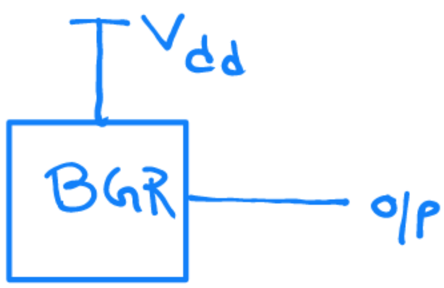
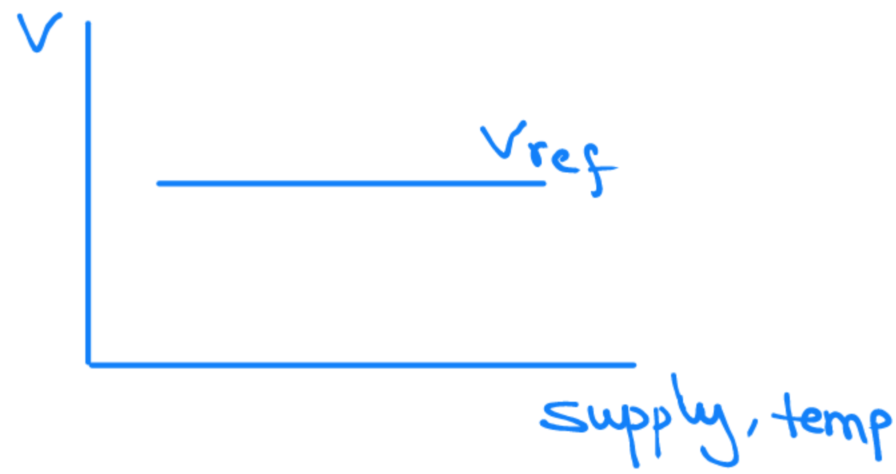
Bandgap Reference Circuit

Bandgap Reference

→ Constant Reference voltage Independent of supply & Temperature variation.

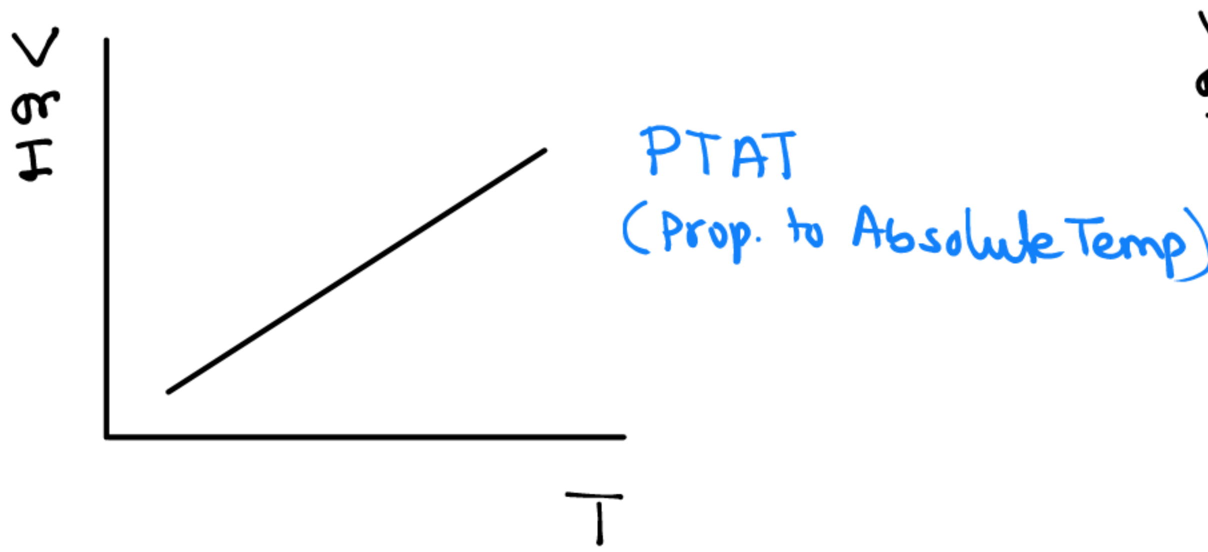


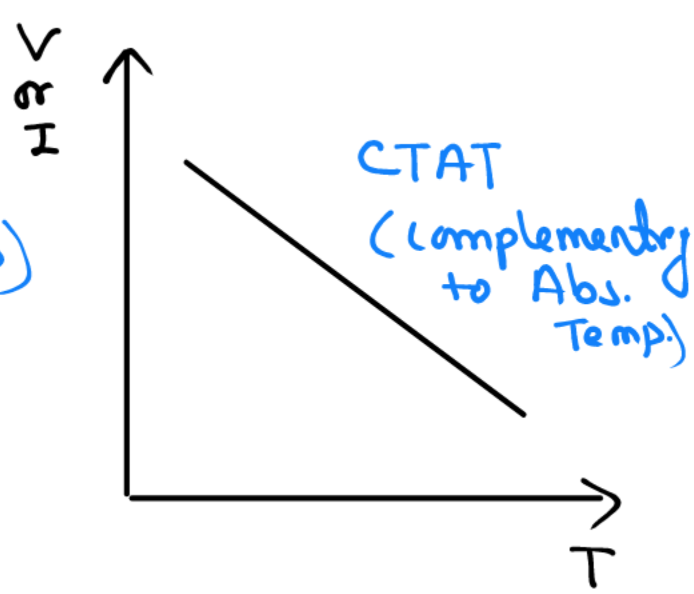


Used: LDO, Buck
ADC, DAC

Industry std. Temp. variation : $-40°$ to $125°C$
Supply variation : 10%, 20%, ...

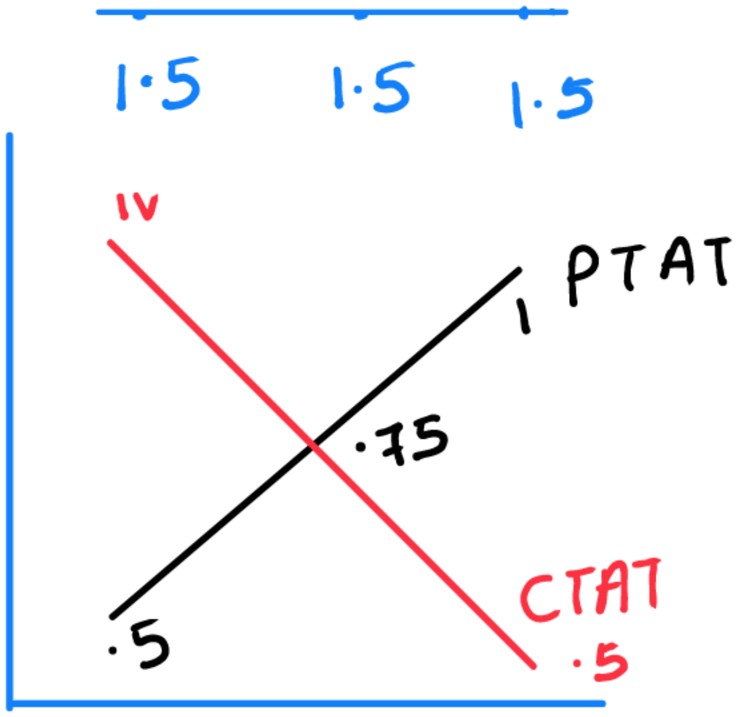
1. Supply Variation
2. Temp. Variation

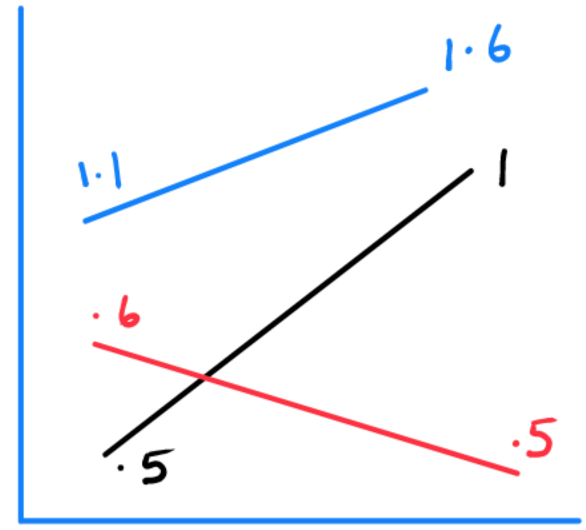




PTAT + CTAT = Constant Voltage

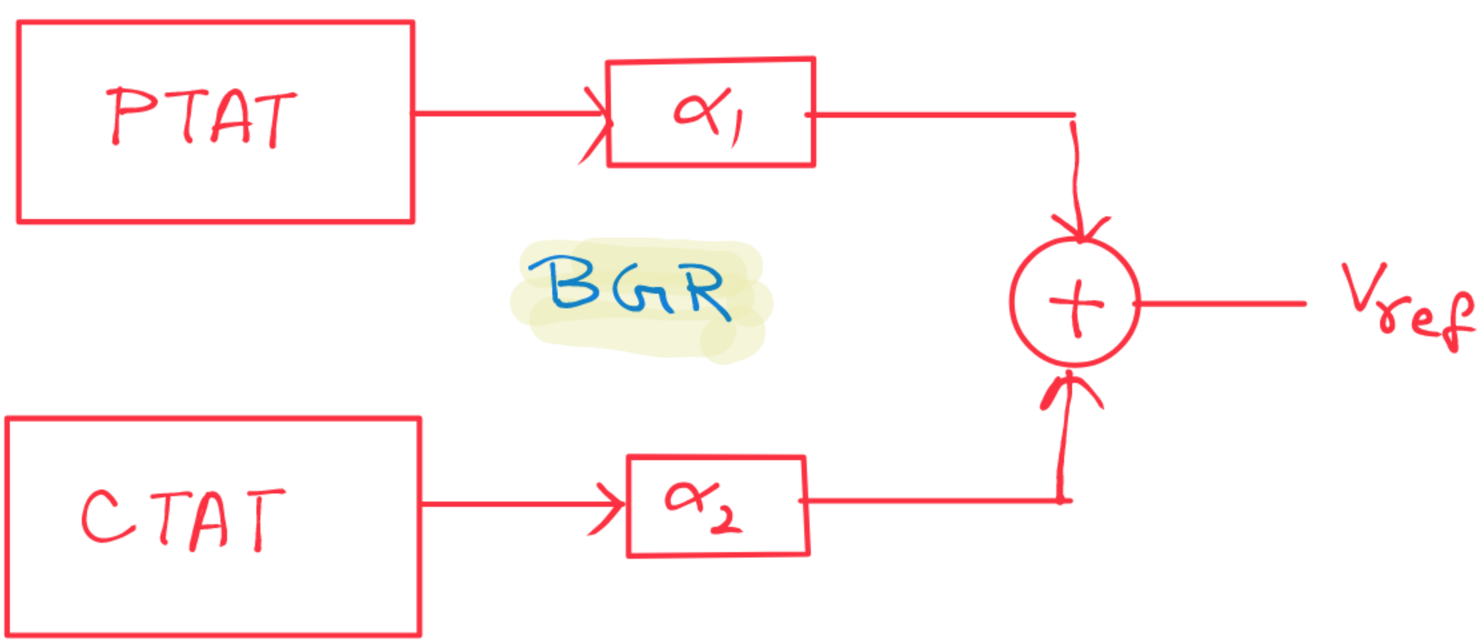
Any PTA + Any CTAT $\neq$ Const. Voltage





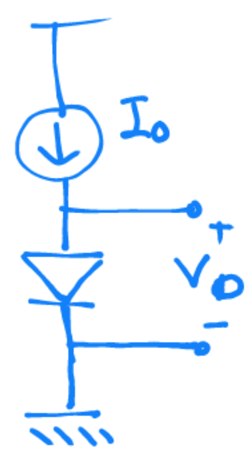
But, $\boxed{\alpha_1 PTAT + \alpha_2 CTAT = \text{Const. Voltage.}}$

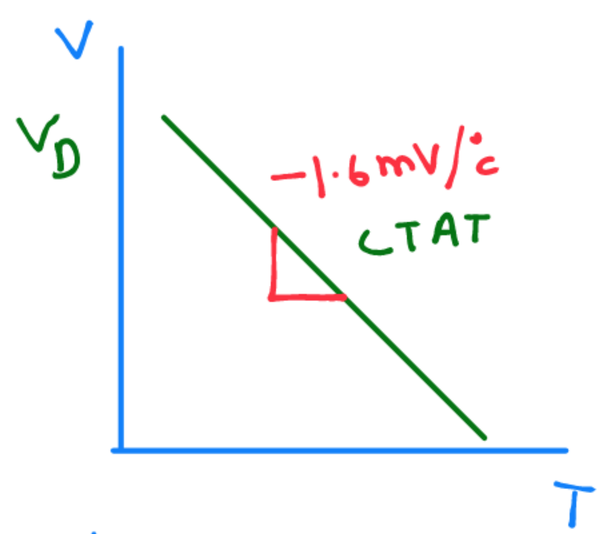
→ Adjusting α_1 & α_2, we can get constant voltages.



