Note Title — 5/7/2013

# Lecture 27

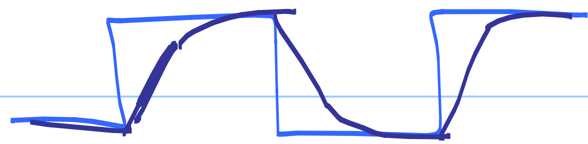
$$SR = \frac{I_{ss}}{C_c} = 500\,\frac{V}{\mu s} = \frac{100\mu}{C_c}$$

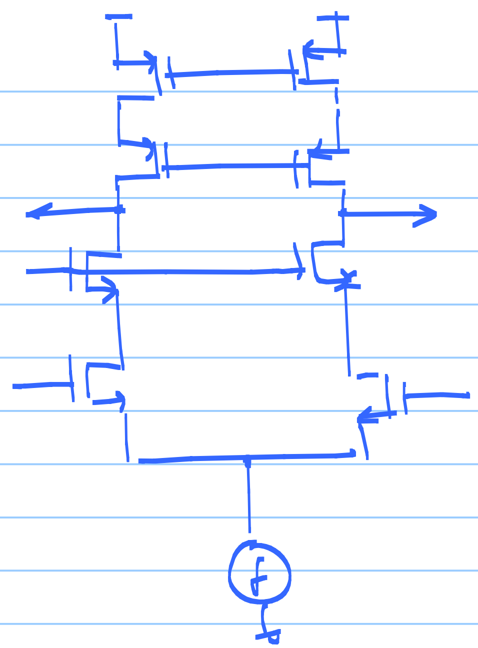
$$\Rightarrow \quad C_c = \frac{100\times10^{-6}\times10^{-6}}{500}$$

$$= 0.2\,pF$$

$$FoM_1 = \frac{f_{un} \cdot A_{oL}}{Power}$$

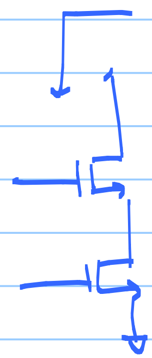
$$FoM_2 = \frac{SR \cdot A_{oL}}{Power}$$



