31-3-12

Lec 36

$$\frac{V_T}{I_S}\frac{\partial I_S}{\partial T} = (4+m)\frac{V_T}{T} + \frac{E_g}{kT^2}\cdot V_T$$

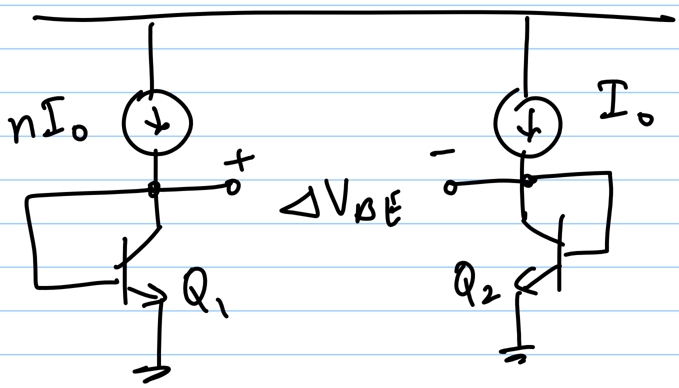
$$\frac{\partial V_{BE}}{\partial V_T} = \frac{V_T}{T}\ln\frac{I_C}{I_S} - (4+m)\frac{V_T}{T} - \frac{E_g}{kT^2}\cdot V_T$$

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

When $V_{BE} \simeq 0.75\,V$ @ $T = 300K$,

$$\frac{\partial V_{BE}}{\partial T} \simeq -1.5\,mV/K$$ [note that this depends on T]

positive TC:



neglect I_Bs

$$\Delta V_{BE} = V_{BE1} - V_{BE2}$$

$$\Delta V_{BE} = V_T\ln\left(\frac{nI_0}{I_{S1}}\right) - V_T\ln\left(\frac{I_0}{I_{S2}}\right)$$

$$= V_T\ln n$$

$$\Rightarrow \frac{\partial\,\Delta V_{BE}}{\partial T} = \frac{k}{q}\ln n$$ [positive T.C., independent of T & I_C]

Bandgap ref.

$$V_{ref} = \alpha_1 V_{BE} + \alpha_2 \underbrace{(V_T \ln n)}_{\Delta V_{BE}}$$

