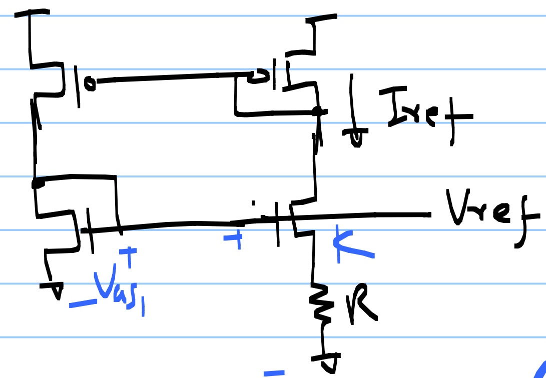
ECE 5411 : Lecture 25.

Note Title 5/2/2011



$$I_{ref} = \frac{2}{\beta R_s^2}\left(1 - \frac{1}{\sqrt{K}}\right)^2$$

$$V_{ref} = \frac{2}{R_s \beta}\left(1 - \frac{1}{\sqrt{K}}\right) + V_{THN}$$

← indep of V_{DD}

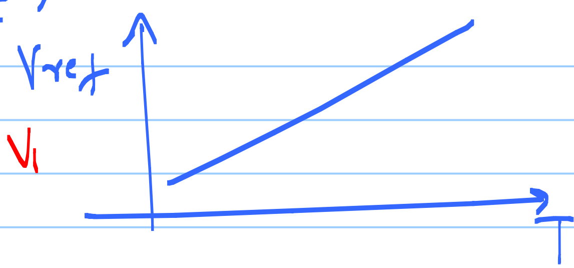
ZTC

$$\frac{\partial V_{ref}}{\partial T} = \left(\frac{\partial V_{THN}}{\partial T}\right) - \frac{2}{\beta R_s}\left(1 - \frac{1}{\sqrt{K}}\right)\left[\frac{1}{R_s}\frac{dR_s}{dT} + \underbrace{\left(\frac{1}{KP_n}\frac{\partial KP_n}{\partial T}\right)}_{-\frac{3/2}{T}}\right] = 0$$

$\frac{W}{L}$, R_s ⇒ $\frac{\partial V_{ref}}{\partial T} = 0$

→ Not practical

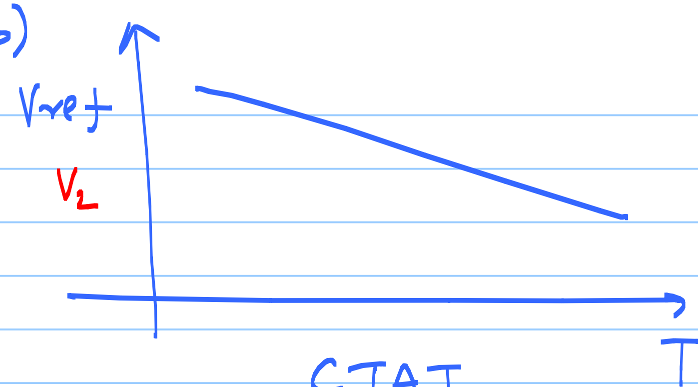
(a)



PTAT

proportional to Absolute Temp

(b)



CTAT

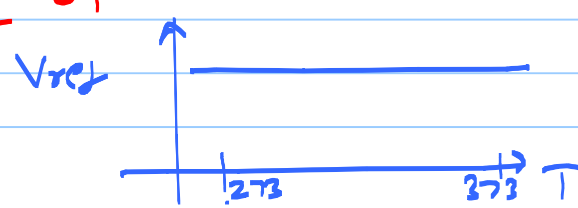
Complementary

(c) $V_{ref} = \alpha_1 V_1 + \alpha_2 V_2$

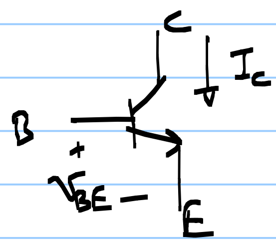
$$\frac{\partial V_{ref}}{\partial T} = \alpha_1 \frac{\partial V_1}{\partial T} + \alpha_2 \frac{\partial V_2}{\partial T} = 0$$

