ECE 511 - Lecture 28

Note Title 5/9/2013

CTAT PTAT

$$V_{ref} = \alpha_1 V_{BE} + \alpha_2 \left(V_T \ln k \right)$$

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

We want $\frac{\partial V_{ref}}{\partial T} = 0$

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

$$\Rightarrow \alpha_2 \ln(k) = - \frac{\alpha_1 \cdot \frac{\partial V_{BE}}{\partial T}}{k/q} = 17.2\, \alpha_1$$

$\frac{\partial V_{BE}}{\partial T}$: $-1.5\,mV/°K$

k/q: $0.087 \frac{mV}{°K}$

choose $\alpha_1 = 1$

$\alpha_2 \ln k = 17.2$

$\Rightarrow V_{REF} = V_{BE} + 17.2\, V_T$

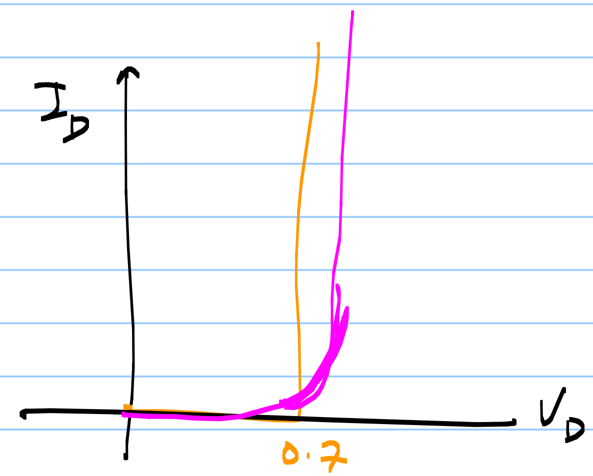
$\simeq 0.75 + 17.2 \times 26\,mV$

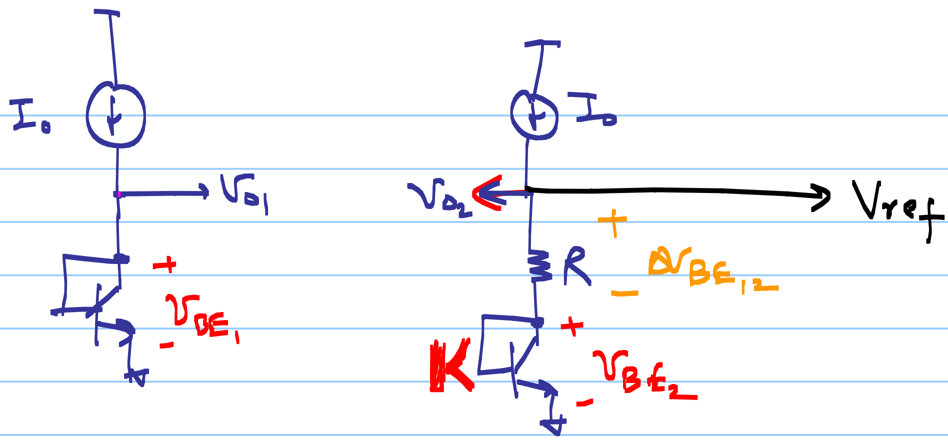
$-\Delta V \qquad \Delta V$

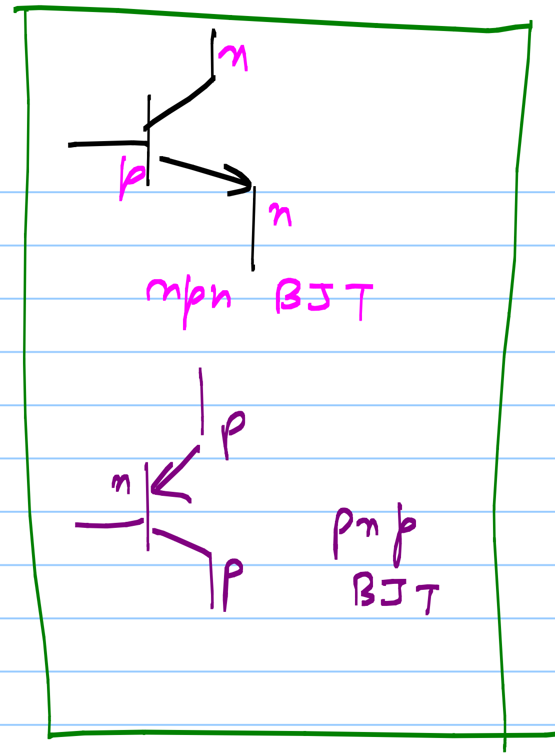
$= 1.2\,V$

$I_1 \rightarrow V_{BE} \rightarrow \frac{\partial V_E}{\partial T} \neq -1.5 \frac{mV}{K}$

α_1, α_2







