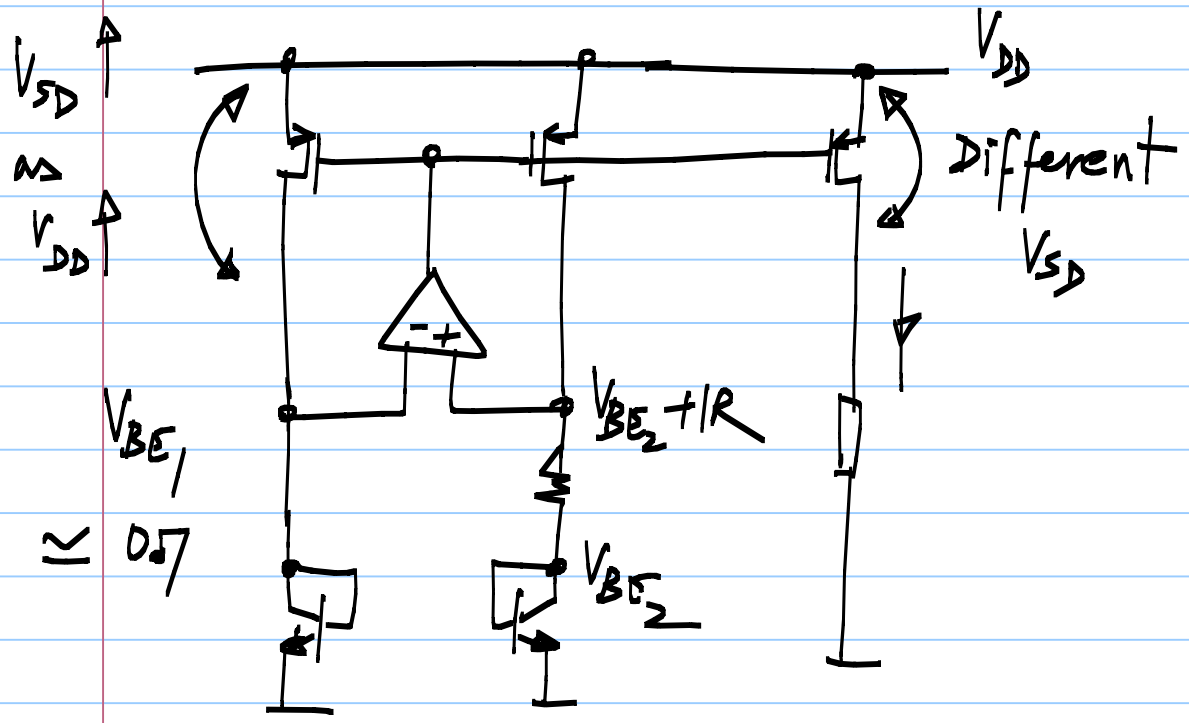