$$\frac{\partial V_{BE}}{\partial T} \simeq -1.5\,mV/K \quad @\ 300K$$

$$\frac{\partial V_T}{\partial T} = \frac{K}{q} \simeq 0.087\ mV/K$$

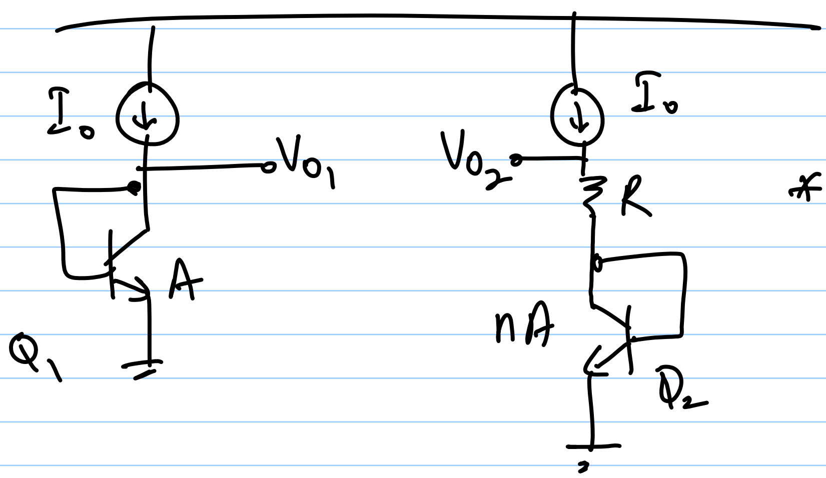
Set $\alpha_1 = 1$

$$\Rightarrow (\alpha_2 \ln n)(0.087\,mV/K) = 1.5\,mV/K$$

$$\Rightarrow \alpha_2 \ln n \simeq 17.2$$

$$V_{ref} = V_{BE} + 17.2\,V_T$$

$$\simeq 1.25\,V \quad @\ 300K$$



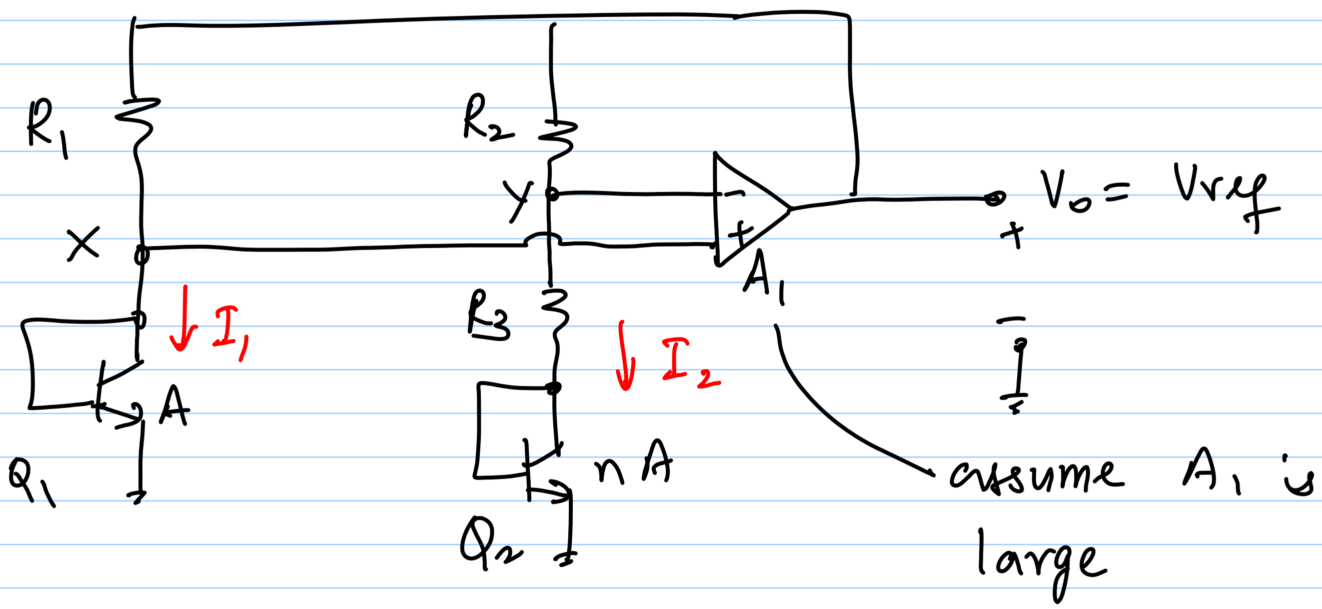
* neglect I_B,
* Force $V_{o_1} = V_{o_2}$

$V_{BE_1} = I_0 R + V_{BE_2}$

$\Rightarrow I_0 R = V_{BE_1} - V_{BE_2} = V_T \ln n$

$V_{O_2} = V_{BE_2} + V_T \ln n \longleftarrow V_{ref}$

* $\ln n = 17.2 \Rightarrow$ extremely large n
* we need to force $V_{O_1} = V_{O_2}$



$\Rightarrow V_X = V_Y$ (due to f.b. loop)

$V_{BE_1} - V_{BE_2} = V_T \ln n$

$$\Rightarrow \quad I_2 = \frac{V_T \ln n}{R_3}$$

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

$$= V_{BE_2} + V_T \ln n \left(1 + \frac{R_2}{R_3}\right)$$

for zero T.C.

$$\left(1 + R_2/R_3\right) \ln n \approx 17.2$$

e.g. $n = 31$ & $\frac{R_2}{R_3} = 4$

also ratio of R's, so indep. of res. tempco

I_C variation

$$I_{C_{1,2}} \propto \frac{V_T \ln n}{R_3} \propto T$$

we assumed I_C indep. of T

here assume $I_{C_1} = I_{C_2} = \frac{V_T \ln n}{R_3}$

$$\frac{\partial V_{BE}}{\partial T} = \frac{\partial V_T}{\partial T} \ln \frac{I_C}{I_S} + V_T \left[\frac{1}{I_C} \frac{\partial I_C}{\partial T} - \frac{1}{I_S} \frac{\partial I_S}{\partial T} \right]$$

$$\frac{\partial I_C}{\partial T} \approx \frac{V_T \ln n}{R_3 T} = \frac{I_C}{T}$$

$$\therefore \frac{\partial V_{BE}}{\partial T} = \frac{\partial V_T}{\partial T} \ln \frac{I_C}{I_S} + \frac{V_T}{T} - \frac{V_T}{I_S}\frac{\partial I_S}{\partial T}$$

earlier: $$\frac{\partial V_{BE}}{\partial T} = \frac{V_{BE} - (4+m)V_T - E_g/q}{T}$$