If we somehow force $V_{o1} \stackrel{\Delta}{=} V_{o2}$

$$V_{BE_1} = V_{BE_2} + I_o R$$

$$I_o R = V_{BE_1} - V_{BE_2} = V_T \ln K \longrightarrow (1)$$

$$v_{G_2} = V_{BE_2} + I_o R$$

↓

$$V_{REF} = \underbrace{V_{BE_2}}_{CTAT} + \underbrace{V_T \ln K}_{PTAT}$$

we can find a value for K s.t.

$$\frac{\partial V_{REF}}{\partial T} = 0$$

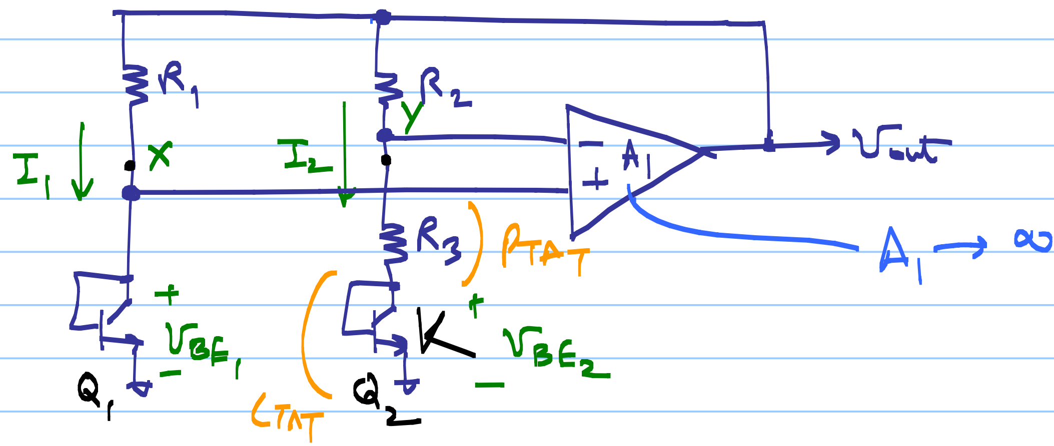
Here, $\alpha_1 = \alpha_2 = 1$

$$\alpha_2 \ln k = 17.2$$

$$\Rightarrow k = e^{17.2}$$ ← Impractical

Need to introduce $\alpha_2 > 1$

"Need a Suitable Start-up Circuit"



Let $R_1 = R_2$, force $V_x = V_y$ using feedback

$$v_{BE_1} - v_{BE_2} = v_T \ln K$$

$$\Rightarrow \boxed{I_2 = \frac{v_T \ln K}{R_3}}$$

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

$$= V_{BE_2} + \frac{V_T \ln k}{R_3} (R_2 + R_3)$$

$$= \underbrace{V_{BE_2}}_{CTAT} + \underbrace{\left(1 + \frac{R_2}{R_3}\right)}_{\alpha_2} \underbrace{V_T \ln k}_{PTAT}$$

