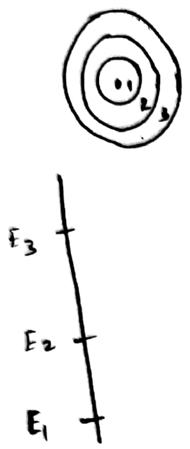
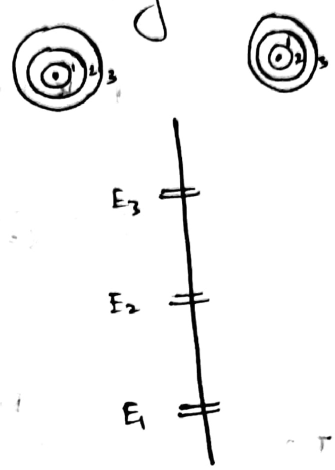
PH 209

Analog Electronics

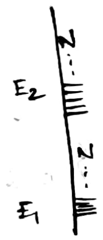
Atom

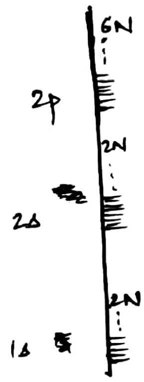


2 Atoms very close

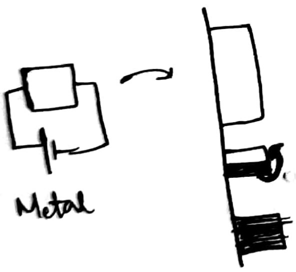


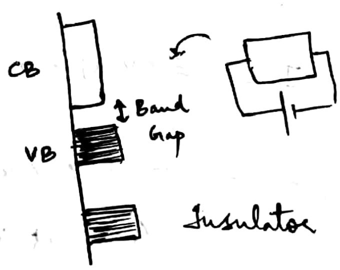
No. of atoms = N





No. of atoms = N
(Considering spin)



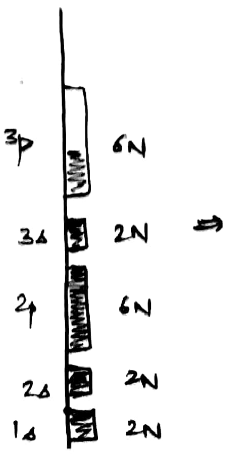


Band Gap is the gap b/w topmost completely filled band & bottom of completely unoccupied band.

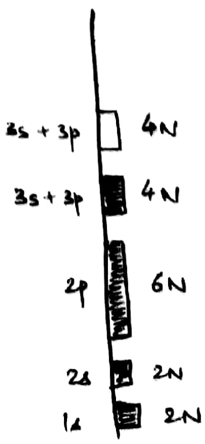
In metal, there is no band gap.

A completely filled band is an inert band.

$14 \Rightarrow 1s^2\ 2s^2\ 2p^6\ 3s^2\ 3p^2$



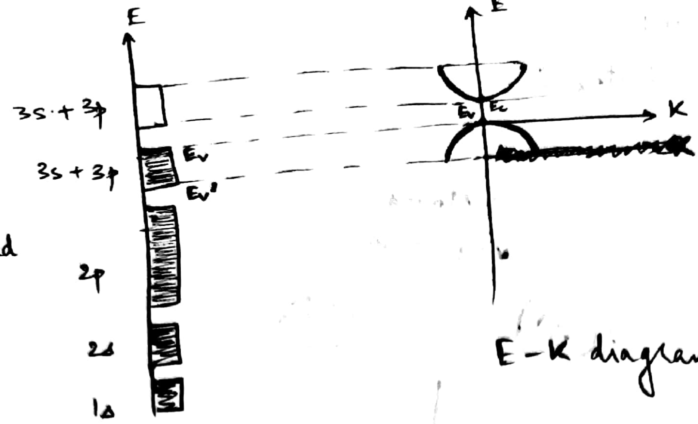
$\Rightarrow$



conduction band

valence band

Flat band model

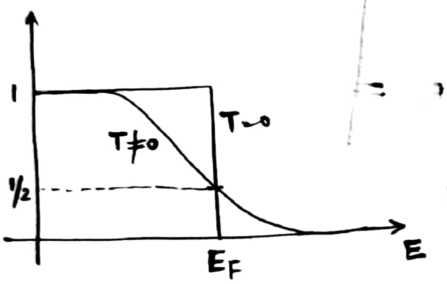


$p = \hbar K$

E-K diagram

$$I = \sum_{i=1} -ev(k_i) = 0$$

$f_e(E)$
probability of occupancy

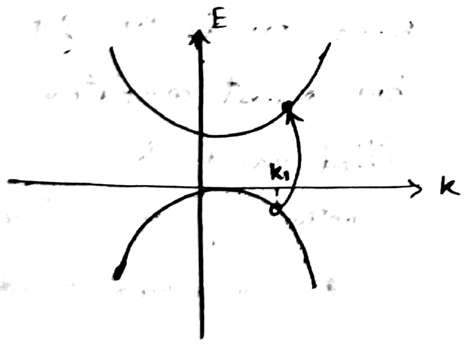


$E_F \Rightarrow$ Fermi Energy

$$n = \int f_e(E)\, D_e(E)\, dE$$

$\downarrow$
no. of electrons

$D_e(E)\, dE \Rightarrow$ No. of states b/w E & $(E + dE)$

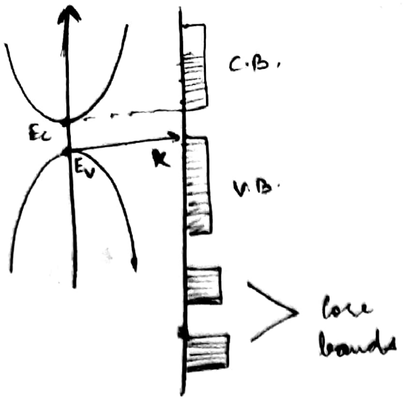


$$I = -\sum ev(k) = 0$$

$$I' = -\sum ev(k) \neq 0$$
(k except $k = k_1$)

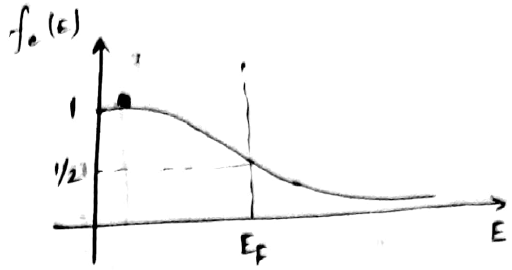
$$-\Big[\underset{(k \text{ except } k=k_1)}{\sum ev(k)} + ev(k_1)\Big] = 0$$

$$I' = \underset{(k \text{ except } k=k_1)}{-\sum ev(k)} = ev(k_1)$$



$$n = \int_{E_c}^{top} f_e(E)\, D_e(E)\, dE$$

$$f_e(E) = \frac{1}{e^{(E-E_F)/k_BT} + 1}$$

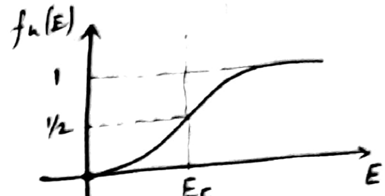


$$D_e(E) = \frac{1}{2\pi^2}\left(\frac{2m}{\hbar^2}\right)^{3/2}(E-E_c)^{1/2}$$

$$D_e(E) \propto (E-E_c)^{1/2}$$

$$f_h(E) = 1 - f_e(E)$$

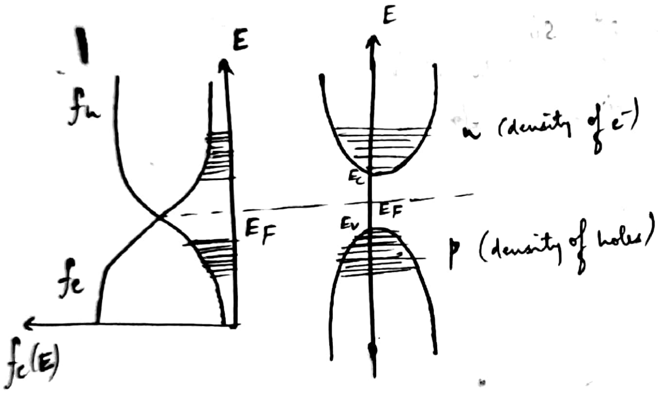
prob. of finding holes



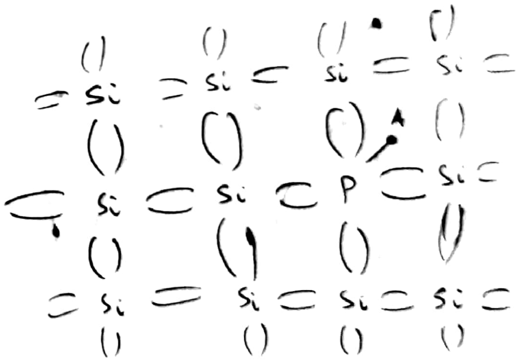
$f_h(E)$ & $f_e(E)$ are symmetric about E_F

