Plot the Vbe temperature profile of a CMOS process diode followed by Design a Bandgap Voltage Generator

Chris Haji-Michael
www.sunshadow.co.uk/chris.htm

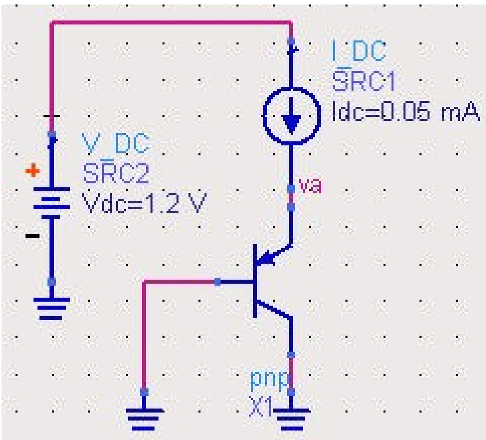
This sheet starts by calculating from the SPICE values how the VBE voltage for a lateral PNP-transistor diode (TLEV=2) varies with temperature. The results are then compared to SPICE simulation results and can be seen to be within 4mV under a variety of conditions.

The equations were found in the **ADS** manual for non linear devices.
AgilentHBT_NPN (Agilent Heterojunction Bipolar Transistor, NPN)
http://cp.literature.agilent.com/litweb/pdf/ads2003c/pdf/ccnld.pdf

Then the VBE rersults are used directly in the design of a Bandgap Voltage generator. The Bandgap is based on a paper by **Maloberti**, July 2001.

The aim of this sheet is to design a bandgap generator directly from the diode spice model. These assume TLEV=0

Define Constants



$q := 1.60217733 \cdot 10^{-19} \cdot coul$ $\mu := 10^{-6}$ $m := 10^{-3}$

$k_b := 1.380658 \cdot 10^{-23} \cdot \frac{joule}{K}$ $k := 10^{3}$

$XTI := 4.0$

$TNOM := 300 \cdot K$

$EG := 1.16 \cdot V$

$NE := 1.8$

$BF := 0.8$

$XTB := 1.25$

$IS := 10 \cdot 10^{-20} \cdot A$

$ISE := 10 \cdot 10^{-18} A$

$GAP2 := 1108K$

$GAP1 := 7.02 \cdot 10^{-4} \frac{V}{K}$

$NF := 1$

$VAR := 20 \cdot V$

$IKF := 0.0002 \cdot A$

$NK := 0.5$

$AREA := 20$

Plot Vt & Eg over Temperature

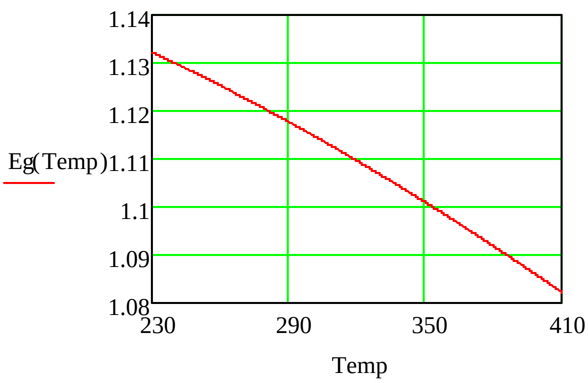
Eg is the energy bandgap page 2-51
refer page 2-39 for GAP1 and GAP2 which are called EgAlpha and EgBeta in the equations.

