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# Bandgap Reference Circuit

- **PTAT:** One that increases proportionately with temperature and is called proportional to absolute temperature or PTAT. $V_{BE} = \frac{kT}{q}\ln\left(\frac{I_C}{I_S}\right)$
- **CTAT:** One that decreases proportionately with temperature and is called complementary to absolute temperature or CTAT. $V_T = \frac{kT}{q}$

## VBE of BJT as CTAT

$$V_{BE} = \frac{kT}{q}\ln\left(\frac{I_C}{I_S}\right)$$

$I_S$ = Saturation Current of BJT

$$I_S = \frac{qAn_i^2 D}{WN_A}$$

Where,
q = Electron Charge (Constant)
A = Area of Emitter (Constant at 1st order)
W = Width of Base(Constant at 1st order)
$N_A$ = Doping Concentration (Constant)
D = Diffusion Constant (NOT CONSTANT)
$n_i^2$ = Number of intrinsic carrier concentration

$$D = \frac{kT}{q}\mu$$

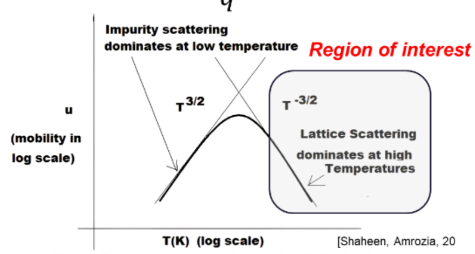


Figure. Temperature dependence of mobility in Si.

$$n_i^2 = D'T^3 e^{-\frac{V_{BG}}{V_T}}$$

$$D = \frac{kT}{q}\mu = \frac{kT}{q}T^{-3/2}$$

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$$V_{BE} = \frac{kT}{q}\ln\left(\frac{I_C}{I_S}\right)$$

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$$n_i^2 = D'T^3 e^{-\frac{V_{BG}}{V_T}}$$

$$D = \frac{kT}{q}\mu = \frac{kT}{q}T^{-3/2}$$

$$I_S = \frac{qA\left(D'T^3 e^{-\frac{V_{BG}}{V_T}}\right)\frac{kT}{q}T^{-3/2}}{WN_A}$$

$$I_S = E \cdot T^3 \cdot T \cdot T^{-\frac{3}{2}} e^{-\frac{V_{BG}}{V_T}}$$

$$\boxed{I_S = E \cdot T^{\frac{5}{2}} e^{-\frac{V_{BG}}{V_T}}}$$

$$V_{BE} = \frac{kT}{q}\ln(I_c) - \frac{kT}{q}\ln(I_s)$$

$$V_{BE} = \frac{kT}{q}\ln(I_c) - \frac{kT}{q}\ln(E) - \frac{5}{2}\frac{kT}{q}\ln(T) + \frac{kT}{q}\cdot\frac{V_{BG}}{V_T}$$

$$V_{BE} = \underbrace{\frac{kT}{q}\ln(I_c)}_{\text{Weak PTAT}} \underbrace{- \frac{kT}{q}\ln(E) - \frac{5}{2}\frac{kT}{q}\ln(T)}_{\text{Strong CTAT}} + \underbrace{V_{BG}}_{\text{Constant BG voltage}}$$

## Extracting PTAT

- Make I1 = I2 = I and V1 = V2 using current mirror or OpAmp
- $V_{BE1} = RI + V_{BE2}$
- $V_{BE1} - V_{BE2} = RI$
- $\frac{kT}{q}\ln\left(\frac{I_C}{I_S}\right) - \frac{kT}{q}\ln\left(\frac{I_C}{NI_S}\right) = RI$ [Assuming identical BJT] $V_{EB1} = V_1$
- $\frac{kT}{q}\ln(N) = RI$
- $I = \frac{kT}{qR}\ln(N)$

**PTAP Current**
**→ Use CM to generate multiple copies**
**→ Drop it across a resistor to generate PTAT Voltage**