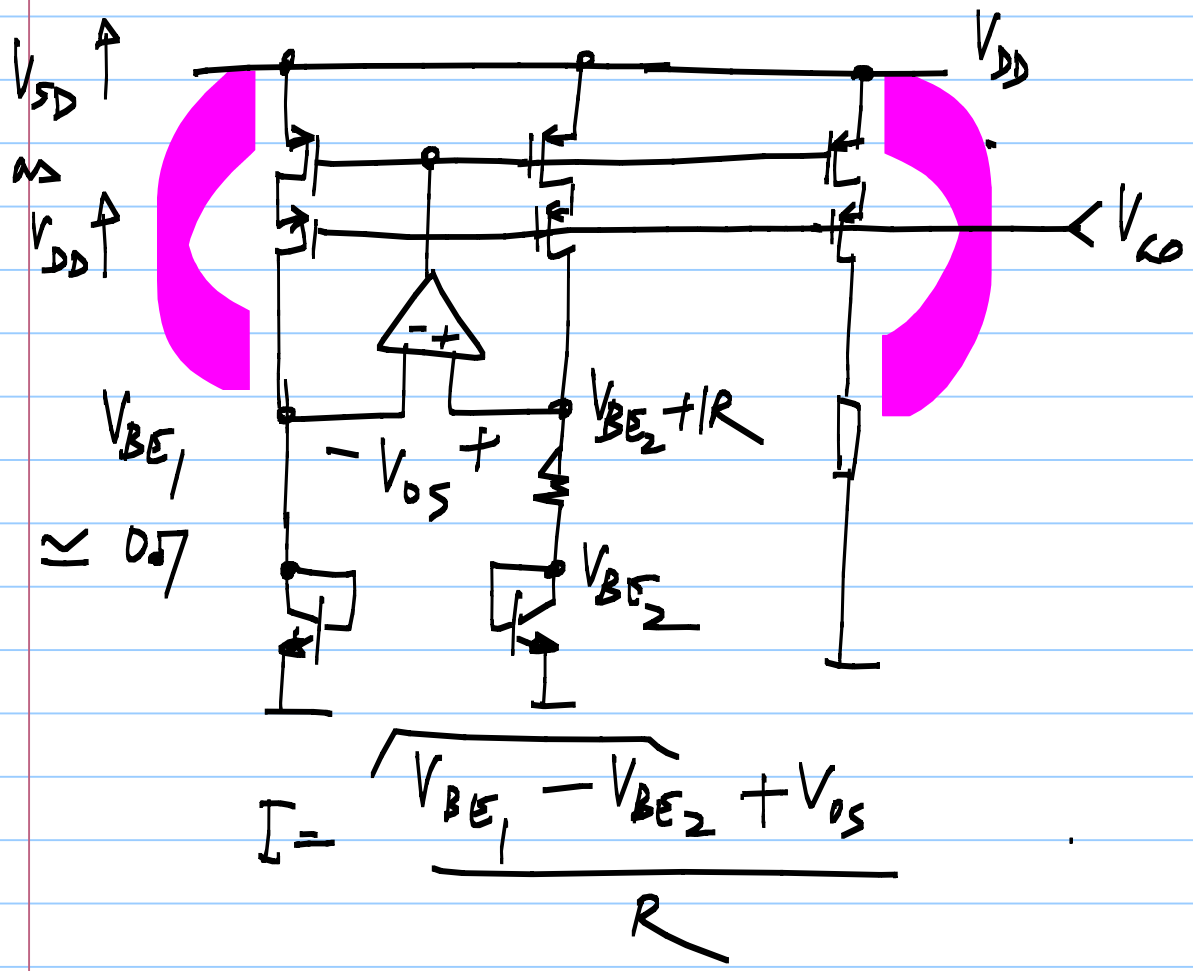
Lecture 54:

