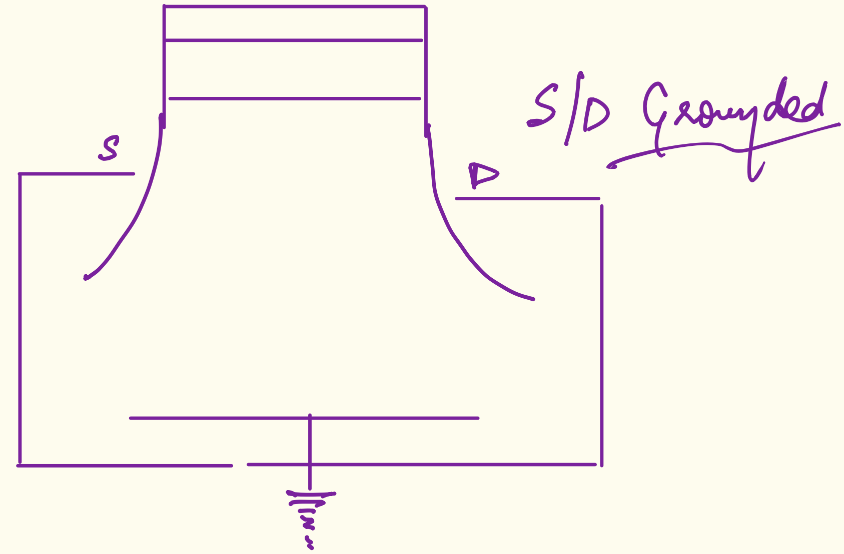
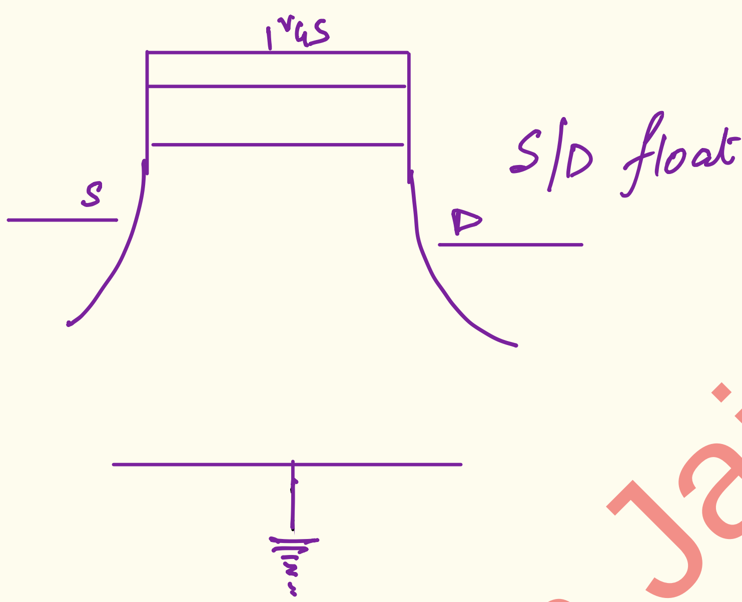
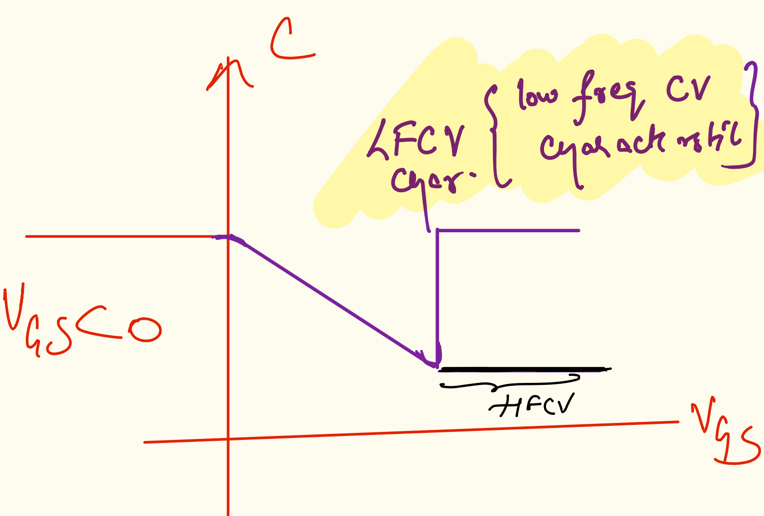




in n-MOS { p-type Sub }

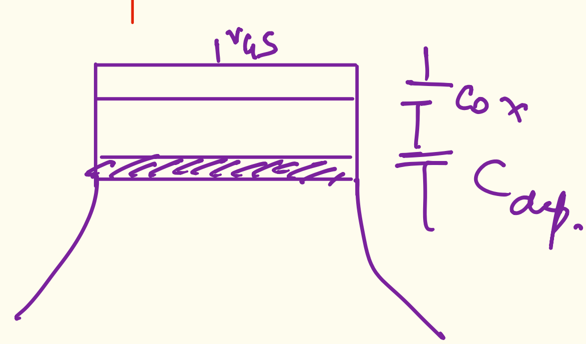
$V_{GS} < 0$

$C_{ox} = \frac{\epsilon_0 \epsilon_{ox}}{t_{ox}}$



when $V_{GS} \geq 0$; inversion & depletion starts

∴ 2 capacitors in working



Flat Band, Accumulation & Inversion

→ Inversion

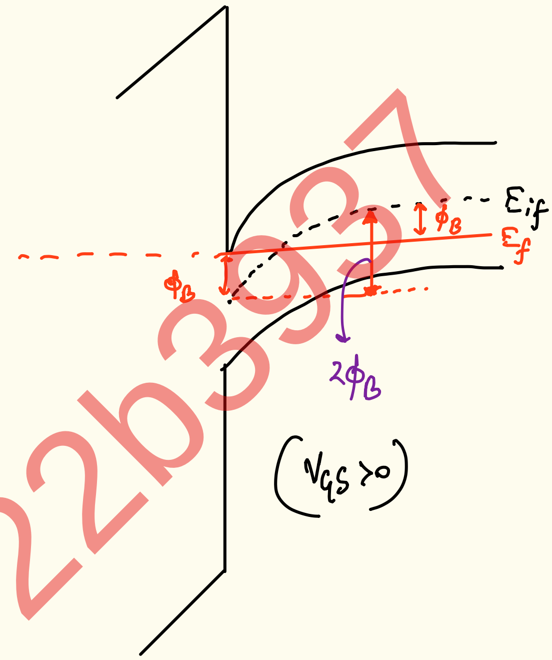
V_{GS} at which e^- Conc^n at oxide - Substrate interface is equal to Conc^n of p is threshold voltage

$$p = N_V \exp\left(\frac{E_V - E_F}{KT}\right)$$

$$p_i = N_V \cdot \exp\left(\frac{E_V - E_{if}}{KT}\right)$$

$$p = p_i \exp\left(\frac{E_{if} - E_F}{KT}\right)$$

$$p = n_i \cdot \exp\left(\frac{\phi_B}{KT}\right)$$



now; @ Si / SiO_2 interface;

$$n = n_i \exp\left(+\frac{\phi_B}{KT}\right)$$

$$\phi_S = 2\phi_B$$

$(V_{GS})_T$ → $V_T = V_{ox} + 2\phi_B$

$$= 2\phi_B + t_{ox} \frac{\mathcal{E}_s \epsilon_s}{\epsilon_{ox}}$$ → Electric field