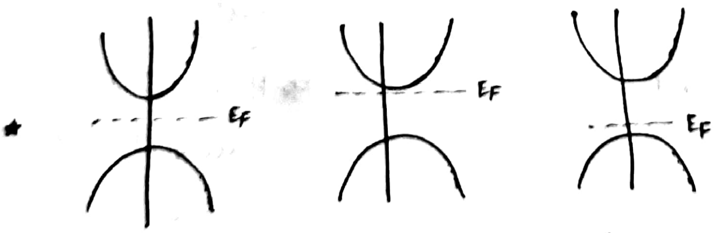
$$D_h(E) \propto (E_v - E)^{1/2}$$

$$p = \int_{bottom}^{E_v} f_h(E)\, D_h(E)\, dE$$

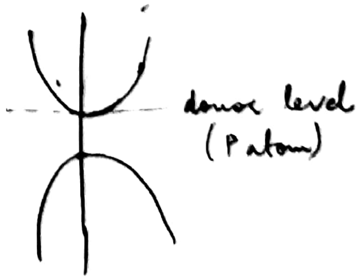


E_F lies exactly in the middle of band gap in intrinsic semiconductor





intrinsic n-type p-type



np = const.

$n = (n_i + n_D) \approx n_D$

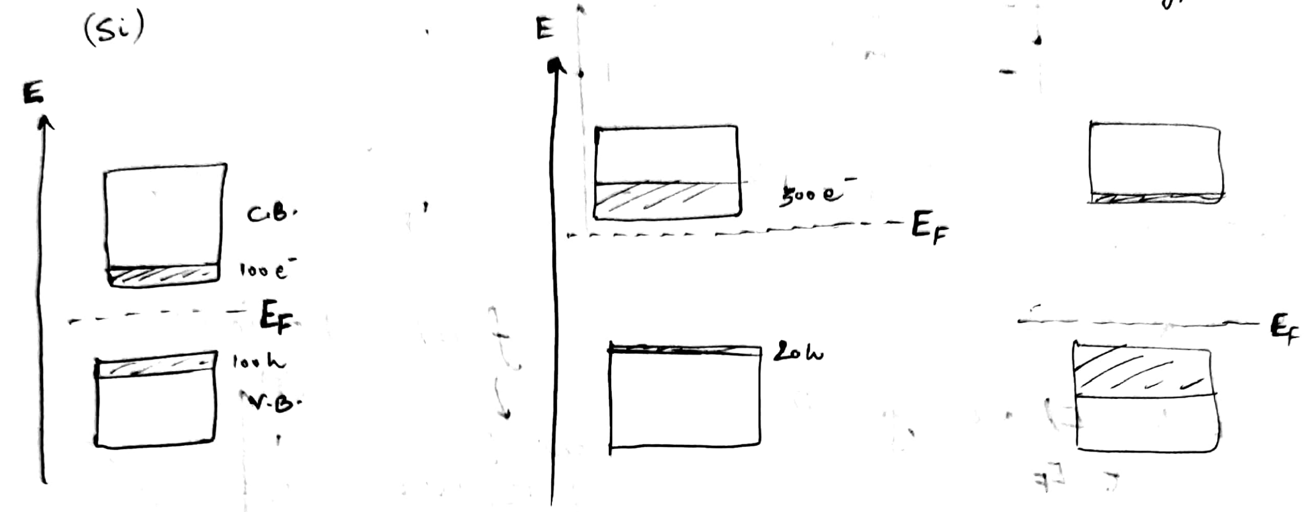
n_i → density of intrinsic

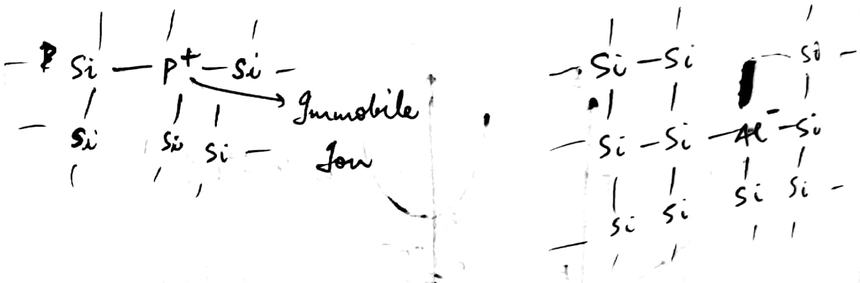
n_D → density of donor atoms

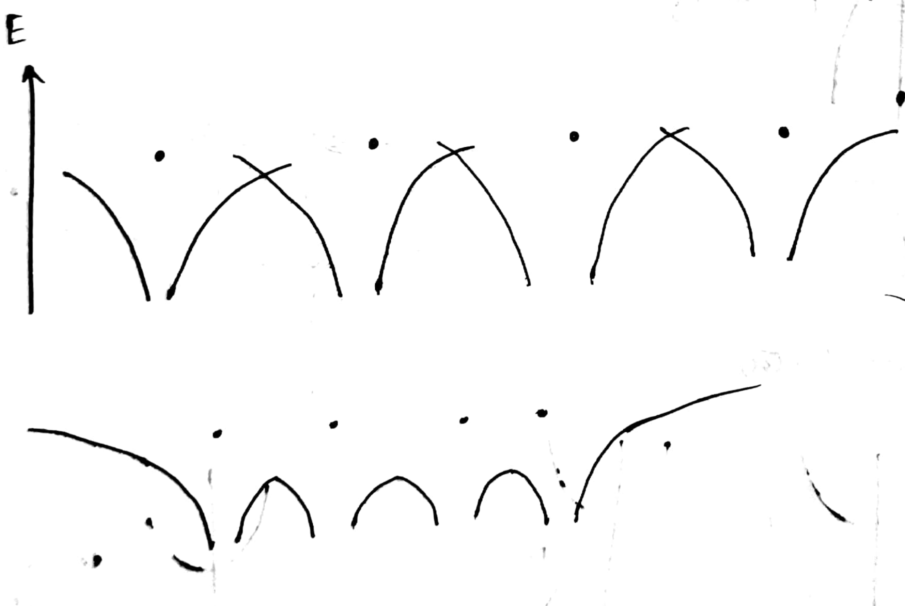
$p_a \Rightarrow$ density of acceptor atoms $\quad p = p_i + p_a \approx p_a$

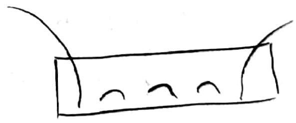
$$n_i = 2\left(\frac{k_B T}{2\pi \hbar^2}\right)^{3/2} \left(m_e^* m_h^*\right)^{3/2} e^{-E_g/2k_BT}$$

Intrinsic (Si) N-type P-type



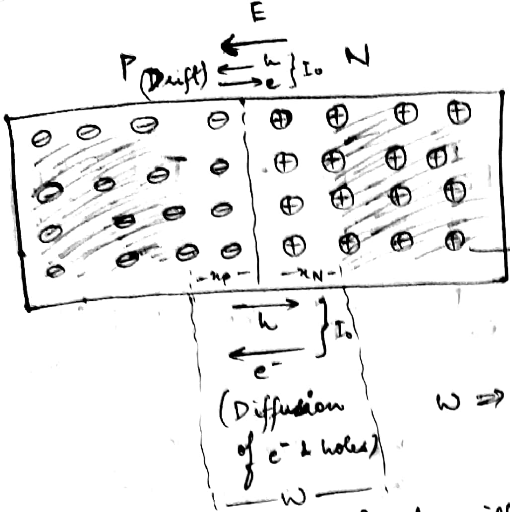






Crystal

Huge potential barrier at the surface (e's cannot eject out)



Immobile Ions

⇒ holes in P & e^- in N

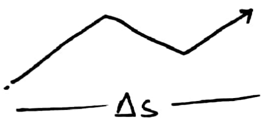
E ⇒ Electric field

W ⇒ width of depletion region

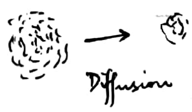
Developed electric field will oppose diffusion of majority carriers

When diffusion & drift of e^- & holes. becomes same, eqbm. is established. Diffusion is never stopped. & no current flows.