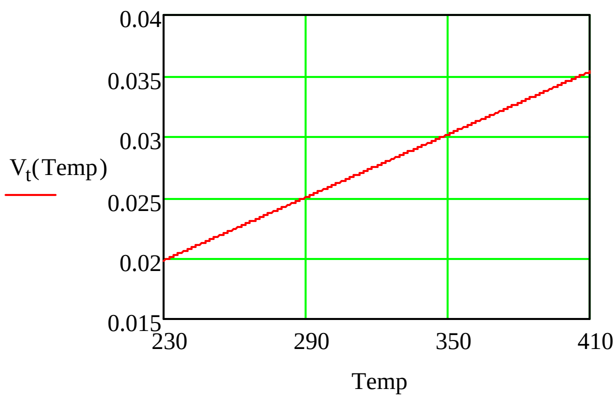
$V_t(Temp) := \frac{k_b \cdot Temp}{q}$

$Eg(Temp) := EG - \frac{GAP1 \cdot Temp^2}{Temp + GAP2}$

$V_t(300K) = 0.02585 \cdot V$

$Eg(TNOM) = 1.115 \cdot V$





Plot Ise over Temperature

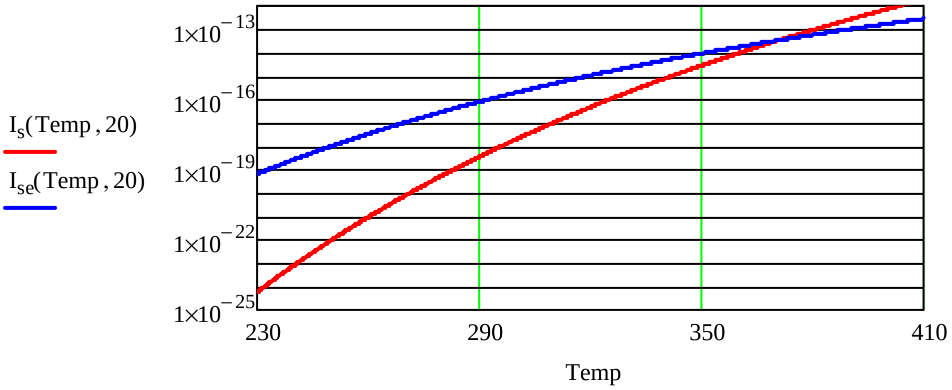
$$I_{se}(Temp, AREA) := AREA \cdot ISE \cdot \left(\frac{Temp}{TNOM}\right)^{-XTB} \cdot \exp\left(\frac{Eg(TNOM)\cdot q}{NE \cdot k_b \cdot TNOM} - \frac{Eg(Temp)\cdot q}{NE \cdot k_b \cdot Temp} + \frac{XTI}{NE} \cdot \ln\left(\frac{Temp}{TNOM}\right)\right)$$

Ise is the emitter saturation current, refer page 2-51 which varies with temperature

Plot Is over Temperature

$$I_s(Temp, AREA) := AREA \cdot IS \cdot \exp\left(\frac{Eg(TNOM)\cdot q}{k_b \cdot TNOM} - \frac{Eg(Temp)\cdot q}{k_b \cdot Temp} + XTI \cdot \ln\left(\frac{Temp}{TNOM}\right)\right)$$

Is the source sauruation current, refer page 2-51 which varies with temperature

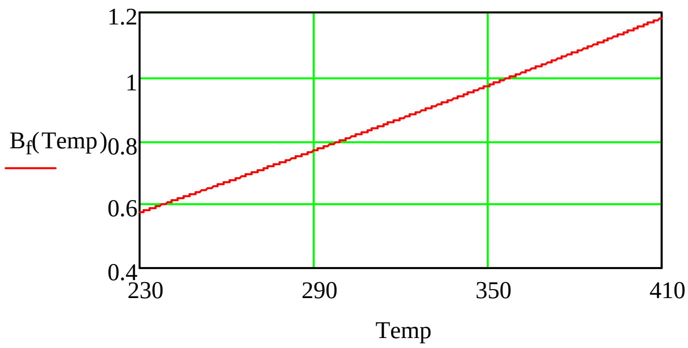


Plot Bf and Q over Temperature

$$B_f(Temp) := BF \cdot \left(\frac{Temp}{TNOM}\right)^{XTB}$$

Bf is the transitor beta or current gain and is usually around 100. In this design the Bf is very low because of the type of transistor

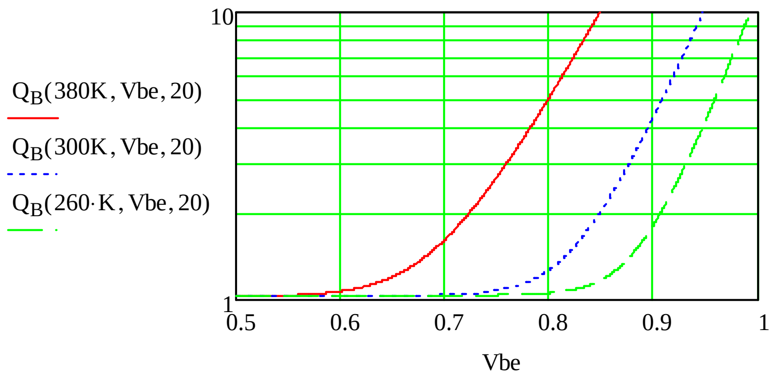
This section looks as though there is an approximation to the equations. These are made because the Bf is low as this is a lateral PNP



$$I_{bei}(Temp, V_{be}, AREA) := I_s(Temp, AREA) \cdot \left(e^{\frac{V_{be}}{NF \cdot V_t(Temp)}} - 1\right)$$

$$I_{ben}(Temp, V_{be}, AREA) := I_{se}(Temp, AREA) \cdot \left(e^{\frac{V_{be}}{NE \cdot V_t(Temp)}} - 1\right)$$

