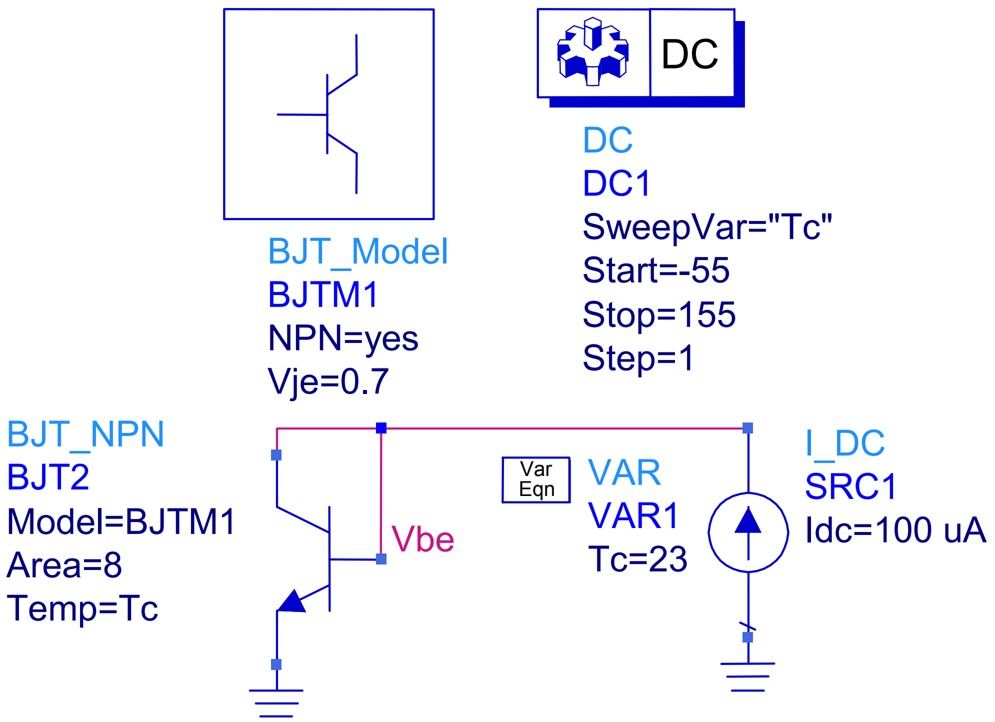


Figure 2 ADS simulation setup to determine the temperature dependence of Vbe. The temperature variable of the BJT model Tc is sweep by the DC simulation from –55 to 155 degrees C.

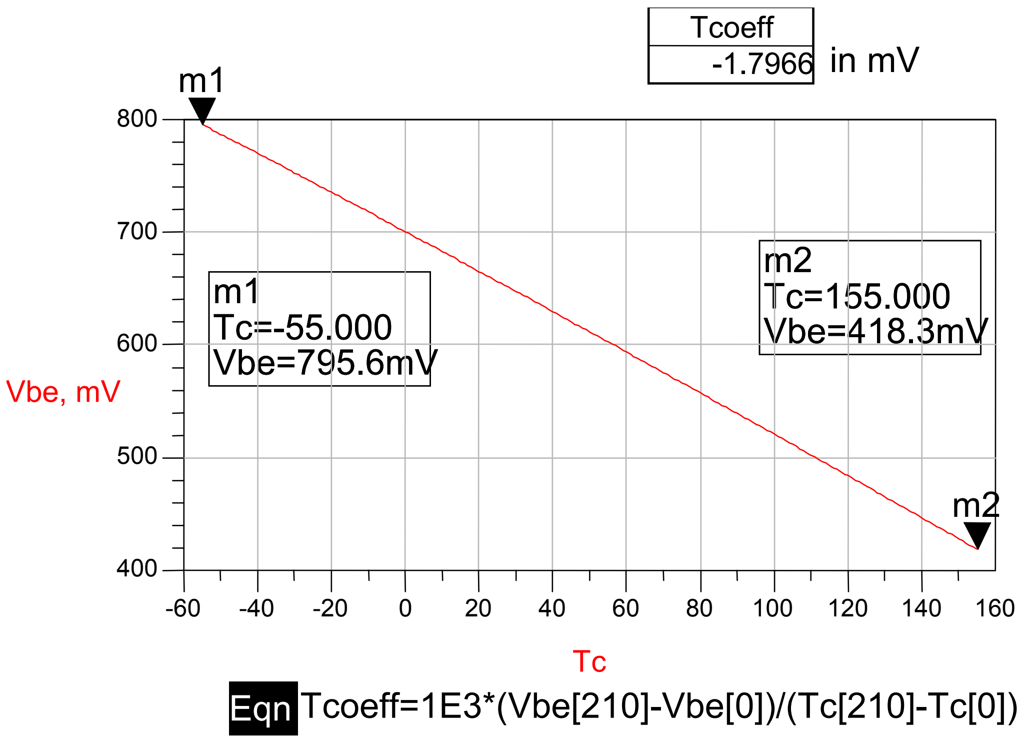


Figure 3 Temperature dependance of Vbe as simulated from the ADS simulation of Figure 2. Temperature coefficient of VBE ~ -1.79mV/˚C.

Temperature dependance of VBE

We can simulate the temperature effect of V_{BE} by using the ADS simulation shown in Figure 2. In this simulation the temperature parameter of the generic spice BJT model (TC) is sweep by the DC simulation from –55 to 155 degrees C.
The resulting plot of Vbe vs temperature is shown in Figure 3. An equation has been added to calculate the temperature coefficient by taking the first and last data points [0] and [210] to calculate the slope of the graph.