PTAT cell:





Sources of error

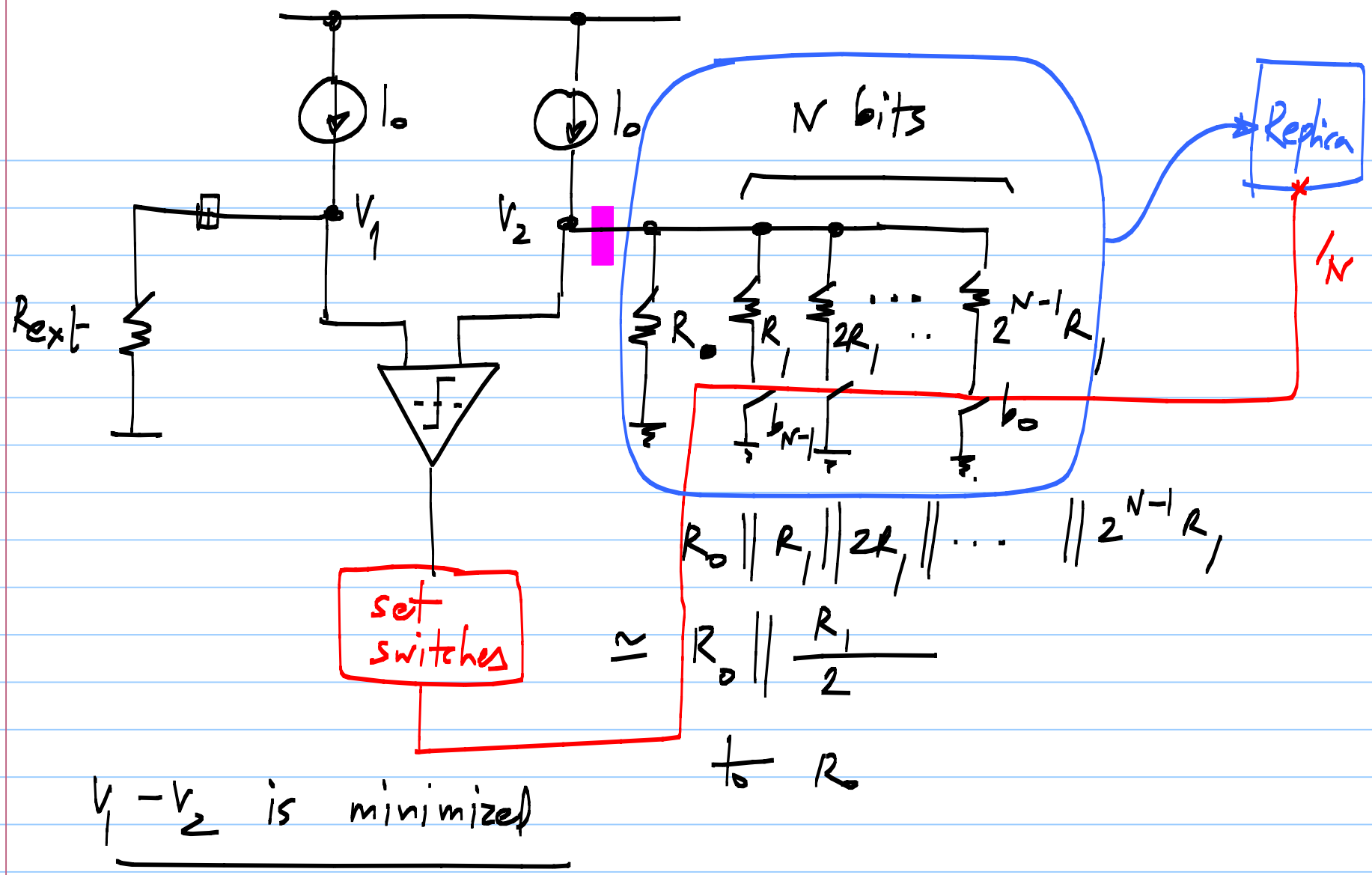
* Channel length mod. of PMOS
  - Cascode
* Opamp offset
  - Use large devices in the input pair

R : small TC

: constant with process variations

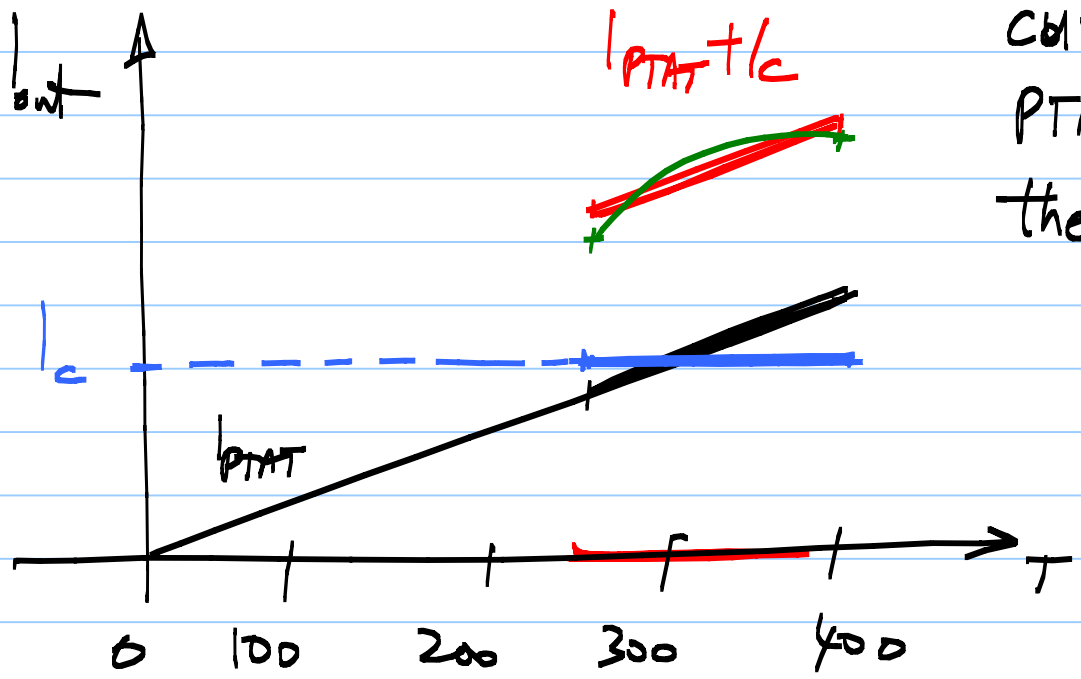
* External resistor:

* Single external resistor – Trim an internal resistor to that value


I_o
I_o
N bits
Replica
V_1
V_2
I_N
R_{ext}
R_0
R_1
$2R_1$
$2^{N-1}R_1$
b_{N-1}
b_0
set switches
$R_0 \| R_1 \| 2R_1 \| \cdots \| 2^{N-1}R_1$
$\simeq R_0 \| \frac{R_1}{2}$
$\to R$
$V_1 - V_2$ is minimized

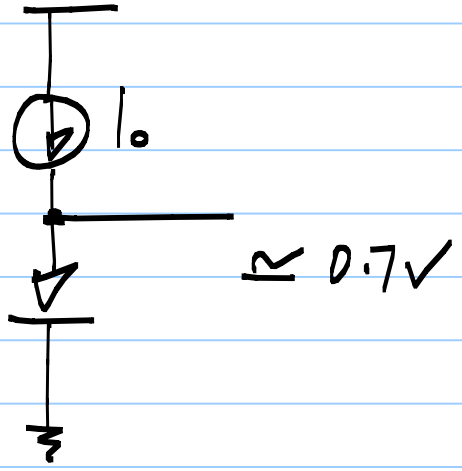
To generate currents with arbitrary dependence on temperature

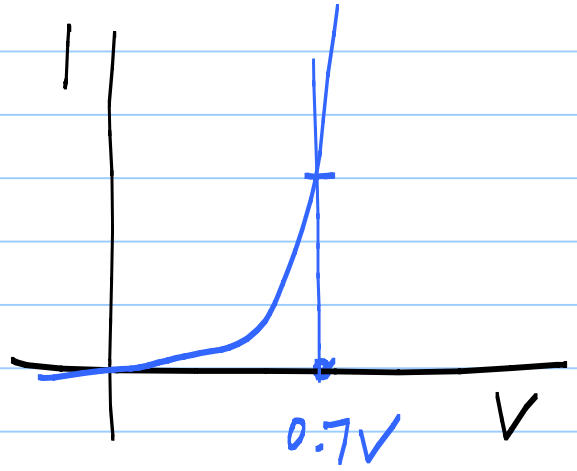
PTAT



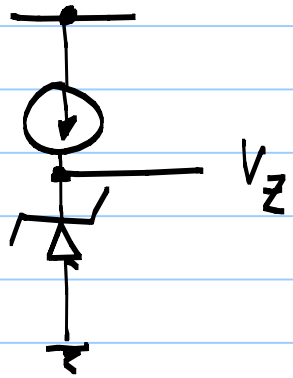
Combine a constant current source & a PTAT current source in the right proportion

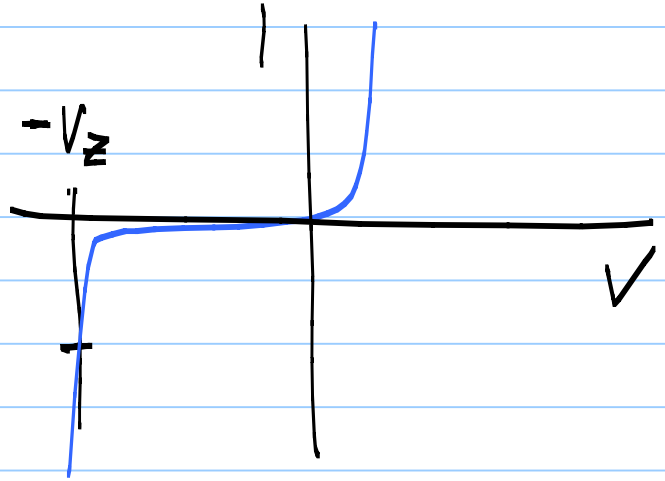
Constant voltage reference:

* 



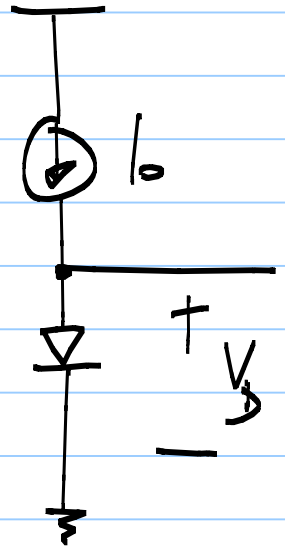
* Zener diode





* Zener diodes around $V_Z = 3.6\,V$ have low temperature coefficient

Diode biased at a constant current:



$$V_j = V_t \ln\left(\frac{I_0}{I_S}\right) = \frac{kT}{q} \ln\left(\frac{I_0}{I_S}\right)$$

$$I_S = b \cdot T^{4+m} \exp\left(-\frac{E_g}{kT}\right)$$

$$I_S \propto \mu \cdot kT \cdot n_i^2$$

$$(\mu_0 T^m)$$

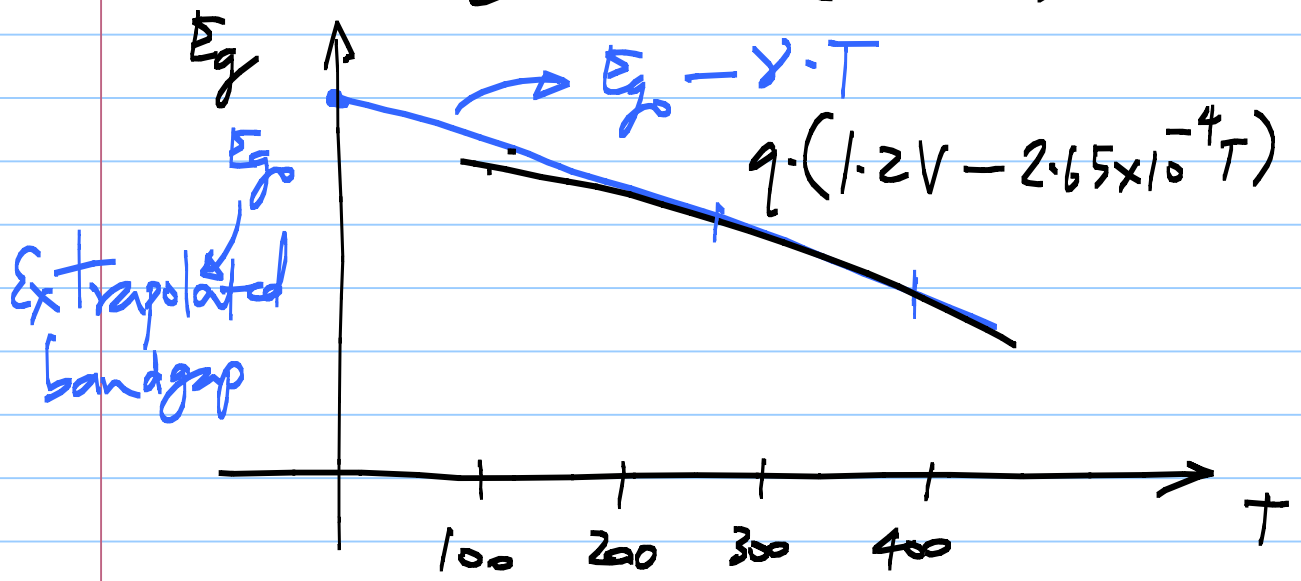
$$T^3 \exp\left(-\frac{E_g}{kT}\right)$$

