Purpose of Bandgap reference circuit:

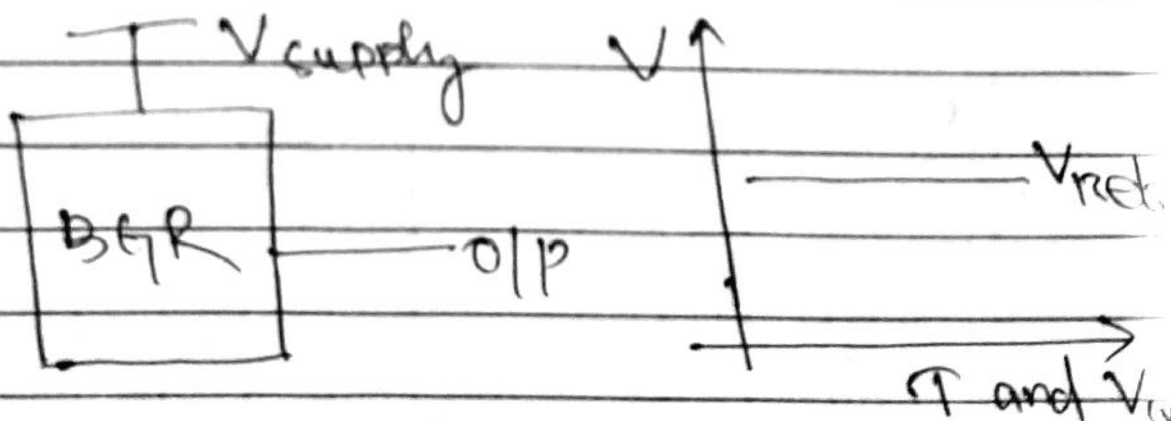
→ Bandgap reference or voltage reference is one of the major building block of every analog circuit.

*

→ The functionality of the bandgap reference is to give constant voltage independent of Temperature and supply voltage variations.

Application of BGR

→ Voltage regulators and LDO's
→ Boost and Buck converters
→ ADC's and DAC's
→ Data acquisition systems.



(*) Temp variation: $-40^\circ c$ to $125^\circ c$
(*) Supply variation: $\pm 10\%$ or $\pm 20\%$.

Before going to discuss about BGR, first, we should discuss ~~ab~~ about ~~ref~~ Reference voltage generators. ~~need~~ ~~need~~

Reference voltage generators are used in DRAM's, flash memories, and ~~abo~~ analog devices. The generators are required to be stabilized over process, voltage and temperature variations.

Different way of implementing voltage reference circuits:

(a) use of a Zener diode that breaks down at a known voltage when reversed biased.

(b) Making use of the threshold voltage of an MOS device.

(c) Cancelling the negative temp. dependence of a p-n junction with a positive temp dependence (proportional to absolute temp. PTAT) ckt.

→ The 3rd one is nothing but the Principle of bandgap reference circuit.

(a) zener diode:

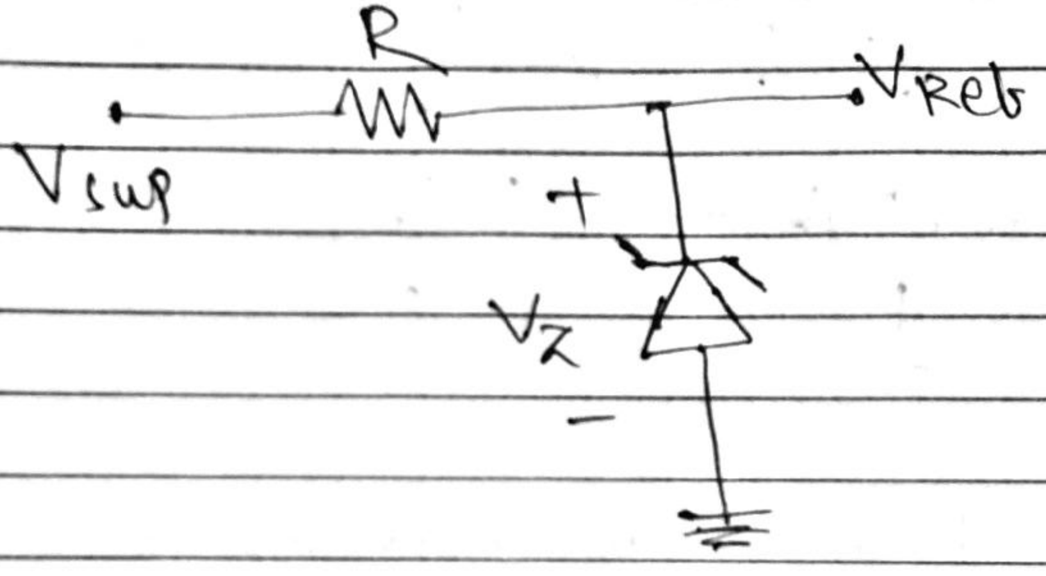


Fig. 1 - Voltage reference using zener diode.

Advantage: (i) simple circuit.

Disadvantage: (i) Breakdown Voltage (V_B) of the zener diode is larger than the power supplies used in most of the modern circuits.
(ii) More power consumption.
(iii) Temp. co-efficient is high.

(b) Making use of threshold voltage of an MOS device.

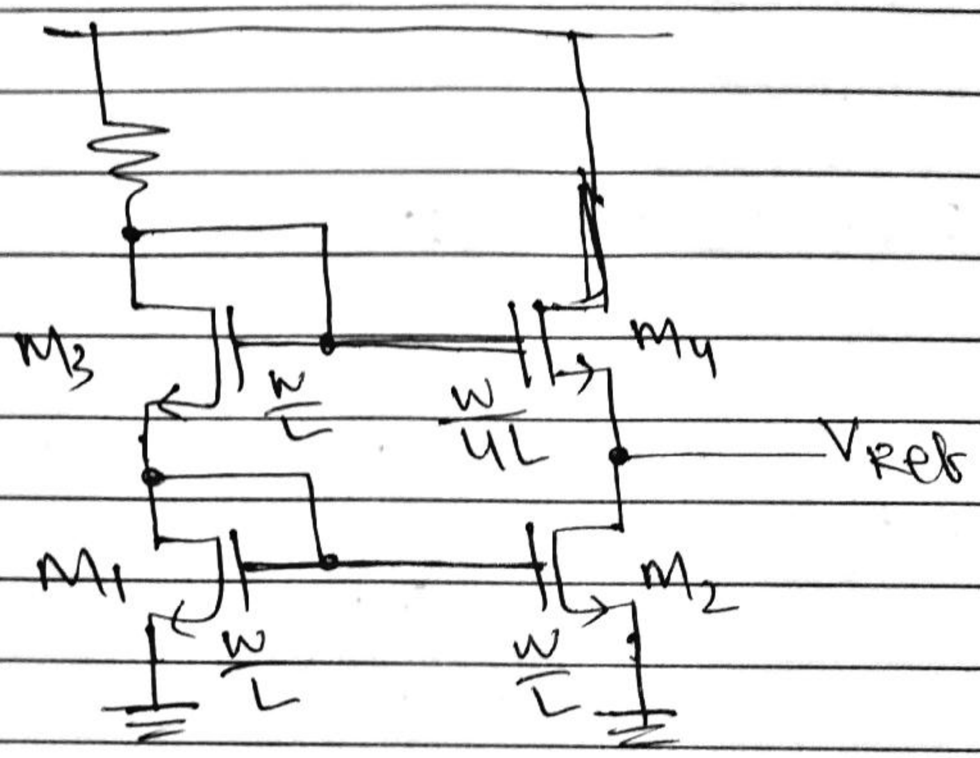


Fig. 2: Voltage reference using threshold voltage of a MOS device.

$$V_{Ref} = V_{t1} + V_{eff1} + V_{t3} + V_{eff3} - V_{t4} - V_{eff4}$$

if the width of the M4 is about 4 times smaller than the width of the other three devices

$$V_{Ref} \simeq V_{t1} + V_{t3} - V_{t4}$$

$$\Rightarrow \boxed{V_{Ref} \simeq V_{t1}}$$

Advantages: V_t is independent to supply voltage variations.