$\mathcal{E}_{ox} \epsilon_{ox} = \mathcal{E}_s \epsilon_s$

Electric field

$$= 2\phi_B + \frac{\epsilon_s}{C_{ox}}\left(\frac{q N_A W_d}{\epsilon_s}\right)$$

depletion width { Gauss law }

$\mathcal{E} (A) \; q/\epsilon$

1

$$W_d = \sqrt{\frac{2\epsilon_s}{q}\left(\frac{1}{N_A} \cdot 2\phi_B\right)}$$

$$= 2\phi_B + \frac{q \cdot N_A}{C_{ox}}\left(\frac{2\epsilon_s \cdot 2\phi_B}{q N_A}\right)^{1/2}$$

$$= 2\phi_B + \frac{1}{C_{ox}}\sqrt{4\,\epsilon_s \cdot q \cdot N_A \cdot \phi_B}$$

$\rightarrow$ Charge:

$\downarrow$ $Q_{depletion}$

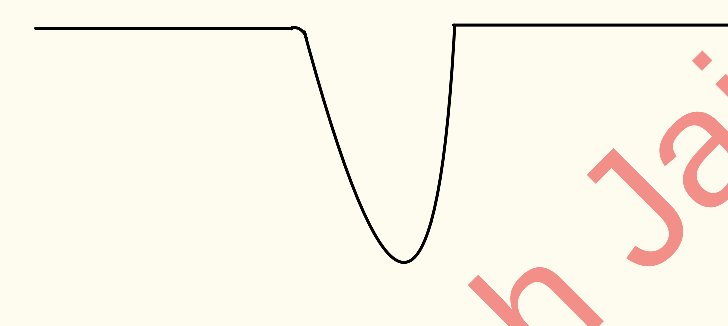
if $\phi_M = \phi_S$

now; initially

if $\phi_m \neq \phi_s$

$$\boxed{V_T = 2\phi_B + \phi_{MS} + \frac{\sqrt{4\,\epsilon_s\, q\, N_A\, \phi_B}}{C_{ox}}}$$

#



$$\phi_s(V_{GS} = V_T) = 2\phi_B = \frac{2KT}{q}\ln\left(\frac{N_A}{n_i}\right)$$

$N_A = 10^{18}$

$n_i = 10^{10}$

$$\phi_B = 0.026 \cdot \ln\left(\frac{10^{18}}{10^{10}}\right) = 0.47$$

$2\phi_B = 0.94$

if $V_{GS} > V_T$

$\phi_B = 0.47 + 0.20 = 0.67$

$$n = n_i \cdot \exp\left(\frac{\phi_B}{KT}\right)$$

$$n = 10^{10} \cdot \exp\left(\frac{0.67}{0.026}\right)$$

$= 10^{21}\ cm^{-3}$

Beyond inversion; Small Change in V_{GS} results in large Change in "n"

$\phi_s = 2\phi_f$

$\phi_f = \frac{E_i - E_f}{q}$

$E_i - E_f = kT\ln\left(\frac{N_A'}{n_i}\right)$

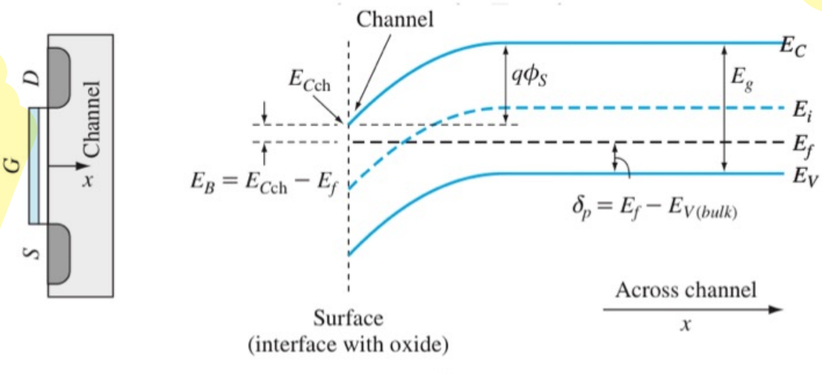
$$n_s = N_C e^{-E_B/kT} \tag{7.5}$$

$$\phi_s = \frac{1}{q}[E_g - E_B - \delta_p]$$

$V_{GS} - V_T = \phi_{ox} - \phi_{ox}^{th}$

$\{V_{GS} > V_T\}$

oxide voltage @ threshold



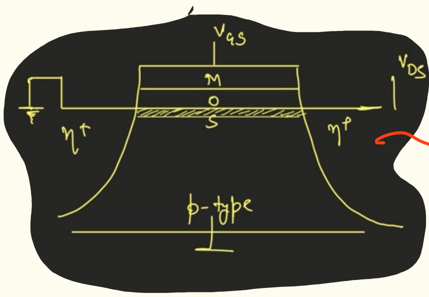
(a)

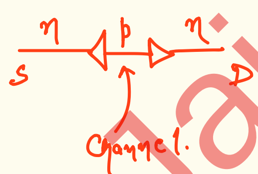
$I_{DS} = 0$, $V_{GS} < V_T$

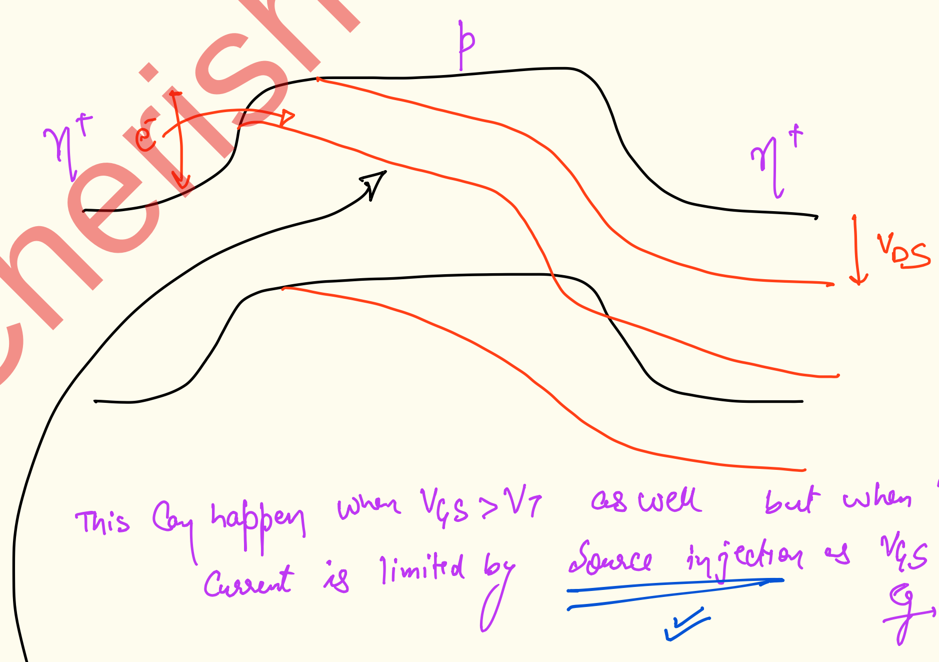
$= I_0 e^{\left(\frac{V_{GS}-V_T}{kT}\right)}$, $V_{GS} < V_T \ \forall \ V_{DS}$

Similar to Diode eqn: $I = I_0\left(e^{\frac{V}{\eta V_T}} - 1\right)$

{ Sub-threshold }







{ Slope of line decided by V_{DS} }

This can happen when $V_{GS} > V_T$ as well but when $V_{GS} < V_T$; Current is limited by Source injection as $V_{GS} \downarrow\downarrow$