Zero temp Co

(ZTC)



① CTAT (Negative TC reference)



Collector current

$$I_c = I_s e^{\frac{n V_{BE}}{V_T}} \triangleq I_s e^{\frac{V_{BE}}{V_T}}$$

$\beta = \frac{i_c}{i_B} = \infty$

$\underline{\underline{n = 1}}$

$V_T \rightarrow \frac{kT}{q} = 26\,mV$

$$\Rightarrow \quad I_c = \underline{\underline{I_s}} e^{\frac{V_{BE}}{V_T}}, \rightarrow ①$$

$I_s \propto \mu k T n_i^2$

$\rightarrow n_i^2 \propto T^3 e^{-E_g/kT}$

$\rightarrow \mu \propto T^m$

$m = -3/2$

$E_g = 1.12\,eV$ for S_i

$$\Rightarrow \boxed{I_s = b\, T^{(4+m)} e^{-E_g/kT}} \rightarrow ②$$

from ①

$$\longrightarrow V_{BE} = V_T \ln\left(\frac{I_c}{I_s}\right) \qquad \underline{\underline{n = 1}}$$

$$\underline{\underline{\frac{\partial V_{BE}}{\partial T}}} = \frac{\partial V_T}{\partial T} \ln\left(\frac{I_c}{I_s}\right) - \underbrace{\frac{V_T}{I_s} \cdot \left(\frac{\partial I_s}{\partial T}\right)} \longrightarrow ③$$

$$* \quad \frac{\partial I_s}{\partial T} = \frac{(4+m)}{T} I_s + I_s \cdot \frac{E_g}{kT^2}$$

$$* \quad \frac{V_T}{I_s} \cdot \frac{\partial I_s}{\partial T} = (4+m) \frac{V_T}{T} + \frac{E_g}{kT^2} \cdot V_T \longrightarrow ④$$

from ③ & ④

$$\frac{\partial v_{BE}}{\partial T} = \frac{v_T}{T}\ln\left(\frac{I_c}{I_s}\right) - (4+m)\frac{v_T}{T} - \frac{E_g}{kT^2}\cdot v_T$$

CTAT

$$\Rightarrow \boxed{\frac{\partial v_{BE}}{\partial T} = \frac{v_{BE} - (4+m)v_T - E_g/q}{T}} \rightarrow 5$$

TC of v_{BE} has a dependence on v_{BE} itself & T with $v_{BE} = 0.75V$, $T = 300^{\circ}K$

$$\frac{\partial v_{BE}}{\partial T} \simeq -1.5 \frac{mV}{^{\circ}K}$$

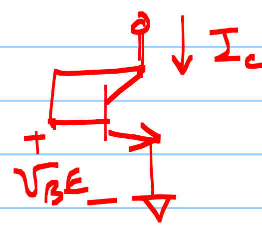
Since $TC_{v_{BE}} \longrightarrow f(v_{BE}, T)$

↳ not a linear CTAT

↳ can't make a perfect ZTC reference

v_{BE}

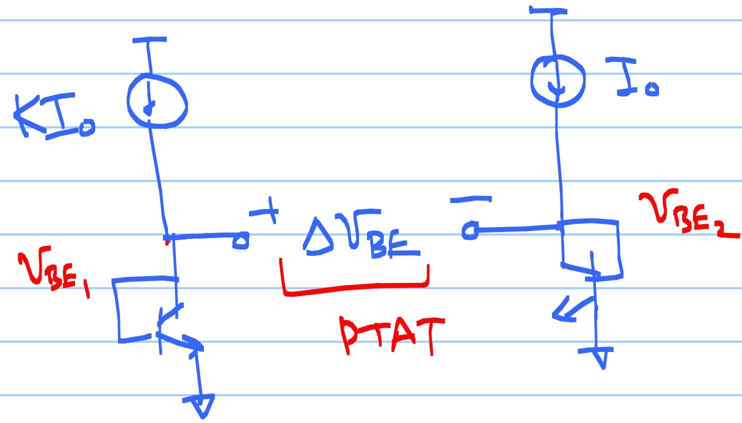
has some curvature



v_{BE} itself is a CTAT.