Bipolar collector current is given by :-

$$Ic = I_s.\exp^{\left(\frac{V_{BE}}{Vt}\right)}$$

Where

$$Vt = \text{Thermal Voltage given by Where } Vt = \frac{kT}{q}$$

$$q = \text{charge on electron} = 1.602 \times 10^{-19}\ C$$

$$K = \text{Boltzmanns constant} = 1.3807 \times 10^{-23}\ J.K-1$$

$$I_S \propto \mu.K.T.n_i^2 \quad - \quad (1)$$

Where

$$n_i^2 = \text{Intrinsic carrier concentration in Silicon } (1.5x10^{10}\, cm^{-3})$$

$$\mu = \text{Mobility of minority carriers}$$

Temperature dependance of key variables

$$\mu \propto \mu_O.T^m \quad \text{Where } m \approx -\frac{3}{2} \qquad - \quad (2)$$

$$n_i^2 \propto T^3.\exp\left[\frac{-Eg}{K.T}\right] \quad - \quad (3) \text{ Where } Eg = \text{bandgap voltage} = 1.12eV \text{ for silicon}$$

Sub equations 3 & 2 into 1

$$I_S \propto \mu_O.T^m.K.T.T^3.\exp\left[\frac{-Eg}{K.T}\right] = A.T^{4+m}.\exp\left[\frac{-Eg}{K.T}\right]$$ Where constant A includes $\mu_O.K$

$$V_{BE} = V_T.Ln\left(\frac{Ic}{Is}\right)$$

$$\frac{\partial V_{BE}}{\partial T} \text{ of } V_T.Ln\left(\frac{Ic}{Is}\right) \quad \frac{\partial V_T}{\partial T}.Ln\left(\frac{Ic}{Is}\right)$$

To find $\frac{\partial Is}{\partial T}$ expand out to get $V_T Ln.Ic - V_T Ln.I_S \quad \therefore \frac{\partial Is}{\partial T} \Rightarrow -V_T.\frac{1}{I_S}.\frac{\partial Is}{\partial T}$

As $Ln.ax = \frac{1}{x}\frac{\partial y}{\partial x}$

$$\frac{\partial V_{BE}}{\partial T} = \frac{\partial V_T}{\partial T}.Ln\left(\frac{Ic}{Is}\right) - \frac{V_T}{I_S}.\frac{\partial Is}{\partial T}$$

$$I_S = A.T^{4+m}.\exp\left[\frac{-Eg}{K.T}\right]$$ Use $ax^n = anx^{n-1}.\frac{dy}{dx}$

$$\frac{\partial Is}{\partial T} = (4+m)A..T^{3+m}.\exp\left[\frac{-Eg}{K.T}\right] + A.T^{4+m}.\exp\left[\frac{-Eg}{K.T}\right].\left[\frac{-Eg}{K.T^2}\right]$$

$$\frac{V_T}{I_S}.\frac{\partial Is}{\partial T} = \frac{V_T(4+m)A.T^{3+m}.\exp\left[\frac{-Eg}{K.T}\right]}{A.T^{4+m}.\exp\left[\frac{-Eg}{K.T}\right]} + \frac{V_T A.T^{4+m}.\exp\left[\frac{-Eg}{K.T}\right].\left[\frac{-Eg}{K.T^2}\right]}{A.T^{4+m}.\exp\left[\frac{-Eg}{K.T}\right]}$$

$$\frac{V_T}{I_S}.\frac{\partial Is}{\partial T} = \frac{V_T(4+m)}{T} + V_T\left[\frac{-Eg}{K.T^2}\right]$$

$$\frac{\partial V_{BE}}{\partial T} = \frac{\partial V_T}{\partial T}.Ln\left(\frac{Ic}{Is}\right) - \frac{V_T}{I_S}.\frac{\partial Is}{\partial T}$$

$$= \frac{V_T}{T}.Ln\left(\frac{Ic}{Is}\right) + \frac{V_T(4+m)}{T} + V_T\left[\frac{-Eg}{K.T^2}\right] \qquad V_{BE} = V_T.Ln\left(\frac{Ic}{Is}\right) \,\&\, Vt = \frac{kT}{q}$$

$$\frac{\partial V_{BE}}{\partial T} = \frac{V_{BE}}{T} + \frac{V_T(4+m)}{T} + \frac{kT}{q}\left[\frac{-Eg}{K.T^2}\right] = \boxed{\frac{V_{BE}}{T} + \frac{V_T(4+m)}{T} + \frac{1}{q}\left[\frac{-Eg}{T}\right]}$$

Evaluation of dVBE/dT

$$V_T = \frac{KT}{q} = \frac{1.3807 \text{ x } 10^{-23}.300}{1.602 \text{ x } 10^{-19}} = 25.8mV$$

Where $Eq = $ Bandgap voltage (for silicon $= 1.12eV$) & $m = -\frac{3}{2}$

and

$K =$ Boltzmanns constant $= 1.3807 \text{ x } 10^{-23}$ J.K - 1

$q =$ charge on electron $= 1.602 \text{ x } 10^{-19}$ C

$$V_{BE} = Vt.Ln\left(\frac{I_E}{I_S}\right) \quad \text{Where} \quad I_S = \frac{q.A.n_i^{\,2}.\overline{Dn}}{Q_B} \quad \text{Typical values are } 10^{-14} \text{ to } 10^{-16}\text{ A}$$

Where

$QB = W_B.N_A$ is the number of doping atoms in the base per unit area of the emitter.