Eg, $V_T = +1V$
$V_{DS} = 5V$
$V_{GS} = 0.5V$

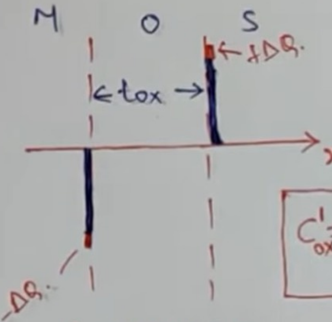
Slope decided by V_{DS}

C-V Characteristics

Techgurukula

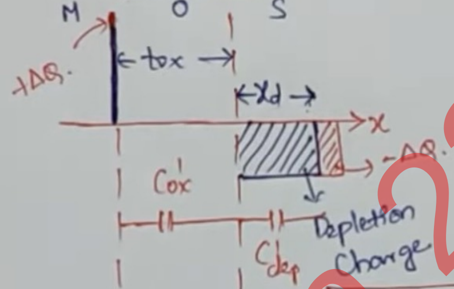
$V + \Delta V$ $\qquad$ $Q + \Delta Q$

$$\boxed{C = \frac{\Delta Q}{\Delta V}}$$



$$\boxed{C'_{ox} = \frac{\varepsilon_{ox}}{t_{ox}}}$$

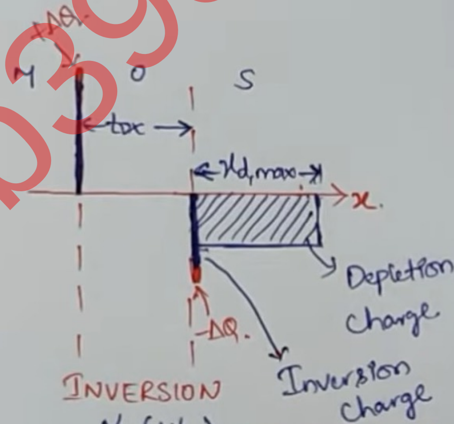
ACCUMULATION
V_G (-Ve)



DEPLETION
V_G (+Ve Small)

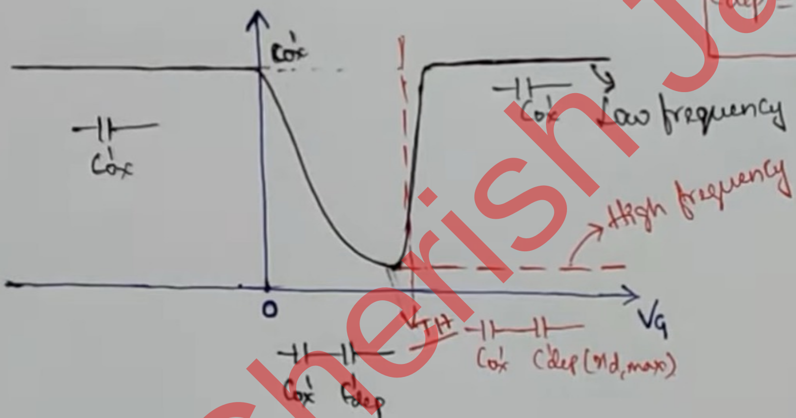
$$\boxed{\frac{1}{C'} = \frac{1}{C'_{ox}} + \frac{1}{C'_{dep}}}$$

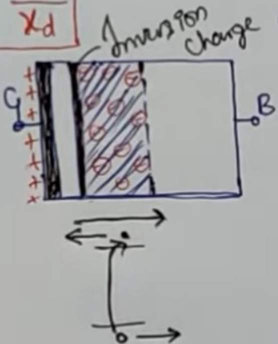
$$\boxed{C'_{dep} = \frac{\varepsilon_{si}}{X_d}}$$

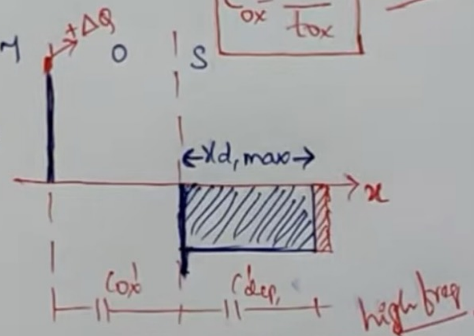


INVERSION
V_G (+Ve)

$$\boxed{C'_{ox} = \frac{\varepsilon_{ox}}{t_{ox}}}$$ low freq.

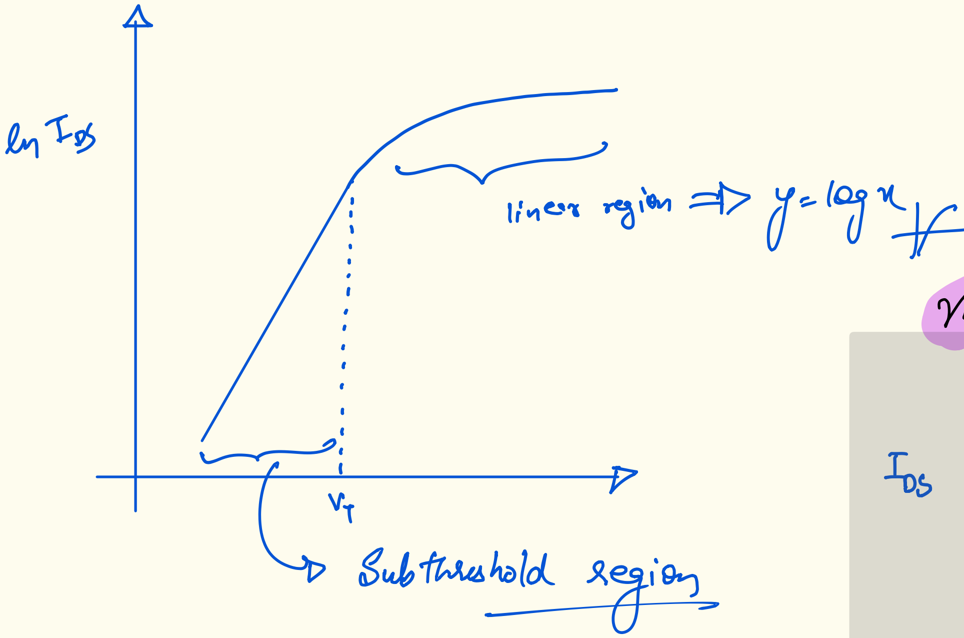






high freq.

$$\boxed{\frac{1}{C'} = \frac{1}{C'_{ox}} + \frac{1}{C'_{dep}(X_{d,max})}}$$



Mosfet Eq^n's

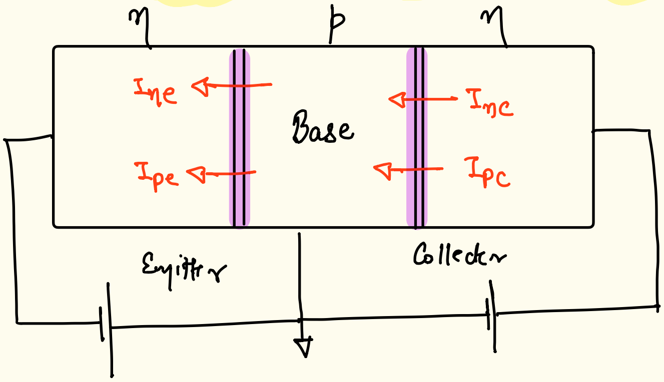
$$I_{DS} = I_0 e^{\frac{V_{GS}-V_T}{\eta V_T}} \quad ; V_{GS} < V_T$$

$$= \frac{\mu_n C_{ox} W}{L}\left[(V_{GS}-V_T)V_{DS} - \frac{V_{DS}^2}{2}\right] \quad ; V_{DS} < V_{GS} - V_T > 0$$

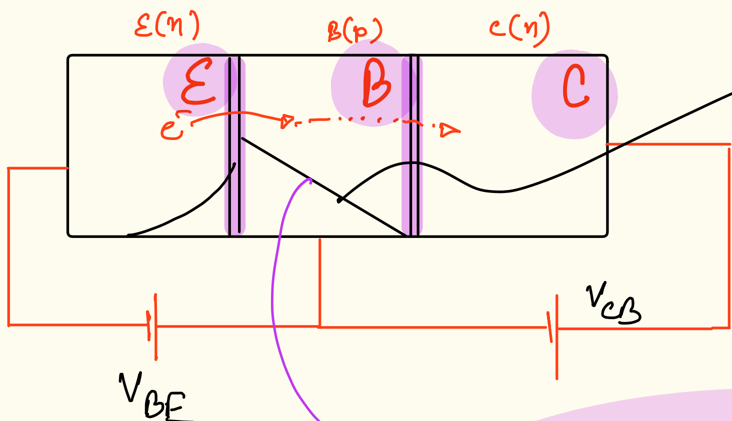
$$= \frac{\mu_n C_{ox} W}{2L}(V_{GS}-V_T)^2 \quad ; V_{DS} > V_{GS} - V_T > 0$$

These eq^n are applicable to JFET as well.