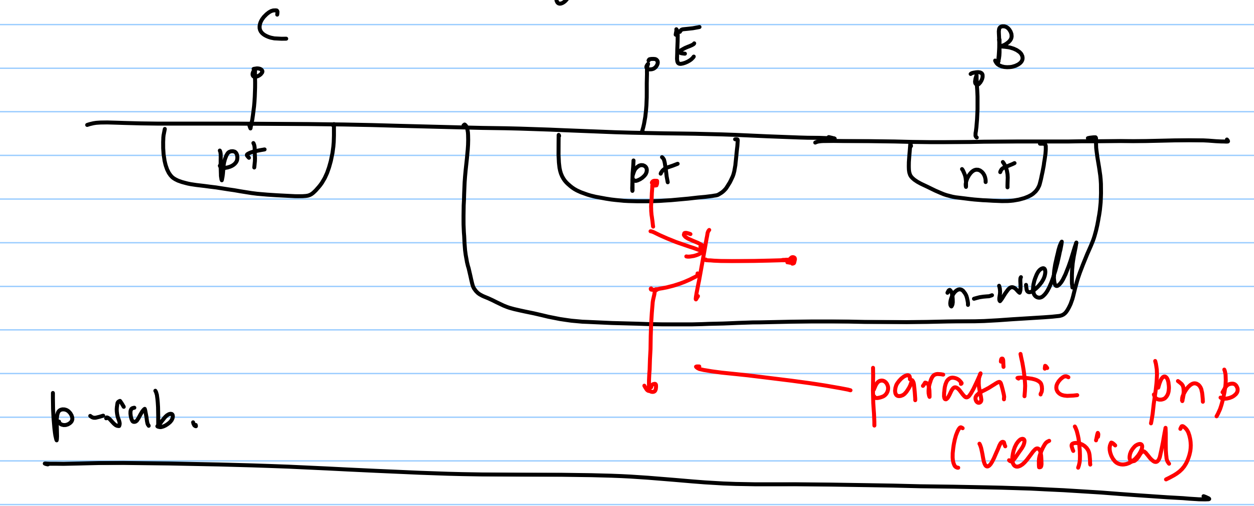
Now, with I_C:

$$\frac{\partial V_{BE}}{\partial T} = \frac{V_{BE} - (3+m)V_T - E_g/q}{T}$$

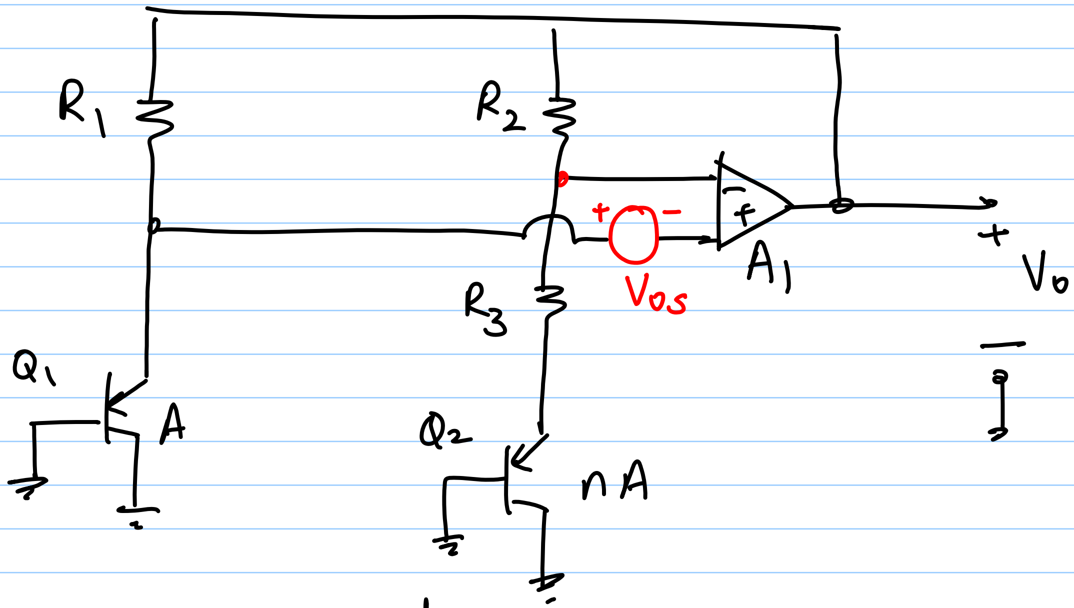
$\Rightarrow$ V_{BE} T.C. is slightly less than $-1.5\,mV/K$