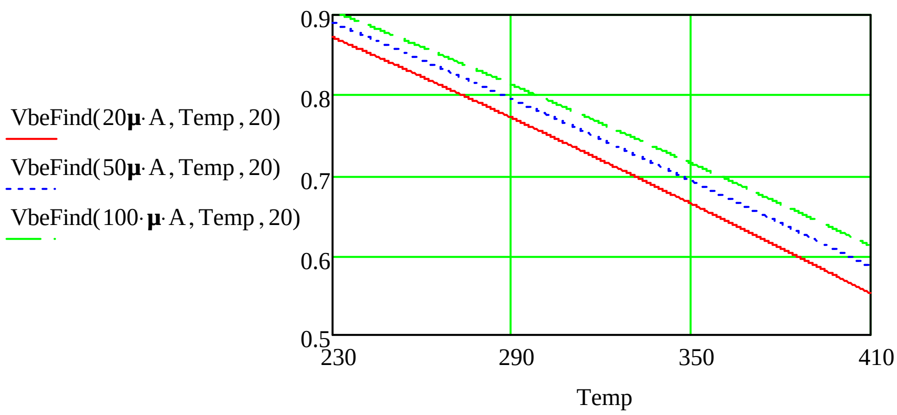
$$Q1(V_{be}) := \frac{1}{1 - \frac{V_{be}}{VAR}} \qquad Q_B(Temp, V_{be}, AREA) := \frac{Q1(V_{be})}{2} \cdot \left[1 + \left[1 + 4 \cdot \left(\frac{I_{bei}(Temp, V_{be}, AREA)}{IKF}\right)\right]^{NK}\right]$$



Find Ib for Vbe and Temperature

$V_{be} := 0.8V$ Given $I_e = \frac{I_{bei}(Temp, V_{be}, Area)}{B_f(Temp)} + I_{ben}(Temp, V_{be}, Area) + \frac{I_{bei}(Temp, V_{be}, Area)}{Q_B(Temp, V_{be}, Area)}$

$VbeFind(I_e, Temp, Area) := Find(V_{be})$



$VbeFind(50\cdot\mu A, 270K - 40K, 20) = 0.89073\cdot V$

$VbeFind(50\cdot\mu A, 300K, 20) = 0.77813\cdot V$

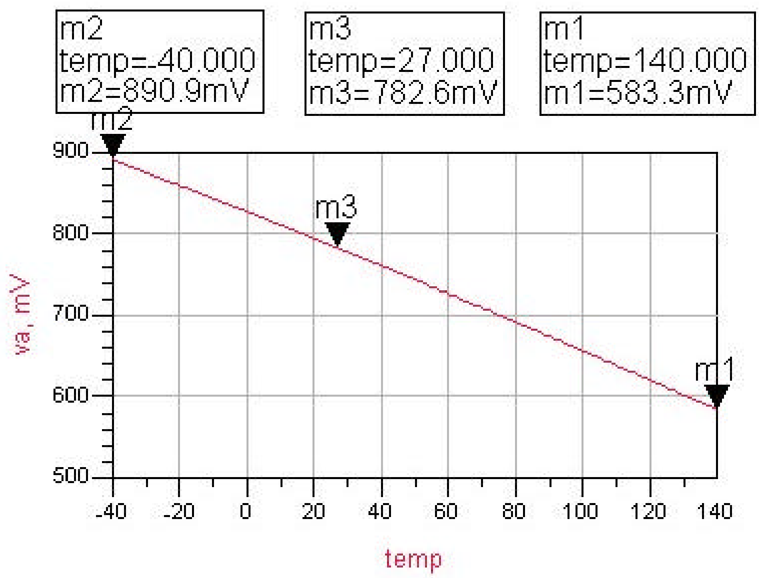
$VbeFind(50\cdot\mu A, 270K + 140K, 20) = 0.58522\cdot V$

Test the Vbe response the diode using a Spice simulator

The plot shown here on the right is from ADS for the diode circuit shown at the top of the sheet.

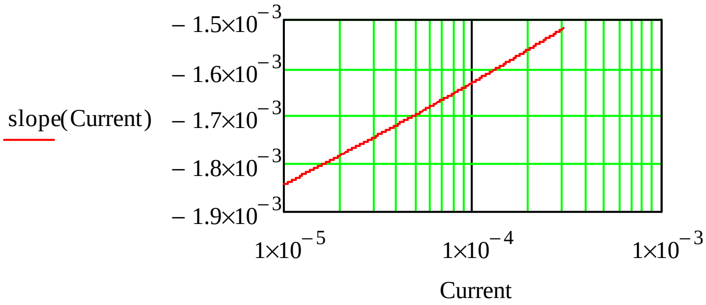
Ibias is 50uA.