Design of BGR

CTAT





$$I_0 = I_s e^{V_D/V_t}$$

V_t = Thermal voltage
$= 26\,mV/300K$

I_s = reverse bias sat. current

$$V_D = V_t \ln\left(\frac{I_0}{I_s}\right) \quad \text{--- } 1$$

I_0 = const. / temp, supply

Voltage across the diode decreases with temp at a rate of $-1.6\,mV/^\circ c$. (when const. current is passing)

$$V_D = V_t \ln\left(\frac{I_0}{I_s}\right)$$

$$\frac{\partial V_D}{\partial T} = -1.6\,mV/^\circ c$$

$V_t = \frac{KT}{q} \propto T$ (PTAT)

$\ln\left(\frac{I_0}{I_s}\right)$ (CTAT) "dominate"

$$\frac{\partial V_t}{\partial T} = \frac{K}{q} \quad \text{--- } 2$$

Now, $I_0 \rightarrow$ constant

$$\frac{\partial I_0}{\partial T} = 0$$

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

$\mu_0 T^m$; $m = -3/2$

$n_i^2 \propto T^3 \exp\left[\frac{-E_g}{KT}\right]$

$$I_s \propto b\, T^m . T . T^3 \exp\left[-\frac{E_g}{KT}\right]$$

$$I_s = b\, T^{(4+m)} \exp\left[\frac{-E_g}{KT}\right] \quad \text{--- } 3$$

$$I_s = b\,T^{(4+m)} \exp\left[\frac{-E_g}{KT}\right]$$

$$\frac{\partial I_s}{\partial T} = b\left[T^{(4+m)} \left(e^{-E_g/kT}\right) -\frac{E_g}{k}\cdot\frac{-1}{T^2} + (4+m)\,T^{3+m}\left(e^{-E_g/kT}\right)\right]$$

$$= b\left(e^{-E_g/kT}\right)\left[T^{4+m}\,\frac{E_g}{kT^2} + (4+m)\,T^{3+m}\right]$$

$$= b\,e^{-E_g/kT}\;T^{4+m}\left[\frac{E_g}{kT^2} + \frac{4+m}{T}\right]$$

$$\frac{\partial I_s}{\partial T} = I_s\left[\frac{E_g}{kT^2} + \frac{4+m}{T}\right] \quad\text{———}\quad (4)$$

$$V_D = V_T \ln\left(\frac{I_o}{I_s}\right) \quad\text{———}\quad (1)$$

$$\frac{\partial V_D}{\partial T} = f\left(V_T\,,\,I_s\right) \qquad \frac{\partial V_T}{\partial T} \;\&\; \frac{\partial I_s}{\partial T}$$

$$\frac{\partial V_D}{\partial T} = \frac{\partial V_T}{\partial T}\ln\left(\frac{I_o}{I_s}\right) + V_T\frac{\partial}{\partial T}\ln\left(I_o/I_s\right)$$

$$= \frac{\partial V_T}{\partial T}\ln\left(\frac{I_o}{I_s}\right) + \frac{V_T}{}\;\frac{1}{I_o/I_s}\;-\frac{I_o}{I_s^2}\,\frac{\partial I_s}{\partial T}$$

$$= \underbrace{\frac{\partial V_T}{\partial T}}_{(2)}\ln\left(\frac{I_o}{I_s}\right) - V_T\,\frac{1}{I_s}\underbrace{\frac{\partial I_s}{\partial T}}_{(4)}$$

$$= \frac{k}{q}\ln\left(\frac{I_o}{I_s}\right) - V_T\,\frac{1}{\cancel{I_s}}\,\cancel{I_s}\left[\frac{E_g}{kT^2} + \frac{4+m}{T}\right]$$

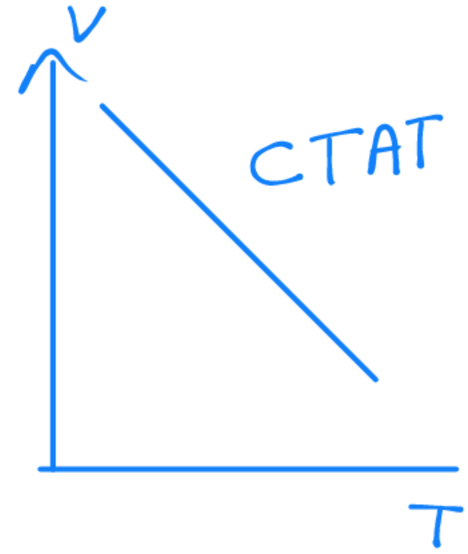
$$= \frac{V_T}{T}\ln\left(\frac{I_o}{I_s}\right) - \frac{V_T}{T}(4+m) - \frac{V_T\,E_g}{kT^2}$$

$$\frac{\partial V_D}{\partial T} = \frac{V_D}{T} - \frac{V_T}{T}(4+m) - \frac{KT}{q}\,\frac{E_g}{KT^2}$$

$$= \frac{V_D}{T} - \frac{V_T}{T}(4+m) - \frac{E_g}{qT}$$

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

slope of CTAT

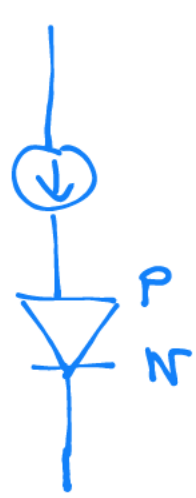


$$\frac{\partial V_D}{\partial T} = \frac{0.7 - (4-3/2)\,26mV - 1.2}{300^\circ K}$$

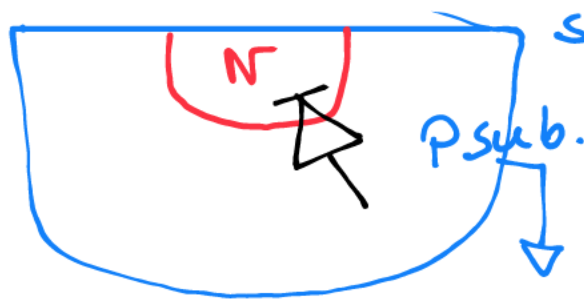
$$= \frac{0.7 - 65mV - 1.2}{300^\circ K} \qquad = -1.6\,mV/K$$

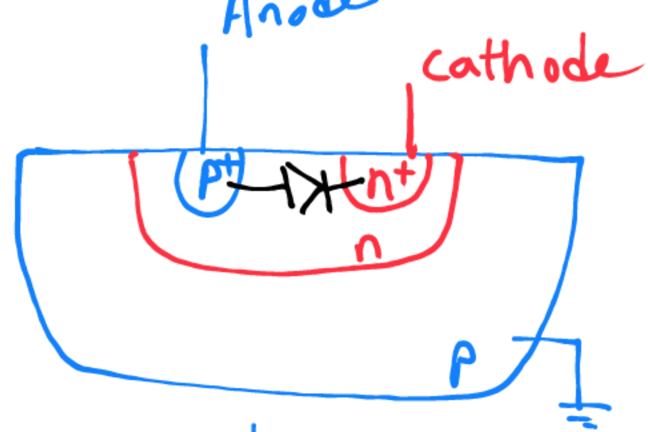
$$= -1.88\,mV/K$$

How to make diode in CMOS Process

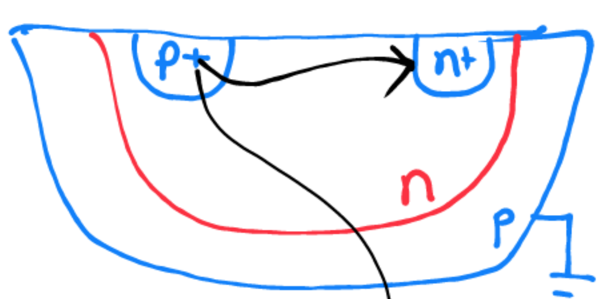


" This implementation isnot sufficient"

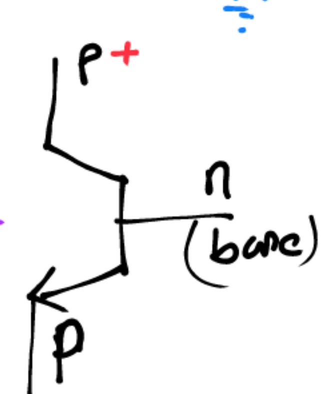




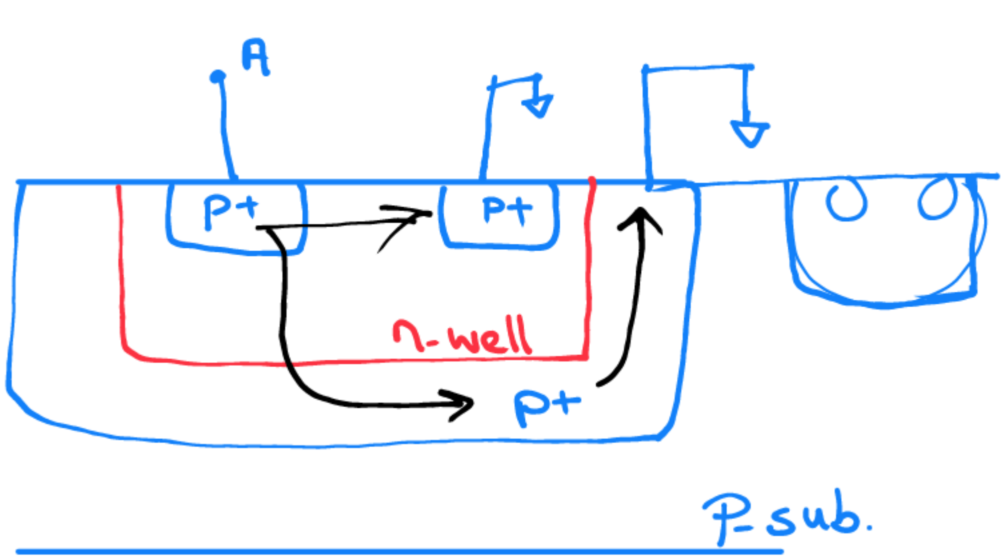
base current leads to large collector current



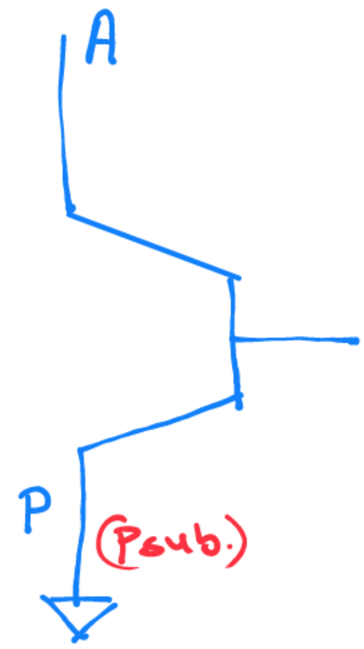
leakage through sub.



Parasitic BJT



"No substrate current"



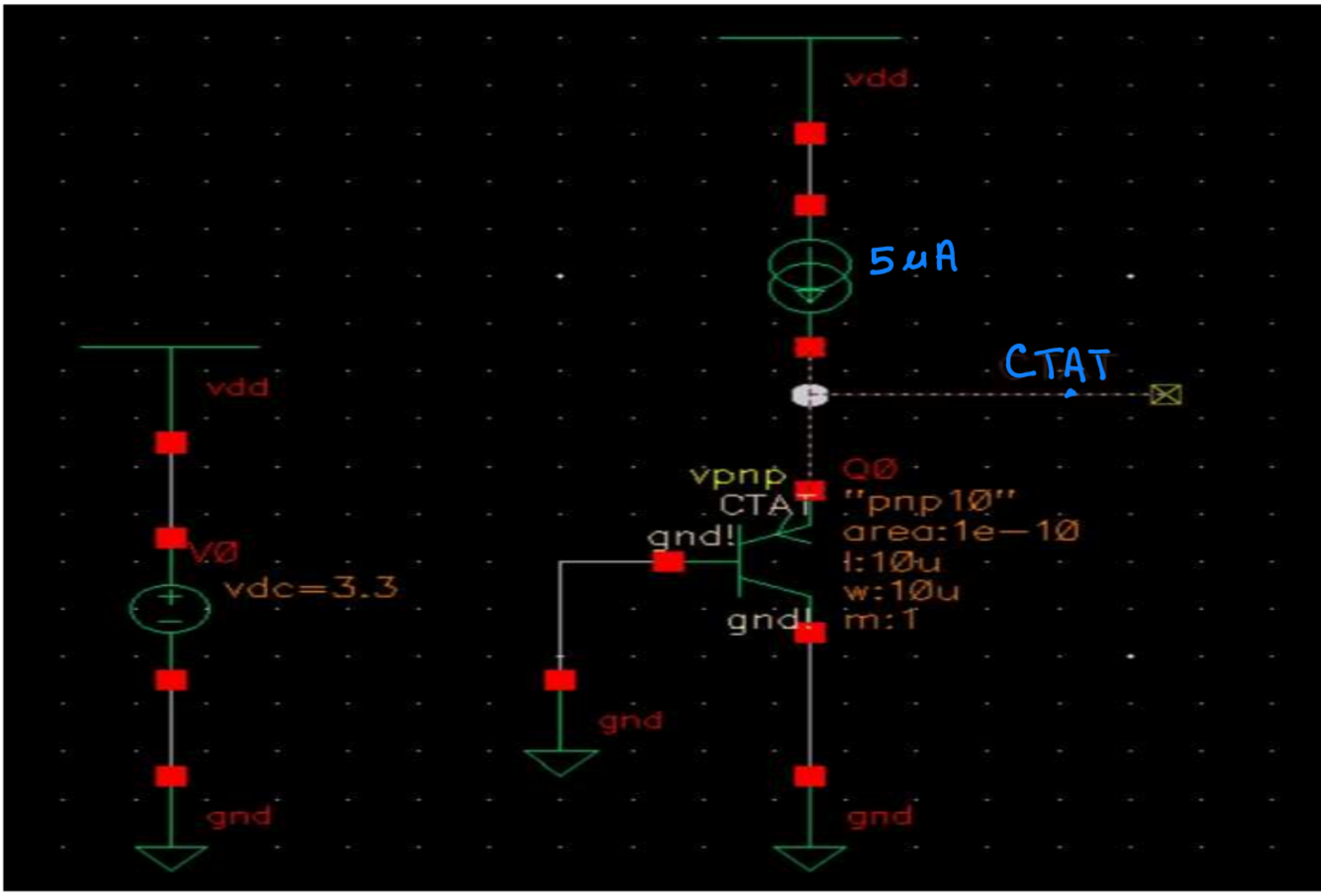
Whenever we want to make diode ckt in CMOS technology, due to various disadvantages, we ended up with parasitic BJT. (can't avoid to form PNP)