$\Rightarrow$ iterate, simulate for accuracy

In CMOS technology



* substrate connected to gnd (C)
* ckt to be modified to include pnp



Opamp offsets

$$V_{BE_1} - V_{OS} = V_{BE_2} + R_3 I_{C_2}$$

$$V_o = V_{BE_1} + (R_3 + R_2) I_{C_2}$$

$$V_o = V_{BE_2} + (R_3 + R_2)\left[\frac{V_{BE_1} - V_{BE_2} - V_{OS}}{R_3}\right]$$

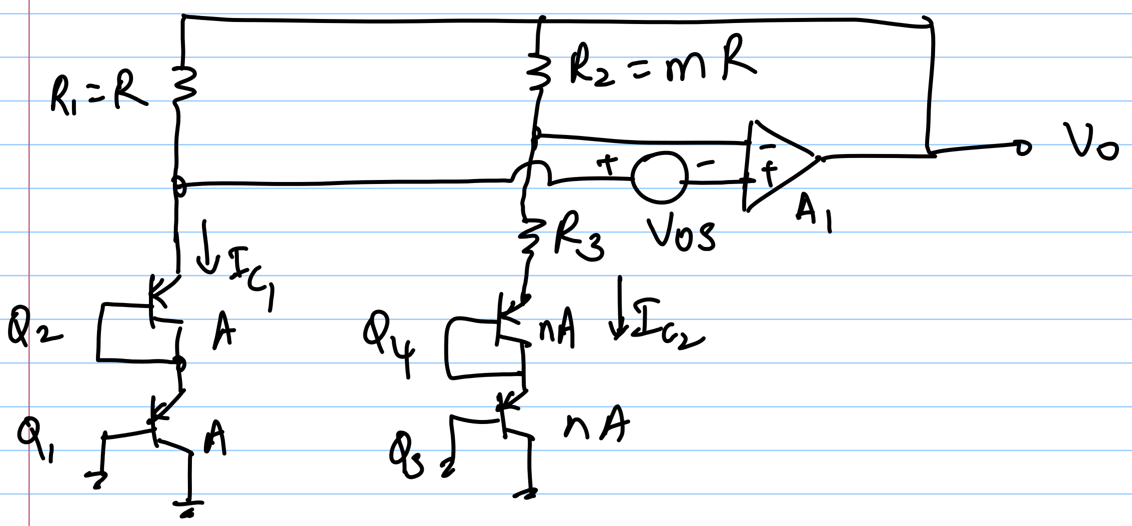
$$= V_{BE_2} + \left(1 + \frac{R_2}{R_3}\right)\left(V_T \ln n - V_{OS}\right)$$

* V_{OS} is amplified by $(1 + R_2/R_3)$
* We have assumed $I_{C_1} \approx I_C$ even in presence of offset
* V_{OS} varies with temperature

1) Use opamp with large devices

2) make $I_{C_1} = m \cdot I_{C_2}$

3) Use 2 pn junctions in series



$$R_2 = m R_1 \Rightarrow I_{C_1} \approx m I_{C_2}$$

$$\Rightarrow \Delta V_{BE} = V_T \ln(mn)$$

$$\Rightarrow V_{BE_1} + V_{BE_2} - V_{OS} = V_{BE_3} + V_{BE_4} + R_3 I_{C_2}$$

$$V_{out} = V_{BE_3} + V_{BE_4} + (R_3 + R_2) I_2$$

$$= V_{BE_3} + V_{BE_4} + (R_3 + R_2)\left[\frac{2V_T \ln(mn) - V_{OS}}{R_3}\right]$$

$$= 2V_{BE} + \left(1 + \frac{R_2}{R_3}\right)\left[2V_T \ln(mn) - V_{OS}\right]$$