Drift of minority carriers depends on conc. of them & not on electric field.



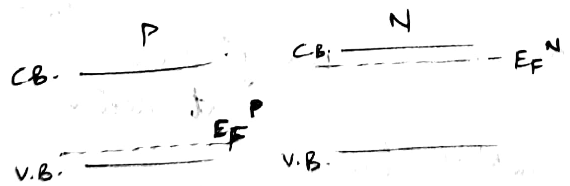
Drift velocity = $\frac{\Delta s}{\Delta t}$

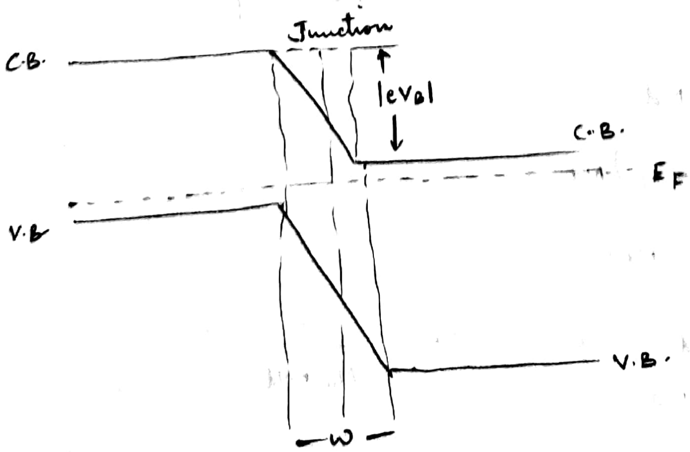


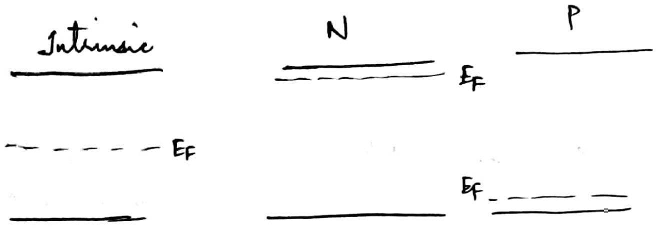
μ = Chemical Potential

At eqbm. μ (or E_F) is uniform.

$E_F \approx \mu$







$$E_F^N = E_F^i + k_B T \ln\left(\frac{n_d}{n_i}\right)$$

$$E_F^P = E_F^i - k_B T \ln\left(\frac{n_a}{n_i}\right)$$

$$eV_B = E_F^N - E_F^P$$

n_d = donor concⁿ
n_a = acceptor concⁿ
n_i = intrinsic e^- concⁿ

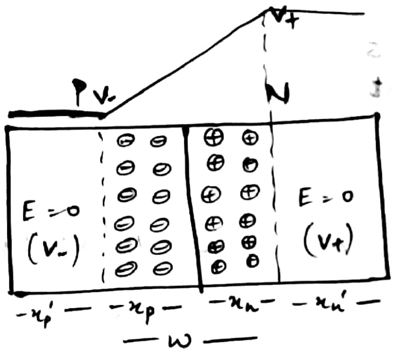
$V_B \Rightarrow$ Barrier Potential
$eV_B \Rightarrow$ Barrier Potential Energy

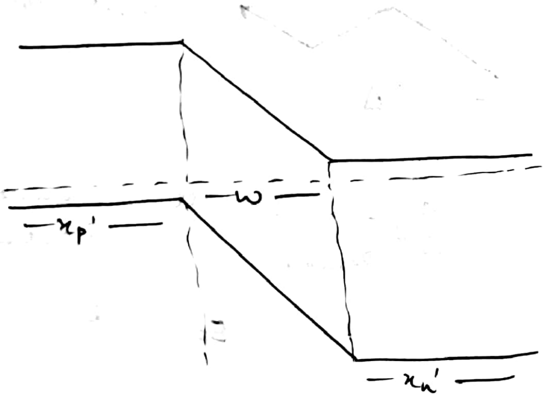
$$eV_B = k_B T \ln\left(\frac{n_a \cdot n_d}{n_i^2}\right)$$

x_p = part of depletion region in p-type
x_N = " " " " n-type

$$I = I_0 \left(\underbrace{e^{\frac{qV}{\eta k_B T}}}_{\text{Diffusion}} - \underbrace{1}_{\text{Drift}} \right)$$

$$w = x_p + x_N$$





$$V_B = V_+ - V_-$$

p-n junction
at electronics

$A \Rightarrow$ cross-sectional area

$$(x_p A) N_a = (x_n A) N_d \quad \text{(charge Neutrality)}$$

$$x_p N_A = x_n N_d$$

$$x_p N_A = (w - x_p) N_d$$

$$x_p (N_A + N_d) = N_d \cdot w$$

$$x_p = \frac{N_d}{N_a + N_d} \cdot w \qquad x_n = \frac{N_a}{N_a + N_d} \cdot w$$

$$\vec{\nabla}\cdot\vec{E} = \frac{\rho}{\varepsilon}$$ (differential form of Gauss law)

$$\vec{\nabla}\cdot\vec{E}_p = \frac{-eN_a}{\varepsilon} \qquad -x_p < x < 0$$

$$\vec{\nabla}\cdot\vec{E}_N = \frac{+eN_d}{\varepsilon} \qquad 0 < x < x_n$$

$$\frac{dE_p}{dx} = \frac{-eN_a}{\varepsilon}$$

$$\int_0^{E_p(x)} dE_p = \frac{-eN_a}{\varepsilon}\int_{-x_p}^{x} dx$$

$$E_p(x) = \frac{-eN_a}{\varepsilon}\left[x + x_p\right] \qquad -x_p < x < 0$$

$$E_N(x) = \frac{eN_D}{\varepsilon}\left[x - x_N\right] \qquad 0 < x < x_N$$

$$\int_{V_-}^{V_+} dV = \int -E(x)\, dx$$

$$= \int_{-x_p}^{0} -E_p(x)\, dx + \int_0^{x_N} -E_N(x)\, dx$$

$$= \int_{-x_p}^{0} \frac{eN_a}{\varepsilon}(x + x_p)\, dx + \int_0^{x_N} \frac{eN_D}{\varepsilon}(x_N - x)\, dx$$

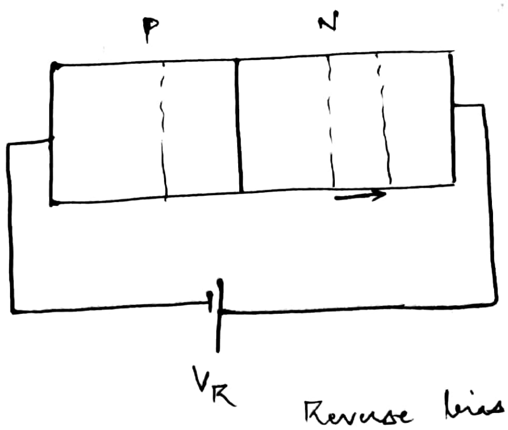
$$= \frac{eN_a}{\varepsilon}\left[\frac{x^2}{2} + x_p x\right]_{-x_p}^{0} + \frac{eN_D}{\varepsilon}\left[x_N x - \frac{x^2}{2}\right]_0^{x_N}$$

$$= \frac{eN_a}{\varepsilon}\left[-\frac{x_p^2}{2} + x_p^2\right] + \frac{eN_D}{\varepsilon}\left(x_N^2 - \frac{x_N^2}{2}\right)$$

$$V_B = \frac{eN_a}{\varepsilon}\cdot\frac{x_p^2}{2} + \frac{eN_D}{\varepsilon}\cdot\frac{x_N^2}{2}$$