② PTAT reference (+ve TC)

Two BJT's operating at unequal currents



$$V_1 = V_T \ln(I_1)$$

$$(V_1 - V_2) = \underbrace{V_T}_{} \ln\left(\frac{I_1}{I_2}\right)$$

$$V_T = \frac{kT}{q}$$

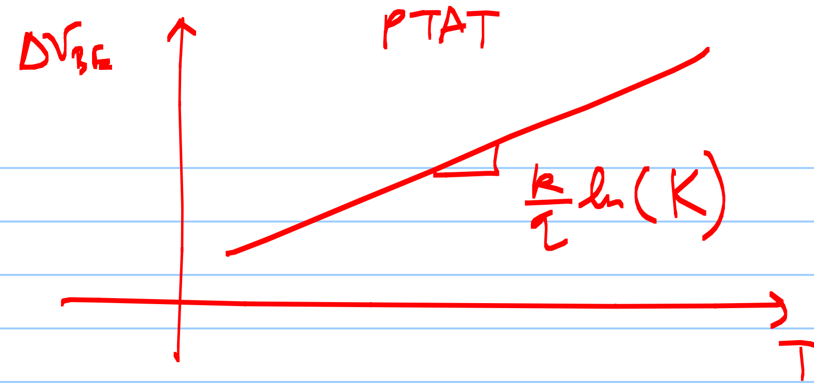
PTAT

$$\Delta V_{BE} = V_{BE_1} - V_{BE_2}$$

$$= V_T \ln\left(\frac{KI_0}{I_{S_1}}\right) - V_T \ln\left(\frac{I_0}{I_{S_2}}\right) \quad , \quad \text{for } I_{S_1} = I_{S_2}$$

$$= V_T \ln(K)$$

$$\Rightarrow \boxed{\frac{\partial \Delta V_{BE}}{\partial T} = \frac{k}{q}\ln(K)}$$



Bandgap Reference:

Let's combine the CTAT & PTAT developed above.

$$V_{ref} = \alpha_1 \underbrace{V_{BE}}_{CTAT} + \alpha_2 \big(\underbrace{V_T \ln(K)}_{\substack{\Delta V_{BE12} \\ PTAT}}\big)$$

$$TC_{V_{ref}} = 0 \Rightarrow \alpha_1 \frac{\partial V_{BE}}{\partial T} + \alpha_2 \left(\frac{k}{q} \ln(K)\right) = 0$$

$$\alpha_2 \ln(K) = \frac{-\alpha_1 \left(\frac{\partial V_{BE}}{\partial T}\right)}{(k/q)}$$