Disadvantages: V_t does vary with temperature.

$$V_{tn} = V_{FB} + 2\phi_{Fn} + \frac{1}{C_{ox}}\sqrt{2\phi_{Fn} 2\epsilon_s q N_A}$$

$$\phi_F = \frac{KT}{q}\ln\left(\frac{N_{sub}}{n_i}\right)$$

$$n_i = 2\left(\frac{2\pi KT}{h^2}\right)^{3/2}(m_n^* m_p^*)^{3/4} e^{\frac{E_c - E_v}{2KT}}$$

where K = Boltzmanns constant

q = electric charge

V_t = threshold voltage

V_{FB} = Flat band voltage

ϕ_{Fn} = Fermi potential

$C_{ox} = \epsilon_{ox}/T_{ox}$

N_A = P-substrate doping

m_n^*, m_p^* = effective mass of electron and hole

h = Planks constant

n_i = intrinsic carrier conc. $(1.5\times10^{10}\ cm^{-3})$

The above expressions shows how V_t ~~varies~~ depends on the temperature. If you are more interested to know about the above expressions, please go through any standard book on MOS devices.

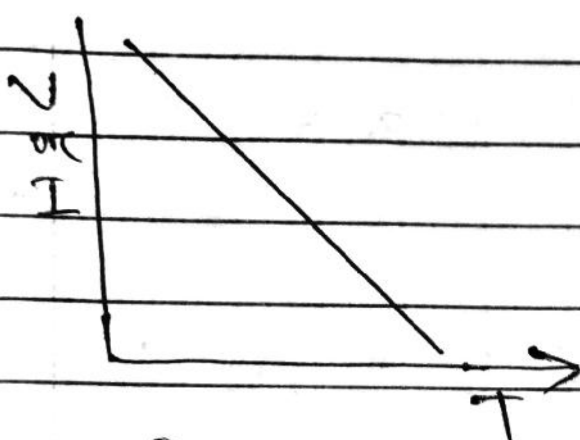
(C) The bandgap reference (BGR) is one of the most popular reference voltage generators that generates a temprature independent voltage.

→ This method involves the generation of a voltage with positive temprature co-efficient.

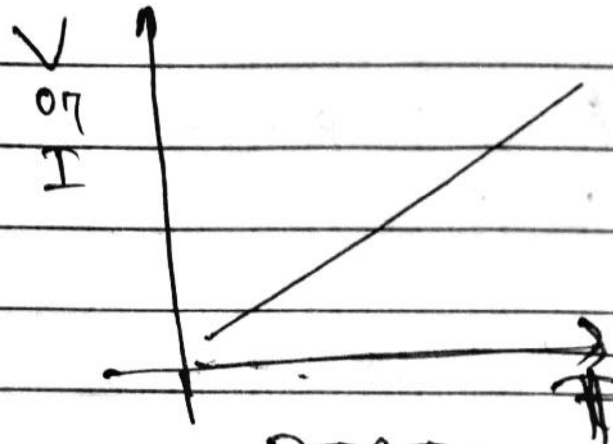
→ The Forward bias Diode voltage or, the base-emitter voltage has a negative temprature co-efficient.

→ Therefore, when the two voltages are added together, the sum has a zero temp co-efficient.