Bipolar Junction Transistor



Signifies Depletion region



linear as $W_B \downarrow\downarrow$

$\therefore e^{-x} \approx 1-x$

we want e^- to not recombine in Base but get Sweeped to Collector due to large E.F.

So, 1) W_B = Small $\Rightarrow$ e^- won't dwell too much in Base.

2) Base lightly doped $\Rightarrow$ less recomb^n in Base

Aim:- e^- that come to E-B junction should go to C-B junction

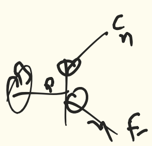
$$J_{nC} = J_{nE}$$

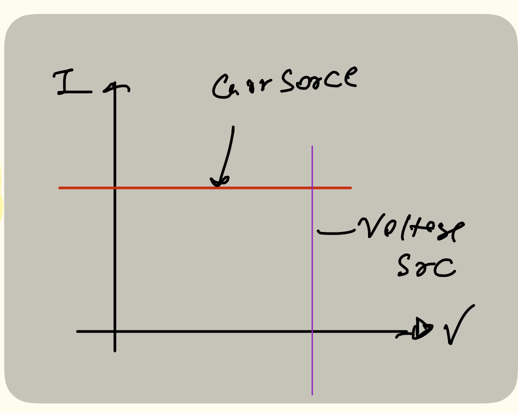
Base Current

Control Signal.

Current depends on V_{BE} ✓

V_{CB} ✗





in mosfet ; $g_m = \frac{\partial I_{DS}}{\partial V_{GS}}$; Voltage Controlled Current Src

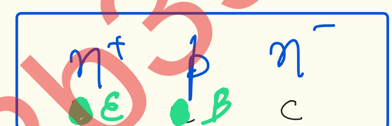
BJT ; $\beta = \frac{I_C}{I_B}$ Current Control Current Src

* We want $J_{nE} >> J_{pE}$ → Achieved by p-moderate Base Doping { if very light then the 2 Depletion regions may Conflict

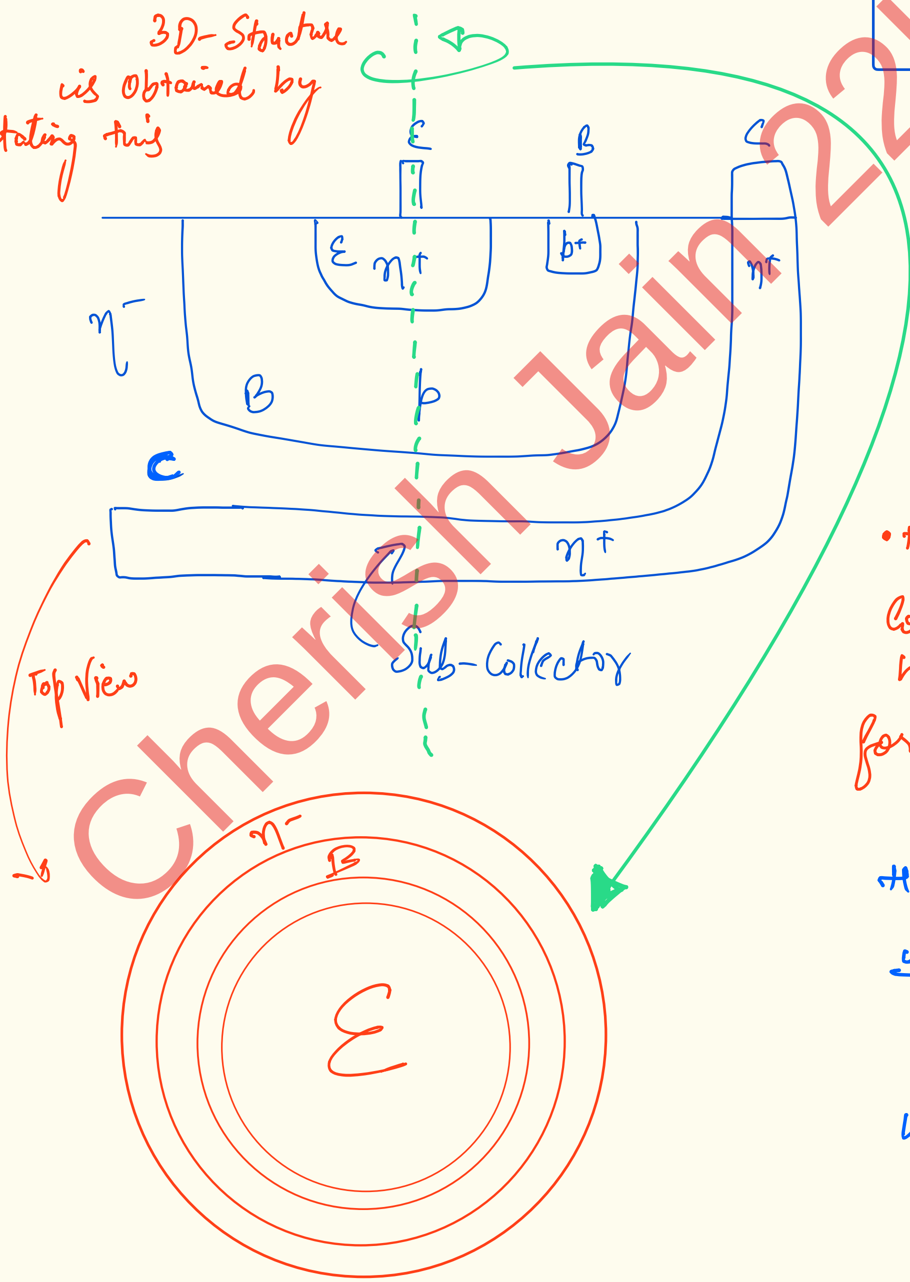
$I_{pE} \downarrow$
$V_{CB} \uparrow$

Emitter → very Heavily Doped

Collector → lightly doped (we want Depletion region to be protruding on Right Side rather than left)



3D-Structure is obtained by rotating this



BJT → Vertical device

MOS → Horizontal "

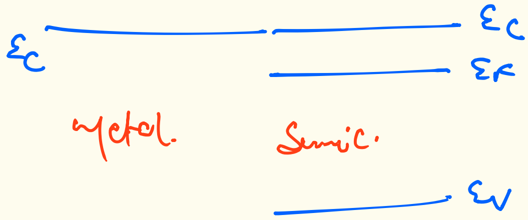
• Heavy doping is req. for Contact ; Hence for Base a heavy p^+ pocket is made for making Contact.