$\alpha_1 = 1$

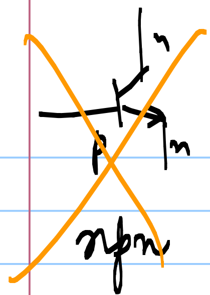
$\alpha_2 = 1 + \frac{R_2}{R_3}$

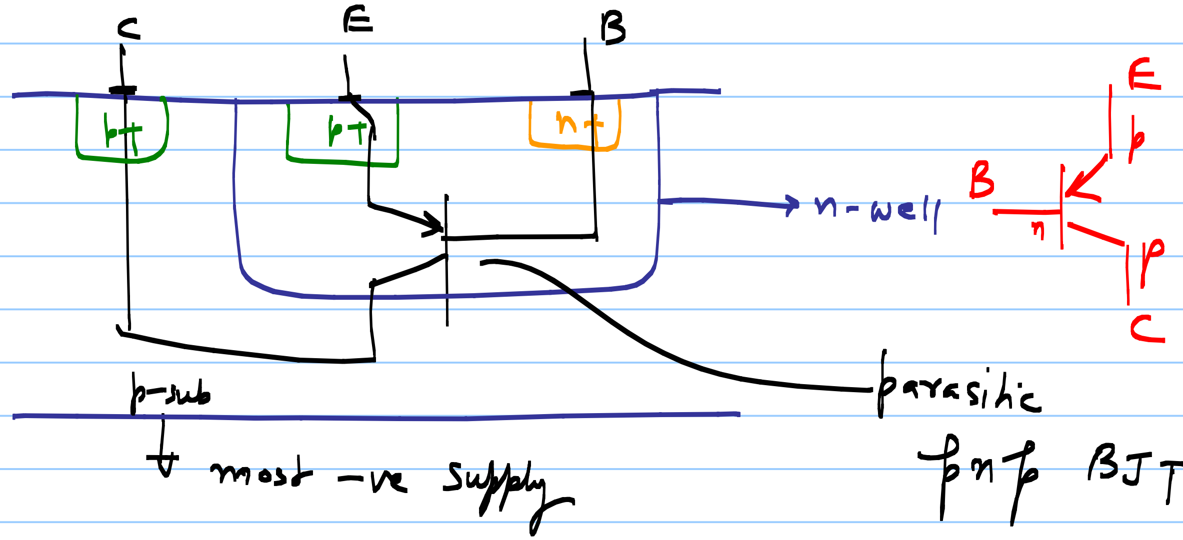
for $TC = 0$,

$$\overbrace{\left(1 + \frac{R_2}{R_3}\right)}^{\alpha_2} \ln k = 17.2$$

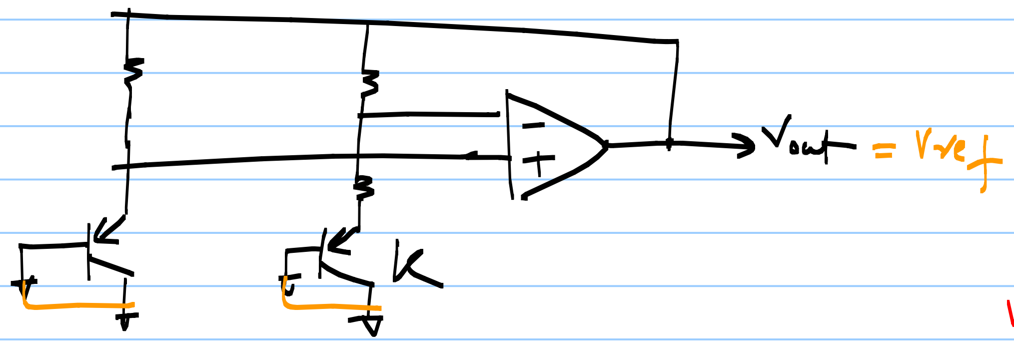
Several solutions (R_2, R_3, k)