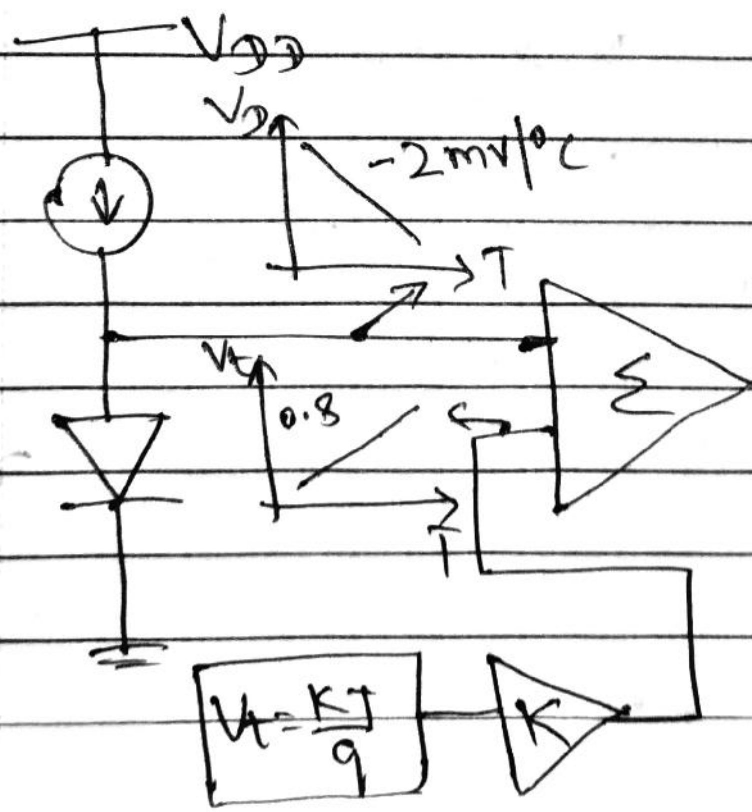
→ For silicon, this (zero temp co-efficient) is achieved when the total voltage equals about 1.2V. This value is the Bandgap voltage of silicon. Hence this method is called Bandgap reference.



CTAT:
complementary to absolute temp.



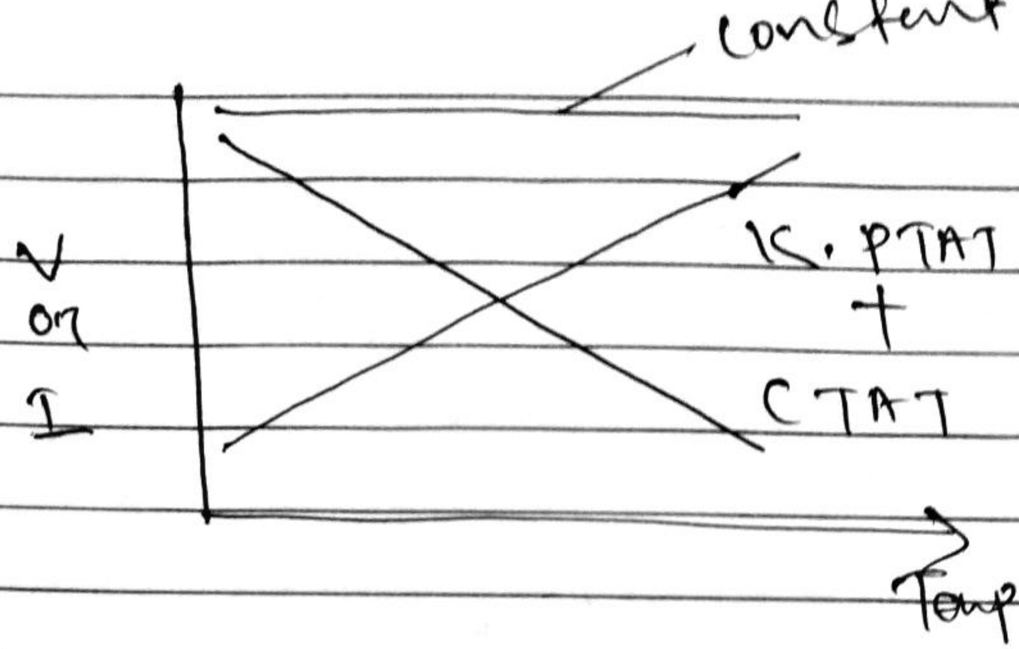
PTAT:
Proportional to absolute temp.