The current which was flowing through the substrate, in this place p+ region was created to collect the current,

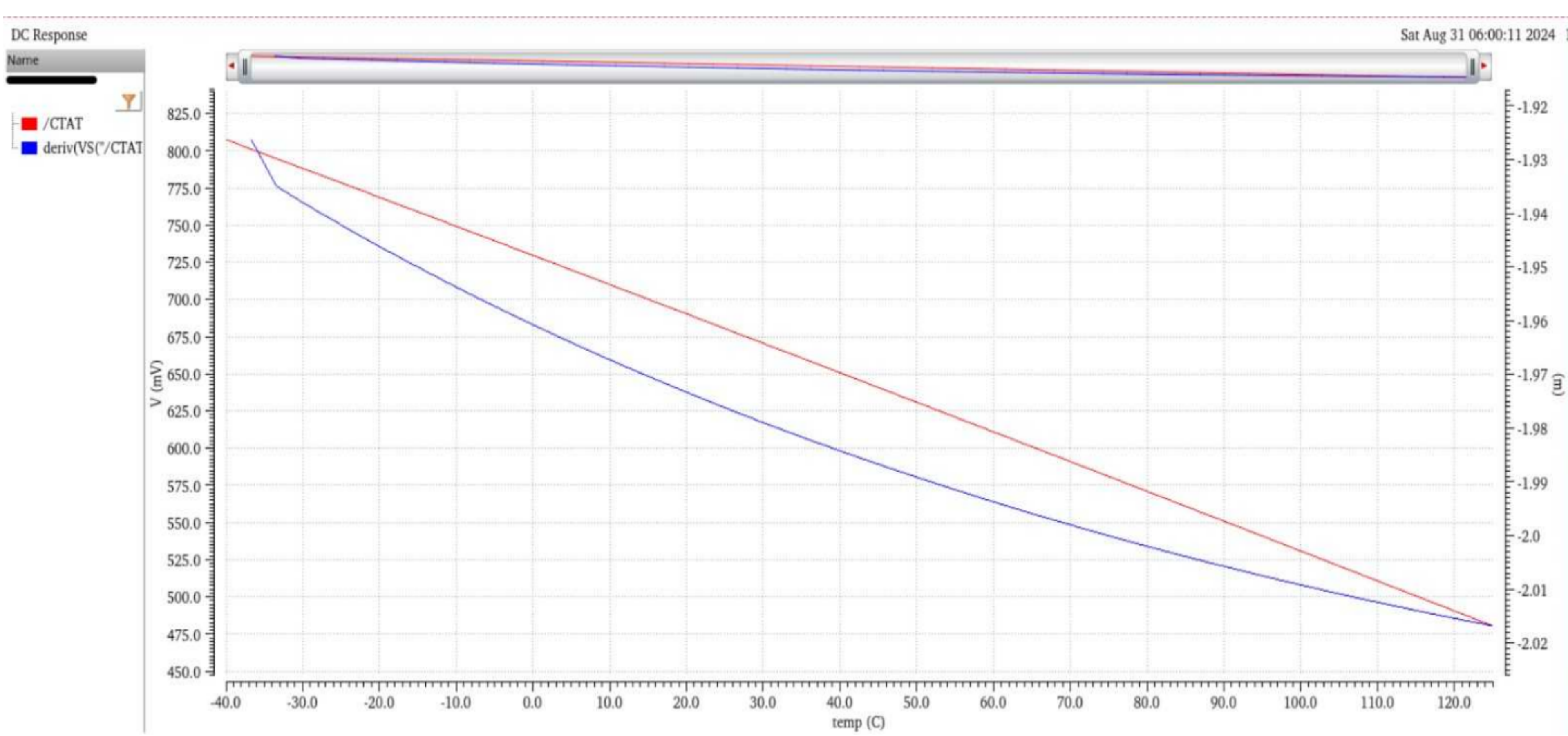
so, other mosfets are not affected by substrate current

DC sweep

Sweep variable : Temp. (−40 to 125)



Output @ CTAT :



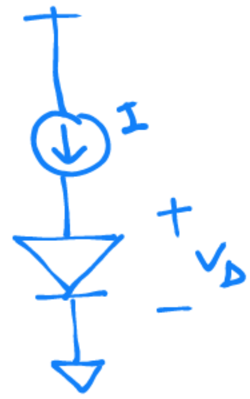
PTAT

$V_t = \frac{KT}{q}$

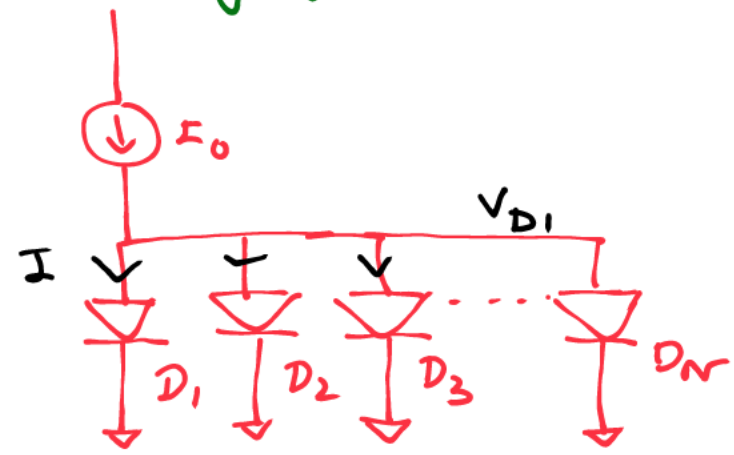
$V_t \propto T$

$V_D = \underbrace{V_t}_{PTAT} \boxed{\underbrace{\ln\left(\frac{I_o}{I_s}\right)}_{CTAT}}$

eliminate $I_s = ?$



Array of Diodes (n)



$V_D - V_{D_1} = ?$

$I = I_s e^{V_{D_1}/V_T}$

$I_o = nI$

$\Rightarrow I_o = n I_s e^{V_{D_1}/V_T}$

$\Rightarrow V_{D_1} = V_T \ln\left(\frac{I_o}{nI_s}\right)$

& $V_D = V_T \ln\left(\frac{I_o}{I_s}\right)$

$\therefore V_D - V_{D_1}$

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

$= V_T \ln\left(\frac{\cancel{I_o}}{\cancel{I_s}} \times \frac{n\cancel{I_s}}{\cancel{I_o}}\right)$

$= V_T \ln(n)$

$\boxed{V_D - V_{D_1} = V_T \ln(n)}$ → constant

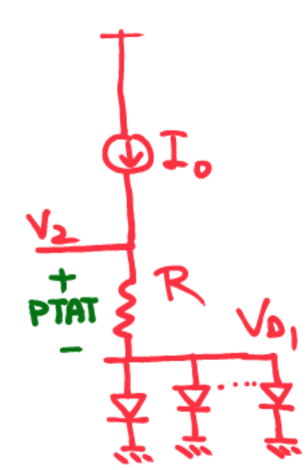
→ PTAT (As $V_T = \frac{KT}{q}$)

Circuit Implementation of these expresions:

Assumption: $V_D = V_2$ Same current I_o

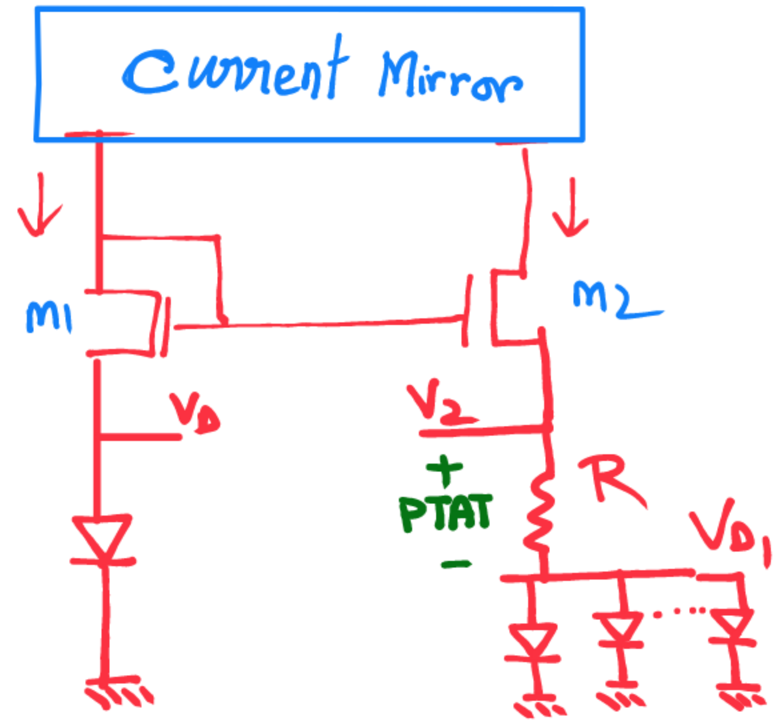
$V_D = I_o R + V_{D_1}$

$\Rightarrow I_o R = V_D - V_{D_1} = \underbrace{V_T \ln(n)}_{PTAT}$



① Current Mirror
② Op amp.

} Two ways.



$I_{Dm_1} = I_{Dm_2}$

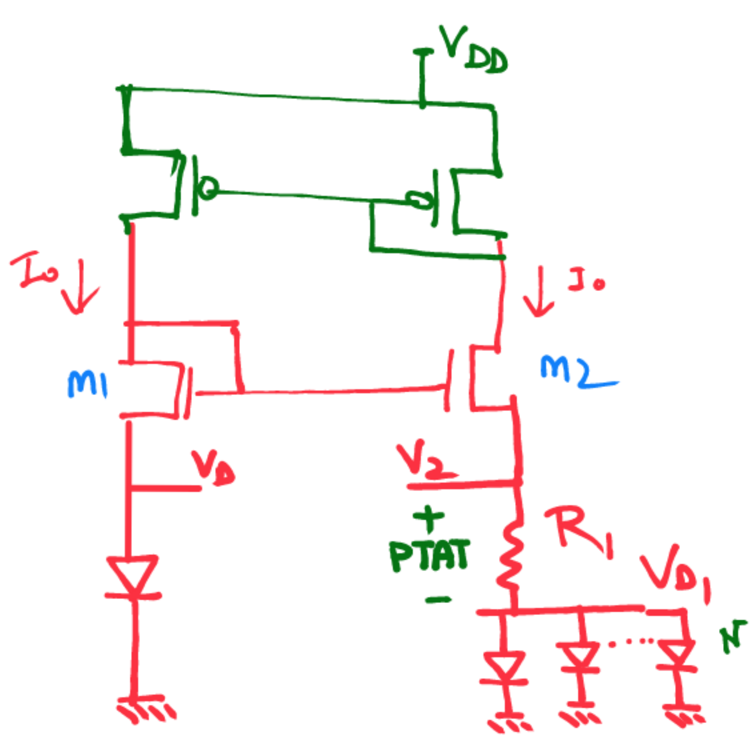
$\Rightarrow k_{n_1}'\left(\frac{W}{L}\right)\frac{(V_{gs_1}-V_t)^2}{2} = k_{n_1}'\left(\frac{W}{L}\right)(V_{gs_2}-V_t)^2$

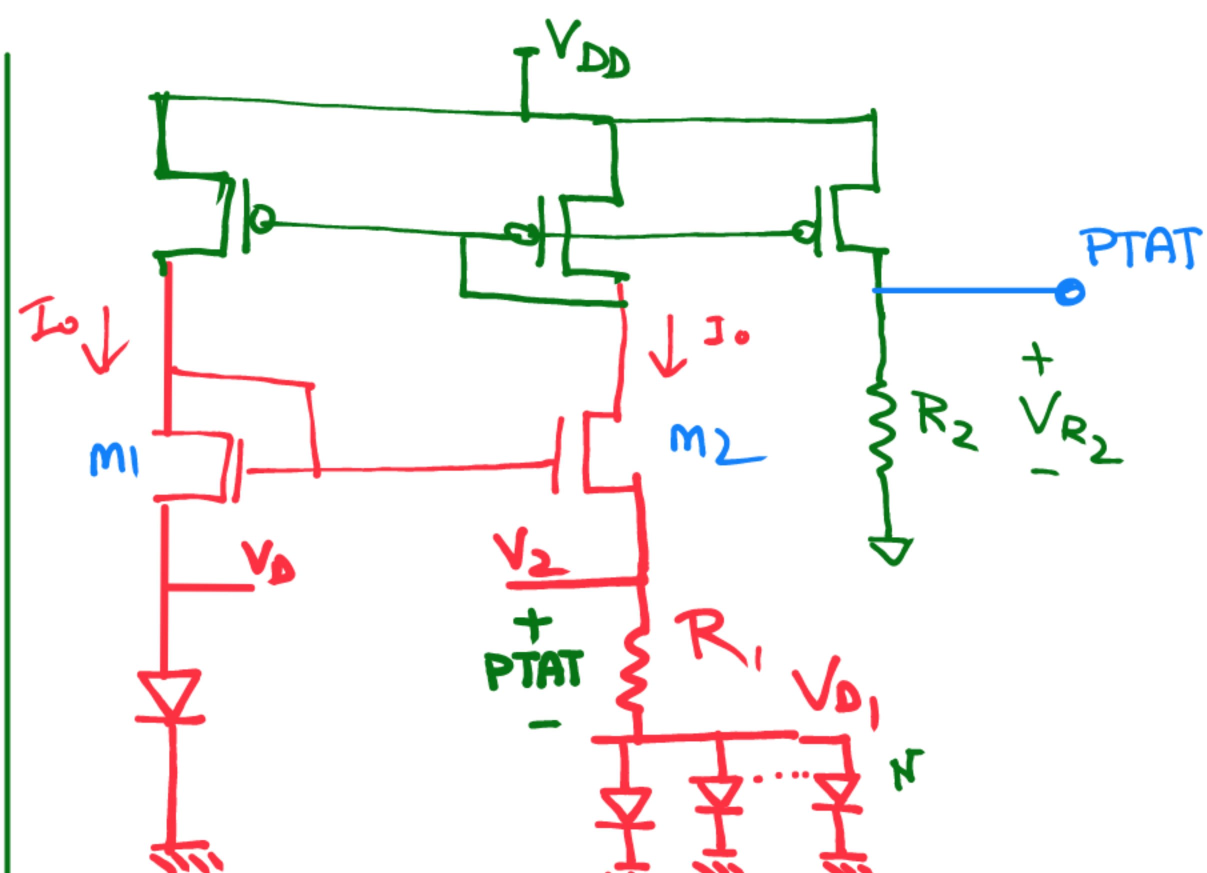
$\Rightarrow V_{gs_1} = V_{gs_2}$

$\Rightarrow V_{s_1} = V_{s_2}$ (source is same)