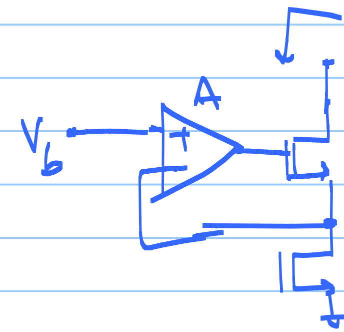


$g_m r_o = 10$

$R_{out} = g_m r_o^2$



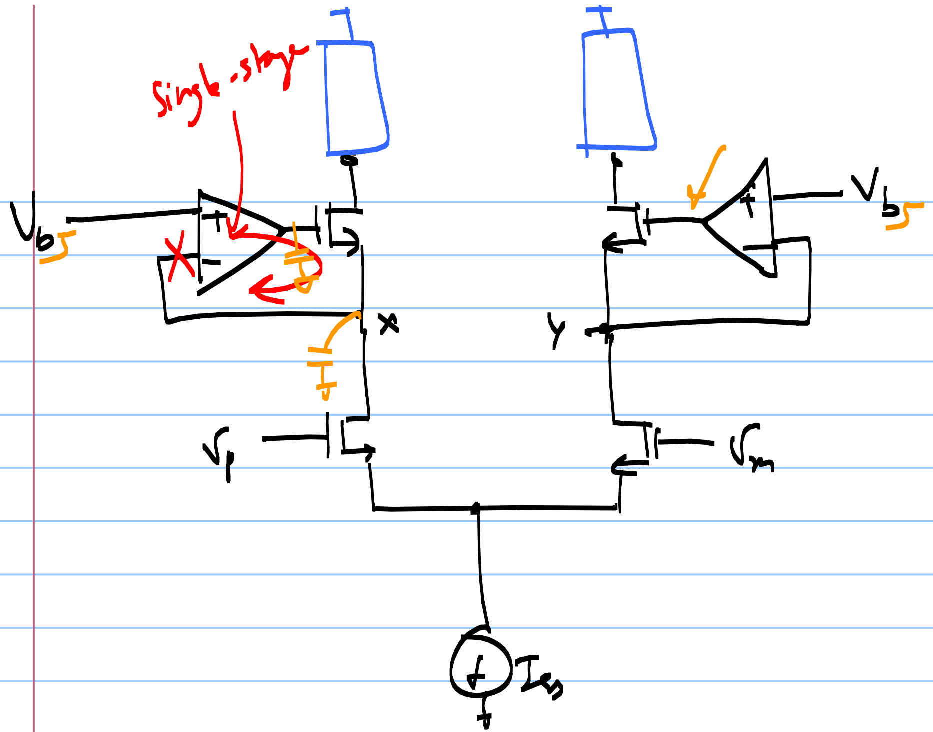
$R_{out} = g_m r_o^2 \cdot A$



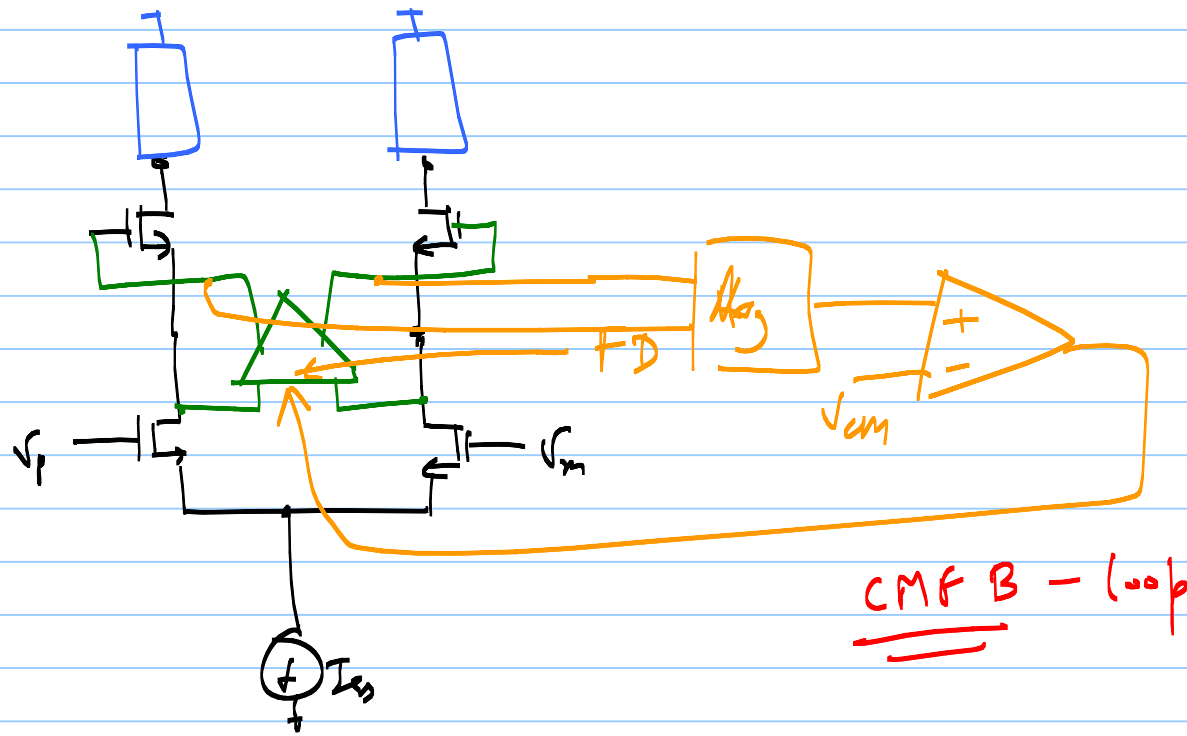

"Gain-Boosting"

nano-- CMOS

$\leq 90$ nm



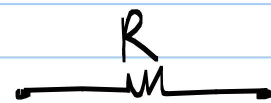

$A_v = -g_m R_{out}$




CMFB - loop

$0^\circ - 60^\circ C$

Temp co.