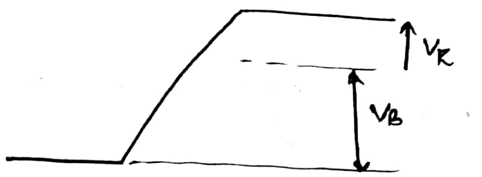
$$V_B = \frac{1}{2\varepsilon}\, e\left[N_a\left(\frac{N_d}{N_a+N_d}\, W\right)^2 + N_d\left(\frac{N_a}{N_a+N_d}\, W\right)^2\right]$$

$$= \frac{eN_aN_DW^2}{2\varepsilon(N_a+N_D)} \Rightarrow V_B = \frac{e}{2\varepsilon}\, W^2\, \frac{N_aN_d}{N_a+N_d}$$



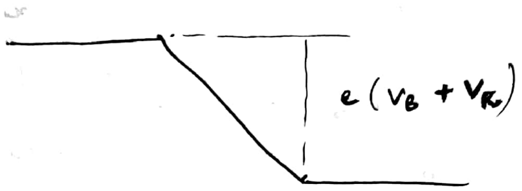
Reverse bias

Potential

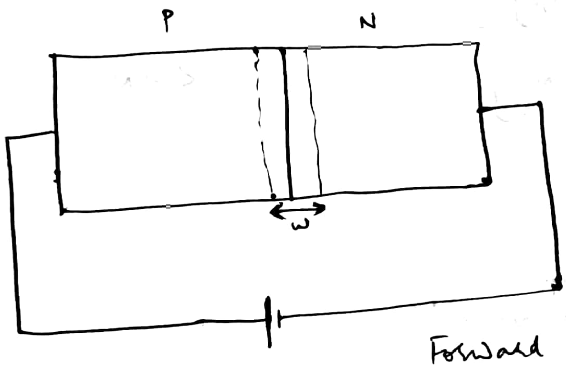


Barrier w increases &

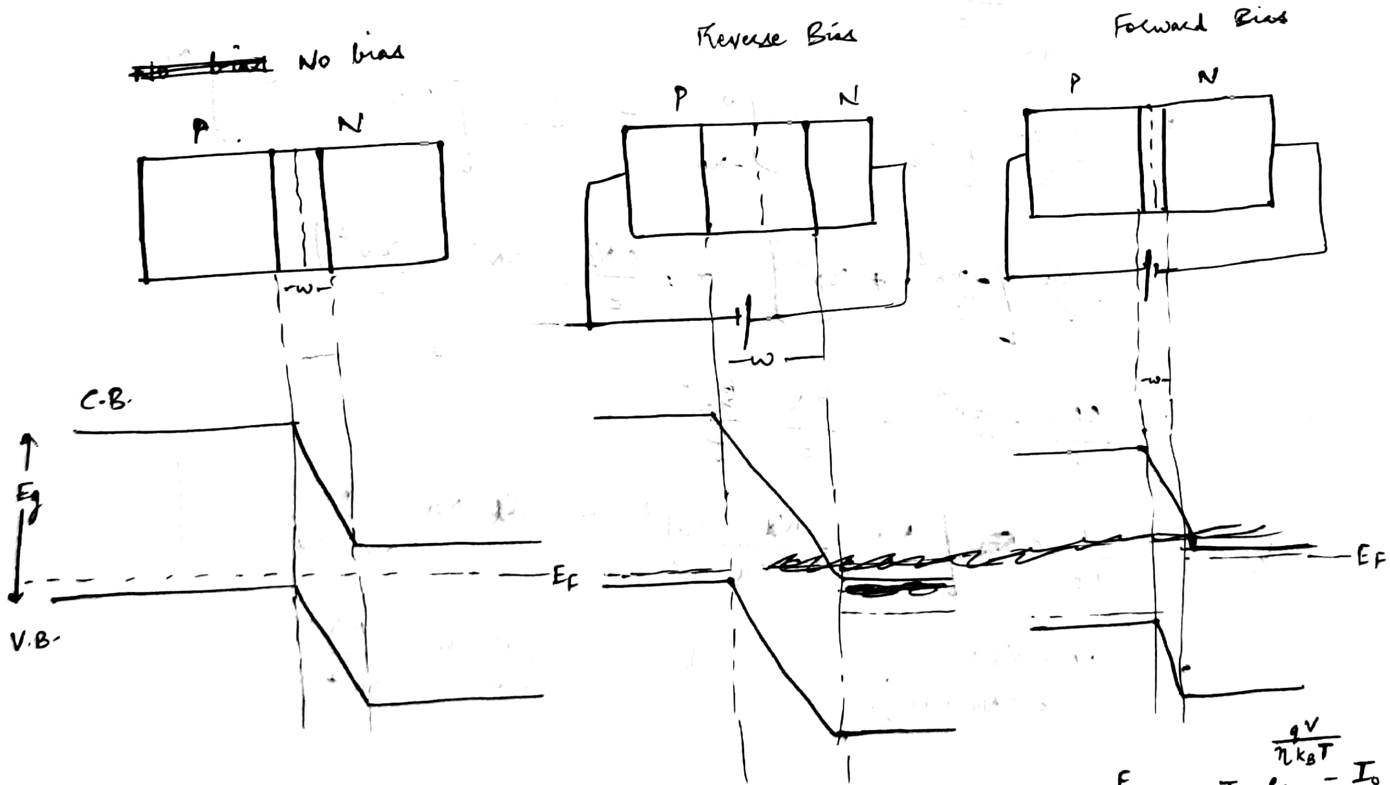
V+ increases



Potential energy



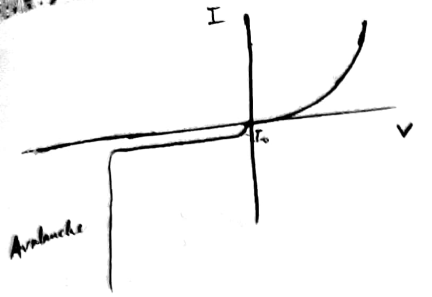
Forward bias B w decreases



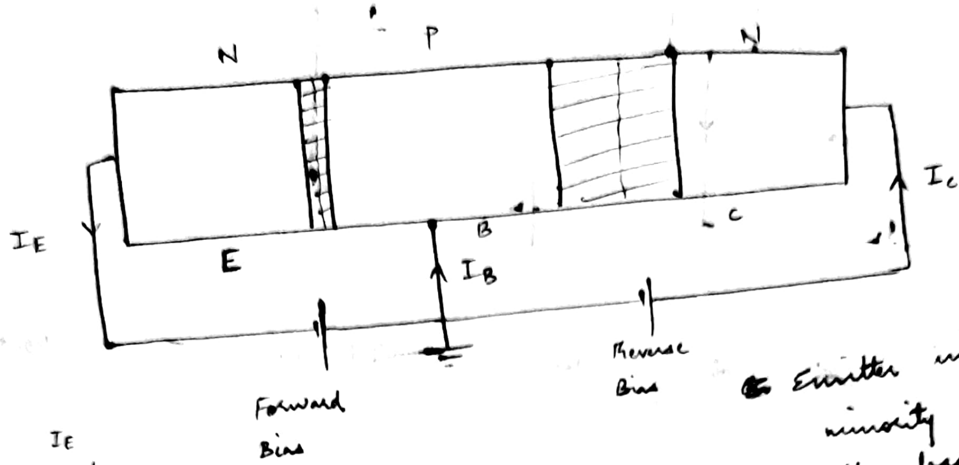
$I_{Total} = 0$

$$I^{R}_{Total} = \underset{\text{majority}}{I_0'} - \underset{\text{minority}}{I_0}$$

$$I^{F}_{Total} = I_0 \cdot e^{\frac{qV}{\eta k_B T}} - I_0$$

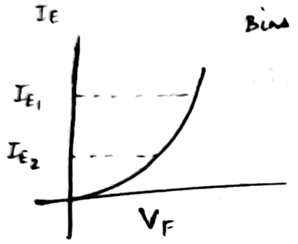


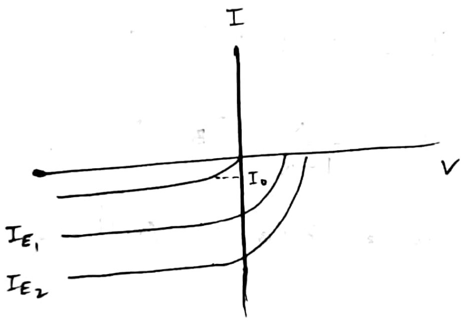
Transistor



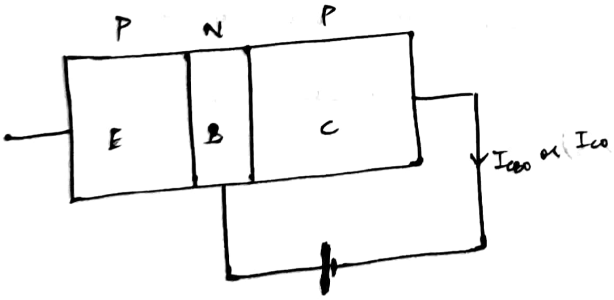
$I_E \Rightarrow -ve$
$I_B \Rightarrow +ve$
$I_c \Rightarrow +ve$