$\boxed{\therefore V_D = V_2}$

$\underbrace{I_0 R_1}_{\text{PTAT}} = V_T \underbrace{\ln(N)}_{\text{Const}}$



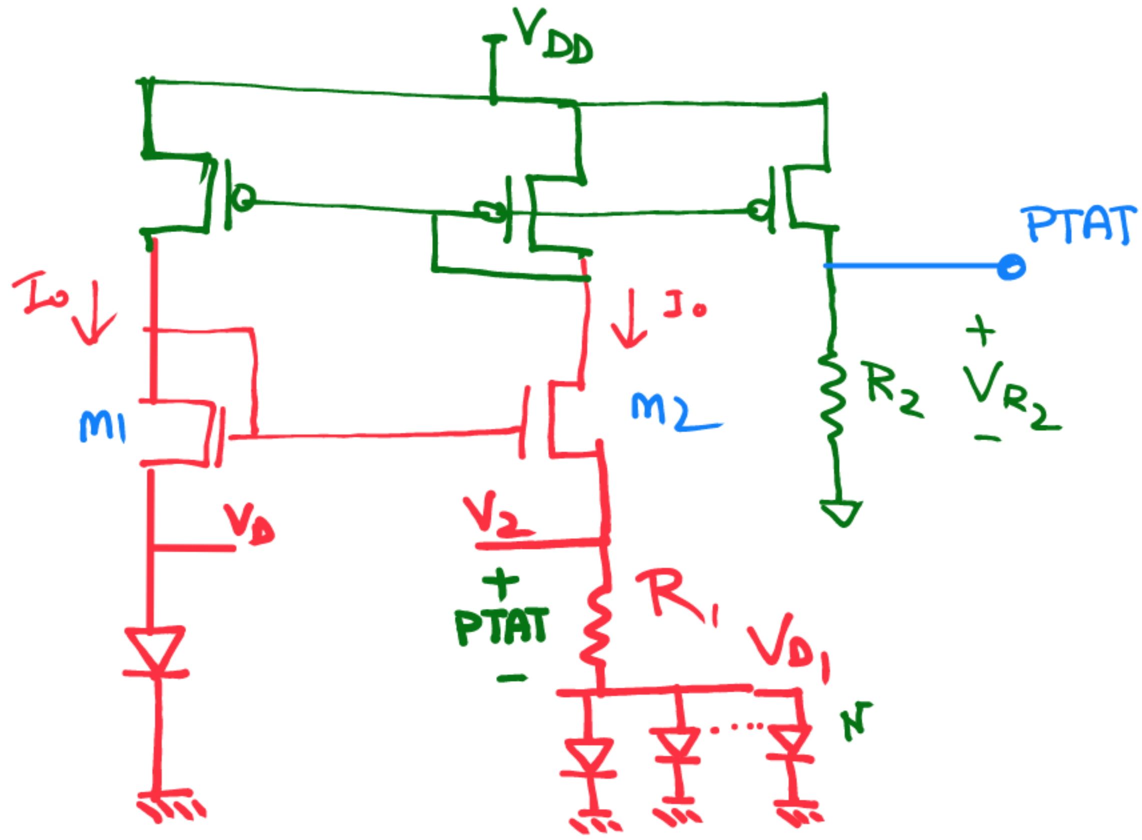


$I_0 R_1 = V_T \ln(N)$

$I_0 = \frac{V_T}{R_1}\ln(N)$

$V_{R_2} = \underbrace{\frac{R_2}{R_1}}_{\text{ratio}} \underbrace{V_T}_{\text{PTAT}} \underbrace{\ln(N)}_{\text{const}}$

$$\boxed{V_{R_2} = \underbrace{\frac{R_2}{R_1}\ln(N)}_{\alpha_1}\ \underbrace{V_T}_{\text{PTAT}}}$$



$$\frac{\partial V_{R_2}}{\partial T} = \frac{R_2}{R_1}\ln(N)\,\frac{\partial V_T}{\partial T}$$

$$\frac{\partial V_T}{\partial T} = \frac{k}{q} = \frac{1.38\times10^{-23}}{1.6\times10^{-19}}$$

$$= 86.25\ \mu V/{}^\circ K$$

87   85

$$\boxed{\begin{aligned} \frac{\partial}{\partial T}(\text{CTAT}) &= -1.6\ mV/{}^\circ K \\ \frac{\partial}{\partial T}(\text{PTAT}) &= 85\ \mu V/{}^\circ K \end{aligned}}$$

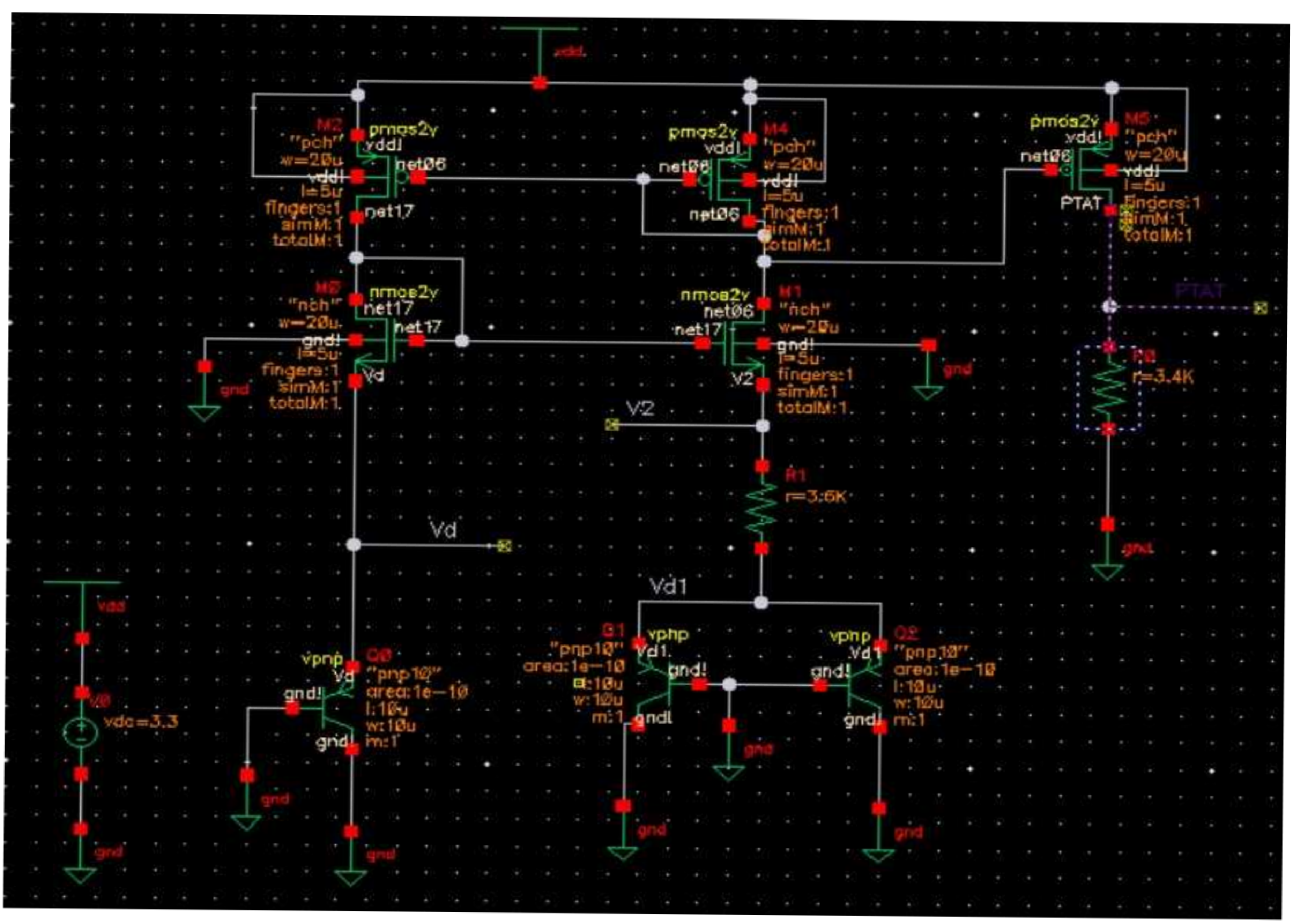
Used large W & L → to reduce the effect of process variation.