(for 0.8um process $NA = 3x10^{16}$ for p - type device); $W_B =$ base width.

$\overline{Dn} =$ The average effective value for the electron diffusion constant in the base.

(Typically $= 13cm^2s^{-1}$).

$n_i^2 =$ Intrinsic carrier concentrat ion in Silicon ($1.5x10^{10}\,cm^{-3}$)

$A =$ Base - Emitter area.

To find a typical value for Vbe and ΔVbe assume $IE = 50uA$, $A = 1um^2$ then

$$V_{BE} = Vt.Ln\left(\frac{I_E}{I_S}\right) \quad \text{Where} \quad I_S = \frac{q.A.n_i^2.\overline{Dn}}{Q_B}$$

$$Q_B = W_B.N_A = 1x10^{-6}.3x10^{16} = 3x10^{10}$$

$$Is \approx \frac{1.602x10^{-19}.1x10^{-6}.(1.5x10^{10})^2.0.013}{3x10^{10}} = 1.562x10^{-17}\,A$$

$$V_{BE} = 25.8x10^{-3}.Ln\left(\frac{50x10^{-6}}{1.562x10^{-17}}\right) = 0.743V$$

$$\frac{\partial V_{BE}}{\partial T} = \frac{V_{BE} - (4+m)V_T - \frac{Eq}{q}}{T}$$

$$V_T = 25.8mV \;\; \& \;\; VBE = 0.743V$$

$$\text{Where} \quad Eq = \text{Bandgap voltage (for silicon} = 1.12eV) \;\; \& \;\; m = -\frac{3}{2}$$

$$\frac{\partial V_{BE}}{\partial T} = \frac{0.743 - \left(4 - \frac{3}{2}\right)25.8x10^{-3} - 1.11}{300} = \boxed{-1.44mV/^{\circ}K}$$

V_{PTAT} generation

The PTAT term is realised by determining the voltage difference between two forward-biased diodes (eg VBE). MOS transistors operating in the weak inversion region can also be used to form the diodes.

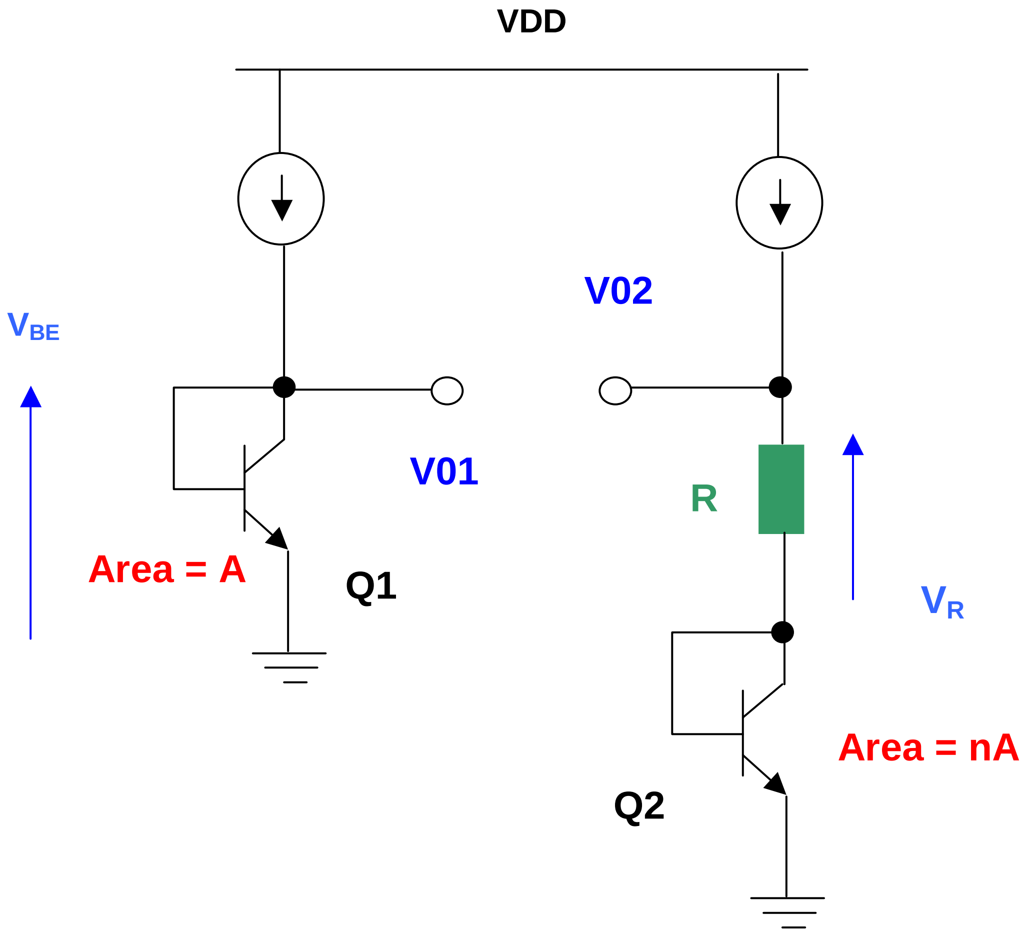


Figure 4 Generation of VPTAT voltage.

We can simulate the variation VPTAT over temperature using the ADS simulation shown in Figure 5.