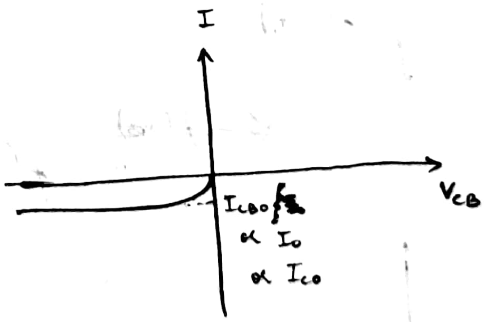
- Emitter injects the minority carriers into the base.
- Base controls the minority carriers.
- Collectors collects the minority carriers.





Current going in $\Rightarrow +ve$
" " out $\Rightarrow -ve$

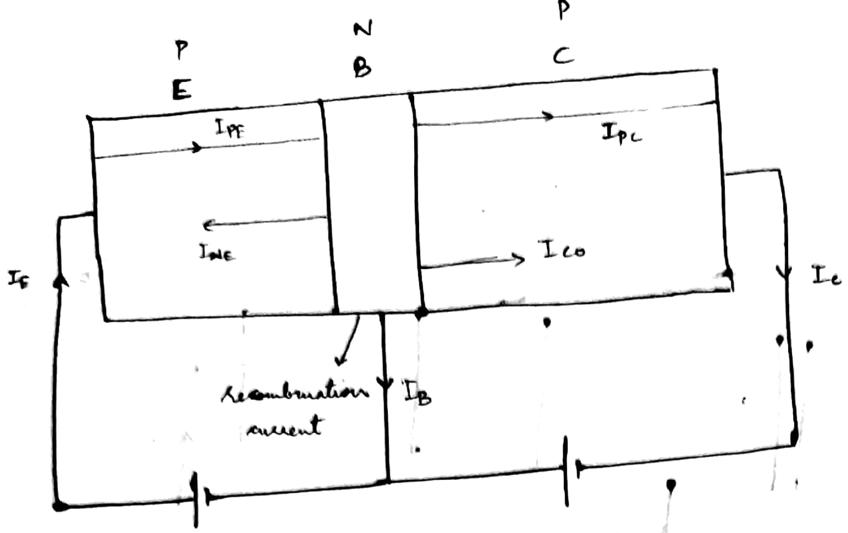




$I_{CBO} \Rightarrow I_{CB}$ when emitter is open

Doping levels are different regions

Emitter - Highly doped
Collector - Moderately doped
Base - Less doped



Width of base is very small

Effective ~~width~~ width of base = Total width W − $W_{depletion}$

$I_c = I_{pc} + I_{co}$

$I_c = \alpha I_E + I_{co}$ (Active region)

$I_c \approx \alpha I_E$

I_{pc} is a fraction of I_E

$I_E = I_c + I_B$

$I_c = \alpha(I_c + I_B) + I_{co}$

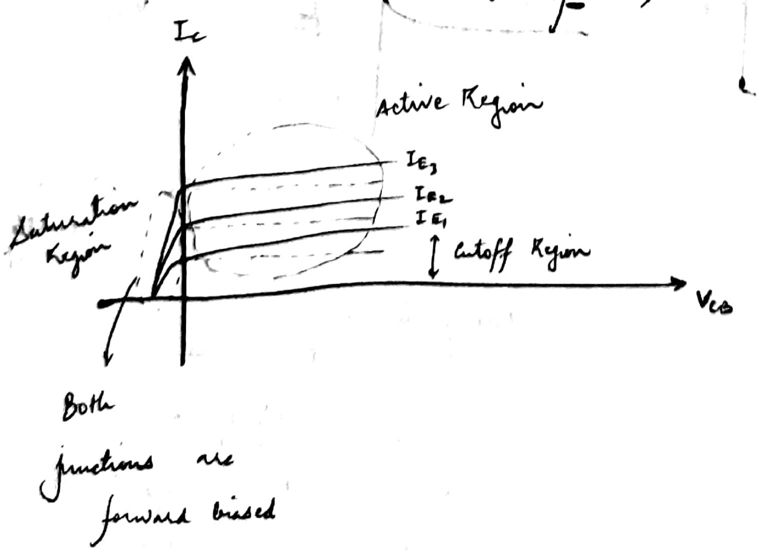
$$I_c = \frac{\alpha}{1-\alpha} I_B + \frac{1}{1-\alpha} I_{co}$$

$I_c = \beta I_B + (\beta+1) I_{co}$

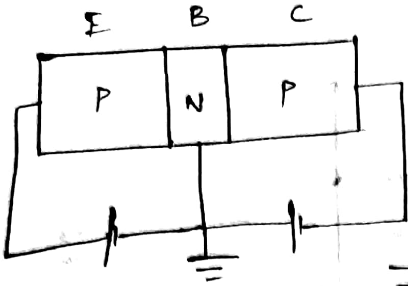
Base width modulation with V_{CB} (Early Effect) ⇒ Increase in V_{CB} will decrease the width & more and more holes will move to the collector increasing I_c

~~$\alpha = f(V_{CB})$~~

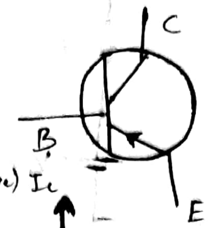
$\alpha = f(V_{CB})$

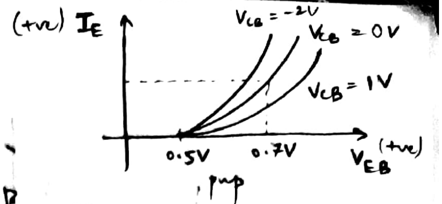


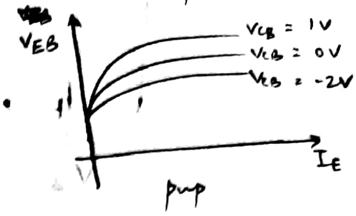
$I_C = \alpha I_E + I_{CO}$

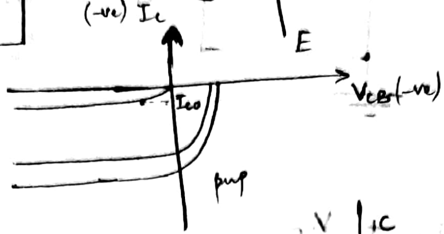


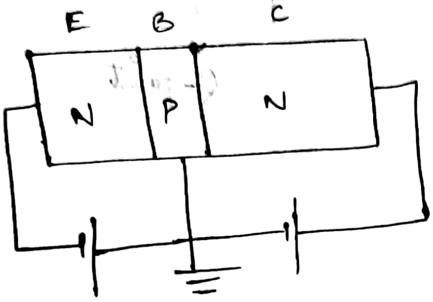
CB configuration

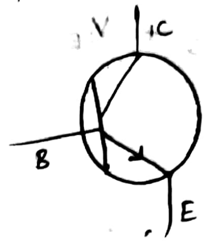


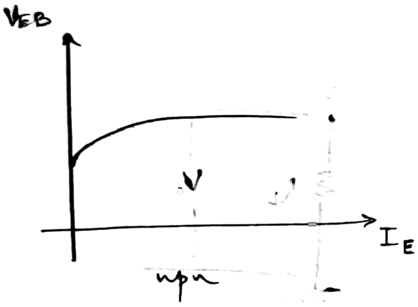




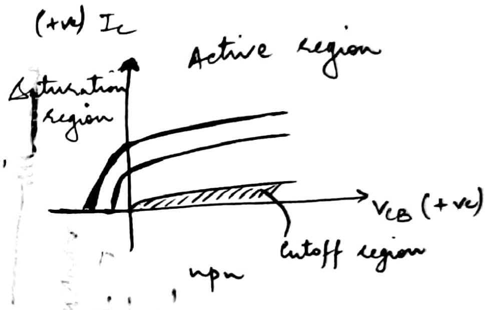








$\uparrow V_{EB}$, $I_E \Rightarrow -ve$,



I_B saturates at saturation region

$I_B > (I_B)_{min}$

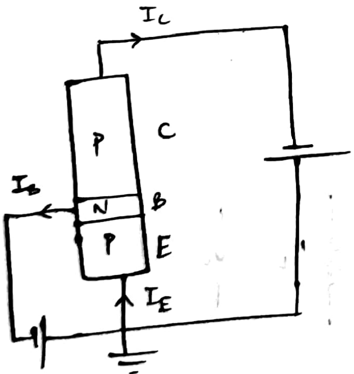
$\Downarrow$

Condition of saturation

Saturation region $\Rightarrow V_{CB} \approx 0.5$ V

$\Rightarrow V_{EB} = 0.8$V

Active region $\Rightarrow V_{EB} = 0.7$V (Si)