$$R_1 = \frac{V_T \ln(N)}{I} \qquad N = 2, \quad I = 5\mu A$$

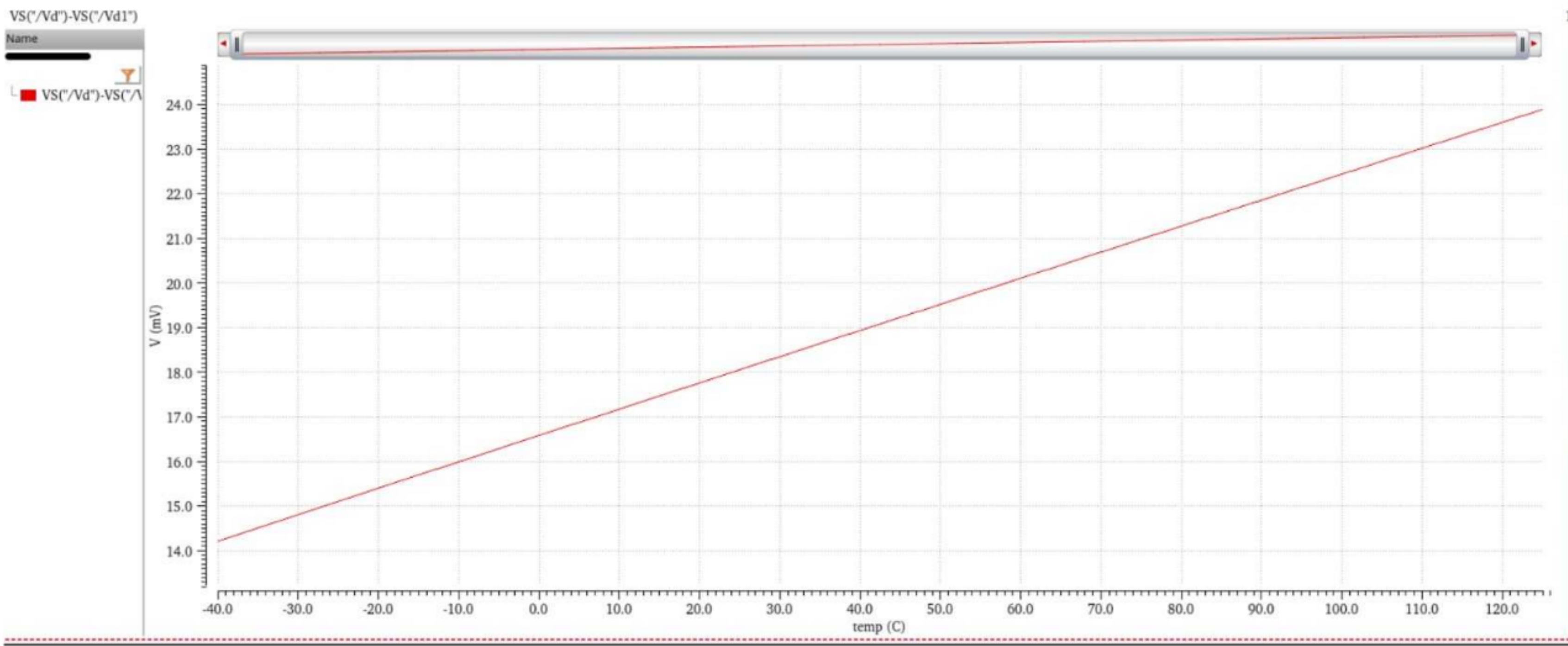
$$= \frac{0.026 \times \ln(2)}{5\mu}$$

$$= 3.6\,k\Omega$$

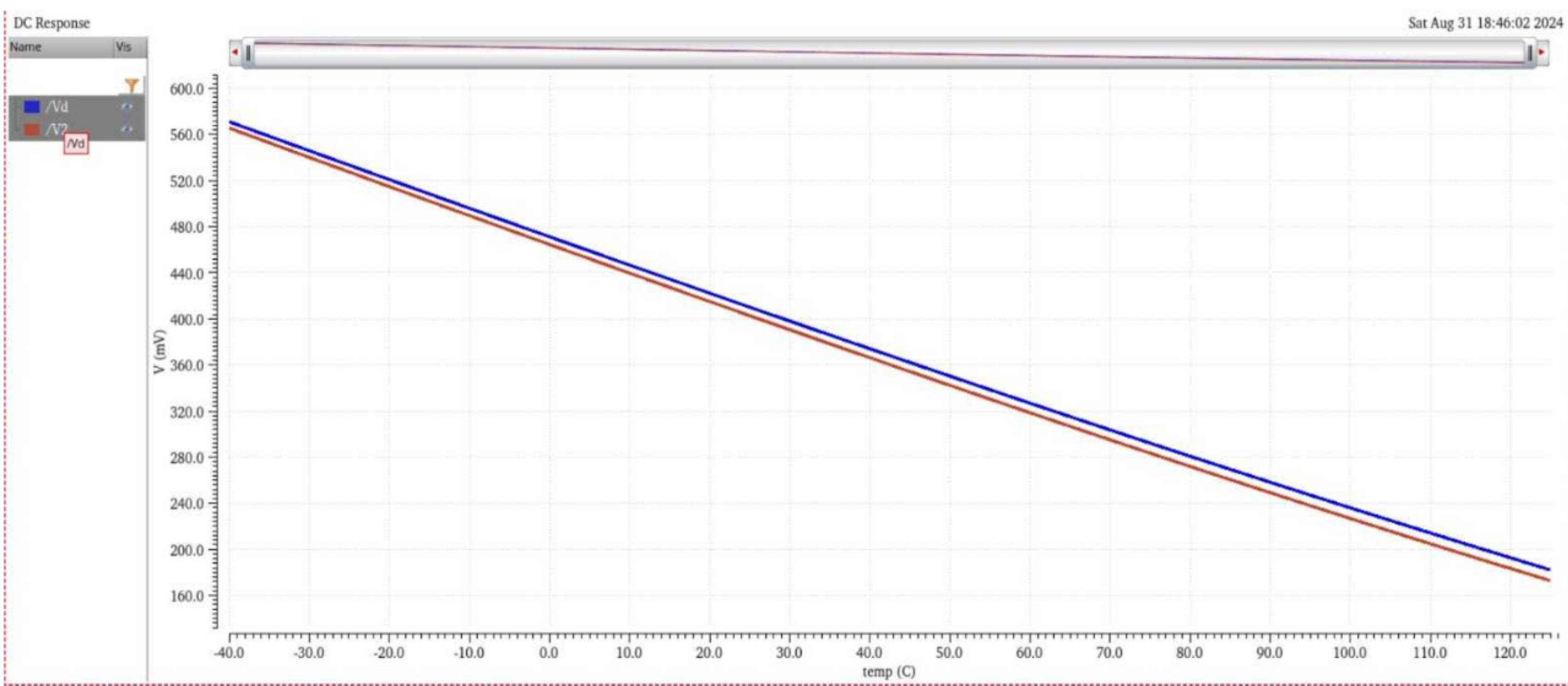
Schematic :



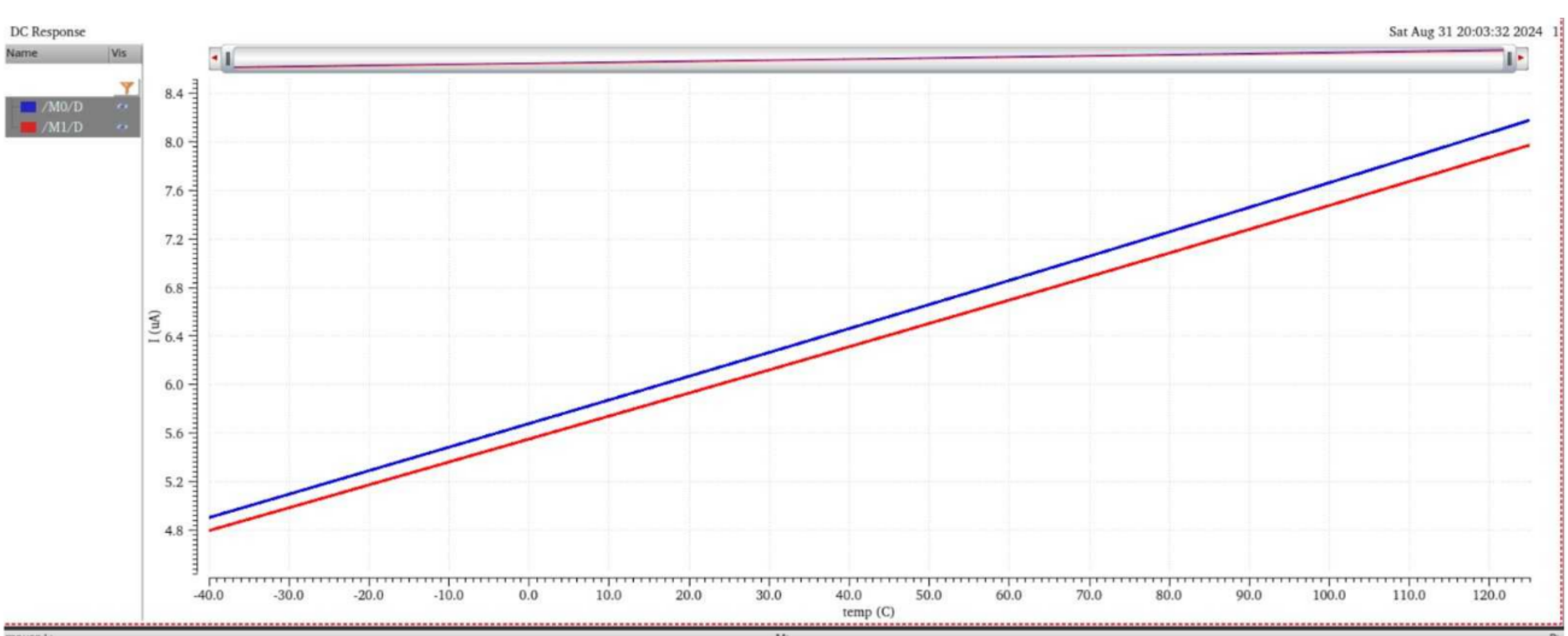
$V_d - V_{d1}$:



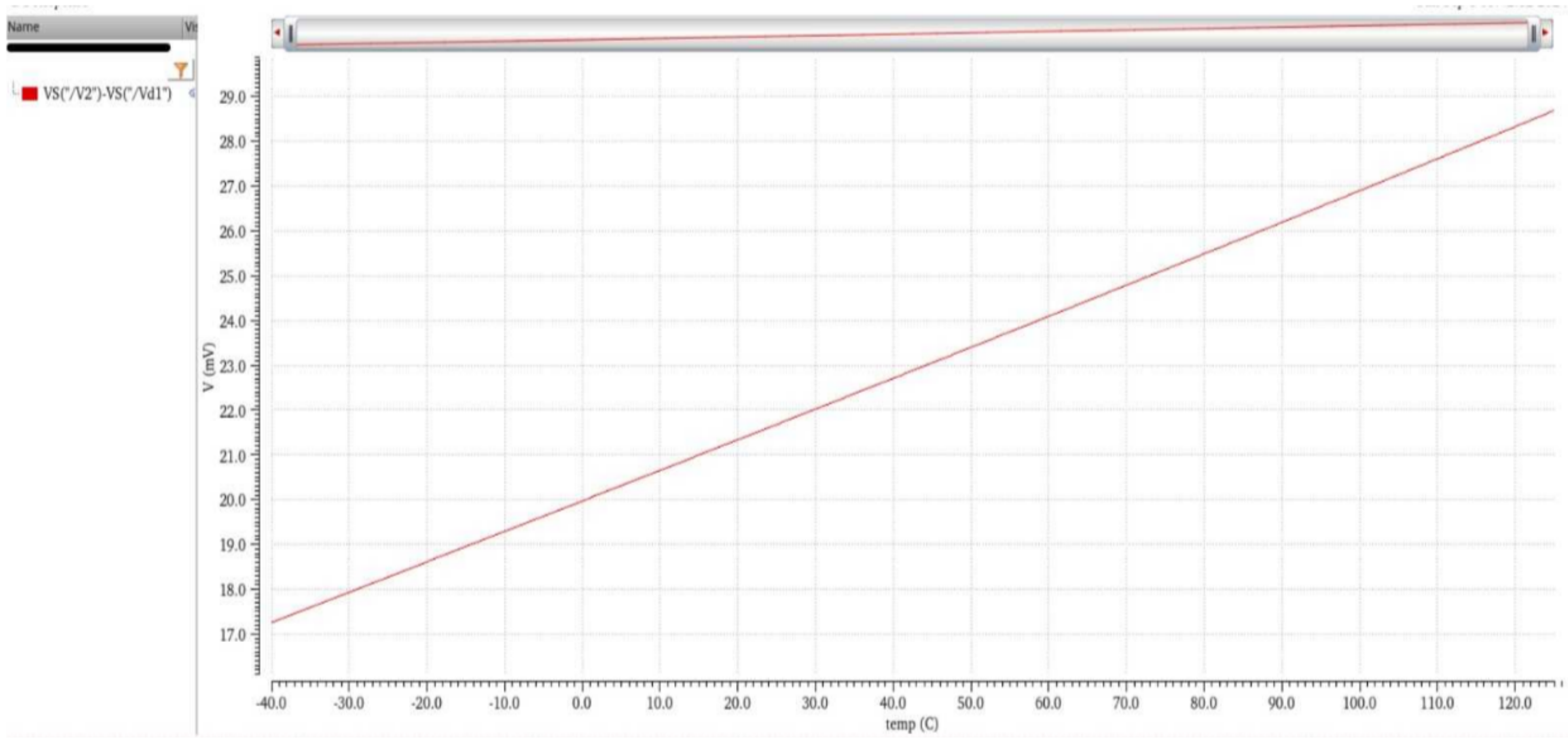
$V_2 \simeq V_d$ (nearly $R_1 = 3.6\,k\Omega$) :



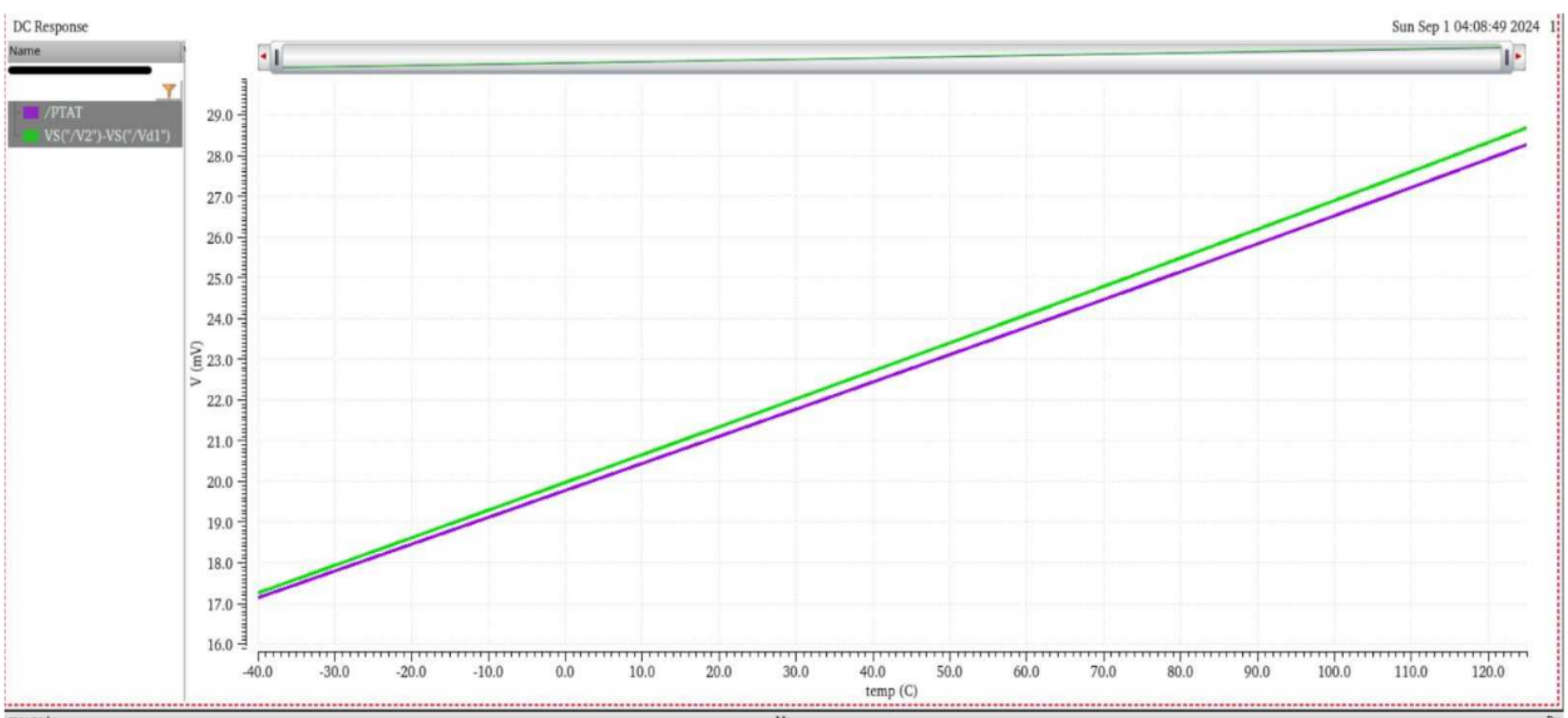
current across M_0 & M_1 mosfets:



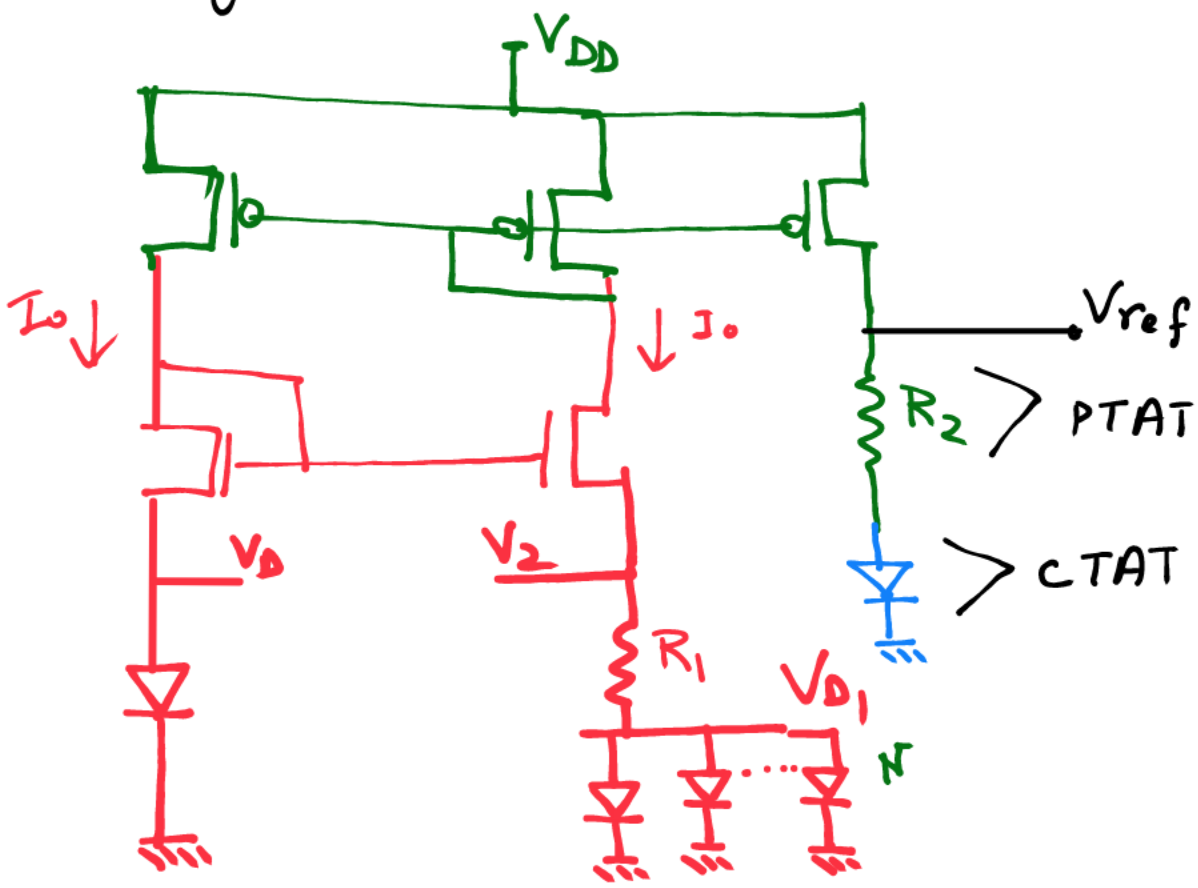
$V_2 - V_{d1}$:



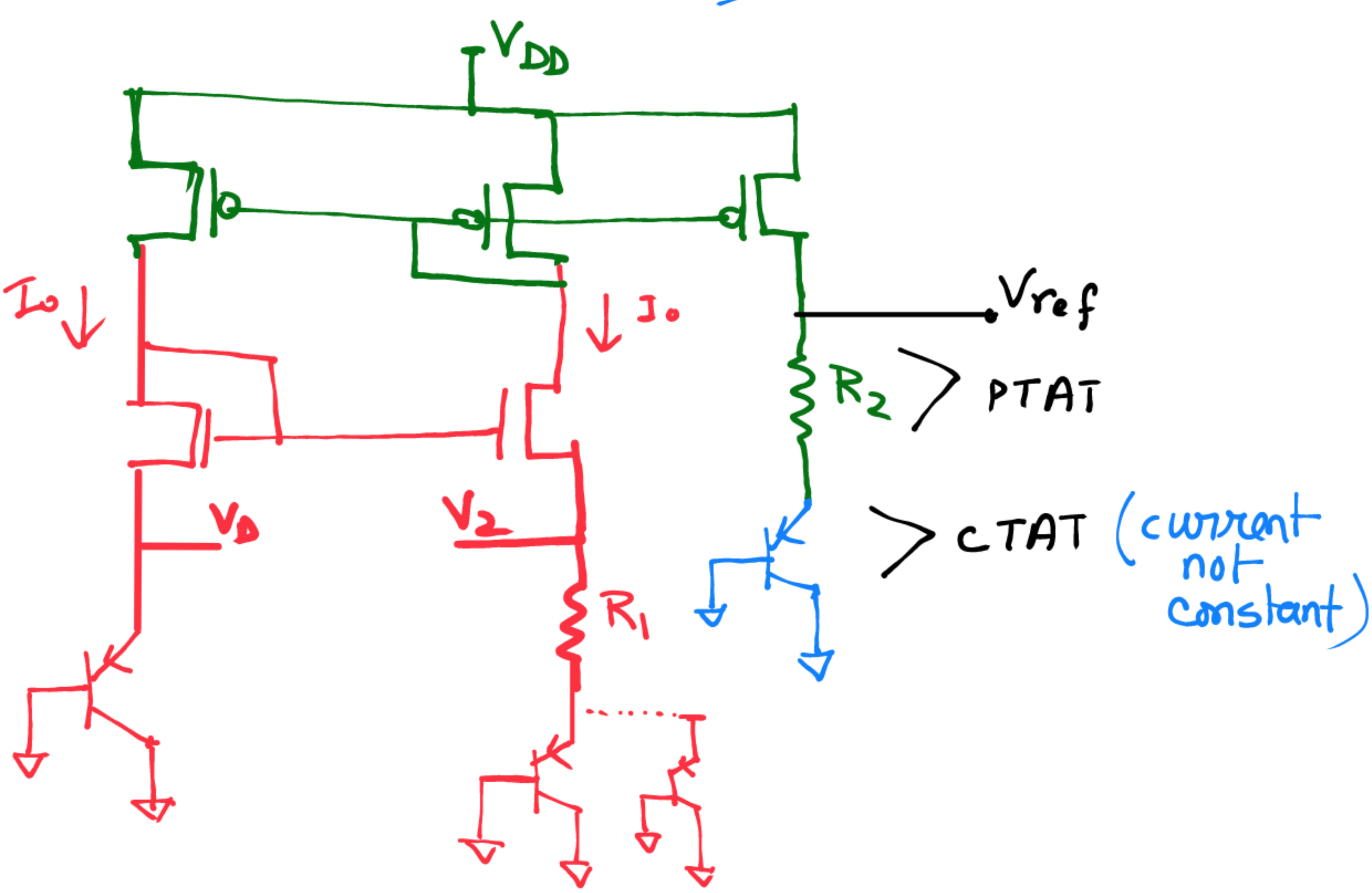
Comparison between $V_2 - V_{d1}$ & PTAT voltage across R_2 :



Adding PTAT & CTAT



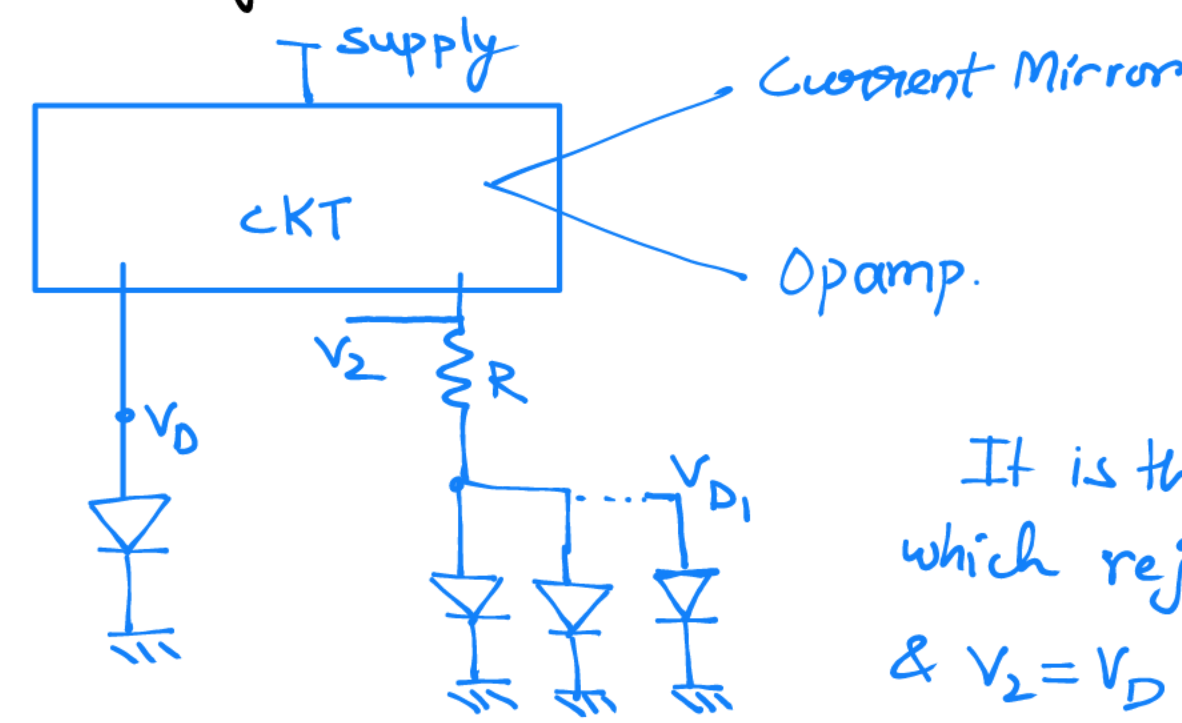
More familiar form (with BJT):



3 issues:

1. Supply Variation
2. Current across the BJT is not constant (PTAT in nature)
3. α_1 & α_2

Supply Variation:



It is the duty of that ckt., which rejects the supply variation & $V_2 = V_D$

$I_0 = \frac{V_T \ln(n)}{R_1}$ → PTAT current.

$V_D = V_T \ln\left(\frac{I_0}{I_s}\right)$ ⟶ effectively CTAT

V_T → weak PTAT

$\ln\left(\frac{I_0}{I_s}\right)$ → strong CTAT

Now, I_0 → PTAT

Considering current as a PTAT :

$$\frac{\partial V_D}{\partial T} = \frac{\partial}{\partial T}\left[V_T \ln\left(\frac{I_o}{I_s}\right)\right]$$

$$= \frac{\partial}{\partial T} V_T\left[\ln(I_o) - \ln(I_s)\right]$$

$$\frac{\partial V_D}{\partial T} = V_T\left[\frac{1}{I_o}\frac{\partial I_o}{\partial T} - \frac{1}{I_s}\frac{\partial I_s}{\partial T}\right] + \left[\ln(I_o) - \ln(I_s)\right]\frac{\partial V_T}{\partial T}$$

only thing which is remaining

$$I_o = \frac{\ln(N)}{R_1} . V_T$$

$$\frac{\partial I_o}{\partial T} = \frac{\ln(N)}{R_1}\frac{\partial V_T}{\partial T}$$

$$\frac{\partial I_o}{\partial T} = \frac{K}{q}\frac{\ln(N)}{R_1}$$

$$\frac{\partial I_o}{\partial T} = \frac{\ln(N)}{R_1} . \frac{V_T}{T}$$

$$\boxed{\frac{\partial I_o}{\partial T} = \frac{I_o}{T}} \qquad (5)$$

Rewriting eq^n (4): $\frac{\partial I_s}{\partial T} = I_s\left[\frac{4+m}{T} + \frac{E_g}{KT^2}\right] \qquad (4)$

$$\frac{\partial V_T}{\partial T} = \frac{K}{q} = \frac{V_T}{T} \qquad (2)$$

$$\frac{\partial V_D}{\partial T} = V_T\left[\frac{1}{\cancel{I_o}} . \frac{\cancel{I_o}}{T} - \frac{1}{\cancel{I_s}} \cancel{I_s}\left(\frac{4+m}{T} + \frac{E_g}{KT^2}\right)\right] + \ln\left(\frac{I_o}{I_s}\right)\frac{V_T}{T}$$

$$= V_T\left[\frac{1}{T} - \frac{4+m}{T} - \frac{E_g}{KT^2}\right] + \frac{V_T}{T}\ln\left(\frac{I_o}{I_s}\right)$$

$$\frac{\partial V_D}{\partial T} = V_T\left(\frac{1-(4+m)}{T} - \frac{E_g}{KT^2}\right) + \frac{V_D}{T}$$

$$\frac{\partial V_D}{\partial T} = \frac{V_D}{T} - \frac{(4+m-1)V_T}{T} - \frac{V_T E_g}{KT^2}$$

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

$$\boxed{\frac{\partial V_D}{\partial T} = \frac{V_D - (3+m)V_T - E_g/q}{T}}$$ $\Rightarrow I_o$ as PTAT

whereas, $\frac{\partial V_D}{\partial T} = \frac{V_D - (4+m)V_T - E_g/q}{T}$ $\Rightarrow I_o$ as const.