If we run the same simulation again but this time on the results graph we calculate Vref given that we know vbe1 and (vbe1-vbe2). Various values of K were tried until the temperature compensation was achieved as shown in the graph of Figure 7. This now forms the basis of the band-gap reference in a practical circuit the voltage summing and setting of K is achieved using a resistive network and an op-amp.

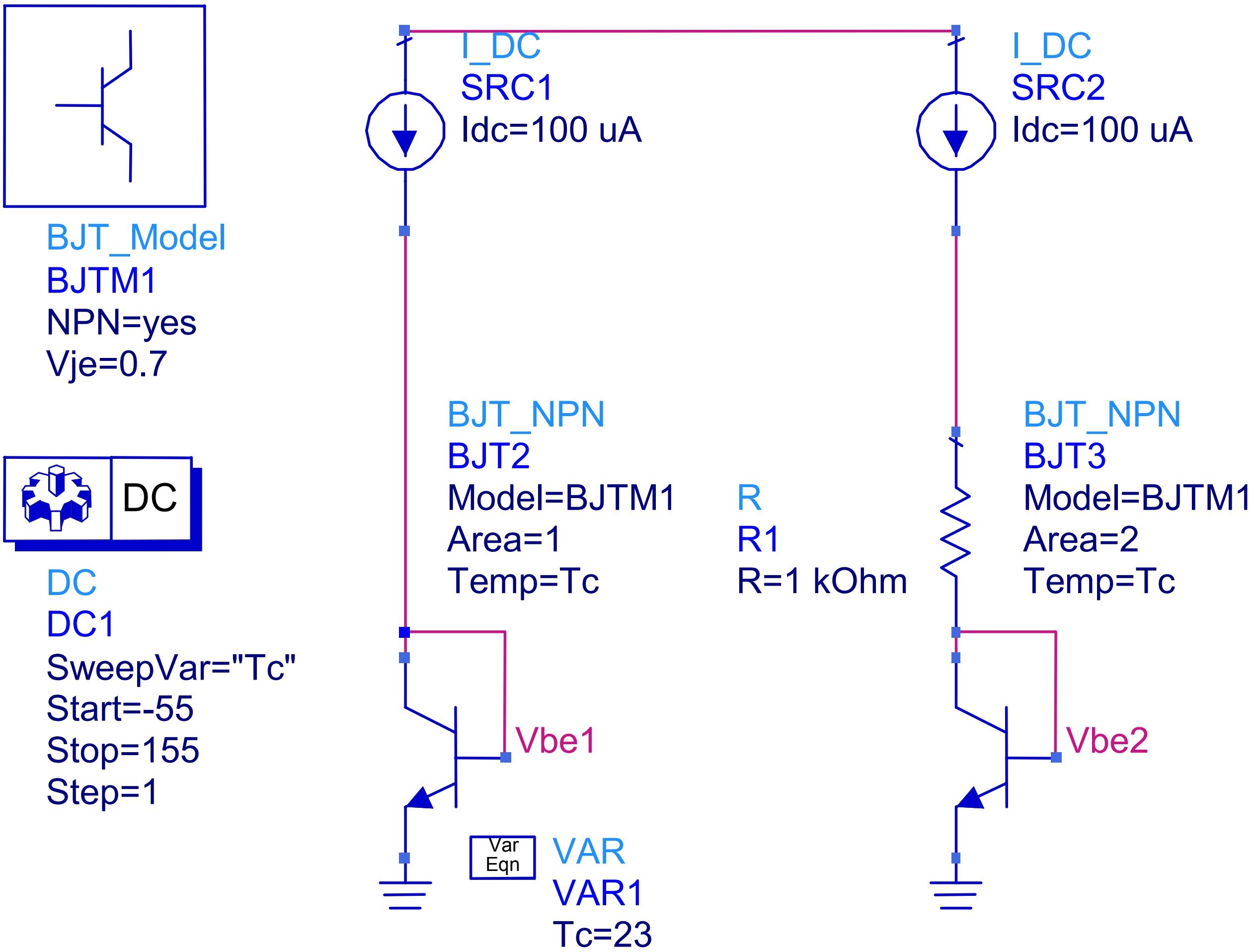
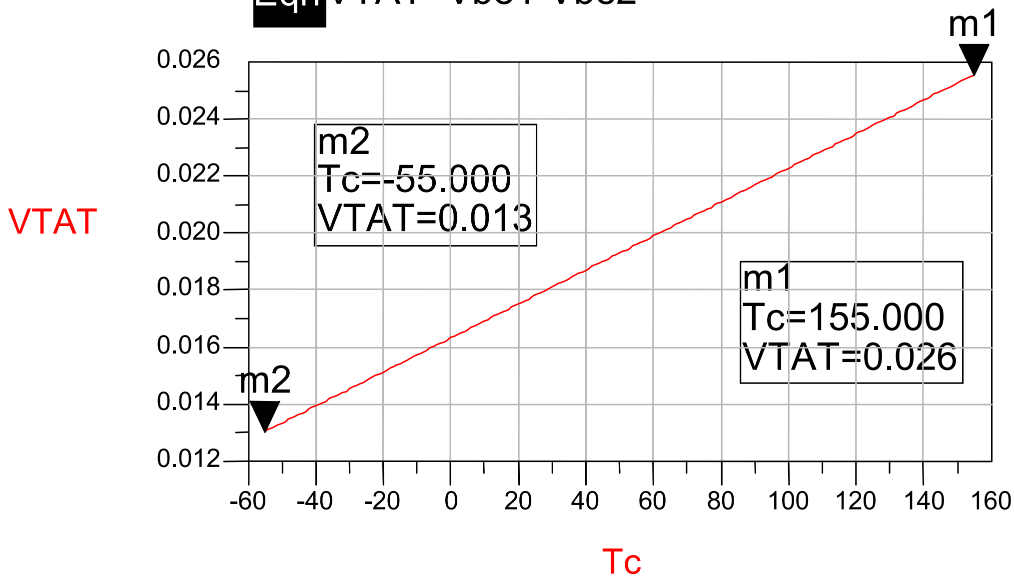


Figure 5 ADS simulation setup to analyse the variation of VPTAT over temperature. As for the previous examples the temperature is swept in the DC simulation box. The resulting plot is shown in Figure 6.