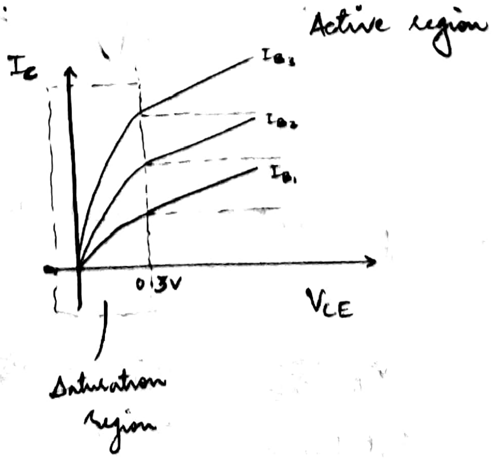
CE configuration

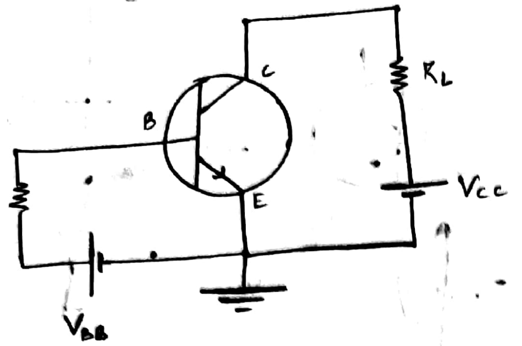
$V_{CE} = V_{CB} + V_{BE}$

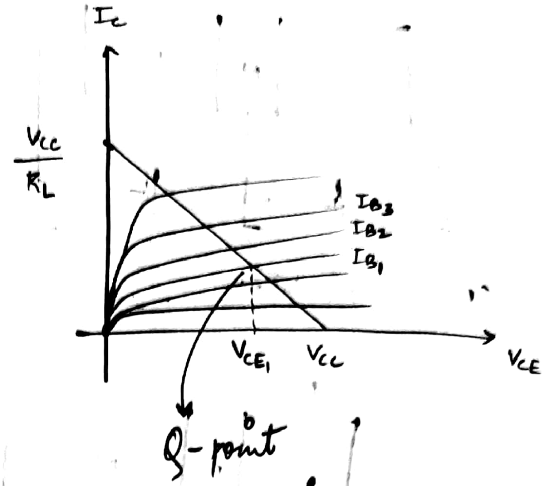
$= 0.3V$ (Saturation region)

$I_C = \beta I_B + (\beta+1) I_{CO}$

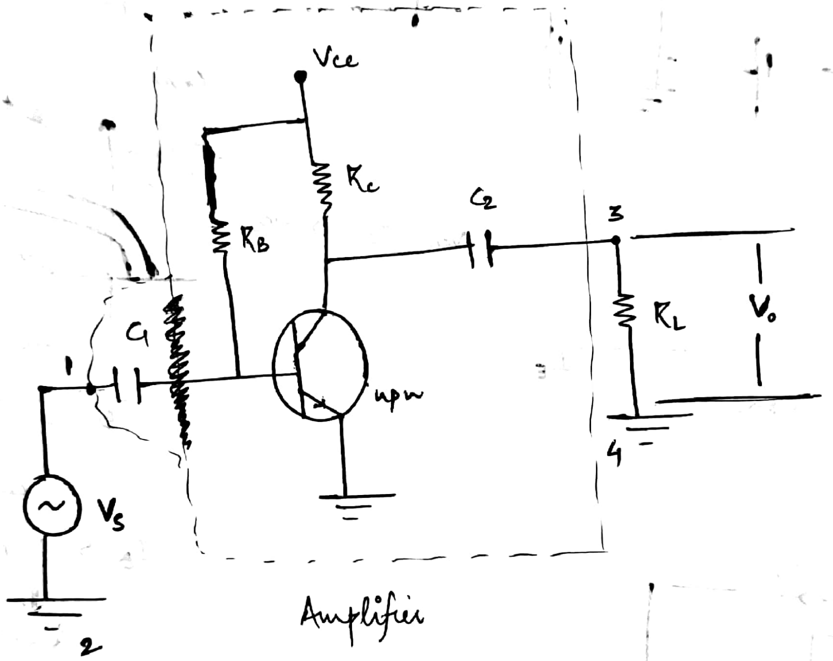
$= \frac{\alpha}{1-\alpha} I_B + \frac{1}{1-\alpha} I_{CO}$



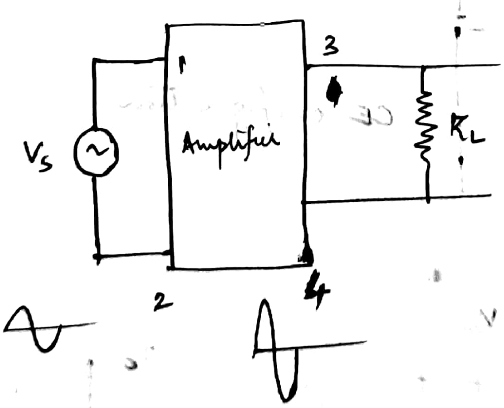




$$V_{CC} = I_C R_L + V_{CE}$$



Amplifier



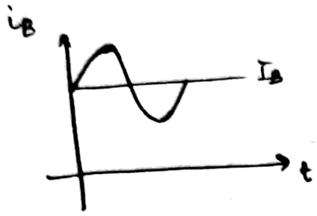
Blocking capacitor is used to block the DC part of the circuit.

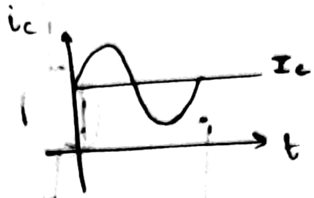
$$v_{BE} = V_{BE} + v_{be}$$

Instantaneous voltage at E-B junction — DC value — AC input signal

$i_B = I_B + i_b$

$i_c = I_c + i_c$ $\qquad V_o = V_{CE} = V_{cc} - i_c R_c$



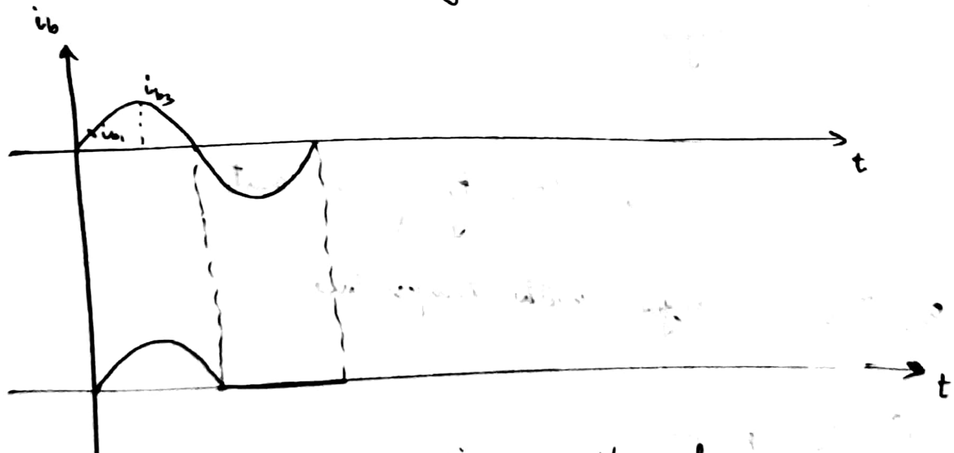


§ Amplification of signal without any distortion can only be made when Q-point is in the middle of the load line.