Example: $k = 31$, $\frac{R_2}{R_3} = 4$ ☆



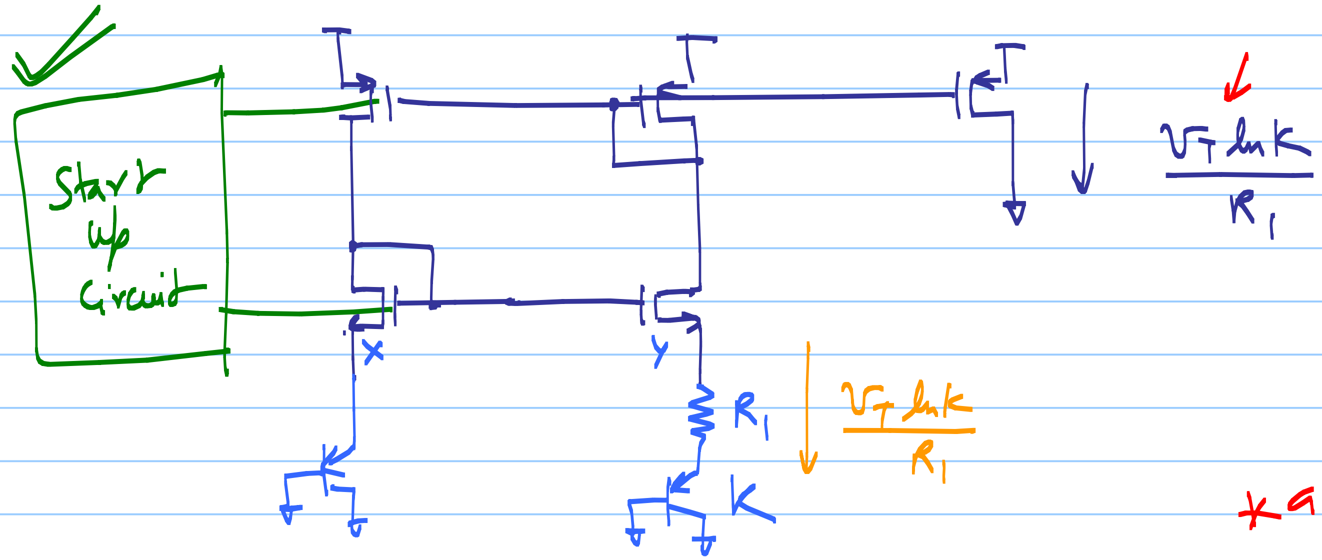


Redraw the BGR for CMOS implementation



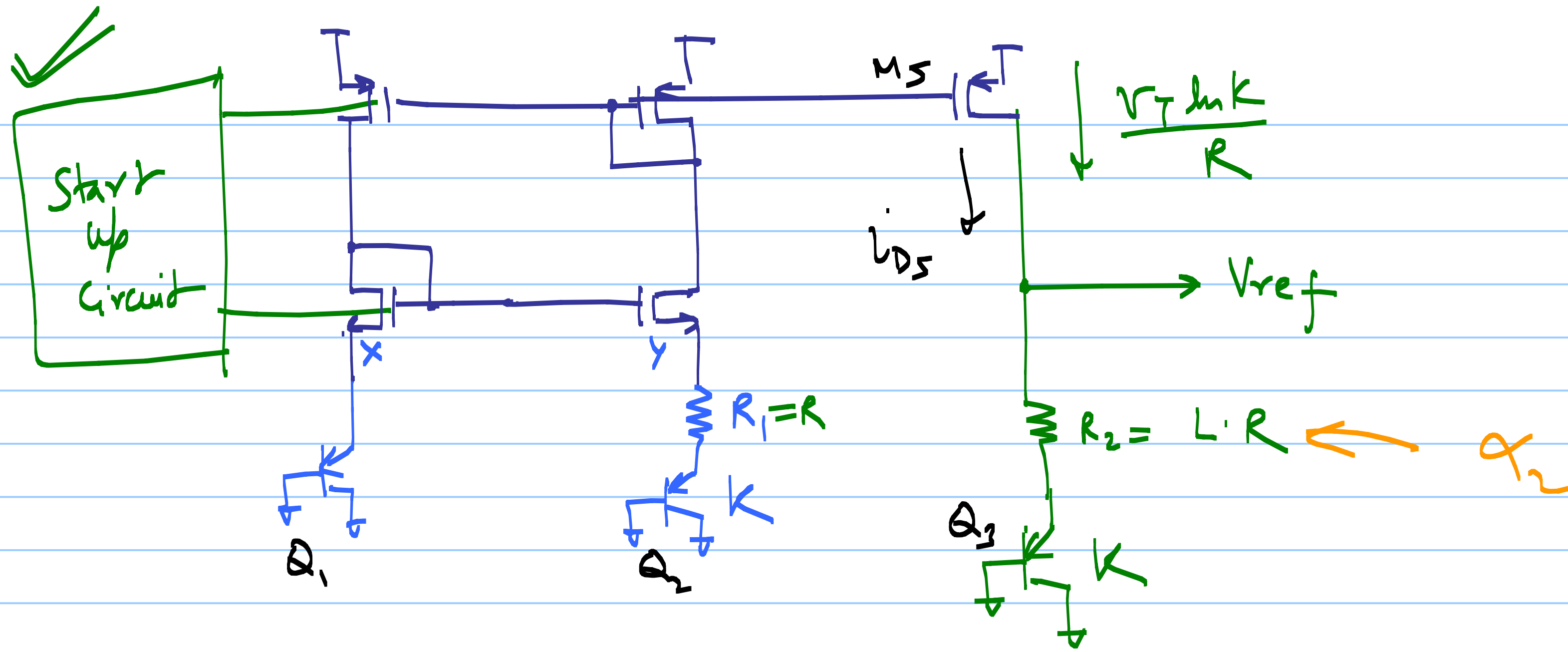
"Start-up Circuit"