Eqn VTAT=Vbe1-Vbe2



VTAT_Temp	
0.060	mV

Eqn VTAT_Temp=1e3*(VTAT[210]-VTAT[0])/(Tc[210]-Tc[0])

Figure 6 Resulting simulation of VPTAT vs temperature after running the simulation shown in Figure 5.

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Figure 4 shows how the VPTAT voltage can be realised. If we force V01 and V02 to be the same then the voltage across the resistor R will be the difference of the two VBE's.

$$I_E = A.J_S\left(e^{\frac{q.VBE}{kT}} - 1\right) \approx A.J_S\left(e^{\frac{q.VBE}{kT}}\right) \quad \text{When } I_E > 0$$

Assume circuit is configured such that $I_{E1} = I_{E2}$ then

$$\frac{I_{E2}}{I_{E1}} = \left(\frac{A_2.J_S}{A_1.J_S}\right)e^{\frac{VBE1-VBE2}{vt}} \quad \text{Where } vt = \frac{kT}{q}$$

Assume transistors are from the same process,
such that Js and vt are the same for each device then

$$e^{\frac{VBE1-VBE2}{vt}} = \left(\frac{I_{E2}}{I_{E1}}\right)\left(\frac{A_1}{A_2}\right) = \left(\frac{A_1}{A_2}\right) \quad \text{If } I_{E1} = I_{E2}$$

$$e^{\frac{VBE1-VBE2}{vt}} = \left(\frac{A_1}{A_2}\right) \quad \text{Rearrange to give } VBE1 - VBE2 = vt.Ln\left(\frac{A_1}{A_2}\right)$$

$$\text{If } A_1 > A_2 \text{ then } VBE2 - VBE1 = Vt.Ln\left(\frac{A_1}{A_2}\right) = \Delta Vbe = I_{E1}.R1 \quad (I_{E1} = I_{E2})$$

$$\text{Let } n = \left(\frac{A_1}{A_2}\right) \quad \text{and} \quad V_T = \frac{KT}{q}$$

$$\therefore \Delta Vbe = \frac{KT}{q}.Ln(n) \quad \therefore \frac{\partial \Delta Vbe}{\partial T} = \frac{K}{q}.Ln(n) \quad \text{Using } ax^n = anx^{n-1}.\frac{dy}{dx}$$

Where

K = Boltzmanns constant = 1.3807 x 10^{-23} $J.K^{-1}$
q = charge on electron = 1.602 x 10^{-19} C
A = Area of base-emitter junction um^2