-1.5 mV/K

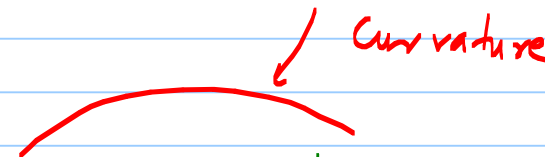
$+0.087 \text{ mV/K}$

$$= \alpha_1 \times 17.2$$

Let $\alpha_1 = 1 \Rightarrow$

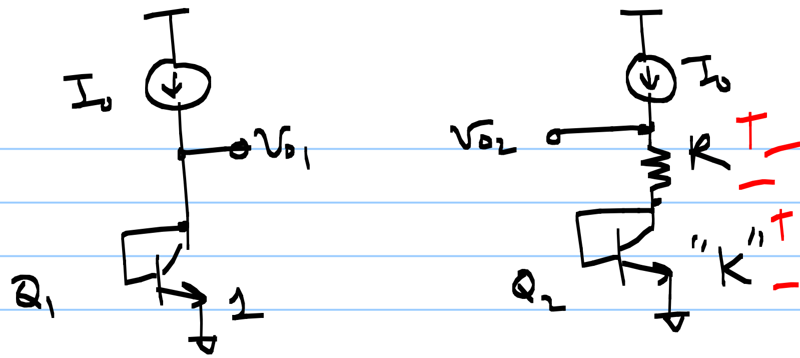
$$\underbrace{\alpha_2 \cdot \ln(K)}_{} = 17.2$$

$$\Rightarrow \quad v_{Ref} = v_{BE} + 17.2 \times v_T$$



* Curvature correction circuits

$\beta \to \infty$



$\to V_T \ln(K)$ (PTAT)

$\to V_{BE_2}$ (CTAT)

for a $\quad V_{o1} = V_{o2}$

$$\Rightarrow \quad V_{BE_1} = IR + V_{BE_2}$$

$$\Rightarrow \quad IR = V_{BE_1} - V_{BE_2}$$

$$= V_T \ln\left(\frac{I_o}{I_s}\right) - V_T \ln\left(\frac{I_o/K}{I_s}\right)$$

$$= V_T \ln(K)$$

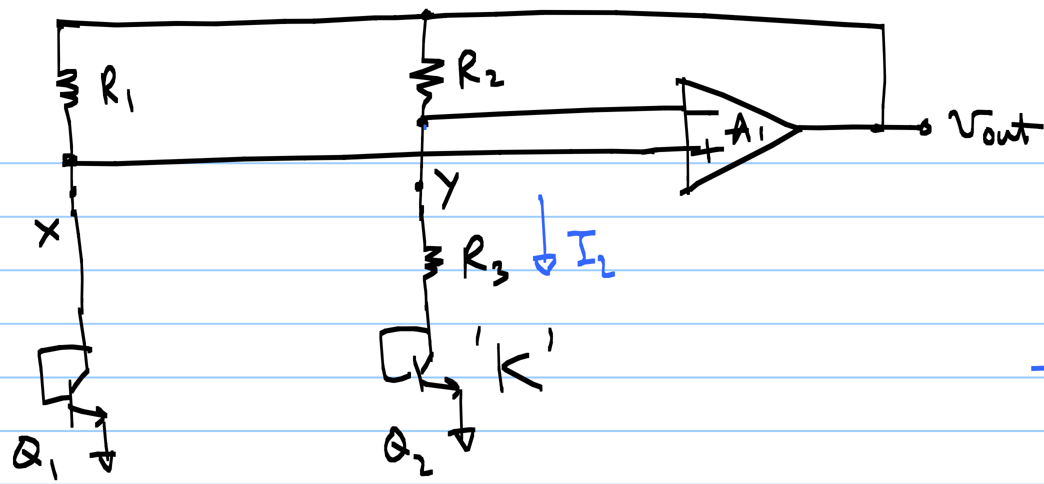
$v_{o_2} = v_{BE_2} + v_T \ln(K)$ ← can act like a ZTC reference

$$\frac{\partial v_{o_2}}{\partial T} = \frac{\partial v_{BE_2}}{\partial T} + \left(\frac{k}{q}\right)\ln(K)$$

$\alpha_1 = \alpha_2 = 1$

$$\cancel{\alpha_2}^{1} \ln(K) = 17.2$$

$$K = e^{17.2}$$ ← impractical !