DC Bias is required to keep it on in the active region to ensure ~~amplified~~ amplification without distortion.

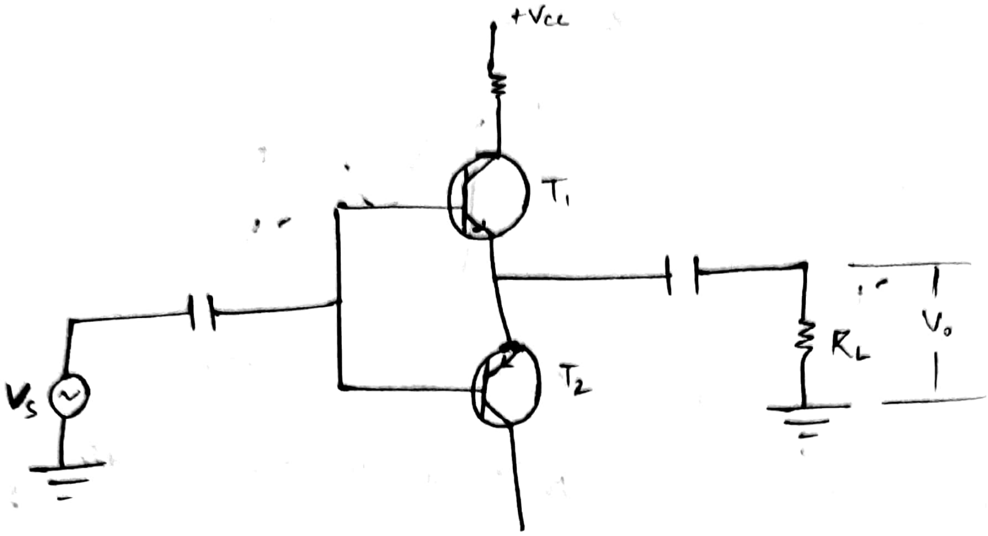
Class-A amplifier is an amplifier in which Q-point is ~~in~~ in middle of load line & is in active region.

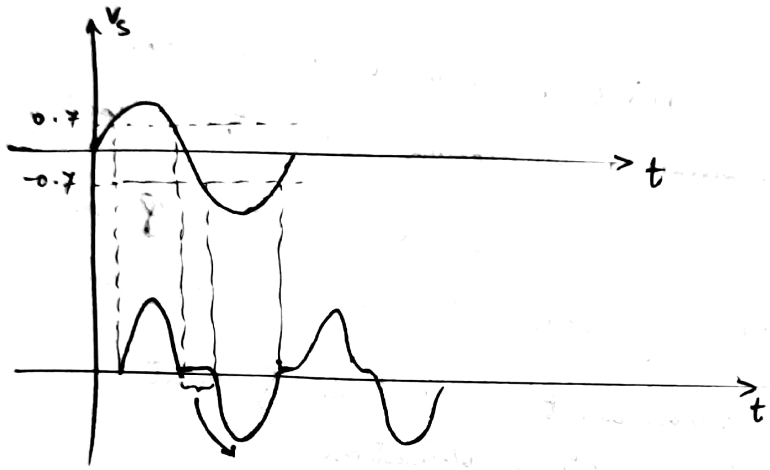
DC bias - Establishment & suitable Q-point
Small signal operation



Class-B Amplifier → Very less energy consumption
Accomodate large signal
Can only amplify one part of signal
Distortion in crossover region

(Q-point is in saturation initially)





distortion in crossover region

Thermal Stability of Q-Point

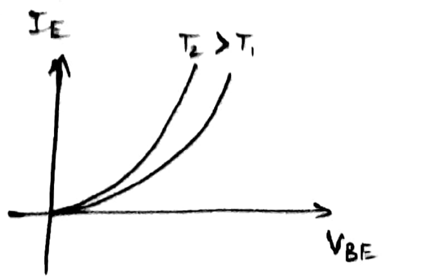
V_{BE}, β, I_{co} changes with temperature

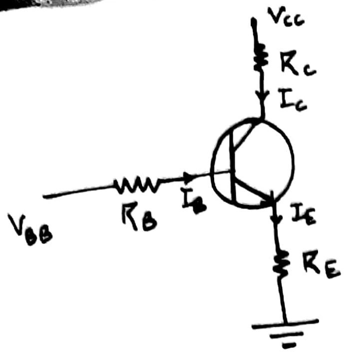
$$Q\,(I_c,\ I_B,\ V_{CE})$$

$$I_c = \beta I_B + (\beta+1) I_{co}$$

$T\uparrow \Rightarrow$ minority carriers $\uparrow \Rightarrow I_{co}\uparrow \Rightarrow I_c \uparrow \Rightarrow$ Q-point shifts

$$I_E = I_{EBO}\left(e^{\frac{eV}{\eta k_B T}} - 1\right)$$





$$V_{BB} = I_B R_B + V_{BE} + I_E R_E$$

$$= I_B R_B + V_{BE} + (I_C + I_B) R_E$$

$$= I_B (R_B + R_E) + V_{BE} + I_C R_E$$

$$V_{BB} = I_C R_E + (R_B + R_E)\left[\frac{I_C}{\beta} - \frac{\beta+1}{\beta} I_{CO}\right] + V_{BE}$$

$$V_{BB} = \left(R_E + \frac{R_B + R_E}{\beta}\right) I_C - \frac{\beta+1}{\beta}(R_B + R_E) I_{CO} + V_{BE}$$

Thermal stability parameters

$$S = \left(\frac{\partial I_C}{\partial I_{CO}}\right)_{V_{BE},\beta} \qquad S' = \left(\frac{\partial I_C}{\partial V_{BE}}\right)_{I_{CO},\beta} \qquad S'' = \left(\frac{\partial I_C}{\partial \beta}\right)_{V_{BE},I_{CO}}$$

$$S = \left(\frac{\partial I_C}{\partial I_{CO}}\right)_{V_{BE},\beta} = \frac{\frac{\beta+1}{\beta}(R_B + R_E)}{\left(R_E + \frac{R_B + R_E}{\beta}\right)}$$

$$S = \frac{(\beta+1)(R_B + R_E)}{R_B + (1+\beta) R_E}$$

$$S = \frac{(\beta+1)\left(1 + \frac{R_B}{R_E}\right)}{1 + \beta + \frac{R_B}{R_E}}$$

$$S = 1 + \beta \quad \text{if } R_E = 0$$

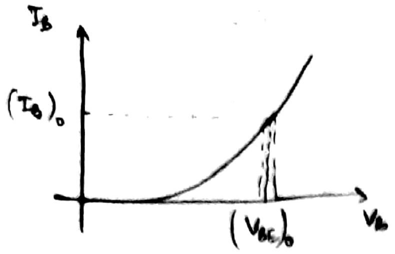
$$S \approx 1 \quad \text{if } \frac{R_B}{R_E} \ll 1$$

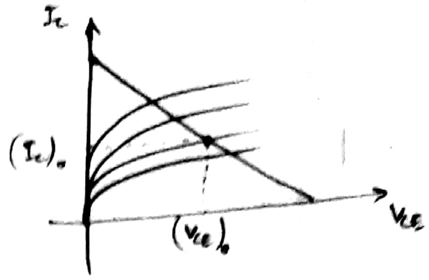
$$S' = \left(\frac{\partial I_C}{\partial V_{BE}}\right)_{\beta, I_{CO}} = \frac{-\beta}{(1+\beta) R_E + R_B}$$