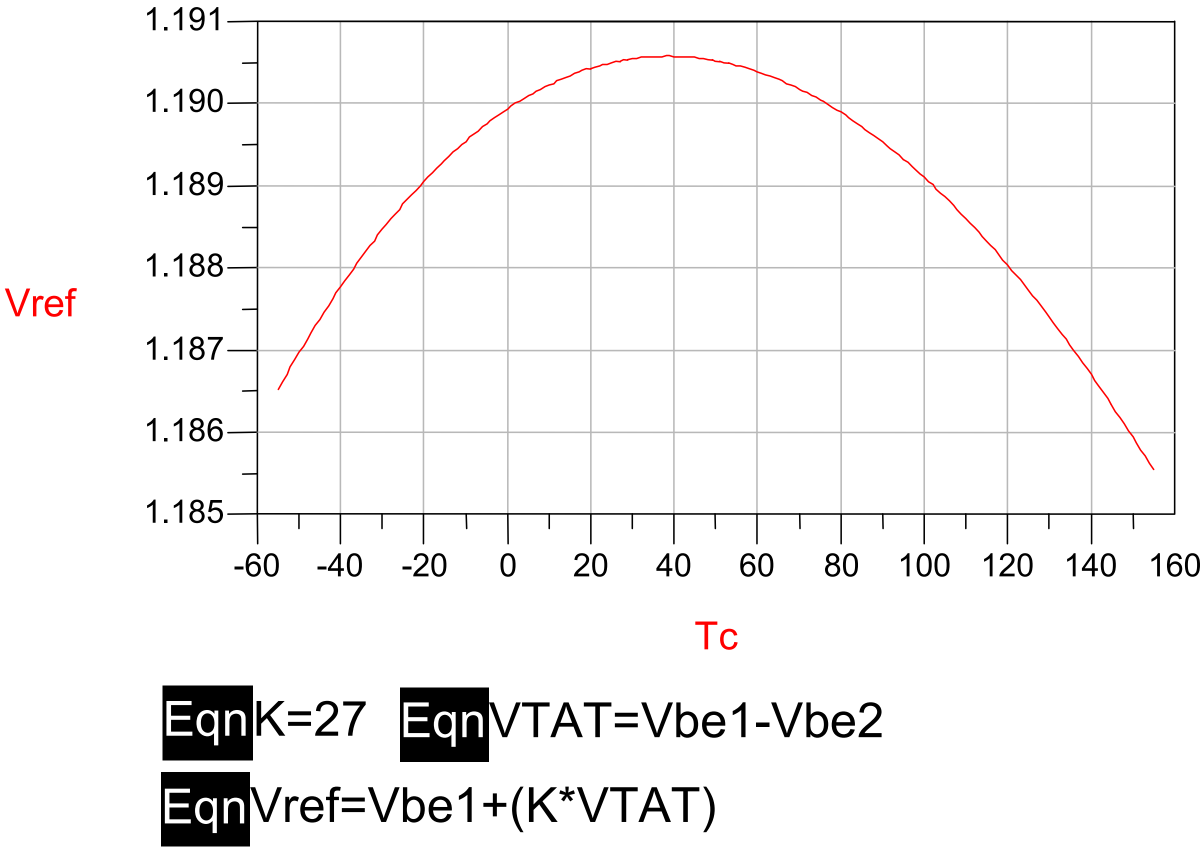

Figure 7 Graph of the simulation shown in Figure 5. In this case we have calculated VTAT ie vbe1-vbe2 and evaluated Vref from Vbe1+(K*VPTAT), where K = 27.

BandGap reference voltage

Previously we found $\Delta Vbe = V_{BE1} - V_{BE2} = \frac{KT}{q} Ln\left(\frac{J_{C1}}{J_{C2}}\right) = \frac{KT}{q} Ln\left(\frac{A_1}{A_2}\right)$

and therefore $\frac{\partial \Delta Vbe}{\partial T} = \frac{V_T}{T} Ln\left(\frac{J_{C1}}{J_{C2}}\right)$

$$\frac{\partial V_{BE}}{\partial T} = \frac{V_{BE}}{T} + \frac{V_T(4+m)}{T} + \frac{1}{q}\left[\frac{-Eg}{T}\right] = -1.44mV/^{\circ}K$$

The band-gap reference voltage is given by:-

$V_{REF} = V_{BE} + K.Vt$

The temperature stable value of V_{REF} at 300˚K is 1.262V. Therefore the value of K required is:

$$V_{REF} = V_{BE} + K.V_T \quad \text{Rearrange to get K}$$

$$K = \frac{V_{REF} - V_{BE}}{V_T} \qquad \text{With } V_{BE} = 0.743 \text{ (Calculated earlier)}$$

$$V_T = \frac{KT}{q} = \frac{1.3807 \times 10^{-23}.300}{1.602 \times 10^{-19}} = 25.8\text{mV}$$

$$K = \frac{1.262 - 0.743}{25.8\text{x}10^{-3}} = \boxed{20.11}$$

With reference to Figure 8.

The cascode current mirror makes I1 = I2 = I3

$$\text{The voltage across R} = \Delta Vbe = V_{BE2} - V_{BE1} = Vt.Ln\left(\frac{A_1}{A_2}\right) \quad \text{Let } N = \frac{A_1}{A_2}$$

$$\text{and so } I2 = \frac{Vt}{R}.Ln(N) = I1 = I3$$

$$V_{OUT} = I3.K.R + V_{BE3} \qquad \text{As } I3 = I2 \text{ sub in } I3 = \frac{Vt}{R}.Ln(N)$$

$$V_{OUT} = \frac{Vt}{R}.Ln(N).K.R + V_{BE3}$$

$$\therefore V_{OUT} = Vt.Ln(N).K + V_{BE3}$$

Assume a temperature of 23°C and that $R = 1K\Omega$; $N = 8$

$$vt = \frac{KT}{q} = \frac{1.38x10^{-23}.(273+23))}{1.602x10^{-19}} = 0.025V$$

$$I_2 = \frac{\Delta Vbe}{R1} = \frac{Vt.Ln\left(\frac{A1}{A2}\right)}{R1} = \frac{(0.025).Ln\left(\frac{8}{1}\right)}{1x10^3} = 52uA \text{ at } 23^\circ C$$

$$\text{With } \Delta\,\Delta V = Vt.Ln\left(\frac{A1}{A2}\right) = (0.025).Ln\left(\frac{8}{1}\right) = 0.0536V$$

The zero temperature coefficient reference voltage at 23°C $= 1.262V$

$$\therefore K = \frac{V_{REF} - Vbe}{V_T.Ln(N)} = \frac{1.262 - 0.63}{0.025.Ln(8)} = 10.45$$