$V_{REF} = V_{BE} + KV_T$

OR

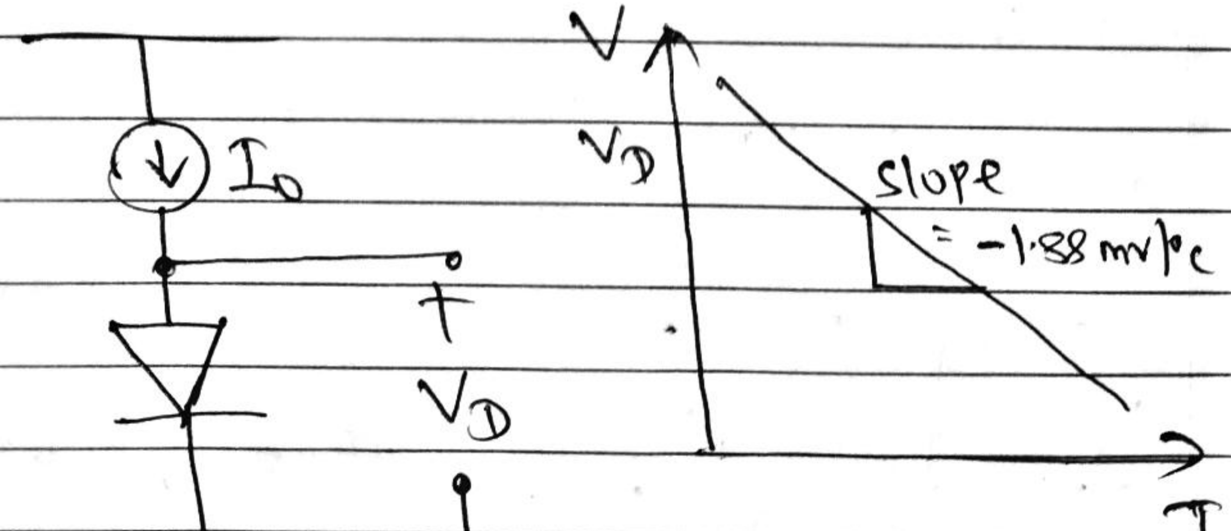
$V_{Ref} = V_D + KV_T$



$\boxed{\text{Any PTAT + any CTAT} \neq \text{Constant}}$

$\boxed{\alpha_1 \text{ PTAT} + \alpha_2 \text{ CTAT} = \text{constant Voltage}}$

CTAT Voltage generator



as we know

$$\boxed{I_D = I_s e^{V_D/V_t}} \quad \text{——— (1)}$$

where I_s = reverse bias saturation current (10^{-15} A)

V_D = Voltage across the diode

V_t = Thermal voltage (26mV/300K)

$$\Rightarrow \frac{I_D}{I_s} = e^{V_D/V_t}$$

$$\Rightarrow \boxed{V_D = V_t \ln\left(\frac{I_D}{I_s}\right)} \quad \text{——— (2)}$$

as I_s is strongly dependent on T so V_D is a CTAT in nature.

we know,

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

where

$\mu = \mu_0 T^m$, $m \simeq -3/2$

K = Boltzmann's constant

T = Temperature

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

$\Rightarrow I_S \propto T \cdot T^m \cdot T^3 \exp\left[-\frac{E_g}{KT}\right]$

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

where C is the constant.