BMR - type BGR Circuit



$\frac{PTAT}{R}$ current

* all R's have same Temp Co



$$V_{ref} = i_{D5} \cdot R_2 + V_{BE_3}$$

$$= \frac{V_T \ln K}{R_1} \cdot R_2 + V_{BE_3}$$

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

Ex. $I_D = 1\mu A$

Select $K = 8$,

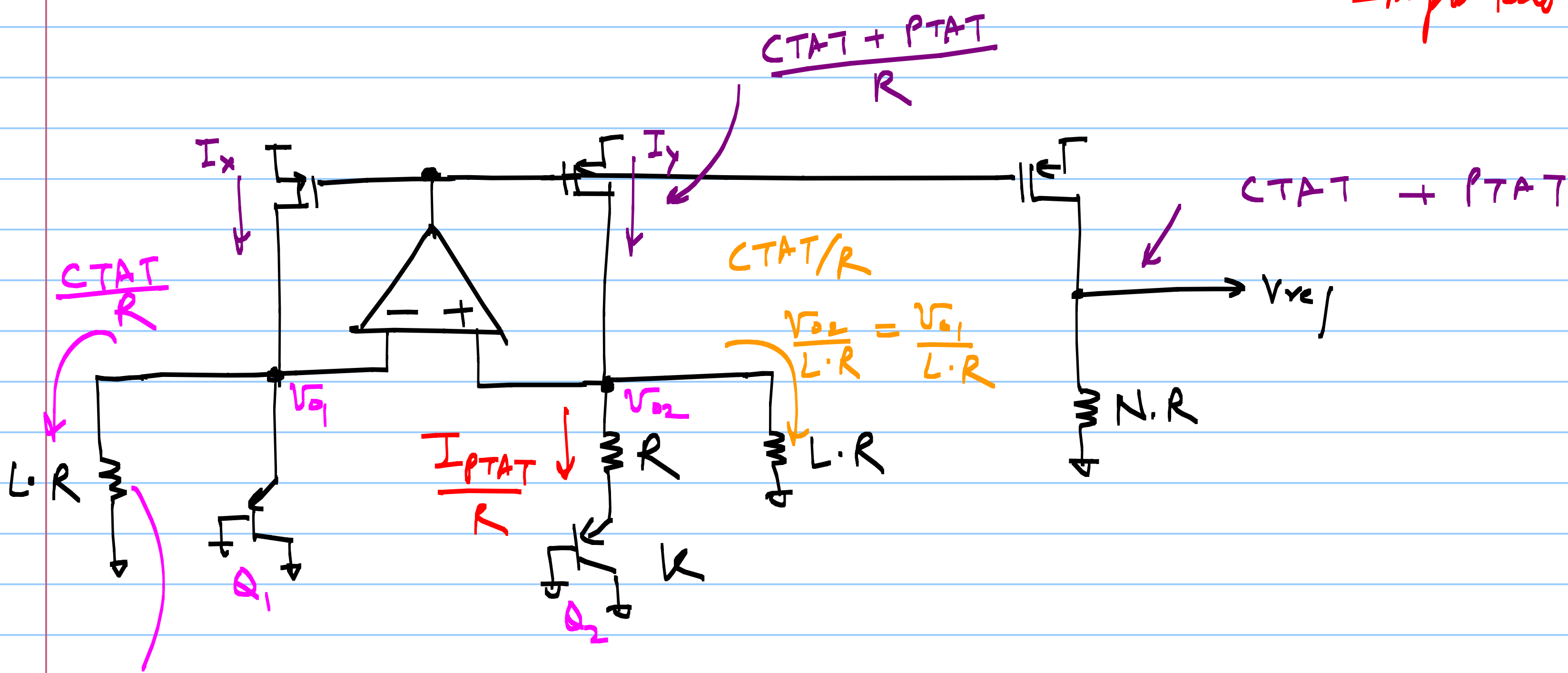
$$L = \frac{\left|\left(\frac{\partial V_{BE}}{\partial T}\right)\right|}{\ln(K)\left(\frac{k}{q}\right)} = \frac{1.5}{0.085 \times \ln(8)} = 8.4834$$