$\rightarrow -1.88\ mV/^{\circ}K$

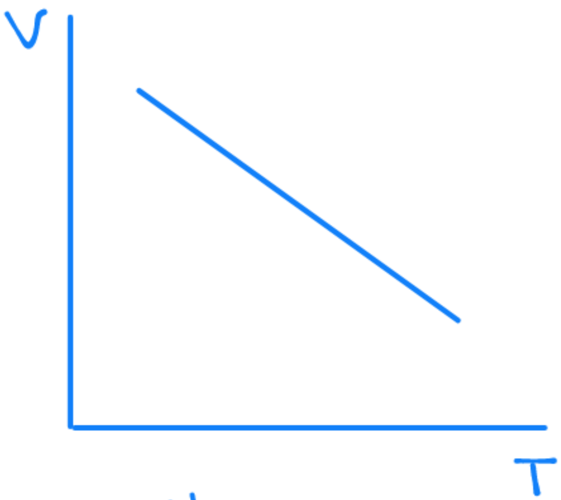
$$\frac{\partial V_D}{\partial T} = \frac{0.7 - (3-1.5)25m. - 1.2}{300}$$

$$= \frac{0.7 - 39\,mV - 1.2}{300}$$

$$= -1.79\ mV/^{o}K$$

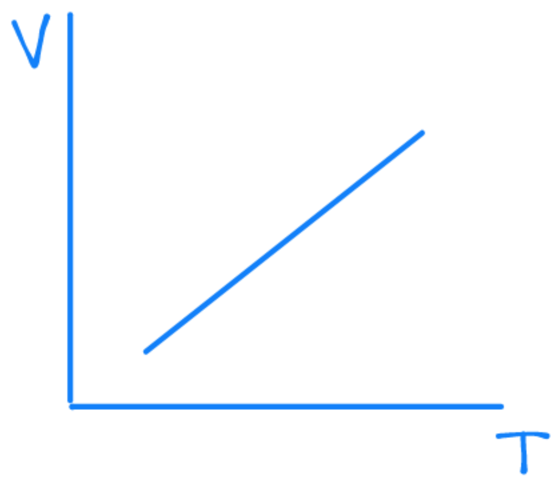
I_o is PTAT in nature, considering that slope of CTAT is -1.79 whereas I_o as a constant source, slope found $-1.88\ mV/^{o}K$. Which is more or less same. So this issue is resolved

Design of α_1 & α_2



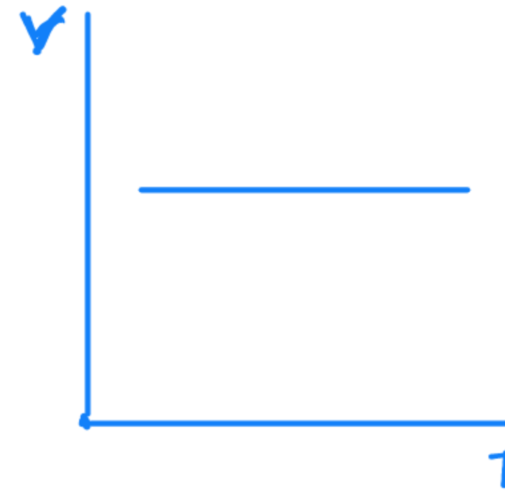
Slope -ve

$-1.6\,mV/^\circ C$



Slope +ve

$85\,\mu V/^\circ C$



slope = 0

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

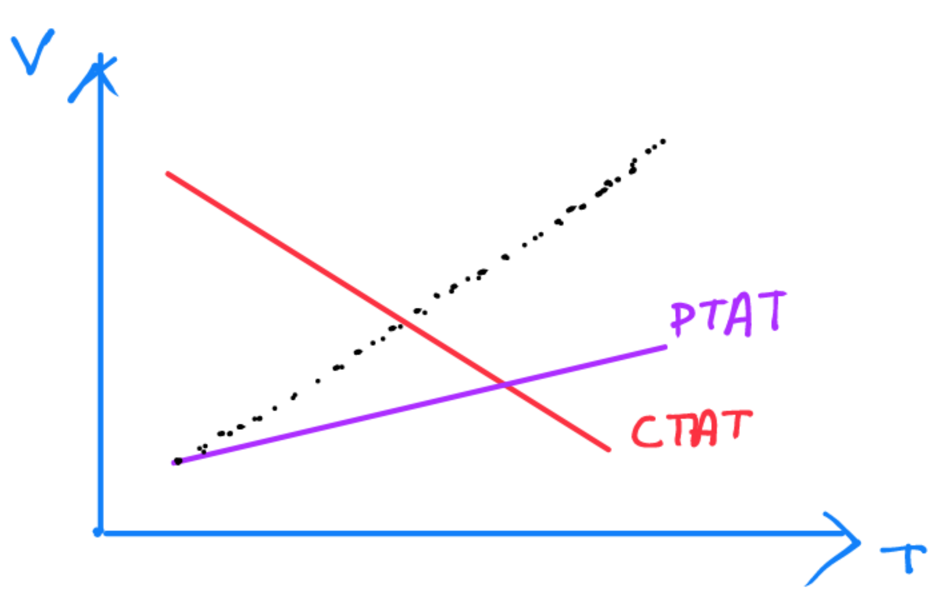
$$V_{ref} = \alpha_1\,CTAT + \alpha_2\,PTAT$$

$$V_{R_2} = \underbrace{\frac{R_2}{R_1}\ln(N)}_{\substack{\alpha_1 \\ \text{constant}}}\;\underbrace{V_T}_{PTAT} \quad \text{———— (A)}$$

$$V_{ref} = \alpha_1 V_T + \alpha_2 V_D \quad \text{———— (B)}$$

$$\frac{\partial V_{ref}}{\partial T} = 0 \;\Rightarrow\; \alpha_1\frac{\partial V_T}{\partial T} + \alpha_2\frac{\partial V_D}{\partial T} = 0$$

$$\alpha_1\,(85\,\mu V/^\circ C) + \alpha_2\,(-1.6\,mV/^\circ C) = 0$$



$\alpha_2 = 1$

$\alpha_1 \rightarrow$ change

(adjusting PTAT)

$$\alpha_1 \cdot 85\,\mu V = \alpha_2 \cdot 1.6\,mV$$

$$\alpha_1 \cdot \underbrace{85\,\mu V}_{PTAT} = \underbrace{1.6\,mV}_{CTAT}$$

$$\alpha_1 = \frac{1.6m}{85\mu} = 18.82$$

$$V_{ref} = \alpha_1 \cdot PTAT + CTAT$$

$$\boxed{V_{ref} = \underbrace{\frac{R_2}{R_1}\ln(N)}_{\substack{\alpha_1 \\ =18.82}} \cdot V_T + V_D} \qquad \alpha_2 = 1$$

Derived from equation (A)

$$\boxed{V_{ref} = 18.82\,V_T + V_D}$$

$$V_{ref} = 18.82 \times 26\,mV + 0.7$$
$$= 1.189$$
$$\simeq 1.2\ V$$

Now, $\alpha_1 = 18.82 = \frac{R_2}{R_1}\ln(N)$

(In layout pt. of view $N = 8$ is a good value)
"For better matching"

eg: $I_0 = 5\mu A$ | $N = 2$, $V_T = 26mV$

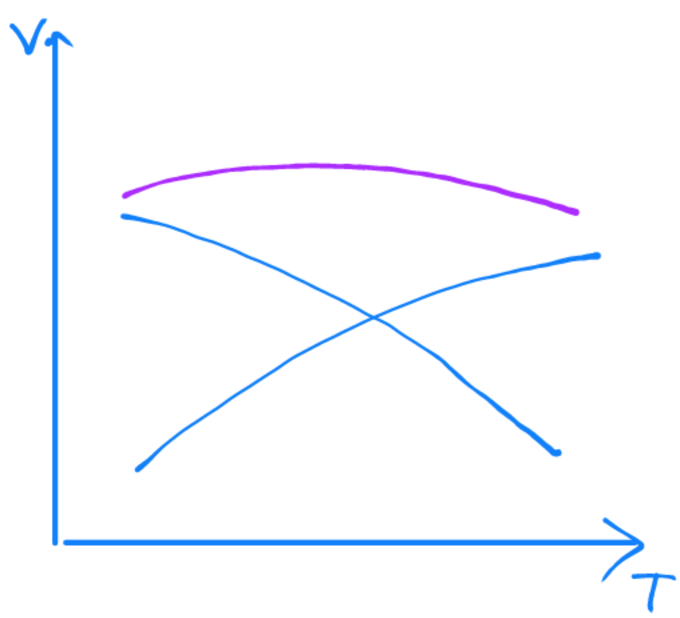
$$I_0 = \frac{V_T \ln(N)}{R_1}$$

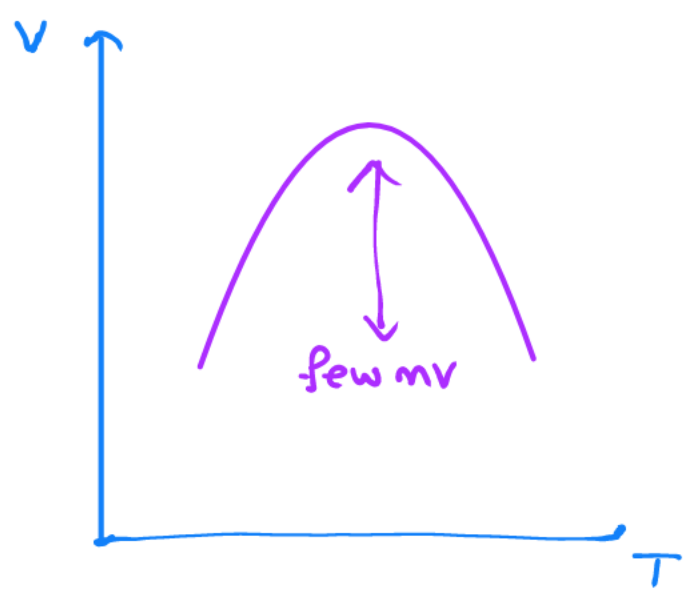
$$\Rightarrow R_1 = \frac{V_T \ln(N)}{I_0} = \frac{26mV \times \ln(2)}{5\mu A} = 3.6k\Omega$$

Now, $\alpha_1 = 18.82$

$$\alpha_1 = \frac{R_2}{R_1}\ln(N)$$

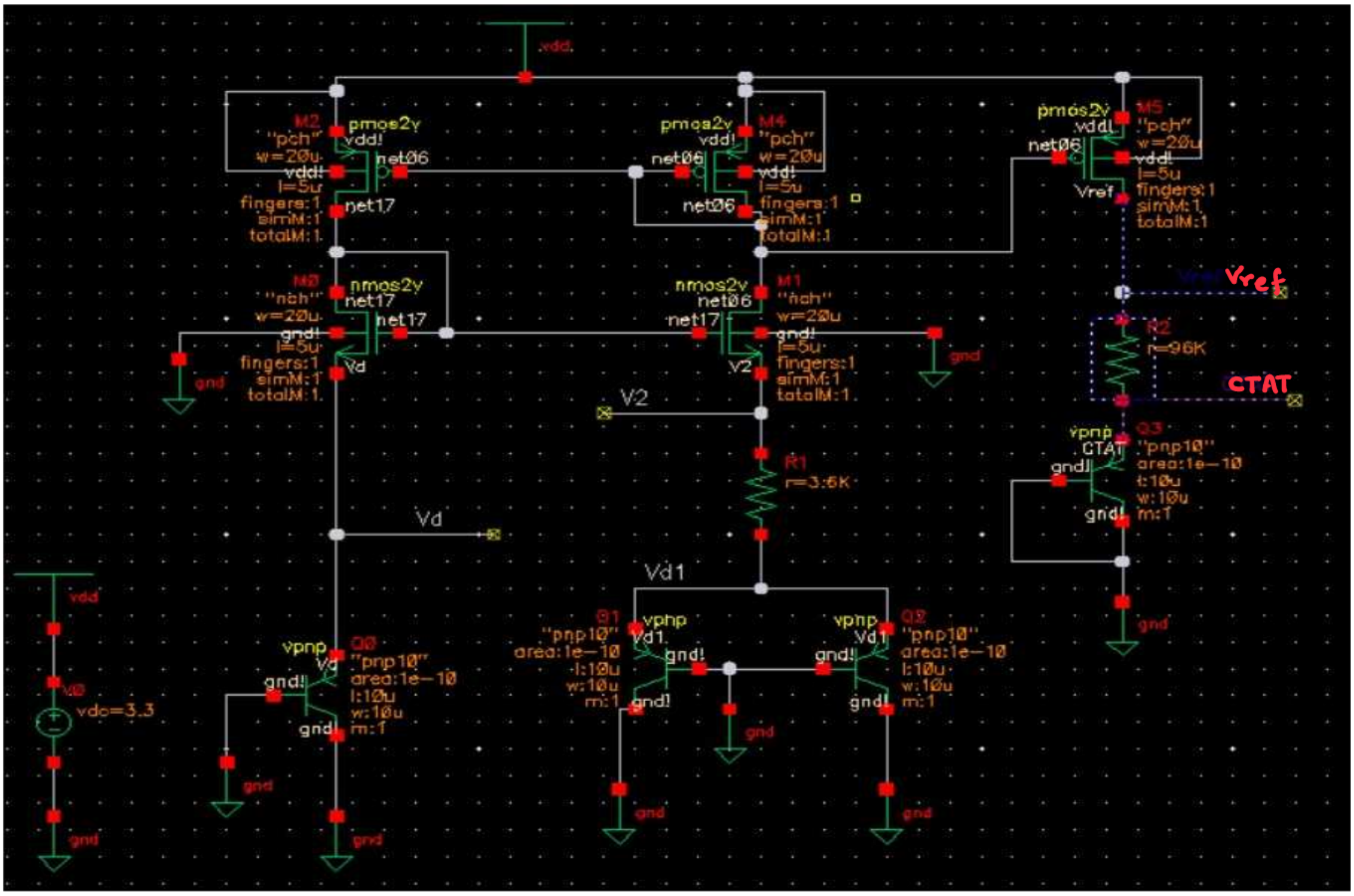
$$\Rightarrow R_2 = \frac{3.6 \times 18.82}{\ln(2)} = 97.7k\Omega$$