Bandgap

$$m \simeq -\frac{3}{2}$$

$$V_\beta = V_t \ln \frac{I_0}{b \cdot T^{4+m} \cdot \exp\left(-\frac{E_g}{kT}\right)}$$

$$= \frac{E_g}{q} + V_t \left[\ln\left(\frac{I_0}{b}\right) - (4+m) \ln(T) \right]$$



$q \cdot (1.2V - 2.65 \times 10^{-4} T)$

$$E_g = E_{g0}' - \frac{\alpha \cdot T^2}{T + \beta}$$

$\alpha = 4.73 \times 10^{-4}$

$\beta = 636\ K$

$$V_D = \frac{E_{g0}}{q} - 3.08\,V_t + V_t\left[\ln\left(\frac{I_0}{b}\right) - (4+m)\ln(T)\right]$$

$$\frac{E_{g0}}{q} = 1.2\,V - 2.65\times10^{-4}\,T$$

$$= 1.2\,V - 3.08\,V_t$$

$$V_D = \frac{E_{g0}}{q} + V_t\left[\ln\left(\frac{I_0}{b}\right) - 3.08 - (4+m)\ln(T)\right]$$

$\simeq 0.7\,V$ $\quad$ $1.2\,V$ $\quad$ Negative voltage; Negative TC

$\simeq -0.5\,V$

Bandgap reference:

* Diode (V_{BE}) drop has a negative temp. coefficient of $\simeq -1.5 mV/K$

* Add a PTAT voltage to realize Zero TC.

$$V_{out} = V_D + \alpha \cdot V_t$$

$$= \frac{E_{g0}}{q} + \underbrace{V_t \left[\ln\left(\frac{I_0}{b}\right) - 3.08 - (4+m)\ln T \right] + \alpha V_T}_{\text{set to zero at 300k}}$$

$$\frac{dV_{out}}{dT} = \frac{k}{q}\left[\ln\left(\frac{I_0}{b}\right) - 3.08 - (4+m)\ln T\right] - \frac{kT}{q}\frac{(4+m)}{T}$$

$$+\alpha\cdot\frac{k}{q} = 0$$

$$\alpha = -\left[\ln\left(\frac{I_0}{b}\right) - 3.08 - (4+m)\ln T\right] + (4+m)$$