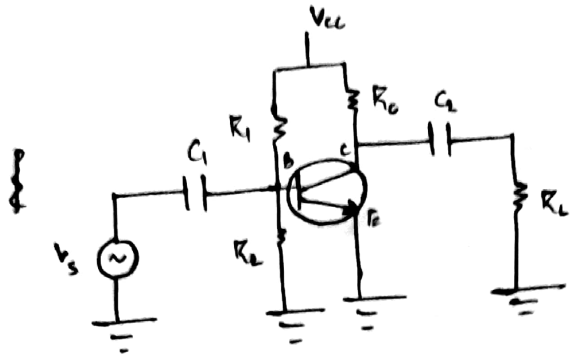
$$S' = \frac{-\beta}{R_B} \quad \text{if } R_E = 0$$

$$S' \approx \frac{-\beta}{1+\beta} \quad \text{if } \frac{R_B}{R_E} \ll 1$$

$$S'' = \left(\frac{\partial I_C}{\partial \beta}\right)_{I_{CO}, V_{BE}} = \frac{\left(\frac{R_B + R_E}{\beta^2}\right) I_C}{R_E + \frac{R_B + R_E}{\beta}} = \frac{S I_C}{\beta(\beta+1)}$$







$$v_{CE} \propto i_c$$
$$v_{BE} \propto i_b$$
$$v_{BE} = h_{ie}\, i_b$$

$$v_{BE} = (V_{BE})_0 + v_{be}$$
$$i_B = (I_B)_0 + i_b$$

$$v_{CE} = (V_{CE})_0 + v_{ce}$$
$$i_c = (I_c)_0 + i_c$$

$$\Delta v_{BE} = v_{BE} - (V_{BE})_0 = v_{be}$$

$$v_{BE} = f(i_B, V_{CE})$$

$$v_{BE} = (V_{BE})_0 + \underbrace{\left(\frac{\partial V_{BE}}{\partial i_B}\right)_{V_{CE}}}_{\text{evaluated at Q-point}} \Delta i_B + \underbrace{\left(\frac{\partial V_B}{\partial V_{CE}}\right)_{i_B}}_{\text{evaluated at Q-point}} \Delta V_{CE}$$

$$v_{be} = v_{BE} - (V_{BE})_0 = \left(\frac{\partial V_{BE}}{\partial i_B}\right)_{V_{CE}} \Delta i_B + \left(\frac{\partial V_{BE}}{\partial V_{CE}}\right)_{i_B} \Delta V_{CE}$$

$$\cancel{v_{be} = h_{ie} i_b}$$
$$v_{be} = h_{ie}\, i_b + h_{re}\, v_{CE}$$

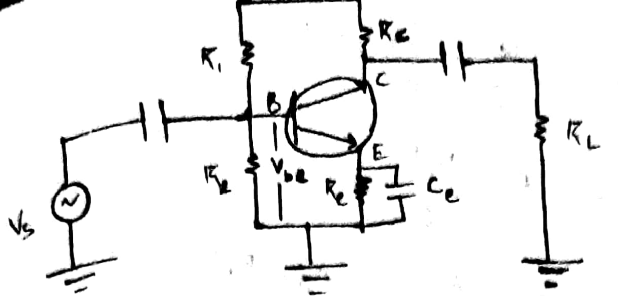
$$i_C = f(v_{CE}, i_B)$$

$$i_C = (I_C)_0 + \underbrace{\left(\frac{\partial i_c}{\partial i_B}\right)_{V_{CE}}}_{\text{Evaluated at Q-point}} \Delta i_B + \underbrace{\left(\frac{\partial i_c}{\partial V_{CE}}\right)_{i_B}}_{\text{Evaluated at Q-point}} \Delta V_{CE}$$

$$i_c = i_C - (I_C)_0 = \left(\frac{\partial i_c}{\partial i_B}\right)_{V_{CE}} i_b + \left(\frac{\partial i_c}{\partial V_{CE}}\right)_{i_B} V_{CE}$$

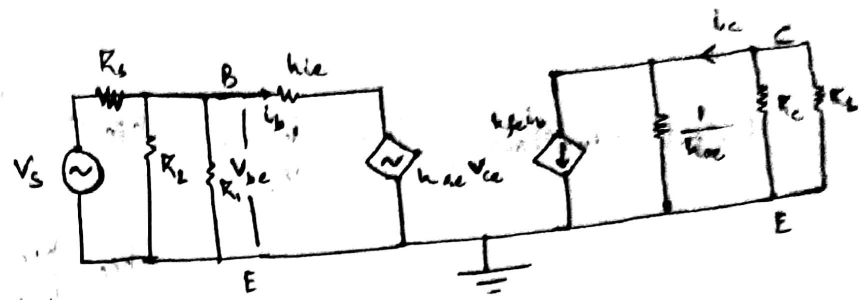
$$i_c = h_{fe}\, i_b + h_{oe}\, V_{CE}$$

$$\frac{1}{h_{oe}} = \frac{v_{CE}}{i_c}$$



$$v_{be} = h_{ie} i_b + h_{re} v_{ce}$$

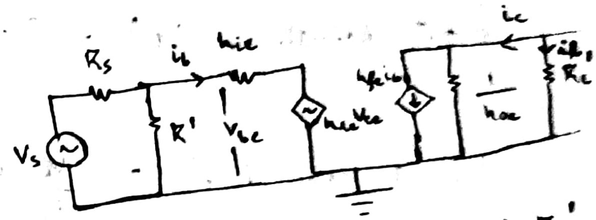
$$i_c = h_{fe} i_b + h_{oe} v_{ce}$$



Small Signal Analysis

$R_s \Rightarrow$ Internal resistance of AC source

1) Remove DC voltage source with short
2) Remove any capacitor with short



$v_{ce} = i_L R_L'$

$i_L = -i_c$

$R' = R_1 \parallel R_2$

$R_L' = R_c \parallel R_L$

Current gain $\Rightarrow$

$$A_I = \frac{i_L}{i_b} = \frac{-i_c}{i_b}$$

$$= h_{fe} + h_{oe} \frac{v_{ce}}{i_b}$$

$$= h_{fe} + h_{oe} \frac{i_L R_L'}{i_b}$$

$$A_I = h_{fe} + \frac{h_{oe}(-i_c)R_L'}{i_b}$$

$$A_I = h_{fe} - A_I R_L' h_{oe}$$

$$A_I = \frac{-h_{fe}}{1 + R_L' h_{oe}}$$

Input impedance (Z_i) seen from BE terminal

$$= \frac{v_{be}}{i_b} = h_{ie} + h_{re} \frac{v_{ce}}{i_b}$$

$$= h_{ie} + h_{re} \frac{i_L R_L'}{i_b}$$

$$Z_i = h_{ie} + h_{re} A_I R_L'$$

Voltage Gain $(A_v) = \frac{i_L R_L'}{v_{be}} = \frac{i_L}{i_b} \cdot \frac{i_b}{v_{be}} R_L'$

$= A_I \frac{R_L'}{Z_i}$

$\Rightarrow A_v = A_I \frac{R_L'}{Z_i}$

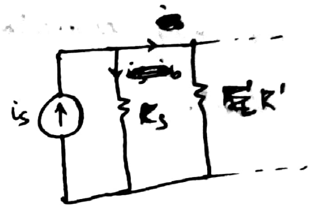
Output Admittance $(Y_o) = \frac{i_c}{V_{ce}} = h_{fe}\frac{i_b}{V_{ce}} + h_{oe}$

$= -h_{fe}\frac{h_{re}}{h_{ie}} + h_{oe}$ $\left(\because i_b h_{ie} + h_{re} V_{ce} = 0 \right)$ $\frac{i_b}{V_{ce}} = \frac{-h_{re}}{h_{ie}}$

Input ~~Admittance~~ Impedance $(Z_{Is}) = R_s + R' \| Z_i$ seen from V_s

Current Gain $(A_{Is}) = \frac{i_L}{i_b}\frac{i_b}{i_s}$

$= A_I \frac{R''}{R'' + Z_i}$



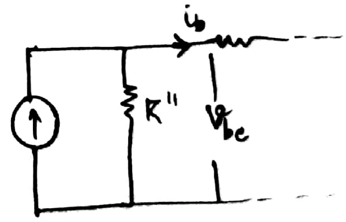
$R'' = R' \| R_s$

$(i_s - i_b) R'' = i_b Z_I$

Voltage Gain $(A_{vs}) = \frac{i_L R_L'}{v_s}$

$= \frac{i_L R_L'}{v_{be}} \cdot \frac{v_{be}}{v_s}$

$= A_v \frac{v_{be}}{v_s}$



$\frac{i_b}{i_s} = \frac{R''}{R'' + Z_i}$

$(i - i_b) R' = i_b Z_i$

$V_s - iR_s - (i - i_b)R' = 0$

$V_s = i(R_s + R') - i_b R'$

$i = \frac{V_s + i_b R'}{R_s + R'}$