↓

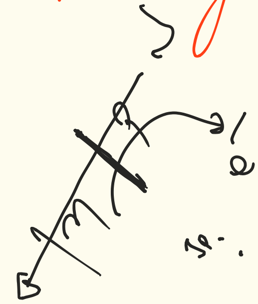
Heavy doping ensures low resistance ; Hence while making Contact ; we deliberately dope more

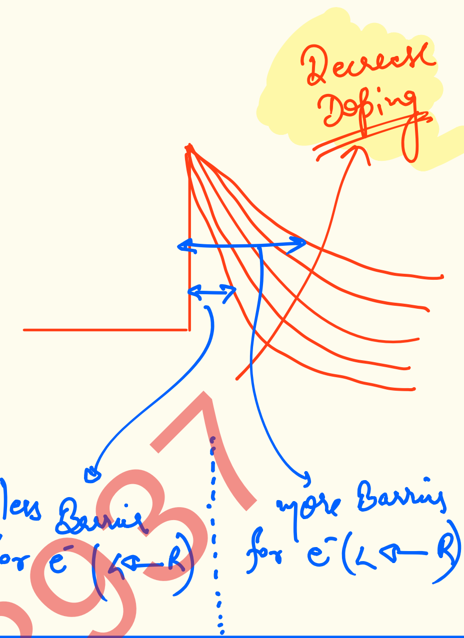
Low Doping ≡ more Resistance

Ideally



actually





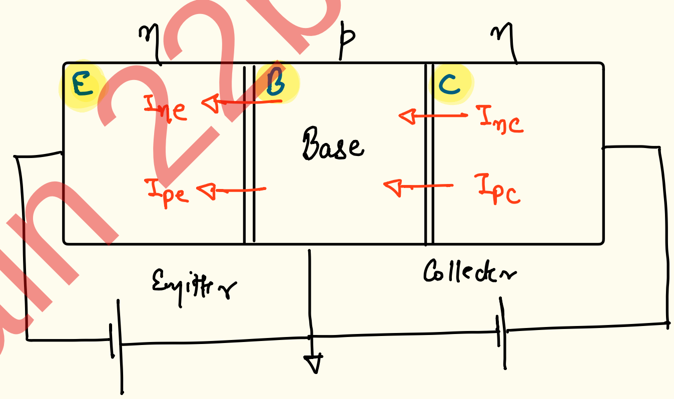
$$I_E = I_{nE} + I_{pE} + I_{recomb}$$

$$I_C = I_{nC} + I_{pC} + I_{gen}$$

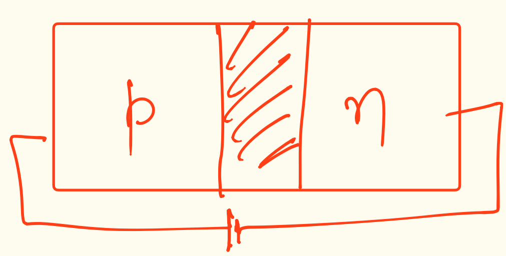
$$I_E = I_C + I_B$$

$$I_{nC} = \alpha_0 I_{nE} + I_{RB,n}$$

$$I_{pC} = I_{RB,p}$$



• Recomb^n I in base region.



in depletion region

$$np > n_i^2$$

$$J_{rec} = B \cdot (np - n_i^2)$$

Bimolecular Recomb^n weight

$J_{nC} = \alpha' \cdot J_{nE}$

$\alpha' < 1$ because of J_{rec}

$$\alpha = \frac{J_C}{J_E} = \frac{J_{nE}}{J_E} \cdot \frac{J_{nC}}{J_{nE}} \cdot \frac{J_C}{J_{nC}}$$

$$= \gamma \, \alpha_T \, M$$

{ we want $\gamma \to 1$, $\alpha_T \to 1$, $M \to 1$ }

for all practical purposes;

$M \approx 1$

$\alpha = \gamma \alpha_T$

$$\alpha_T = \frac{J_{nE} - J_{rec}}{J_{rec}}$$

γ = Emitter injection efficiency

$$= \frac{J_{nE}}{J_{nE} + J_{pE}}$$

α_T = Base transport factor

M = Collector efficiency

$$= \frac{J_{nC} + J_{pC}}{J_{nC}} \approx 1$$

$\alpha \to$ Common Current gain

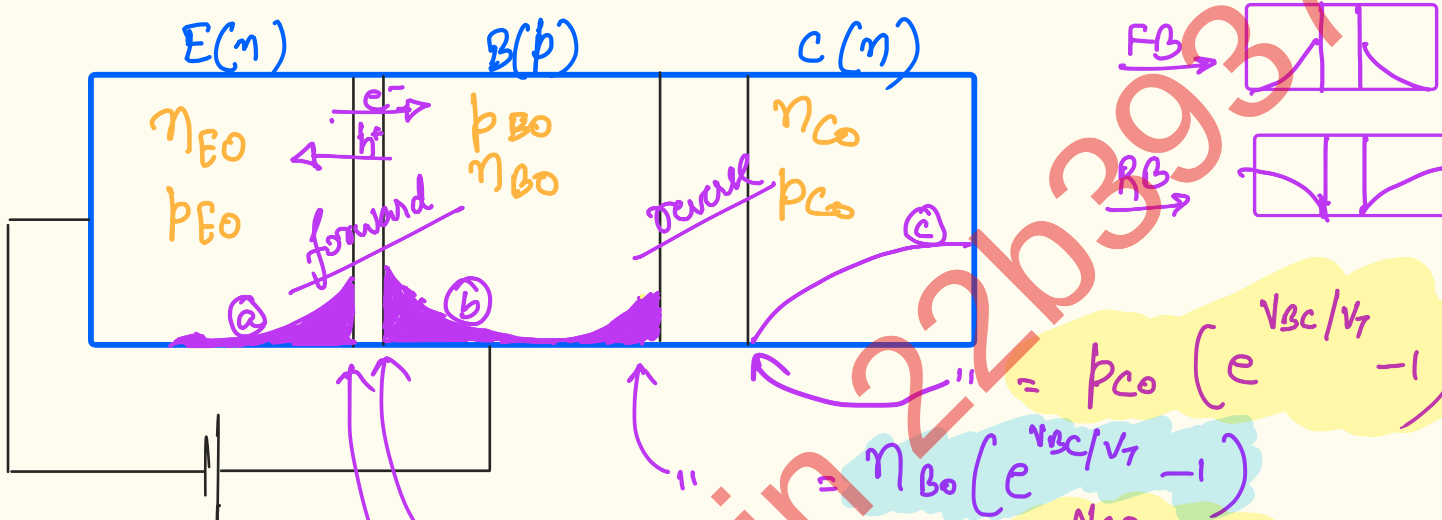
Typical α in BJT ≈ 0.99 (always < 1 except when $M > 1$)

E-B → FB
C-B → RB

Normal operating Cond^n is Forward Active Mode

$\alpha = \frac{I_C}{I_E} \approx$ eg 0.99 → Typical Si Homojunction

$\beta = \frac{I_C}{I_B} = \frac{I_C}{I_E - I_C} = \frac{\alpha}{1-\alpha}$ → eg ≈ 100



" $= p_{C0}\left(e^{V_{BC}/V_T} - 1\right)$

" $= n_{B0}\left(e^{V_{BC}/V_T} - 1\right)$

XS Carrier density $= n_{B0}\left\{e^{\frac{V_{BE}}{V_T}} - 1\right\}$

" $= p_{E0}\left(e^{\frac{V_{BE}}{V_T}} - 1\right)$

(a) hole density in emitter region

$$p_E(x) = p_{E0}\left(e^{V_{BE}/V_T} - 1\right)\left(e^{-x/L_p}\right)$$ → ignore offset!

(b) rise only when BC → for. biased. ∴ generally there is no rise.

$$n_B(x) = A\cdot e^{-x/L_n} + Be^{x/L_n}$$

(offset ignored)!