$$= -\frac{V_D - E_{g0}/q}{V_t} + (4+m)$$

$\frac{500mV}{25mV} + 2.5 = 22.5$

$$= \frac{E_{g0}/q - V_D}{V_t} + (4+m)$$

$3+m$ $\quad$ 21.5

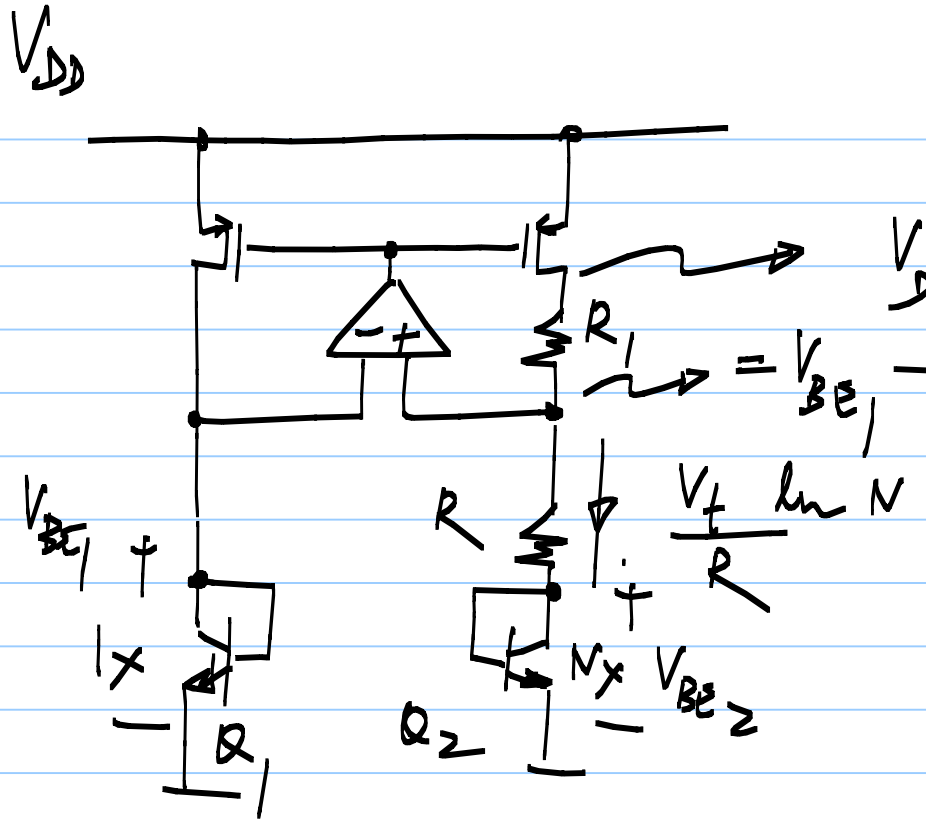
$E_{g0}/q : 1.2V$

$V_D : 0.7V$

$V_t : 25mV$

$m : -\frac{3}{2}$

PTAT cell



V_{BE_1}

$V_D + V_t \cdot \alpha$

$V_D + \frac{V_t \cdot R_1}{R} \cdot \ln(N)$

Set $\frac{R_1}{R} \ln(N) = \alpha$

Currents are PTAT $\quad I_c = I_0 \frac{T}{T_0}$

$$V_D = V_t \ln\left(\frac{I_C}{I_S}\right)$$

$$= \frac{E_{g0}}{q} + V_t \left[\ln\left(\frac{I_0}{b}\right) - 3.08 - (4+m)\ln T \right]$$

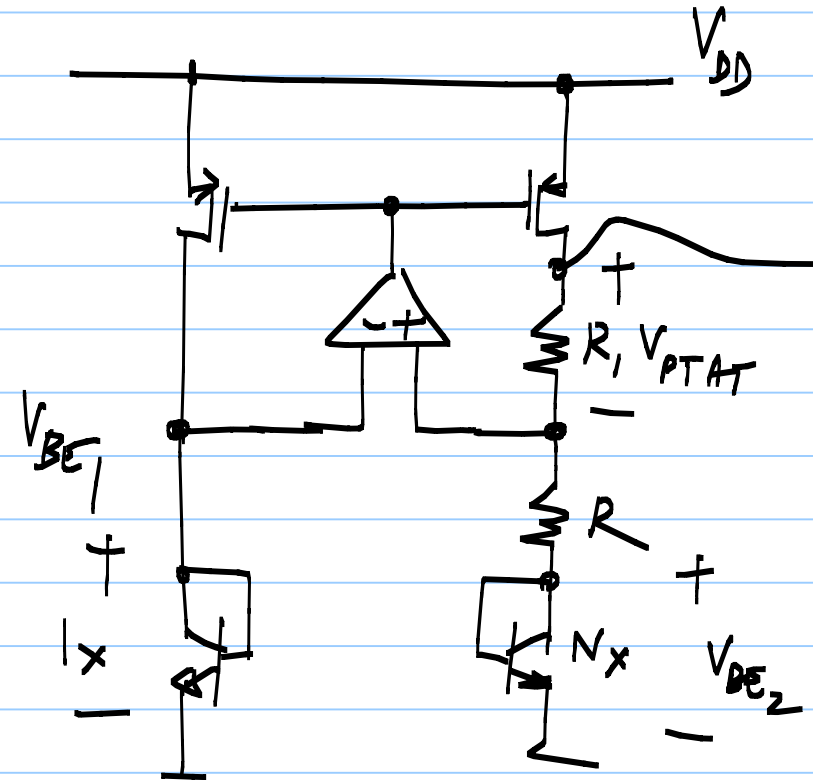
$$I_0 = I_0' \cdot \frac{T}{T_0}$$

$$\ln\left(\frac{I_0'}{T_0 b}\right) + \ln T$$

PTAT

$$\frac{E_{g0}}{q} + V_t \left[\ln\left(\frac{I_0'}{T_0 b}\right) - 3.08 - (3+m)\ln T \right]$$