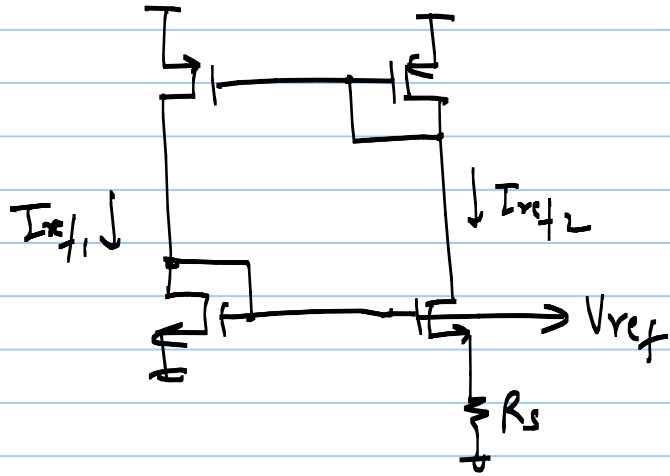



$$R(T) = R(T_0)\left[1 + TC_R\left(\frac{T - T_0}{T_0}\right)\right]$$

$$\boxed{TC_R = \frac{1}{R}\cdot\frac{\partial R}{\partial T}}$$

"Temperature Coefficient"

<u>BMR</u>




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

$\mu_n C_{ox}$

$$\frac{\partial V_{ref}}{\partial T} = \left(\frac{\partial V_{THN}}{\partial T}\right) - \frac{2}{R_s KP_n \cdot \frac{W}{L}}\left(1 - \frac{1}{\sqrt{K}}\right)\left(\frac{1}{R}\cdot\frac{\partial R}{\partial T} + \underbrace{\frac{1}{KP_n}\cdot\frac{\partial KP_n}{\partial T}}_{-\frac{1.5}{T}}\right)$$

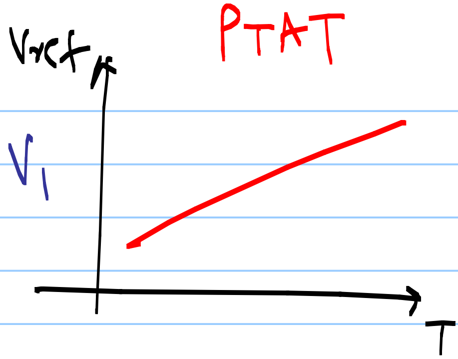
$\neq 0$

Select an $R$ such that $\dfrac{\partial V_{ref}}{\partial T} \to 0$ ← zero temp co. $ZT_C$

$$R = \frac{2}{\frac{\partial V_{THN}}{\partial T} \cdot k P_n' \frac{W}{L}} \left(1 - \frac{1}{\sqrt{K}}\right)\left[\frac{1}{R} \cdot \frac{\partial R}{\partial T} - \frac{1.5}{T}\right]$$

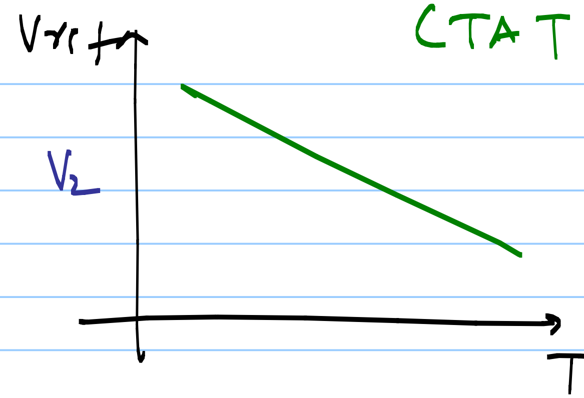
→ impractical to make BMR with $ZT_C$

PTAT




prop. to absolute temperature

CTAT



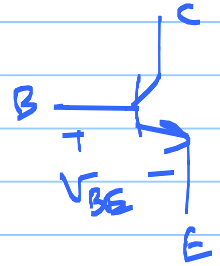

Complementary to the absolute Temperature

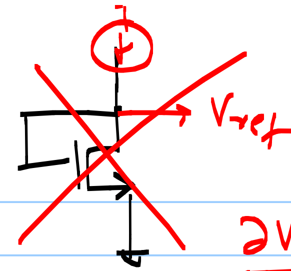
ZTC (zero temp co)
reference


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

s.t. $\dfrac{\partial V_{ref}}{\partial T} = 0$ or $\boxed{\alpha_1 \dfrac{\partial V_1}{\partial T} + \alpha_2 \dfrac{\partial V_2}{\partial T} = 0}$