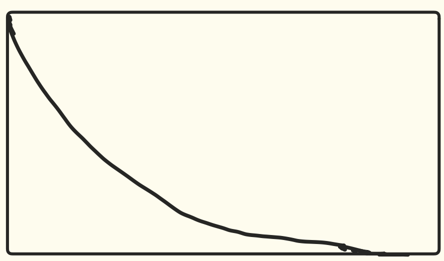
$\hookrightarrow n_B(x=0) = n_{B0}\left(e^{V_{BE}/V_T} - 1\right)$

$$n_B(x=W_B) = n_{B0}\left(e^{-V_{CB}/V_T} - 1\right)$$

(c) Reve. Biased region

$$p_C(x) = p_{C0}\left(e^{-V_{CB}/V_T} - 1\right) e^{-x/L_n}$$

(offset ignored)



$x=0$ $\quad$ $x=W$

✓ $W >>> L_n$

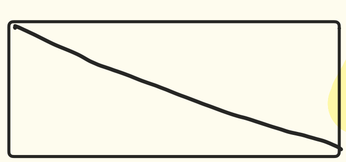
$$\Delta n(x) = \Delta n(x=0) \cdot e^{-x/L_n}$$

✓ $W << L_n$ $\quad$ {assume $x=W$ is Sink}

$$\Delta n(x=W) = 0$$

High Order Terms

$$\Delta n(x) = \Delta n(x=0) \cdot \left[1 - \frac{x}{L_n} + \cdots - \cdots\right]$$



$x=0$ $\quad$ $x=W$

$$\underbrace{\Delta n(x) = \Delta n(x=0) \cdot \left[1 - \frac{x}{L_n}\right]}_{\text{Linear Profile}}$$

($W << L_n$) Linear Profile

√ for all practical purposes, we keep $\boxed{W_E << L_p}$

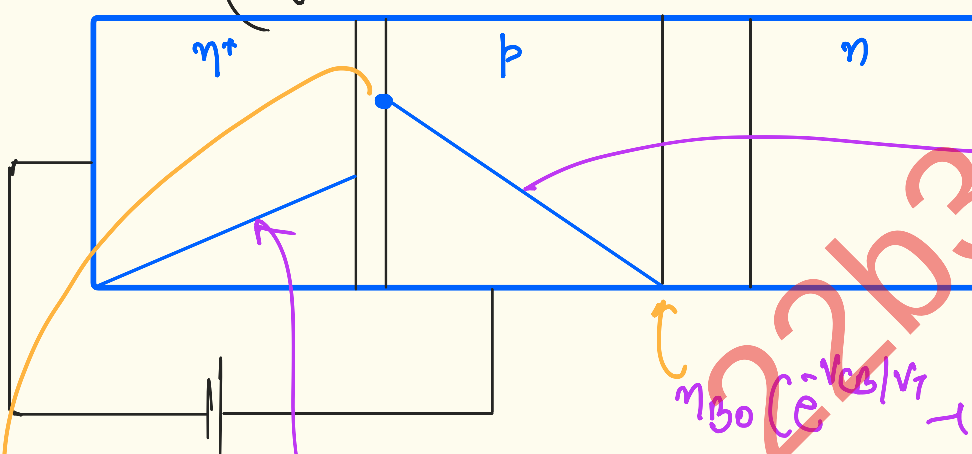
$+\infty \leftarrow 0$, x

∴ Linear profile

$$p_E = p_{E0}\left(e^{V_{BE}/V_T}-1\right)\left[1-\frac{x}{W_E}\right]$$

√ for all practical; CB is rev. biased; also $\boxed{W_B << L_n}$

(large width gives recombⁿ which isn't desired)



$J = q D_n \frac{n_{B0}}{W_B}$

$n_{B0}\left(e^{-V_{CB}/V_T}-1\right) \simeq 0$

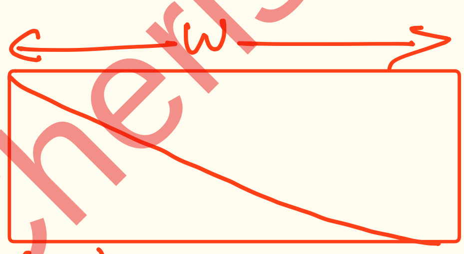
$$n_B = n_{B0}\left(e^{V_{BE}/V_T}-1\right)\left[1-\frac{x}{\ }\right]$$

$x : 0 \longrightarrow \infty$

larger cuz more e^- injection as compared to holes.

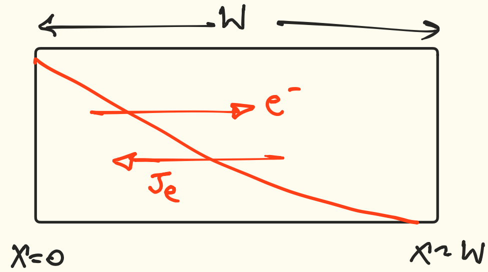
$J = q D_p \cdot \frac{p_{E0}}{W_E}$

#



$$J = +q D_n \left(\frac{\partial(\Delta n)}{\partial x}\right)$$

$$J = -q D_n \left(\frac{\Delta n(x=0)}{W}\right)$$



$\Delta n(x=0)$ $\quad\quad$ $\Delta n(x=W)=0$

$W << L_n$ — $0.1 - 0.2\,\mu m$ — μ-m

$$D_n \frac{\partial^2 \Delta n}{\partial x^2} = -\frac{\Delta n}{\tau_n}$$

$$\frac{\partial^2(\Delta n)}{\partial x^2} = \frac{-\Delta n}{L_n^2} \;;\; L_n = \sqrt{D_n \tau_n}$$

$x = w$

$\Delta n = 0$ $\quad (\Delta n) = 0$

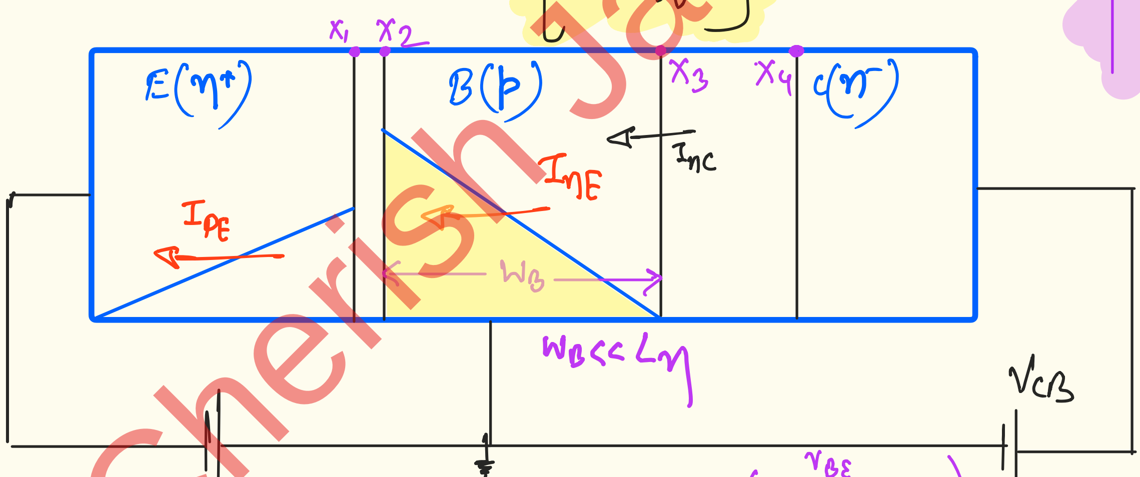
$\frac{d^2y}{dx^2}$

$$\frac{\partial^2 \Delta n}{\partial x^2} = 0 \quad \text{if } L_n << x$$ {negligible recombn}