$$\Rightarrow I_S = \underbrace{C}_{\text{const.}} \cdot \underbrace{T^{(4+m)}}_{\text{temp.}} \cdot \underbrace{\exp\left(-E_g/KT\right)}_{\text{temp.}} \quad \text{--- (3)}$$

~~By~~ taking derivative of I_s with temp

$$\boxed{\frac{\partial I_s}{\partial T} = I_S\left\{\frac{E_g}{KT^2} + \frac{4+m}{T}\right\}} \quad \text{--- (4)}$$

Now, $V_D = V_T \cdot \ln\left(\frac{I_0}{I_s}\right)$

$$\frac{\partial V_D}{\partial T} = \frac{\partial V_T}{\partial T} \cdot \ln\left(\frac{I_0}{I_s}\right) + V_T \frac{\partial}{\partial T} \ln\left(\frac{I_0}{I_s}\right)$$

$$= \frac{K}{q} \cdot \ln\left(\frac{I_0}{I_s}\right) + V_T \frac{\partial}{\partial T} \ln\left(\frac{I_0}{I_s}\right)$$

$$= \frac{K}{q} \ln\left(\frac{I_0}{I_s}\right) + V_T \cdot \frac{I_s}{I_0} \cdot \frac{-I_0}{I_s^2} \cdot \frac{\partial I_s}{\partial T}$$

applying $\frac{\partial I_s}{\partial T}$ in the ~~a~~ above expression,

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

putting the the approximate value of V_D, E_g/q at 300°K

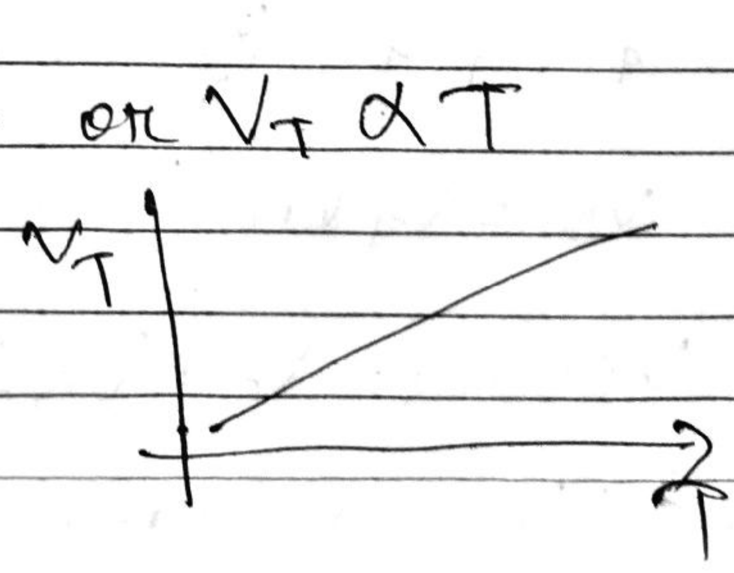
$$\frac{\partial V_D}{\partial T} = \frac{0.7V - 65\,mV - 1.2V}{300°K}$$

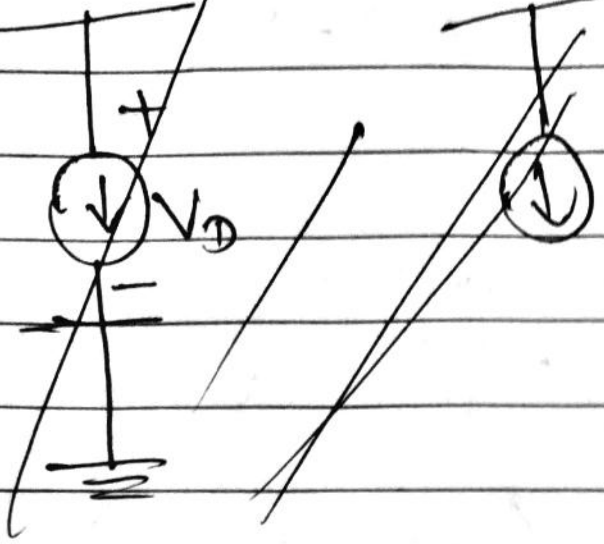
$$\Rightarrow \boxed{\frac{\partial V_D}{\partial T} = -1.88\,mV/°K}$$