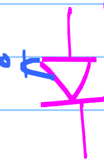
⊛ CTAT ⇒ −ve Temp Co




$\frac{\partial V_{THN}}{\partial T} < 0$

$I_c = I_s\, e^{\frac{V_{BE}}{V_T}} \rightarrow$ ① , $V_T = \frac{kT}{q} = 26\,mV$ @ $T = 300K$




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

$\mu \propto \mu_0 T^m$ , $m = -\frac{3}{2}$

$n_i^2 \propto T^3 \cdot e^{-E_g/kT}$ → Bandgap

$S_i \rightarrow 1.12\,eV$

$V_{BE} = V_T \ln\left(\frac{I_c}{I_s}\right)$

$$I_S = b\, T^{(4+m)} \cdot e^{-E_g/kT} \quad (2)$$

* Compute the TC of $V_{BE}$

$$\frac{\partial V_{BE}}{\partial T} = \frac{\partial V_T}{\partial T} \cdot \ln\left(\frac{I_C}{I_S}\right) - \frac{V_T}{I_S} \cdot \left(\frac{\partial I_S}{\partial T}\right) \quad (3)$$

$$\frac{\partial I_S}{\partial T} = \frac{(4+m)}{T}\, b\, T^{4+m} \cdot e^{-E_g/kT} + b T^{4+m} e^{-E_g/kT} \cdot \frac{E_g}{kT^2}$$

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

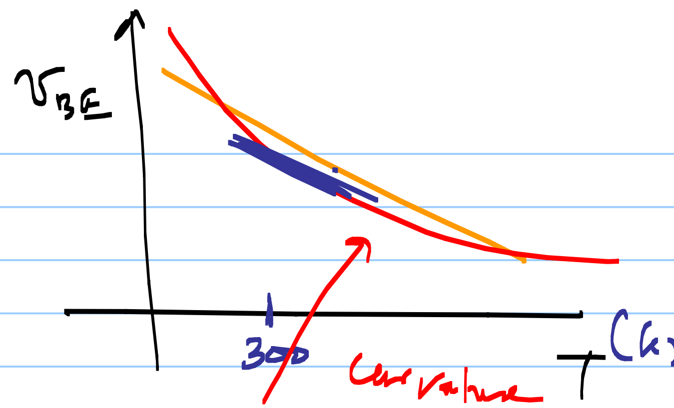
$$\frac{\partial V_T}{I_s} \cdot \frac{\partial I_s}{\partial T} = (4+m)\frac{V_T}{T} + \frac{E_g}{kT^2} \cdot V_T$$

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

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

$q = 1.6 \times 10^{-19}\ C$

* $\dfrac{\partial V_{BE}}{\partial T}$ depends upon $V_{BE}$ itself besides the temperature




* with $V_{BE} = 0.75V$, $T = 300°K$

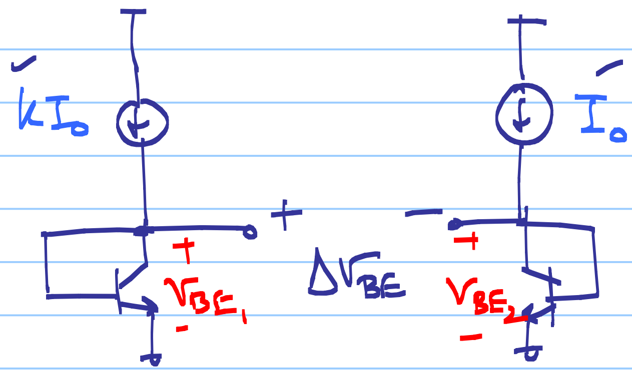
$$\boxed{\frac{\partial V_{BE}}{\partial T} \simeq -1.5 \frac{mV}{°K}}$$