This graph should be compared to the graph above.



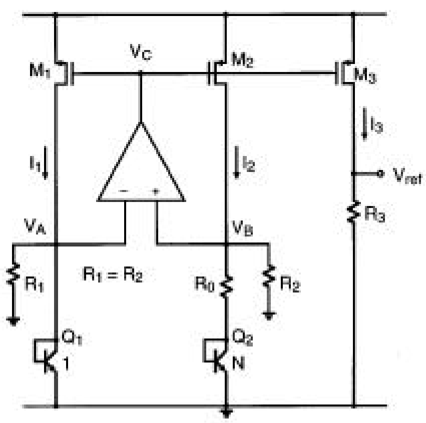
Calculate slope for Vbe against Temperature at different currents

$$\text{slope}(\text{Current}) := \frac{\text{VbeFind}(\text{Current}, 410\cdot K, 20) - \text{VbeFind}(\text{Current}, 230\cdot K, 20)}{410K - 230K}$$



$$\text{slope}(50\mu\cdot A) = -1.697\cdot\frac{mV}{K}$$

Design a Bandgap Voltage Reference



The diode response can now be used to design a bandgap voltage reference. The circuit used here is from Maloberti, Curvature Compensated BiCMOS bandgap with 1V supply voltage. IEEE solid state July 2001.

Vbe has a negative temperature coefficient.
Vt has a positive temperature coefficient.
Start by calculating the Vbe to Vt ratio = **G**
Set I1 = 2*Iq1

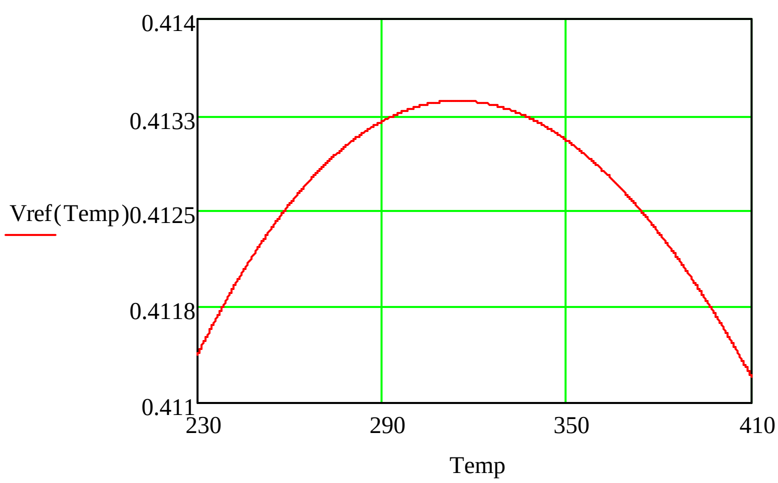
$I_{q1} := 50\cdot\mu\cdot A$ $N := 16$ $\text{VrefRequired} := 0.5V$

$$Vt(N) := \frac{\left[\begin{array}{l}\left(\text{VbeFind}(I_{q1}, 410\cdot K, 20) - \text{VbeFind}(I_{q1}, 410\cdot K, 20\cdot N)\right) \ldots \\ + -\left(\text{VbeFind}(I_{q1}, 230\cdot K, 20) - \text{VbeFind}(I_{q1}, 230\cdot K, 20\cdot N)\right)\end{array}\right]}{(410\cdot K - 230\cdot K)}$$

$\text{Vbs} := -\text{slope}(I_{q1})$ $G(N) := \dfrac{\text{Vbs}\cdot\ln(N)}{Vt(N)}$

$R1 := \dfrac{\text{VbeFind}(I_{q1}, \text{TNOM}, 20)}{I_{q1}}$ $R0 := \dfrac{R1\cdot\ln(N)}{G(N)}$ $R3 := \dfrac{\text{VrefRequired}}{2\cdot I_{q1}}$

$$\text{Vref}(\text{Temp}) := V_t(\text{Temp})\cdot\left(\frac{R3\cdot\ln(N)}{R0}\right) + \text{VbeFind}(I_{q1}, \text{Temp}, 20)\cdot\left(\frac{R3}{R1}\right)$$



$Vt(15) = 234\cdot\dfrac{\mu\cdot V}{K}$

$G(16) = 19.661$

$R3 = 5.00\cdot k\cdot ohm$

$R0 = 2.2\times 10^{3}\cdot ohm$

$R1 = 15.563\times 10^{3}\cdot ohm$

The bandgap reference is simulated using ADS with the circuit shown below. Apologies for not getting the component numbering to be the same.

R0 which is shown as R1 below is adjusted to get an optimised response. It is theoretically 2.2k and simulates to be 2.33k.

This is close enough for me, enjoy.