$$V_{ref} = V_{BE_3} + L \cdot v_T \ln k \Rightarrow 1.25V$$

* Can use Cascoding or drain regulated BMR for improved current matching in nano-CMOS

Short-channel BGR Design:

"Important"



$$I_1 = \frac{V_{o1}}{L \cdot R} = \frac{V_{BE1}}{L \cdot R}$$

$$V_{ref} = (I_{PTAT} + I_{CTAT}) \cdot N \cdot R$$

$$= \left(\frac{V_T \ln K}{R} + \frac{V_{BE_1}}{L \cdot R} \right) \cdot N \cdot R$$

$$\Rightarrow \boxed{V_{ref} = \underbrace{N \cdot}_{\alpha_2} \underbrace{V_T \ln(K)}_{PTAT} + \underbrace{\left(\frac{N}{L}\right)}_{\alpha_1} \underbrace{V_{BE_1}}_{CTAT}}$$

$\alpha_2 > 1$

$\alpha_1 < 1$

$V_{ref} < 1V$

$$V_{ref} = N \cdot (V_T \ln K) + \left(\frac{N}{L}\right) V_{BE_1}$$

$$\frac{\partial V_{ref}}{\partial T} = 0 \Rightarrow N \cdot \ln(K) \left(\frac{k}{q}\right) + \frac{N}{L} \cdot \left(\frac{\partial V_{BE_1}}{\partial T}\right) = 0$$

$$\Rightarrow L = \frac{1.5\,mV/K}{\ln(K) \times 0.085\,mV/K}$$

choose $\boxed{K = 8}$ $\Rightarrow$ $\boxed{L = 9.41}$ ☆

$$\ast \quad V_{ref} = V_T \ln(K)\, N + \frac{N}{L} V_{BE_1}$$

$$\Rightarrow N = \frac{V_{ref}}{V_T \ln(K) + V_{BE}/L}$$

for $V_{Ref} = 0.5V$

$$\Rightarrow \quad N = \frac{0.5}{0.052 + \frac{0.7}{9.41}} = \boxed{3.91}$$

* Why its called "Bandgap" Reference

$$V_{ref} = v_{BE} + v_T \ln(k)$$

k/q

Also $\frac{\partial V_{ref}}{\partial T} = 0 \Rightarrow \frac{\partial v_{BE}}{\partial T} + \frac{v_T}{T}\ln(k) = 0$

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

↓ gives a value for V_{BE}

$$V_{ref} = V_{BE} - V_{BE} + (4+m)v_T + E_g/q$$

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

ZTC voltage is given by two fundamental numbers

→ Bandgap Energy of Si

→ m & V_T

$$T \to 0k \Rightarrow V_{ref} \to \frac{E_g}{q} \approx 1.12V$$