$$\therefore K.R = 10.45K\Omega$$

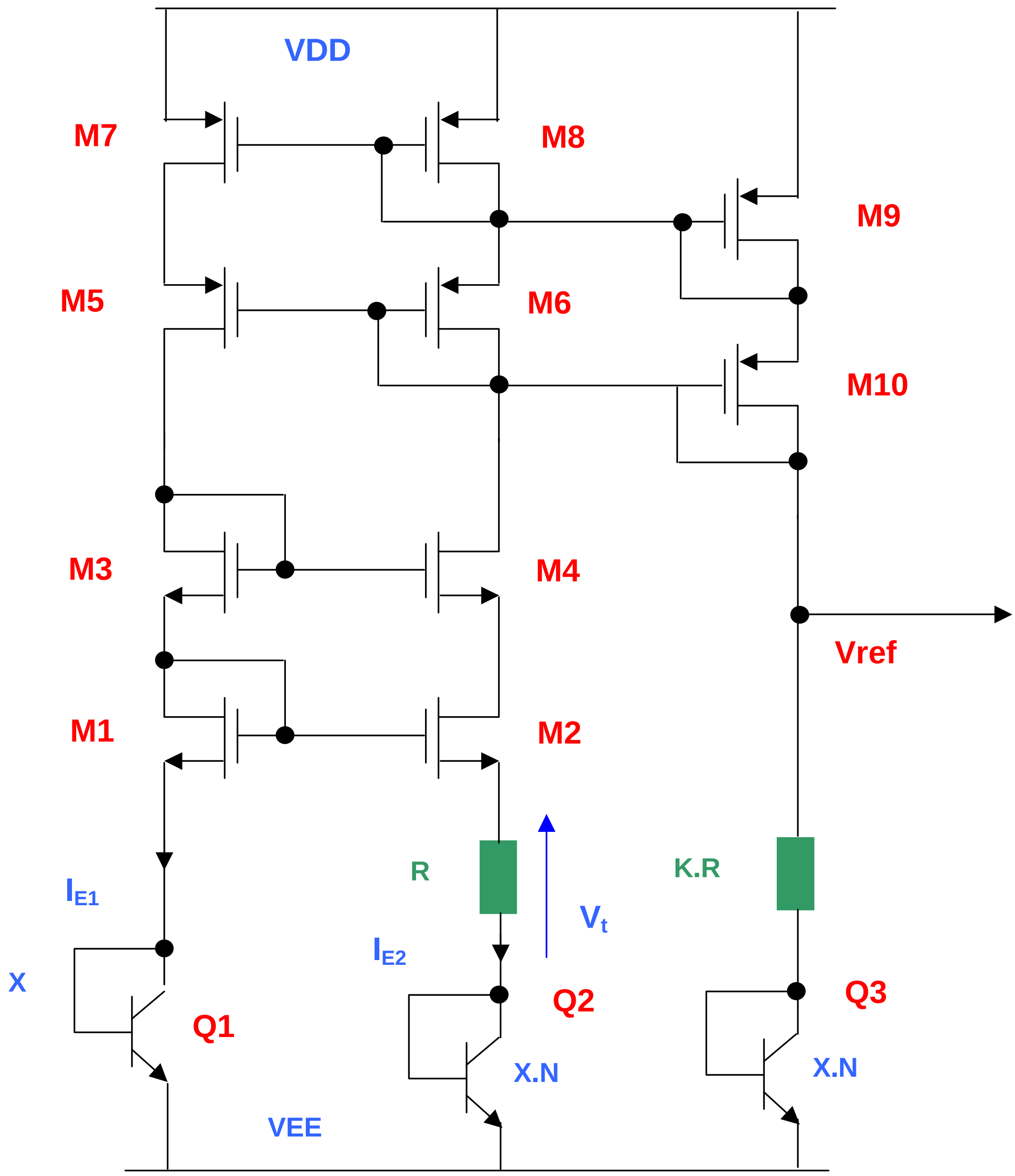

Figure 8 Circuit of the bandgap reference used in the example.

The Bandgap circuit of Figure 8 was entered as a schematic into ADS as shown in figure and analysed using a DC simulation block. For the simulation, the Temperature variable was added to the active devices and resistor and the resistor initially set to 10K was varied until the correct compensated curve resulted.