Hence linear profile; now put Boundary Condn's

$$\Delta n = \Delta n(x=0)\left[1 - \frac{x}{W}\right]$$

$$J = q\, D_n \frac{\partial \Delta n}{\partial x} = \left| q \cdot D_n \cdot \frac{\Delta n(x=0)}{W} \right|$$



n_i^2 / N_D

$$\Delta p(x_1) = p_{E0}\left(e^{V_{BE}/V_T} - 1\right)$$

$$\Delta n(x_2) = n_{B0}\left(e^{V_{BE}/V_T} - 1\right)$$

{@ eqm}

$$J_{pE} = \left| q\, D_p \left(\frac{\partial \Delta p_E}{\partial x}\right) \right| = \frac{q \cdot D_p \cdot \Delta p(x_1)}{W_E}$$

{Current Constituted by holes in emmitter}

$$\therefore \quad I_{pE} = A \cdot q \cdot D_p \cdot \frac{\Delta p(x_1)}{W_B}$$

$$I_{nE} = A \cdot q \cdot D_n \cdot \frac{\Delta n(x_2)}{W_E}$$

$$\gamma = \frac{I_{nE}}{I_E} = \frac{I_{nE}}{I_{nE} + I_{pE}}$$

$$= \frac{1}{1 + \frac{I_{pE}}{I_{nE}}}$$

$$\gamma = \frac{1}{1 + \frac{D_p \cdot p_{E0}}{D_n \cdot n_{B0}} \left(\frac{W_B}{W_E}\right)}$$

$\gamma \approx 1$

$\frac{W_B}{W_E} \rightarrow$ as small as possible

* $\frac{p_{E0}}{n_{B0}} \rightarrow$ as small as possible

$p_{E0} \ll n_{B0}$

$$\frac{n_i^2}{N_{D,E}} \ll \frac{n_i^2}{N_{A,B}}$$

Base Transport factor: (α_T)

$$\frac{I_{nC}}{I_{nE}} = \frac{I_{nE} - I_{rec}}{I_{nE}}$$

$$= 1 - \frac{I_{rec}}{I_{nE}} = 1 - \frac{q \frac{1}{2} \cdot \Delta n(x_2) \cdot W_B}{q \cdot D_n \cdot \frac{\Delta n(x_2)}{W_B}}$$

$$J_{rec} = \frac{A \cdot q \cdot \frac{1}{2} \Delta n(X_2) \cdot W_B}{\tau_n}$$

$$I = \frac{dQ}{dt}$$

Hence $\alpha_T = 1 - \dfrac{W_B^2}{2 L_{nB}^2}$

for $\alpha_T \to 1$

$W_B << L_{nB}$

Si BJT

$\alpha \simeq 0.99$

$\beta = \dfrac{I_C}{I_B} = \dfrac{I_C}{I_C - I_E} = \left(\dfrac{I_C/I_E}{I_C/I_E - 1}\right)$

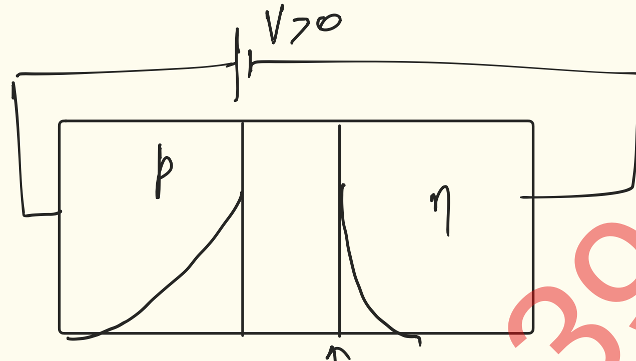
$$\boxed{\beta = \left|\frac{\alpha}{\alpha - 1}\right|}$$

$\underline{\beta \simeq 99}$

$I_C \approx I_E$

$I_C \gg I_B$

rev. Bias profile

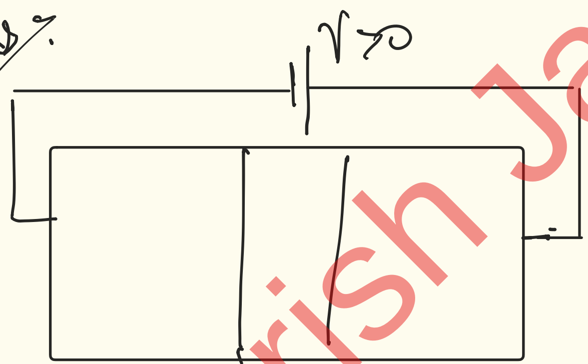


forw. bias

$$\Delta p = \Delta p(x=0)\left[1 - e^{-x/L_p}\right]$$

$$\Delta p(x,V) = p_{n0}\left(e^{V/V_T}\right)\left(1 - e^{-x/L_p}\right]$$

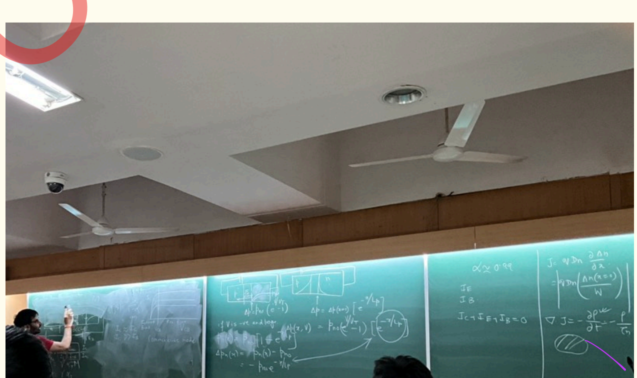
rev. bias:

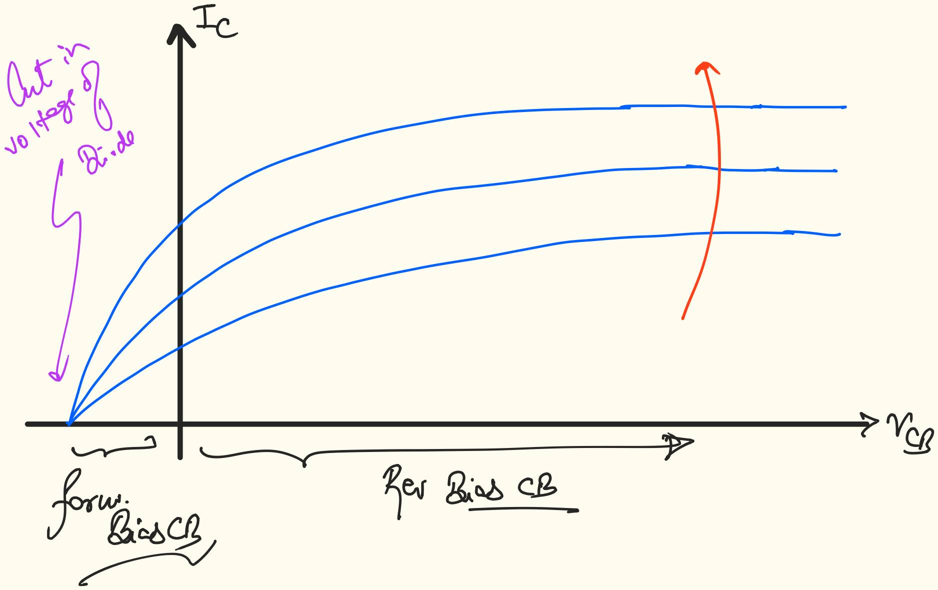


$p_{n0}\left(e^{V/V_T} - 1\right)$

upper V

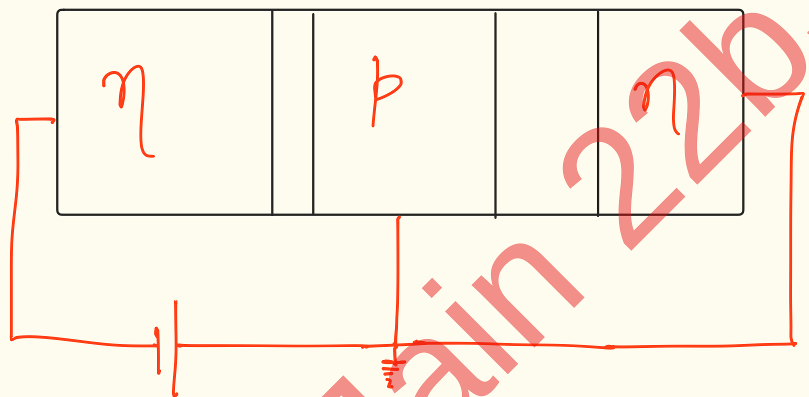
if $V \ll 0$ & large



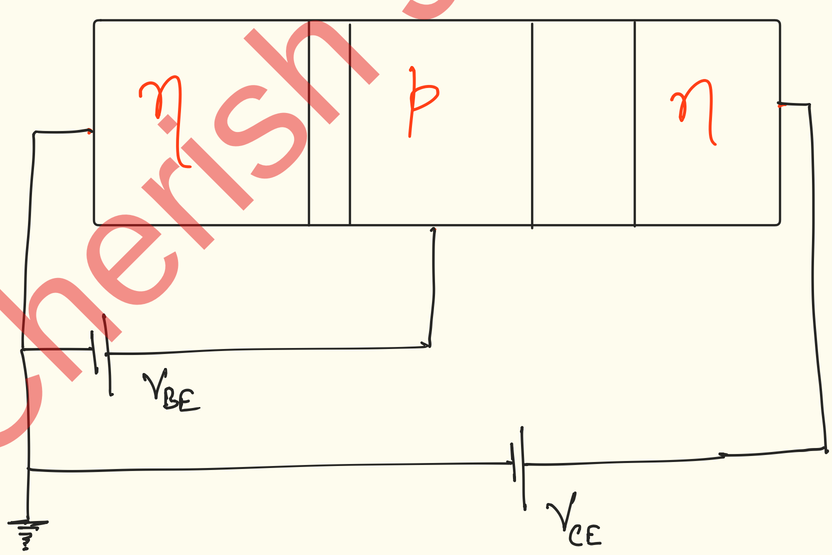


Common Base Mode

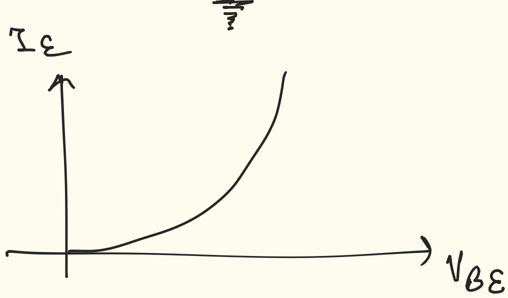
#

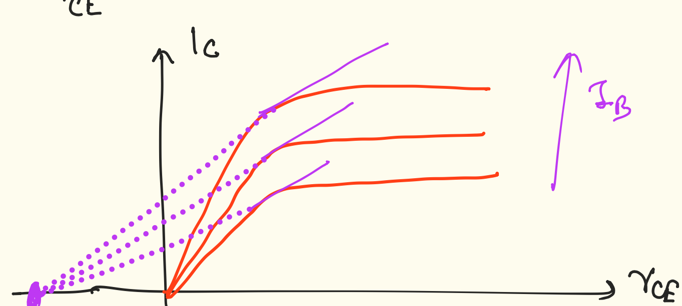


#



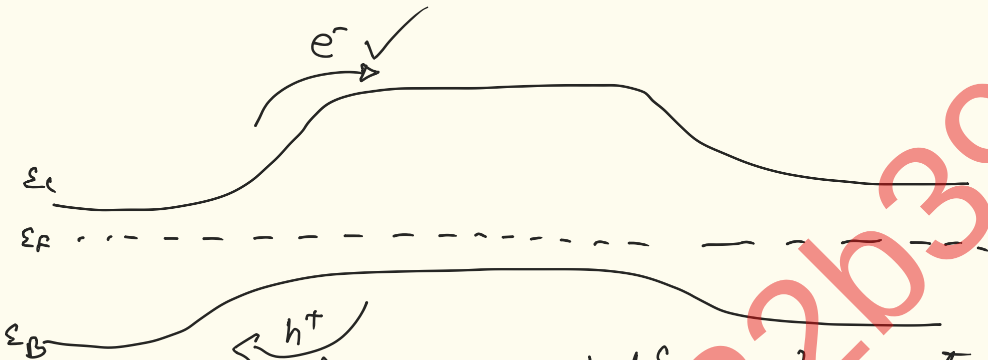
$V_{CE} = V_{CB} + V_{BE}$





Early Voltage {We want high Early Voltage}

Technique to ↑ α, β

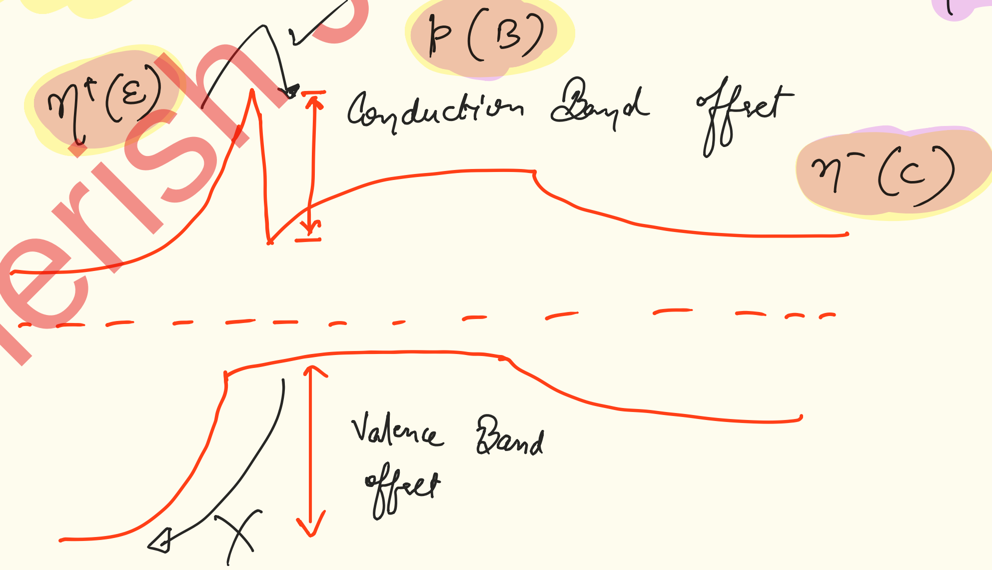


X → not required {no use} as no transfer to Collector

so a technique used :-

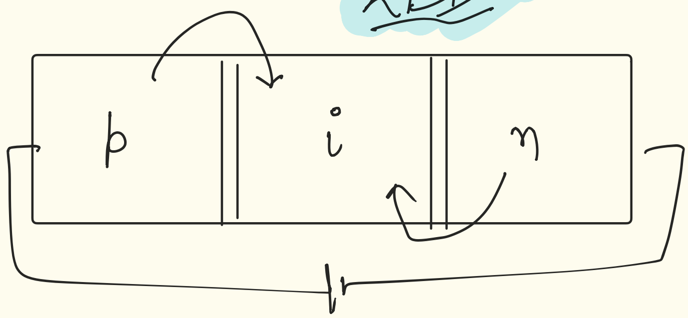
Heterojunction Bipolar Transistor (HBT) {multiple material}

2-3 material



p-i-n diode.

LED



Laser Characteristics

1) Directional
2) Intensity
3) faster recombination
4) Spectral Purity

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