$= V_{ref}$

$R_1 = R_2$

$$I_2 = \frac{V_T \ln(K)}{R_3}$$

$$V_{out} = V_{BE_2} + (R_2 + R_3) I_2$$

$$= \underbrace{1}_{\alpha_1} \cdot \underbrace{V_{BE_2}}_{} + \underbrace{\left(1 + \frac{R_2}{R_3}\right)}_{\alpha_2} \cdot \underbrace{V_T \ln(K)}_{}$$

$$= V_{BE_2} + 17.2 \cdot V_T$$

$TC = 0$

$$\left(1 + \frac{R_2}{R_3}\right) \ln(K) = 17.2$$

$$\Rightarrow \quad K = 31 \quad \& \quad \frac{R_2}{R_3} = 4$$

* why it is called BGR ?

$\alpha_1 = \alpha_2 = 1$

$$V_{REF} = V_{BE} + V_T \ln(k)$$

$$\frac{\partial V_{REF}}{\partial T} = \frac{\partial V_{BE}}{\partial T} + \frac{V_T}{T}\ln(k) = 0 \qquad ZTC$$

$$\frac{V_{BE} - (4+m)V_T - E_g/q}{T} = -\frac{V_T}{T}\ln(k)$$

$$\Rightarrow V_{ref} = \frac{E_g}{q} + (4+m)V_T \leftarrow$$

ZTC voltage $\rightarrow \frac{E_g}{q}$ (Band gap voltage for Si) $\simeq 1.12$ V

$\rightarrow \underline{\underline{m}}$ & V_T

as $T \to 0 \Rightarrow V_{ref} \longrightarrow \dfrac{E_g}{q} \Rightarrow$ "Bandgap Reference"

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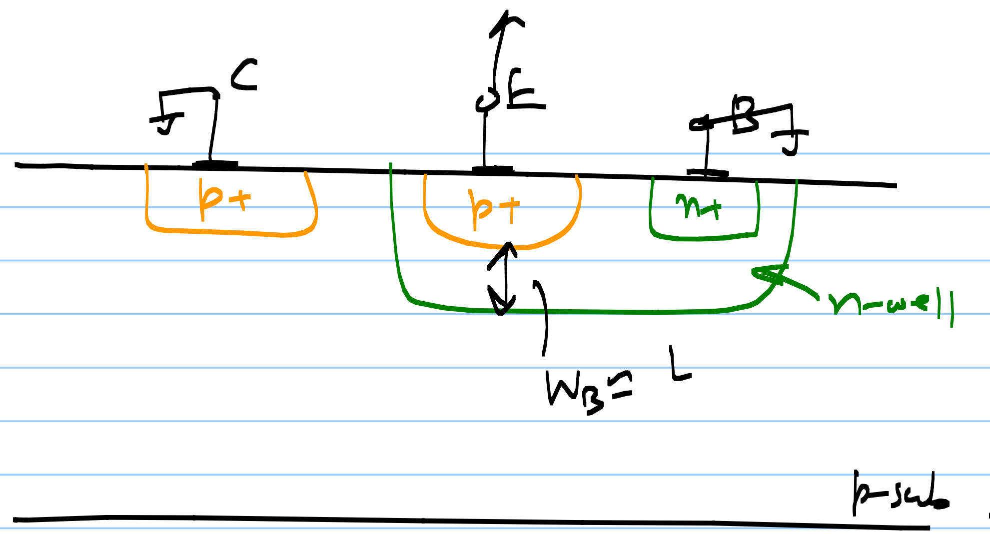
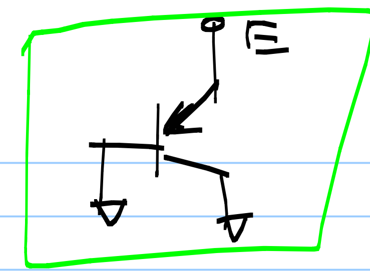
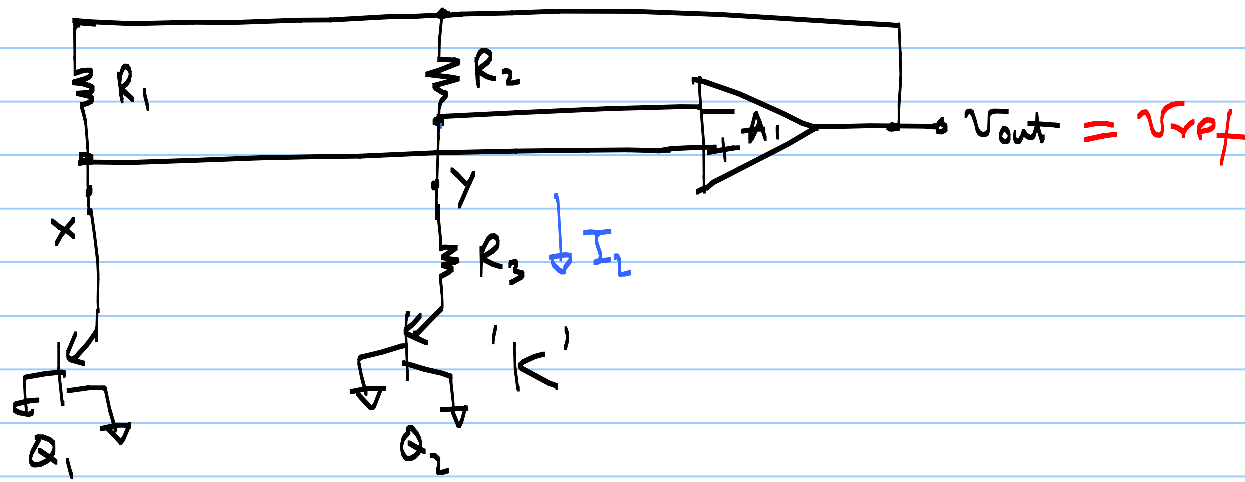