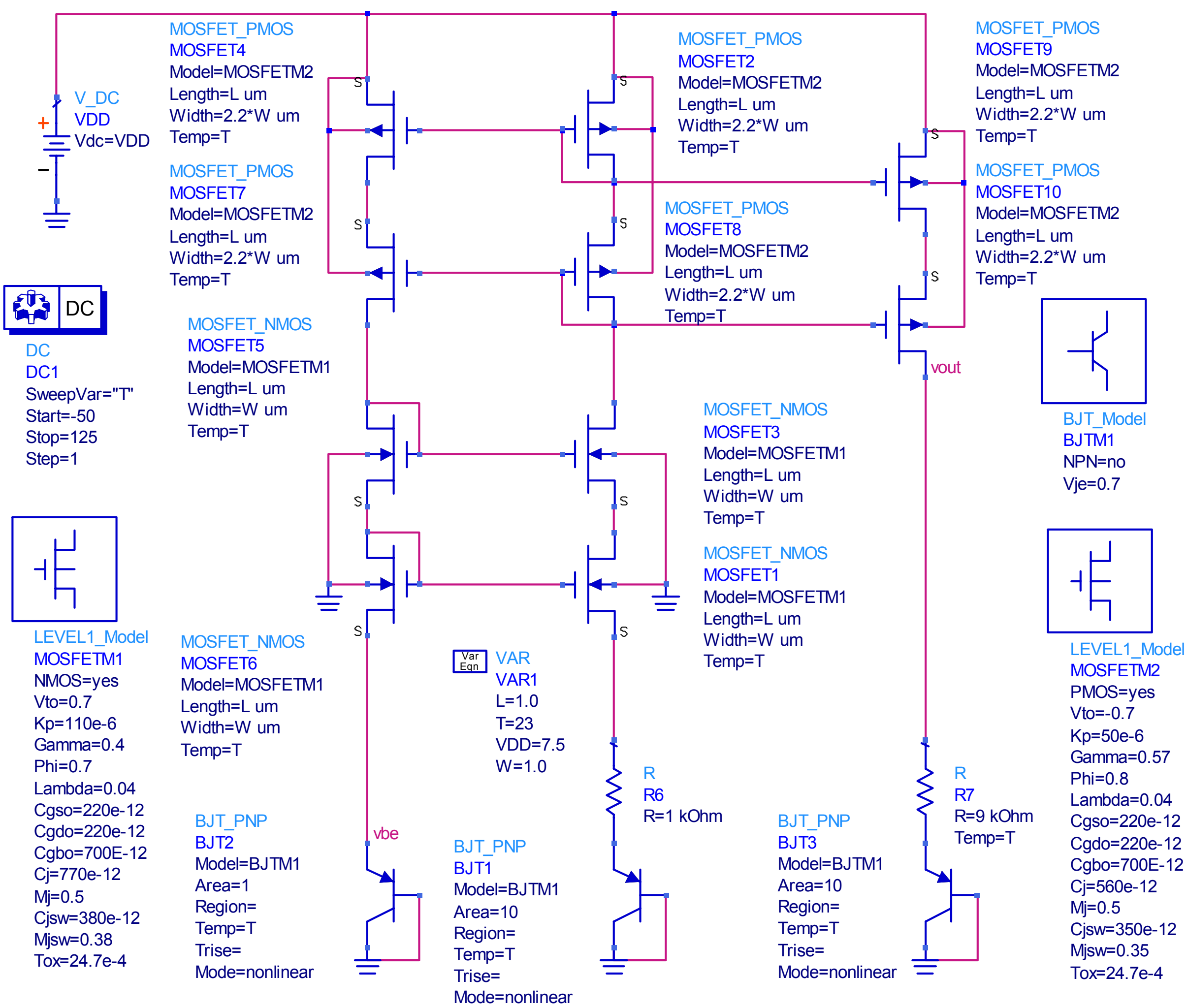

Figure 9 ADS schematic setup for analysing the bandgap example circuit. R7 was initially set to 10K (as per the hand calculations) and then varied to optimise the bandgap voltage vs temperature curve shown in Figure 10

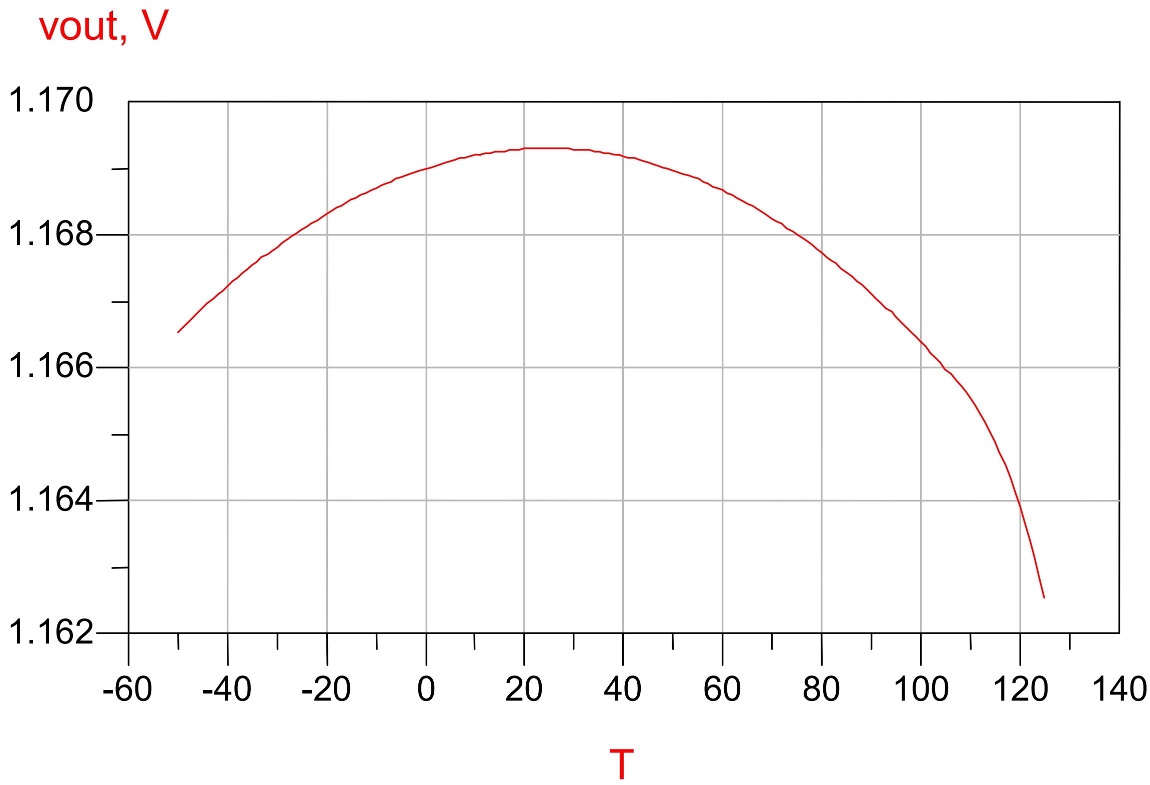

Figure 10 Resulting plot from the simulation shown in Figure 8. For this simulation the temperature parameter for the active devices and resistor was varied over the temperature range –50 to 125 deg C using the parameter sweep within the DC simulation block.

One disadvantage of the example circuit is the headroom required on the supply rails. This is because there are 4 V_{SAT}+V_T and a Vbe, resulting in the need to raise the supply from the nominal +5V to +7.5V. Lower rail circuits tend to use low supply differential op-amp circuits.