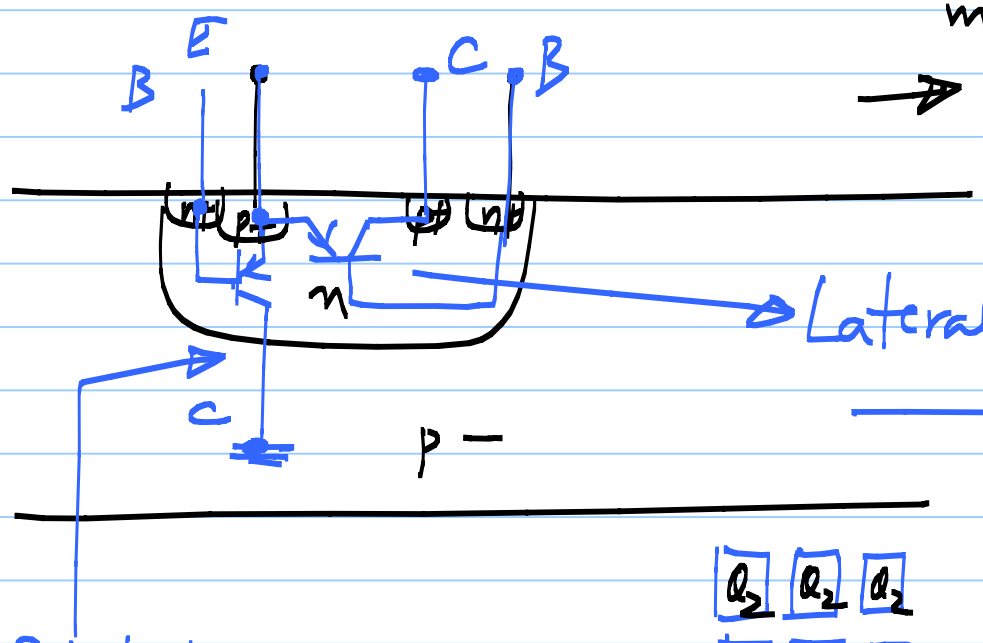
Bandgap voltage reference:



$$V_{BG} = \frac{E_{g0}}{q}$$

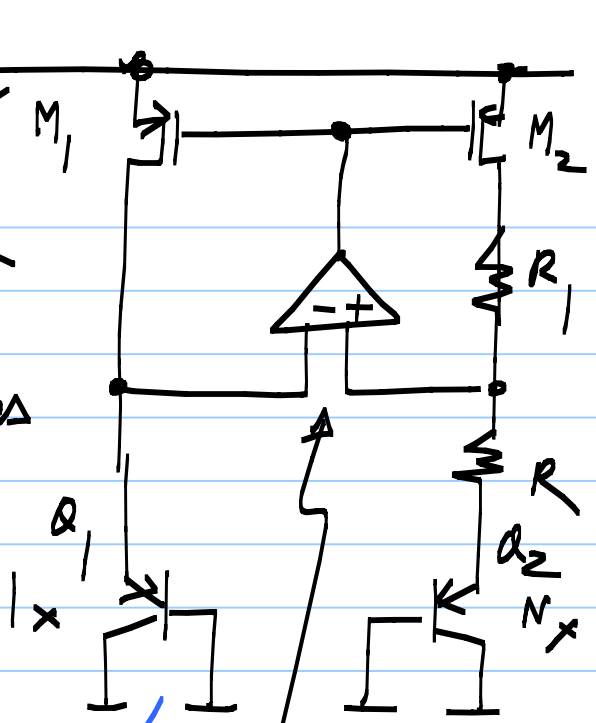
$$\frac{R_1}{R} \cdot \ln(N) \simeq 22.5$$

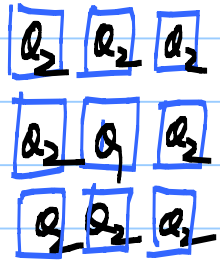
In a CMOS process:



Channel length mod.

→ Cascodes





Matching

$\frac{Q_1 : Q_2}{1 : 8}$

Offset

[Large devices]