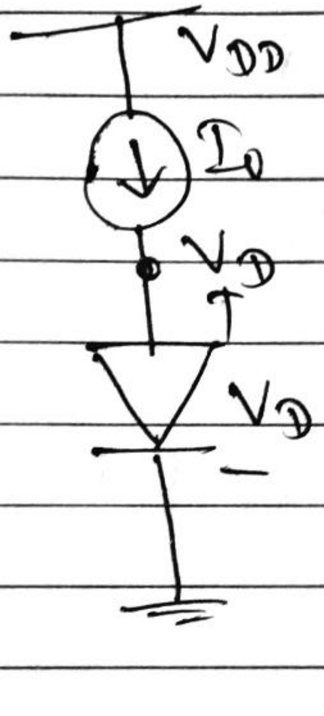
PTAT Voltage generation

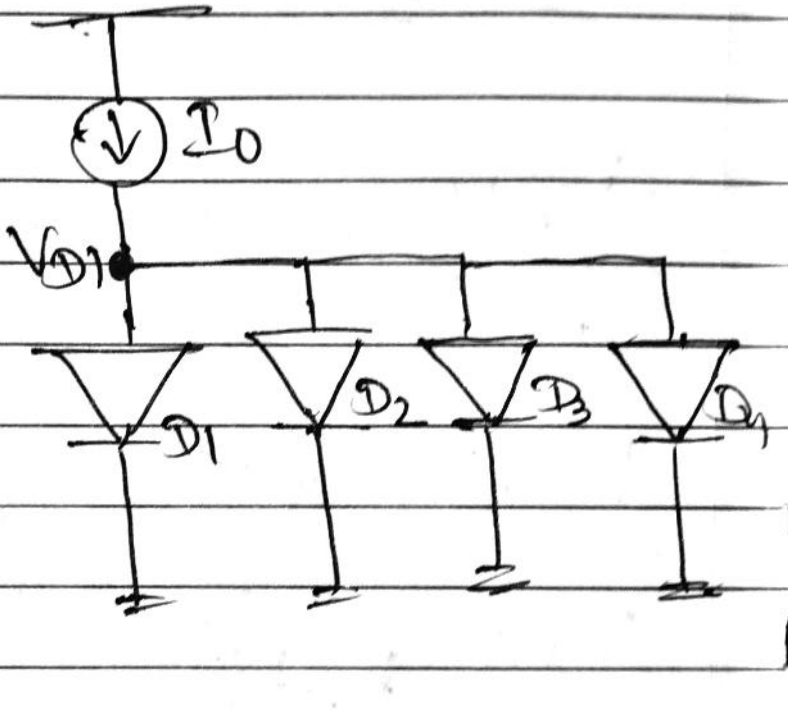
$$V_D = \underbrace{V_T}_{PTAT} \underbrace{\ln\left(\frac{I_D}{I_S}\right)}_{CTAT}$$

$$V_T = \frac{KT}{q} \text{ or } V_T \propto T$$









$$I_0 = I_s e^{\frac{V_D}{V_T}}$$

$$I_0 = n I_s e^{\frac{V_{D1}}{V_T}} \quad , \; n = \text{no. of diode}$$

$$V_{D1} = V_T \ln\left(\frac{I_0}{n I_s}\right) \;\&\; V_D = V_T \ln\left(\frac{I_0}{I_s}\right)$$

$$V_D - V_{D1} = V_T \left[\ln \frac{I_0}{I_s} \times \frac{n I_s}{I_0}\right]$$

$$\Rightarrow \boxed{\Delta V_D = V_T \ln(n)} \rightarrow \text{PTAT}$$