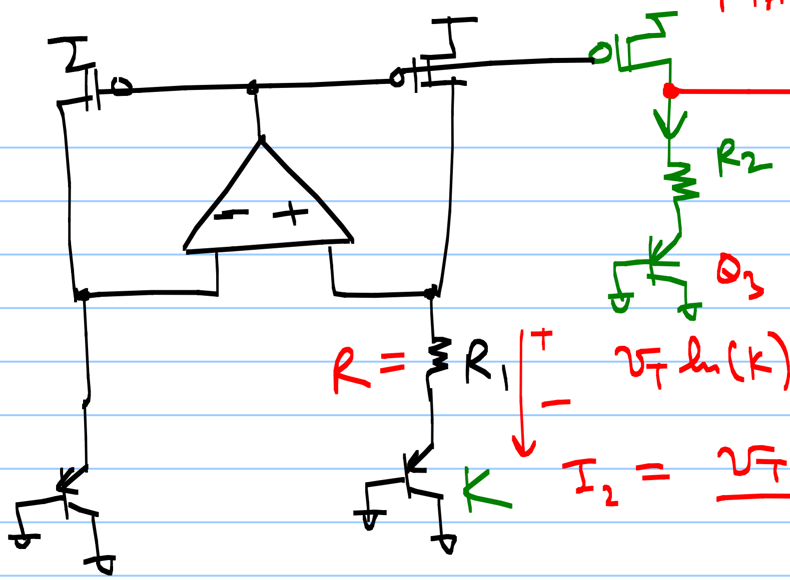


"Vertical PNP BJT"



R_1
R_2
A_1
V_{out} = V_{ref}
X
Y
R_3
I_2
'K'
Q_1
Q_2

PTAT current



$$v_{ref} = v_{BE_3} + v_T \ln K \cdot \left(\frac{R_2}{R_1}\right)$$

$$= v_{BE_3} + v_T \cdot \underbrace{L}_{\alpha_2} \cdot \ln(K)$$

$$I_2 = \frac{v_T \ln(K)}{R_1}$$

$$I_2 = \frac{v_T \ln(K)}{\cancel{R_1}} \quad \cancel{R}$$

PTAT current