* $V_{BE}$ is not a linear CTAT

## ② PTAT

npn BJT's

diode connected




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

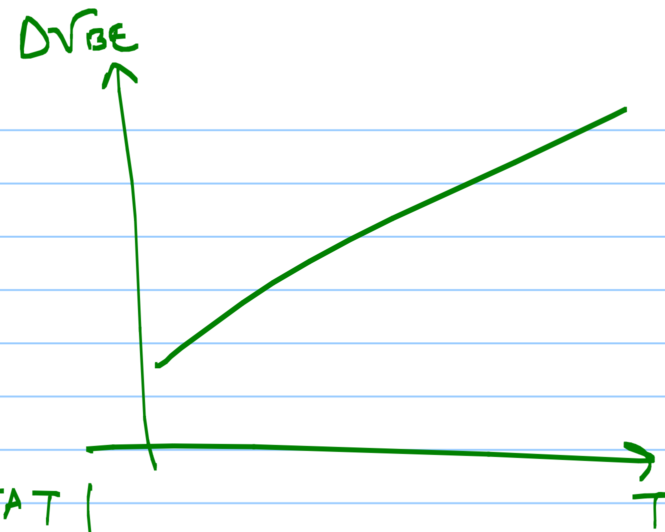
$$= V_T \ln\left(\frac{kI_0}{I_s}\right) - V_T \ln\left(\frac{I_0}{I_s}\right)$$

$$= V_T \ln(k)$$

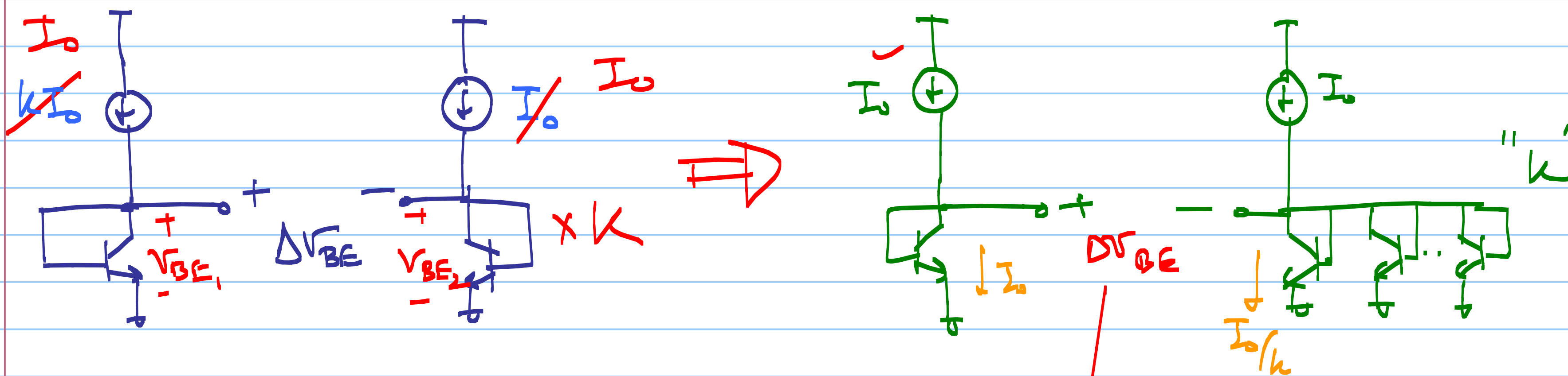
$$\Delta V_{BE} = V_T \ln(k)$$

$$\frac{\partial V_{BE}}{\partial T} = \frac{k}{q} \ln(k) > 0$$

independent of $I_C$.




linear PTAT !




$V_T \ln(k)$

"PTAT"

Bandgap Reference $\Rightarrow$ $\alpha_1 \cdot \text{CTAT} + \alpha_2\, \text{PTAT} \Rightarrow \text{ZTC}$

$$V_{ref} = \alpha_1 V_{BE} + \alpha_2 \overbrace{\left(V_T \ln(K)\right)}^{\Delta V_{BE}}$$

* How do we choose $\alpha_1$ & $\alpha_2$ ?

Boltzmann

ratio of diodes

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

$$\alpha_2 \ln K = \frac{-\alpha_1 \cdot \frac{\partial V_{BE}}{\partial T}}{k/q}$$

$-1.5 \frac{mV}{°K}$

$\frac{\partial V_T}{\partial T} = 0.087 \frac{mV}{°K}$

$$\alpha_2 \ln(n) = \alpha_1 \cdot \frac{1.5 \, \frac{mV}{n}}{0.087 \, \frac{mV}{n}}$$

$$\boxed{\alpha_2 \ln(n) = \alpha_1 \times 17.2}$$

Arbitrarily choose $\alpha_1 = 1$

$$\Rightarrow \alpha_2 \ln(n) = 17.2$$

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

$$= 0.75V + 17.2 \times 26 \, mV$$

$$\approx 1.2V$$