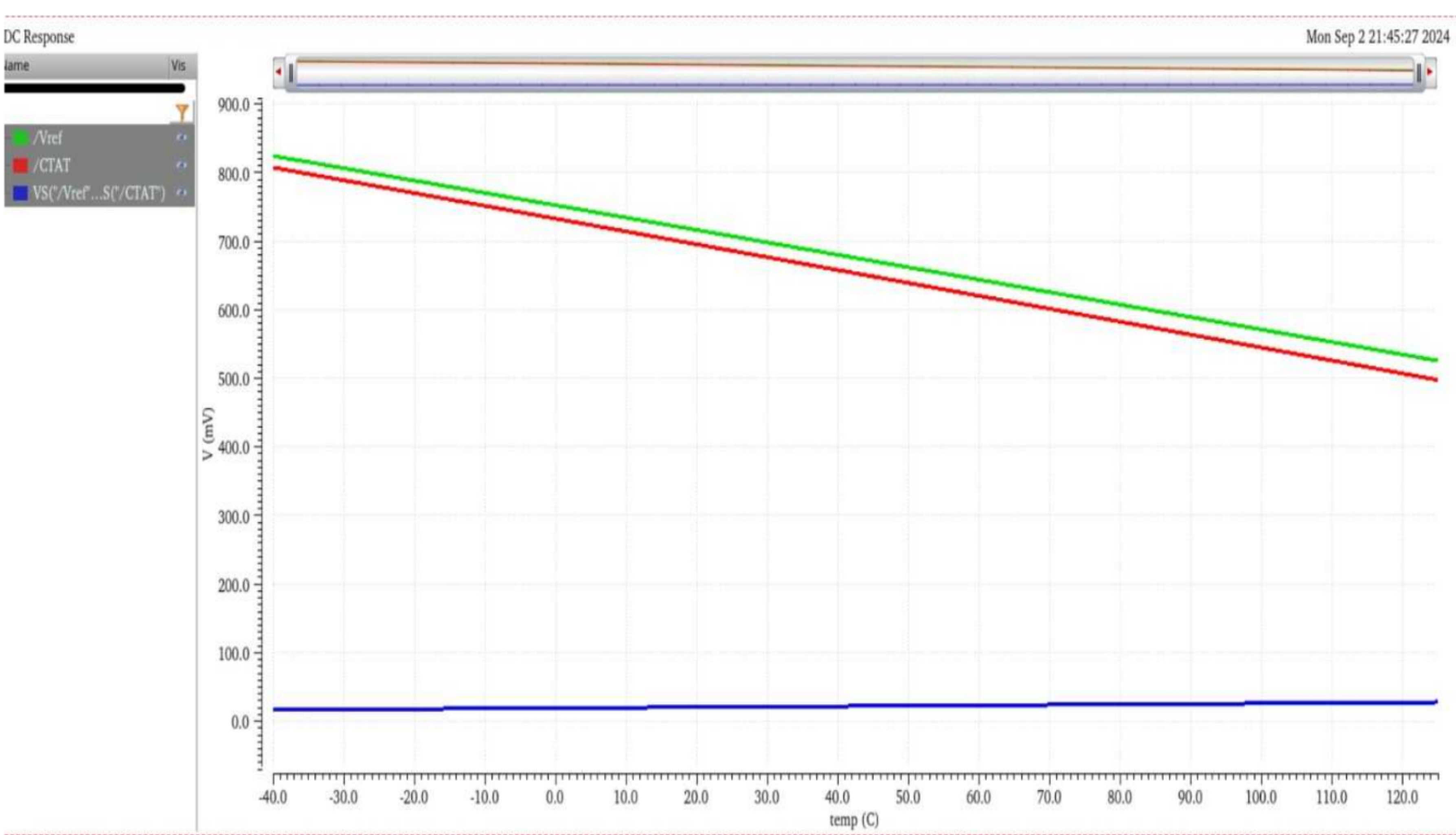


This bell shaped curve appears because of the Non-linearity of PTAT & CTAT

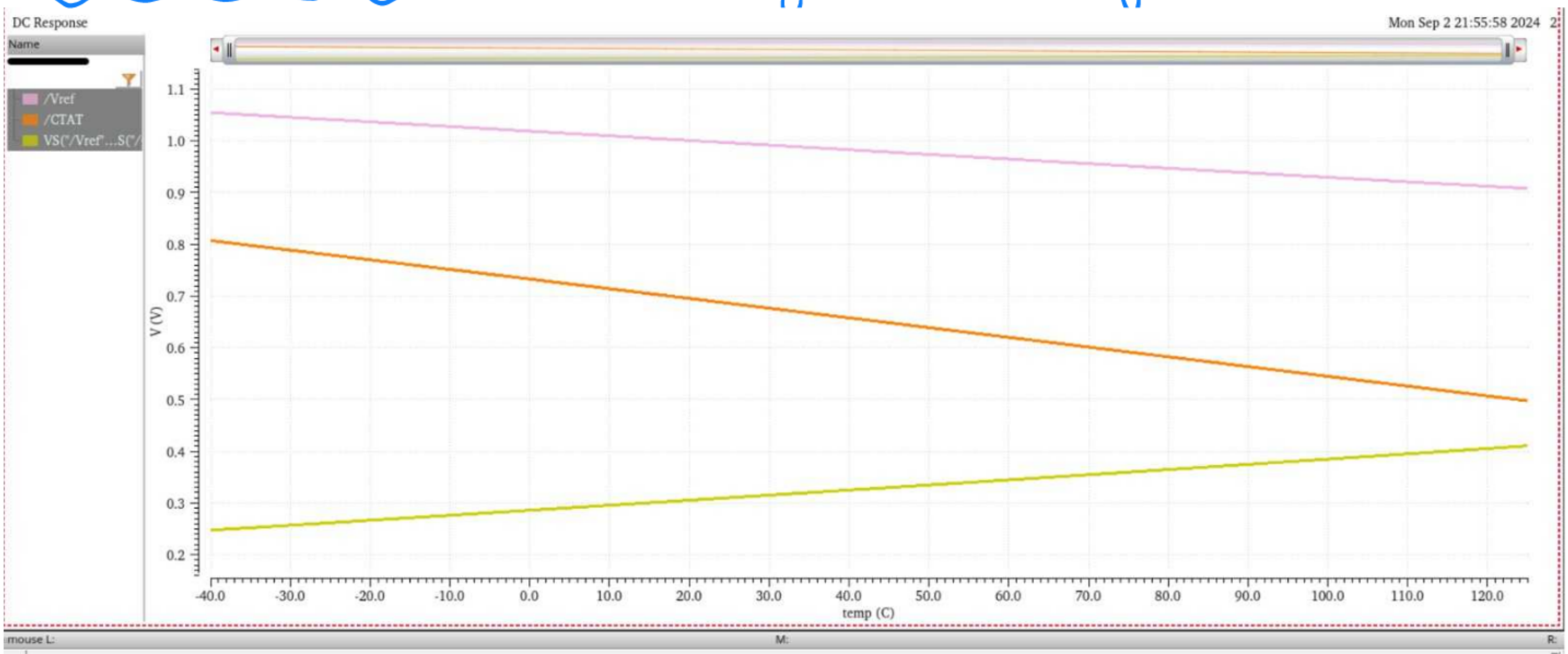
Schematic :



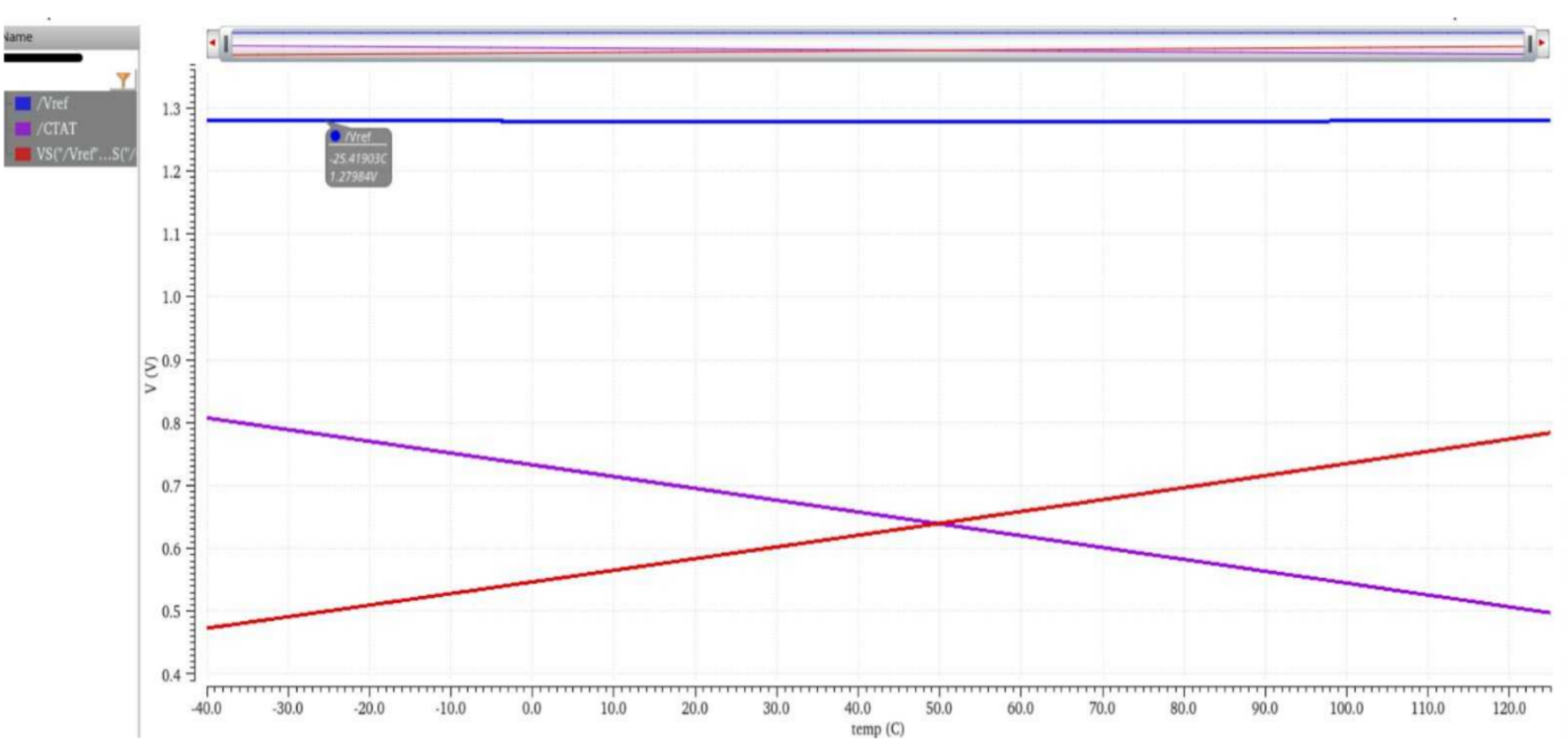
For $R_2 = 3.4K\Omega$ CTAT is strong & effectively Vref → CTAT



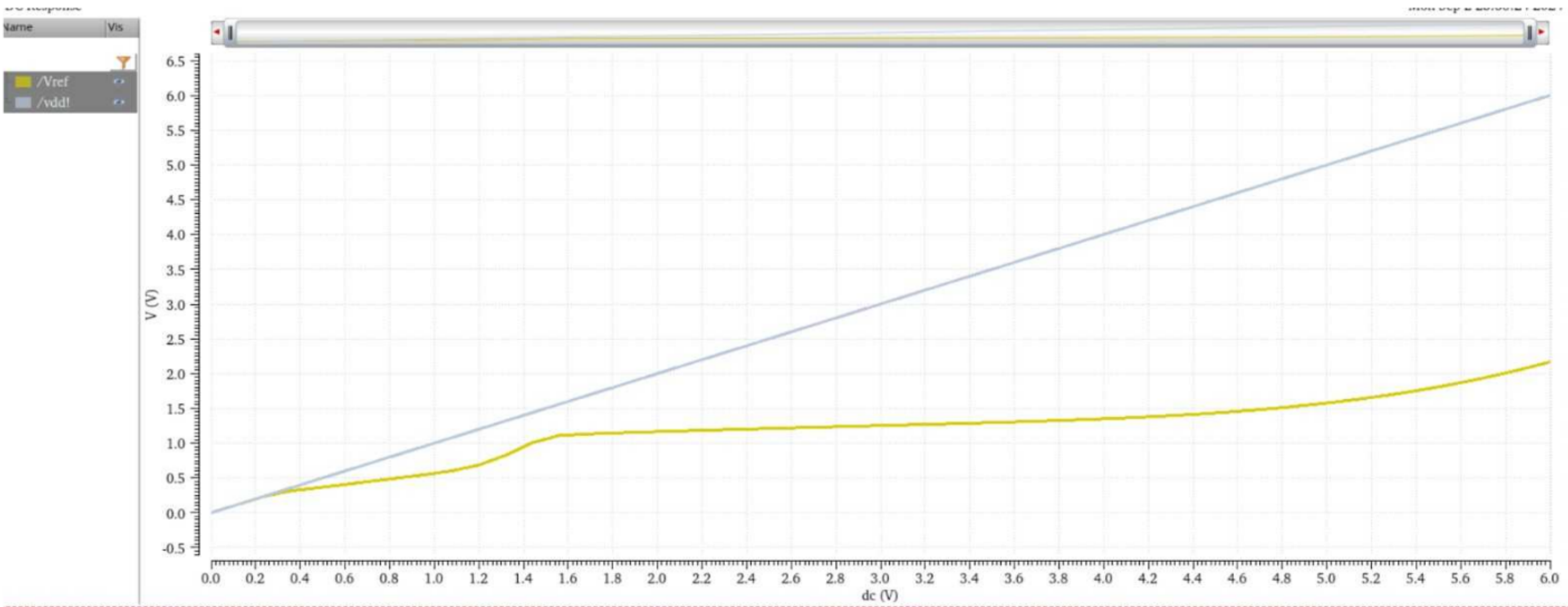
For $R_2 = 50\,k\Omega$ CTAT is strong & effectively $V_{ref} \to$ CTAT



For $R_2 = 96\,k\Omega$, $V_{ref} \simeq$ Constant.



Vref variation with supply voltage:



→ For better supply variation rejection → improve the current mirror. → cascode structure
(But min supply voltage should be higher to turn all the Mosfets in saturation)

For higher variation of voltage → need cascode structure

With Cascode Structure: