

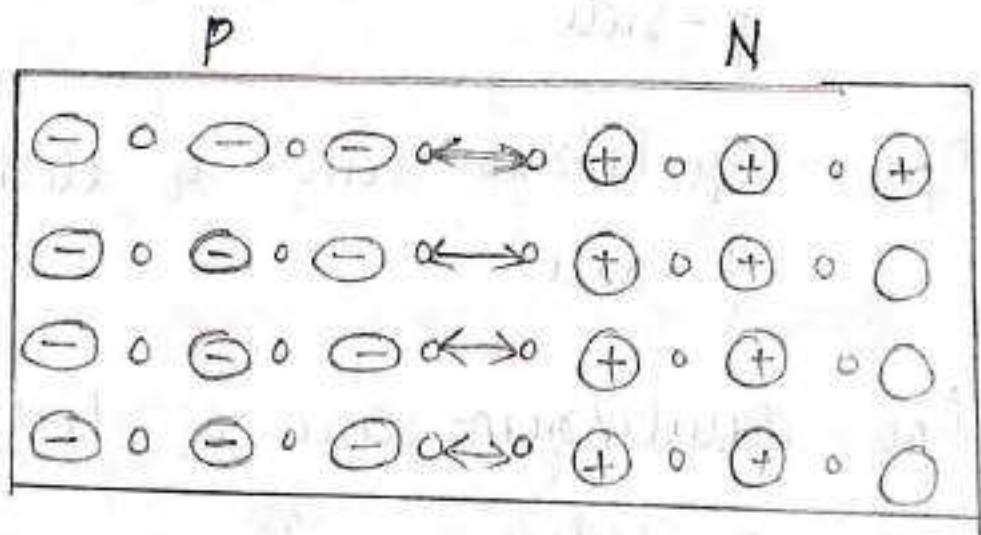
09/10/20  
Monday

## MODULE - 3

### P-n junction diode

A semiconductor diode is a junction b/w P type and N type semiconductor.  
 $\therefore$  it is also designated as a p-n junction.

Let a p-type material with doping concentration  $10^{16}/\text{cm}^3$  and n-type material doping  $10^{15}/\text{cm}^3$  are drawn together to form a contact at a room temperature.

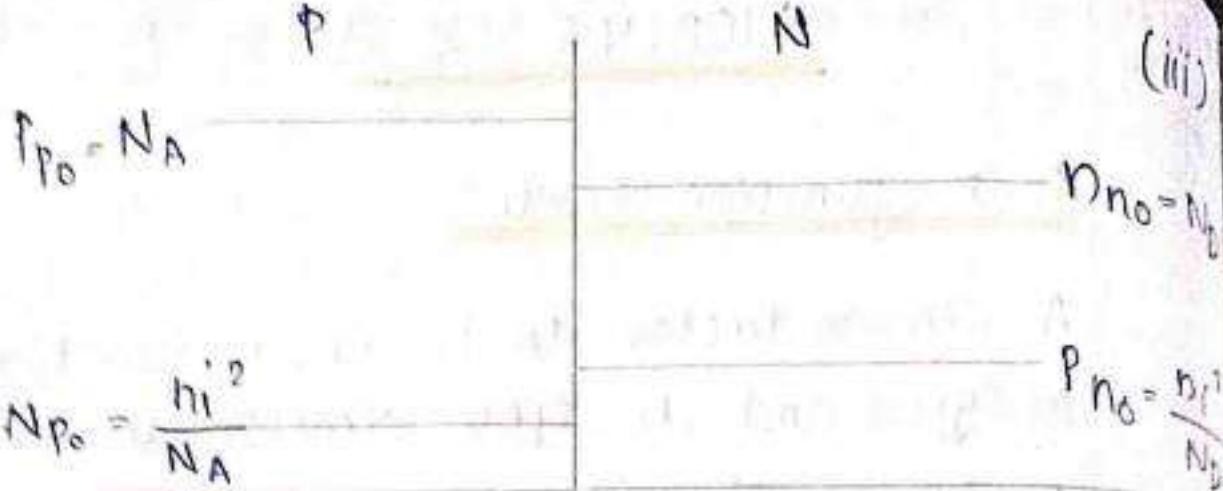


P -       $\leftarrow$       + N

$- \circ - \circ$	$\Theta$	$+ \circ + \circ + \circ$
$- \circ - \circ$	$\Theta$	$+ \circ + \circ + \circ$
$- \circ - \circ$	$\Theta$	$+ \circ + \circ + \circ$
$- \circ - \circ$	$\Theta$	$+ \circ + \circ + \circ$

(ii)

$\brace{}$  Barrier potential



The carrier concentration in the P and N material just before the formation of Junction is shown in Fig 3 where

$N_{p0}$  - equilibrium conc. of ~~electron~~<sup>holes</sup> in the p-side

$n_{p0}$  - equilibrium conc. of electrons in the p-side

$N_{n0}$  - equilibrium conc. of electrons in the n-side

$P_{n0}$  - equilibrium conc. of holes in the n-side

$\Delta V$  is evident from the figure.

(i) (ii) that large gradient in hole concentration exist b/w p-material and n-material. Therefore hole diffuse from p-side to n-side of the junction. diffuse to holes recombine with in n-material as a result un-bated acceptor ions are left b in the side and donor ions O similarly, electron diffuse from n-side to p-side which recombine with holes. The p-side thus also form unco ted ions on both n and p

The diffusion of charge carrier the junction forms a region of pensoated -ve ions on p-side and +ve ions n side. This region of pile charges is called depletion region or space charge region.

The dipole effect depletion changes results in a potential hense between the two ends of depletion layer. This

which is directed from n side to p side. This electric field aids the flow of minority carriers or drift carriers across

the junction. At the same time, the presence of depletion layer reduces the gradient of carrier concentration resulting in the decrease of diffusion current.

As the diffusion process continues, the depletion layer widens and the electric field across the depletion layer increases i.e., drift current increases and diffusion current decreases. A thermal equilibrium is at red when drift current balances diffusion current since the dir. of drift and diffusion current are opposite to each other. The net current at equilibrium is zero.

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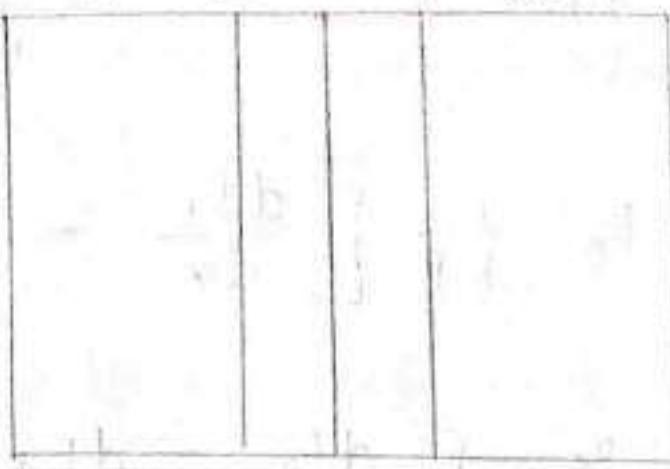
### Constancy of Fermilevel at equilibrium

At thermal equilibrium, the <sup>net</sup> current through the diode is zero.

$$I_n = I_n \text{ drift} + I_n \text{ diffusion}$$

$$I_p = I_p \text{ drift} + I_p \text{ diffusion}$$

P - + N



$$J_p = q \nu P \mu_p \epsilon_x - q D_p \frac{d}{dx} P(x) = 0 \quad \text{--- (1)}$$

$$\cancel{q \nu P \mu_p \epsilon_x} = \cancel{q \nu D_p} \frac{d}{dx} P(x) \quad \text{--- (2)}$$

$$P(x) \epsilon_x = \frac{D_p}{\mu_p} \frac{d}{dx} P(x) \quad \text{--- (3)}$$

$$\underline{P(x) \epsilon_x = \frac{kT}{q} \frac{d}{dx} P(x)} \quad \text{--- (4)}$$

$$\epsilon_x = \frac{kT}{q} \frac{1}{P(x)} \frac{d}{dx} P(x) \quad \text{--- (5)}$$

$$-\frac{dv}{dx} = \frac{kT}{q} \frac{1}{P(x)} \frac{d}{dx} P(x) \quad \text{--- (6)}$$

$$P_0 = n_i e^{(E_i - E_F)/kT} \quad \text{--- (7)}$$

$$\frac{dp_0}{dx} = n_i e^{(E_i - E_f)/kT} \times \frac{1}{kT} \left( \frac{dE_i}{dx} - \frac{dE_f}{dx} \right)$$

$$= p_0 \frac{1}{kT} \left[ \frac{dE_i}{dx} - \frac{dE_f}{dx} \right] \quad \text{--- (9)}$$

$$= \frac{p_0}{kT} \left[ \frac{dE_i}{dx} - \frac{dE_f}{dx} \right] \quad \text{--- (9)}$$

$$\epsilon_x = -\frac{dv}{dx} = -\frac{d}{dx} \left[ \frac{E_i}{q} \right]$$

$$= -\frac{1}{q} \frac{d}{dx} E_i \quad \text{--- (10)}$$

$$\frac{DP}{\mu_p} = \frac{kT}{q} \quad \text{--- (11)}$$

Apply (9), (10), (11) in (4)

~~$$P(x) = \frac{1}{q} \frac{d}{dx} E_i = \frac{RT}{q} \frac{p_0}{kT} \left[ \frac{dE_i}{dx} - \frac{dE_f}{dx} \right]$$~~

$$\frac{d}{dx} E_i = \frac{dE_i}{dx} - \frac{dE_f}{dx}$$

$$\frac{dE_f}{dx} = 0 \quad \text{hence proved}$$

Permit level is constant //

## Equilibrium energy band diagrams

The equilibrium energy band diagram of an p-n junction can be drawn with the help of the following principles:

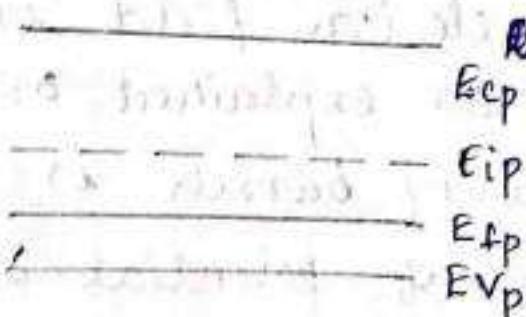
1. The fermi level is single horizontal line  $\left[ \frac{d}{dx} E_F = 0 \right]$  under thermal equilibrium.
2. Depletion layer is depleted of mobile charge carriers and the region outside the depletion layer is neutral. (This is called depletion approximation).
3. The electric field in the neutral region is zero. Therefore, the bands are flat in the neutral n and p regions. The fermi level position in the neutral regions depend only on the doping. (This is true for diodes with bias also).
4. The energy bands bend upwards in the direction of the electric field in the depletion layer as explained or the direction of energy barrier is opposite to the direction of potential barrier.

The steps involved in the fig. I, II, III, IV and listed below.

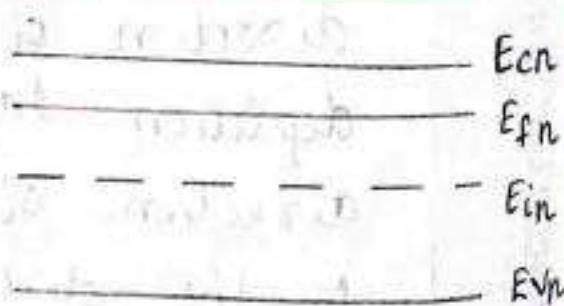
1. Draw the equilibrium fermilevel.
2. Mark the depletion region (where the electric field exist and band bends)
3. Draw the valence band edge  $E_V$  on the p-side ( $E_{Vp}$ ) and conduction band edge  $E_C$  on the n side ( $E_{Cn}$ ) relative to  $E_F$ .
4. Draw the other edges of the band,  $E_{Cp}$  and  $E_{Vn}$ , keeping constant band gap on both sides.
5. Connect  $E_{Cp}$  to  $E_{Cn}$  and  $E_{Vp}$  to  $E_{Vn}$  which completes the energy band diagram.

### Diagrams

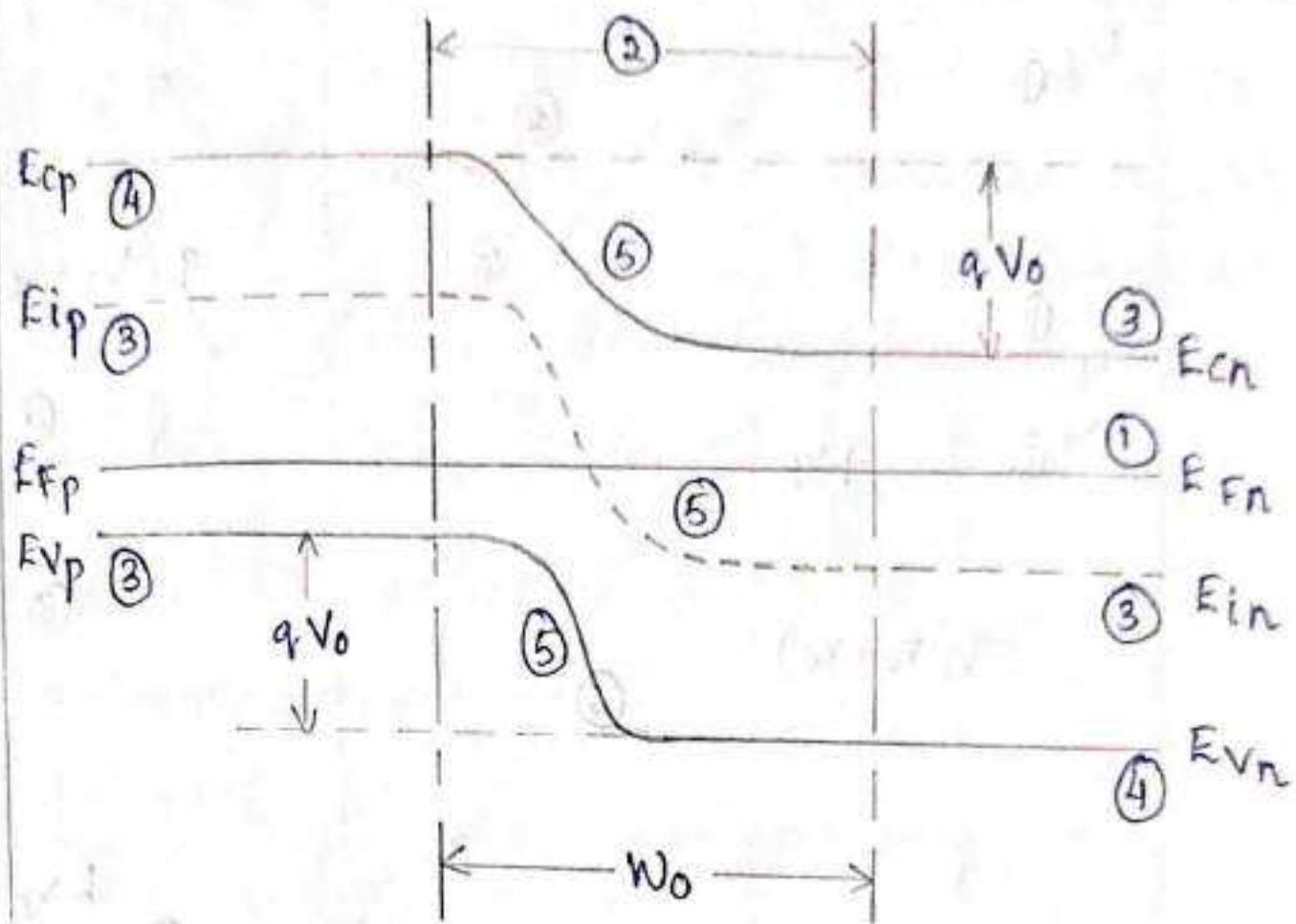
I)



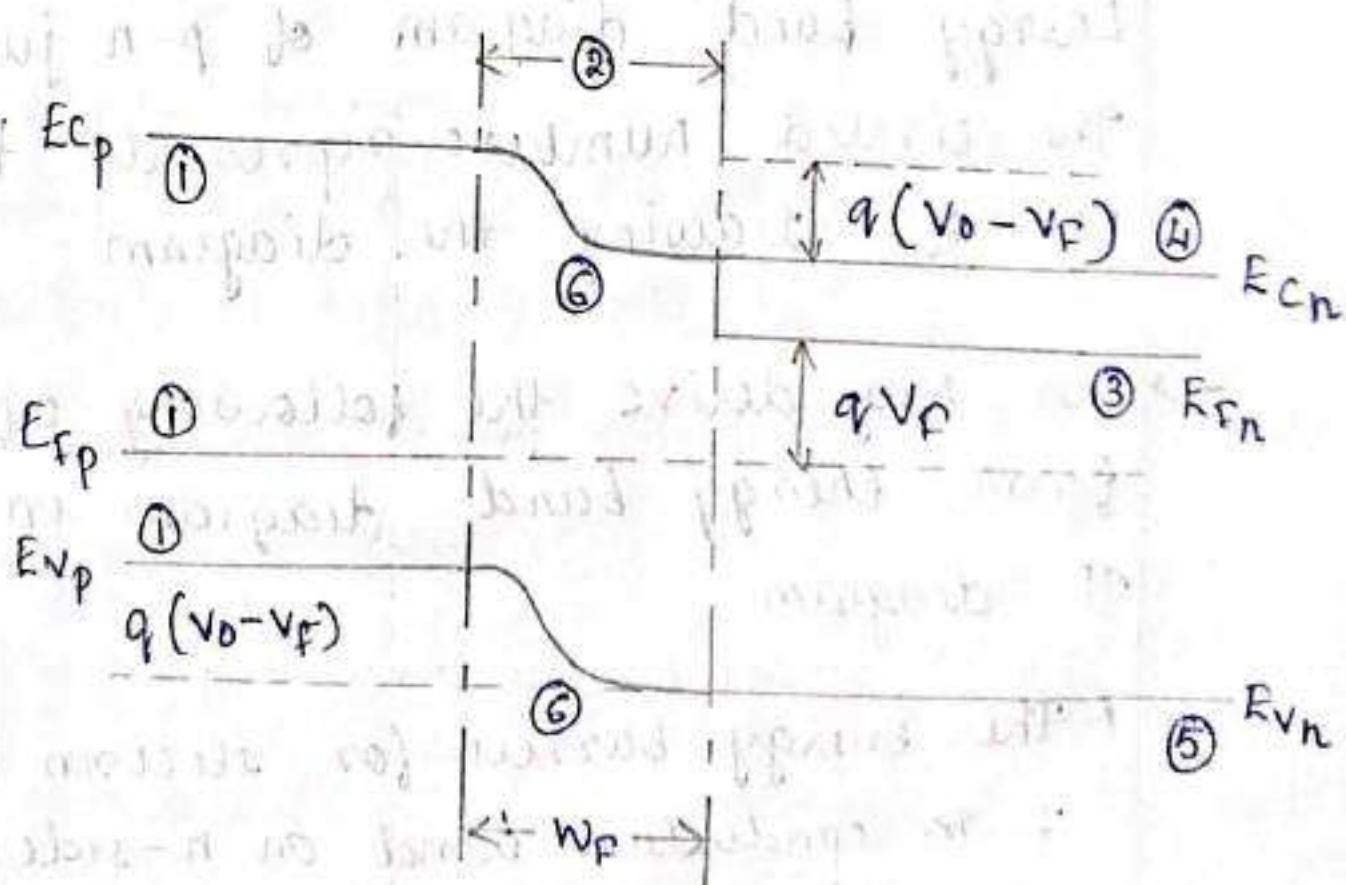
### Isolated p & n materials



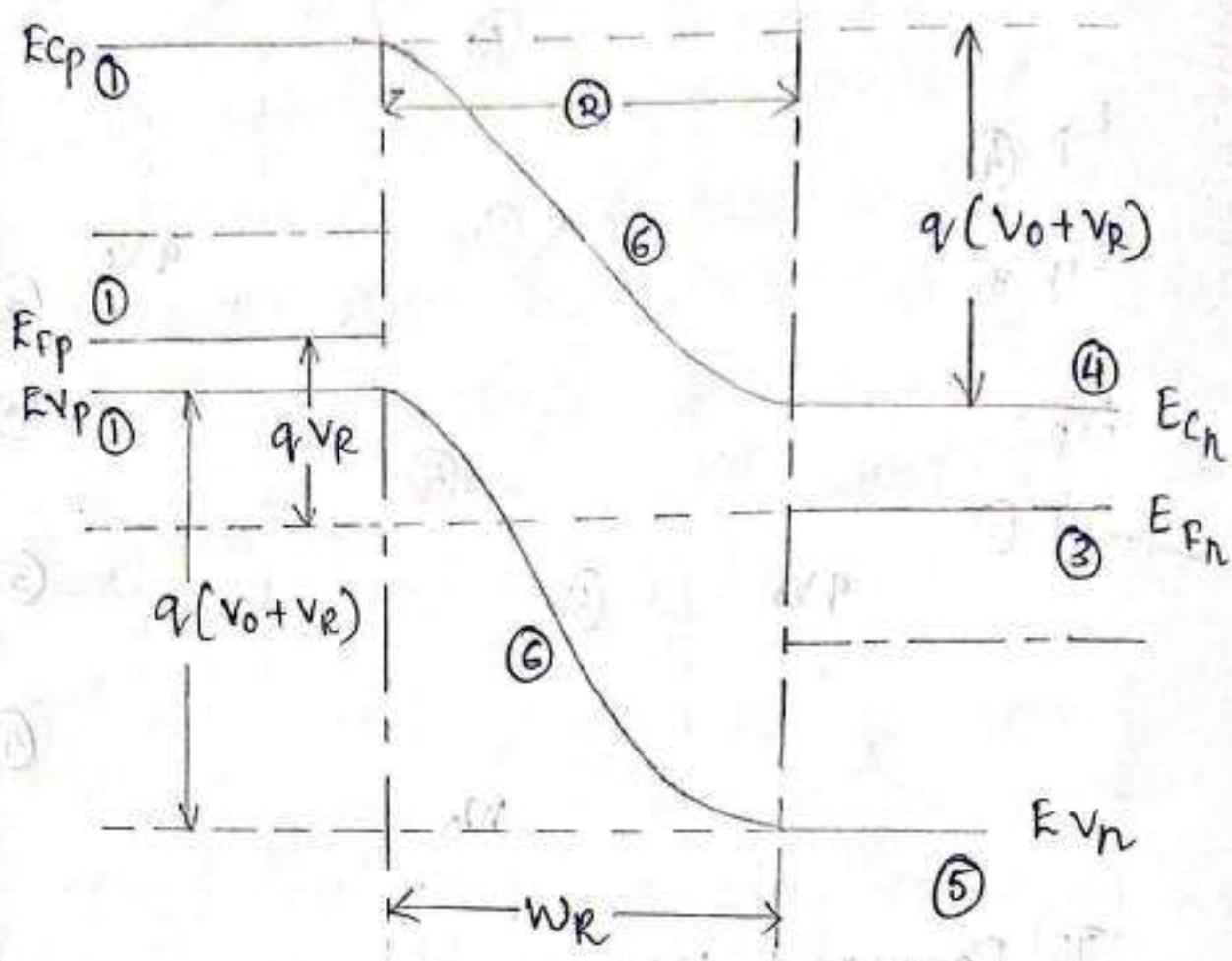
### II) Equilibrium



### III) Forward bias



#### IV) Reverse bias



Energy band diagram of p-n junction.  
The circled numbers represents the sequence of drawing the diagram.

→ We may derive the following information from energy band diagram in the II diagram.

1. The energy barrier for electron movement from conduction band on n-side to

conduction band on p-side is  $E_{cp} - E_{cn}$ . The energy barrier for the hole movement from p-side valence band to n-side valence band is  $E_{vp} - E_{vn}$ . The gradient in all energies ( $E_c$ ,  $E_v$  and  $E_i$ ) are identical in the energy band diagram.

$$\text{i.e., } E_{cp} - E_{cn} = E_{vp} - E_{vn} = E_{ip} - E_{in}$$

Thus, the potential across the junction is,

$$V_0 = \frac{E_{ip} - E_{in}}{q} \quad \text{--- ①}$$

$$= \frac{(E_{ip} - E_F)}{q} - \frac{(E_{in} - E_F)}{q}$$

$$= \underline{\phi_{fp} - \phi_{fn}} \quad \text{--- ②}$$

where  $\phi_{fp}$  and  $\phi_{fn}$  are the fermi potential on the p and n side of the junction. Notice the Fermi potential on the n-side ( $\phi_{fn}$ ) is negative.

2. The fermi potential increases with increase in doping. Therefore, the built

-in potential also increases with increase in doping on the p and n side

3. The equilibrium energy band diagram confirms that an electric field exist in the depletion layer which is directed from n-side to p-side (energies band upward in the direction of electric field).

### Distribution of carrier concentration, potential, electric field and charge density

The distribution of carrier concentration, potential, electric field and charge density. In an abrupt p-n junction under thermal equilibrium, meanings of the symbols used are:

$P_{po}$  - equilibrium hole conc. on p-side

$n_{po}$  - equilibrium electron conc. on p-side

$n_{no}$  - equilibrium electron conc. on the n-side

$p_{no}$  - equilibrium hole conc. on the p-side.

$W_0$  - equilibrium depletion layers width

$x_{no}$  - equilibrium depletion layers width  
towards n-side.

$x_{po}$  - equilibrium depletion layer width  
towards p-side.

$V_{no}$  - equilibrium potential at neutral  
n-side.

$V_{po}$  - equilibrium potential at neutral  
p-side.

Suffixes n and p stands for n and p regions and o stands for equilibrium.

Under thermal equilibrium the carrier concentration in the neutral regions as same as the carrier concentration in the isolated p and n materials.

The depletion layer is depleted of mobile charge carriers. (By depletion approximation)

The potential rises from  $V_{po}$  on the p-side to  $V_{no}$  on the n-side of the depletion layer. The region outside depletion layer is neutral and potential remains constant throughout the neutral regions. The built-in potential equals the difference in potential b/w the 2 sides of depletion layer

$$V_0 = V_{no} - V_{po}$$

The electric field in the neutral region is zero, as there is no gradient in potential. The electric field is maximum ( $E_m$ ) at the interface due to the abrupt transition from negative charges on n-side to positive charges on p-side of the depletion layer. For abrupt p-n junction its distribution is linear as shown in fig (d).

The charge density distribution is shown in fig (e). The density is zero in the neutral region. Charge is negative on the p-side and positive on the n-side.

The charge density is charge per unit volume. This is equal to the charge of ionized impurity multiplied by the doping concentration. Therefore charge density on the p-side is  $-qN_A$  and charge density on the n side is  $+qN_D$ .

The total charge on both sides are equal. so that net charge is zero.

$$|Q_{Dp}| = |Q_{Dn}|$$

where,

$|Q_{Dp}|$  = Total negative charge on the p-side of depletion layer

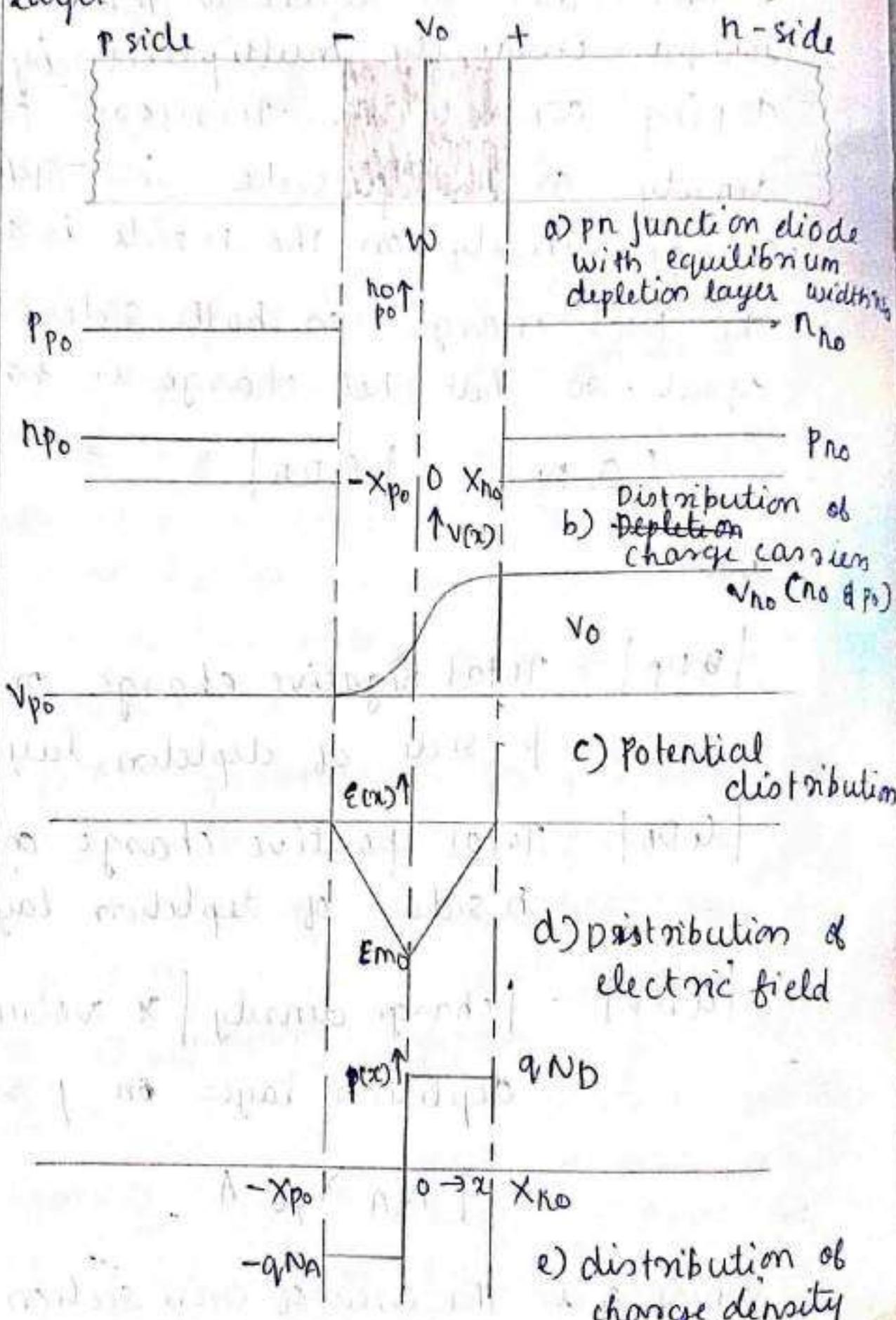
$|Q_{Dn}|$  = Total positive charge on the n side of depletion layer

$|Q_{Dp}| = |\text{charge density}| \times \text{volume of depletion layer on p side}$

$$= qN_A \times p_0 A$$

Where A is the area of cross section of diode

which is equal for both sides of depletion layer



$$|qDn| = qN_p \times n_0 A$$

$$\text{ie, } qN_p X_{p0} A' = qN_A X_{n0} A'$$

$$N_A X_{p0} = N_A X_{n0}$$

Derive the expression for built-in potential of a p-n junction.

Under thermal equilibrium,

$$P_p = 0 \quad \text{and} \quad P_n = 0$$

Let us start with one of these equations to arrive at an expression for built-in potential ( $V_0$ ), as it is a thermal equilibrium quantity.

$$P_p = -qD_p \cdot \frac{dp_0(x)}{dx} + qP_0(x)\mu_p \epsilon(x) = 0$$

As the hole concentration differs from p-side to n-side of depletion layer it is assumed as a function of  $x$  ( $P_0(x)$ ).

$$\epsilon(x) = \frac{D_p}{\mu_p} \times \frac{1}{P_0(x)} \cdot \frac{dp_0(x)}{dx} \quad \text{--- (1)}$$

$$\text{But } \frac{dp}{n_p} = \frac{kT}{q} \text{ and } \epsilon_x = -\frac{dv}{dx}$$

$\therefore$  ① reduces to

$$-\frac{dv}{dx} = \frac{kT}{q} \cdot \frac{1}{p_0(x)} \cdot \frac{dp_0(x)}{dx} \quad \text{--- ②}$$

Integrating eqn ② from edge of depletion layer on p-side to edge of depletion layer on n-side

$$-\int dv = \int \frac{kT}{q} \cdot \frac{1}{p_0(x)} \cdot dp_0(x)$$

On LHS integration is with respect to potential and on RHS integration is wrt hole concentration. By sub. values of potential and carrier concentration at edges of depletion region.

$$-\int_{V_{p0}}^{V_{n0}} dv = \frac{kT}{q} \int_{P_{p0}}^{P_{n0}} \frac{dp_0(x)}{p_0(x)}$$

$$-[V_{n0} - V_{p0}] = \frac{kT}{q} \ln \left[ \frac{P_{n0}}{P_{p0}} \right]$$

$$= \frac{kT}{q} [\ln p_{no} - \ln p_{po}]$$

$$v_{no} - v_{po} = \frac{kT}{q} [\ln p_{po} - \ln p_{no}]$$

$$= \frac{kT}{q} \ln \frac{p_{po}}{p_{no}}$$

From fig,  $v_{no} - v_{po} = v_o$

$$\therefore v_o = \frac{kT}{q} \ln \frac{p_{po}}{p_{no}}$$

But,  $p_{po} = N_A$  [equilibrium majority carrier concentration on p-side]

$$p_{no} = \frac{n_i^2}{N_D}$$
 [Equilibrium minority carrier concentration on n-side]

So,

$$v_o = \frac{kT}{q} \ln \frac{N_A N_D}{n_i^2}$$

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Derive the distribution of electric field in p-n junction.

Applying Poisson equation to the depletion layer of p-n junction, electric field distribution can be obtained.

Poisson equation is

$$\frac{d E(x)}{dx} = \frac{\rho}{\epsilon}$$

which relates gradient in electric field to charge density.

Applying this to a semiconductor,

$$\frac{d E(x)}{dx} = \frac{q}{\epsilon} (N_D^+ - N_A^- + p - n)$$

For  $-x_{p0} < x < 0$

$$\rho = -qN_A \quad (\text{by depletion approximation}) \\ p - n = 0$$

$$\frac{d E(x)}{dx} = \frac{-qN_A}{\epsilon}$$

$$E(x) = \int \frac{-q}{\epsilon} N_A dz + C$$

$$= -\frac{q}{\epsilon} N_A x + C$$

$$E(x) = 0 \text{ at } x = -x_{p_0}$$

$$\therefore C = -\frac{q}{\epsilon} N_A x_{p_0}$$

$$E(x) = -\frac{q}{\epsilon} N_A (x + x_{p_0}); \quad \text{--- (1)}$$

$-x_{p_0} < x < 0$

Similarly, applying poisson equation to the n side of the depletion layer, we get

$$E(x) = \frac{q}{\epsilon} N_D (x - x_{n_0}); \quad \text{--- (2)}$$

$$0 < x < x_{n_0}$$

Electric field is maximum at  $x = 0$ .

Therefore, by eqn (1) and (2)

Maximum electric field

$$E_{mo} = -\frac{q}{\epsilon} N_A x_{p_0} = -\frac{q}{\epsilon} N_D x_{n_0} \quad \text{--- (3)}$$

$$\therefore E(x) = E_{mo} \left( 1 + \frac{x}{x_{p_0}} \right); \quad -x_{p_0} < x < 0$$

$$E(x) = E_{mo} \left( 1 - \frac{x}{x_{n_0}} \right); \quad 0 < x < x_{n_0}$$

Eqn ③ shows that electric field varies linearly with distance in the depletion region.

Barrier potential in terms of electric field distribution and width

We know that,

$$E(x) = -\frac{d}{dx} V_0$$

$$V_0 = - \int E(x) dx$$

$$= - \int E_{mo} \left( 1 + \frac{x}{x_{po}} \right) dx$$

$$= -E_{mo} \int \left( 1 + \frac{x}{x_{po}} \right) dx$$

$$= -E_{mo} \left[ x + \frac{x^2}{2x_{po}} \right] + C$$

$$\text{at } x = -x_{po}, V_0(x) = 0$$

$$\therefore C = -E_{mo} \frac{x_{po}}{2}$$

$$\therefore V_0 = -E_{mo} \left[ x + \frac{x^2}{2x_{p0}} + \frac{x_{p0}}{2} \right];$$

$-x_p < x < 0$

$$ii, V_n(x) = - \int \epsilon(x) dx$$

$$V_n(x) = -E_{mo} \left[ x - \frac{x^2}{2x_n} \right] + C$$

$$V_n(x) = -E_{mo} \left( x - \frac{x^2}{2x_{n0}} + \frac{x_{n0}}{2} \right);$$

$0 < x < x_n$

$$\boxed{V_0 = -\frac{E_{mo} w_0}{2}}$$

### Width of the depletion region

Let  $|Q_{Dp}|$  is the total -ve charge on the p-side of the depletion layer.

$|Q_{Dp}| = \text{charge density} \times \text{volume of depletion layer on p-side}$

$$= q \times N_A \times A \times x_{p0}$$

$$= q N_A A x_{p0} \quad \text{--- } ①$$

Similarly total +ve charge on n-side of depletion region

$$|Q_{Dn}| = q N_D A \times x_{no} \quad \text{--- (2)}$$

where area of cross section of the diode is equal for both side of the depletion layer.

$$|Q_{DP}| = |Q_{Dn}|$$

$$q N_A A \times x_{po} = q N_D A \times x_{no} \quad \text{--- (3)}$$

$$N_A \times x_{po} = N_D \times x_{no} \quad \text{--- (4)}$$

$$\frac{N_A}{N_D} = \frac{x_{no}}{x_{po}} \quad \text{--- (5)}$$

$$W_0 = x_{po} + x_{no}$$

$$W_0 = \frac{x_{no} + x_{po}}{N_A} + x_{no} \quad \text{--- (6)}$$

$$W_0 = x_{no} \left( \frac{N_D}{N_A} + 1 \right) \quad \text{--- (7)}$$

$$\{ W_0 = X_{ho} \left( \frac{N_A + N_D}{N_A} \right) \} \quad ⑧$$

$$\{ W_0 = X_{po} \left[ \frac{N_A + N_D}{N_D} \right] \} \quad ⑨$$

$$⑨ \rightarrow \{ X_{po} = \frac{W_0 N_D}{N_A + N_D} \} \quad ⑩$$

$$\{ X_{ho} = \frac{W_0 N_A}{N_A + N_D} \}$$

Depletion & region in terms of  $V_0$   
[barrier potential]

$$\epsilon_x = \frac{d}{dx} V_0$$

$$V_0 = \int_{-X_{po}}^{X_{ho}} \epsilon_x dx$$

$$V_0 = -\frac{\epsilon_m w_0}{2}$$

$$\epsilon_{m_0} = -\frac{q}{\epsilon} N_A x_{p_0}$$

$\epsilon \rightarrow$  permittivity of the depletion region

$$V_0 = \frac{q}{\epsilon} N_A x_{p_0} \frac{w_0}{2}$$

$$x_{p_0} = w_0 \frac{N_D}{N_A + N_D}$$

$$V_0 = \frac{q N_A N_D w_0^2}{2 \epsilon N_A + N_D}$$

$$w_0^2 = \frac{2 \epsilon V_0}{q} \frac{N_A + N_D}{N_A + N_D}$$

$$w_0 = \sqrt{\frac{2 \epsilon V_0}{q} \frac{N_A + N_D}{N_A N_D}}$$

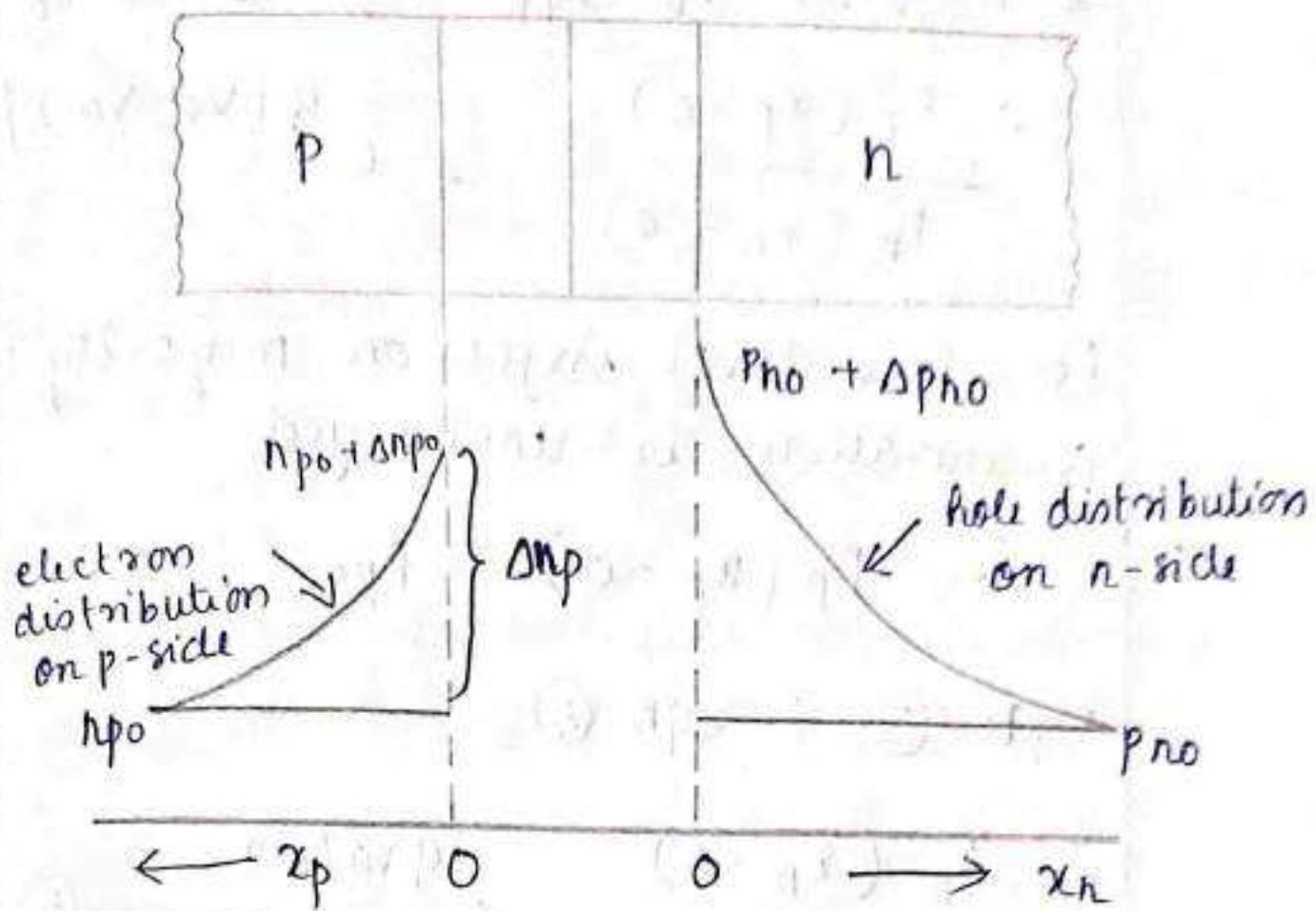
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## Derive Ideal Diode Equation.

Diode equation represent the equation for diode current in terms of diode parameters. It represents the relationship b/w applied voltage and current.

we derive the equation based on the following approximation:

- 1) Diode is long.
- 2) The depletion layer is completely depleted of mobile charge carriers and region outside the depletion layer is perfectly neutral.
- 3) The p-n junction is abrupt
- 4) The two end contacts are ohmic
- 5) Low-level injection
- 6) Impurities are completely ionized
- 7) There is no generation and recombination within the depletion region.
- 8) The diode is in steady state condition



The current in a p-n junction can be evaluated as the sum of minority carrier diffusion current at the edge of depletion layer.

$$\text{ie, } I = I_p + I_n \quad \text{--- (1)}$$

$$= I_p(x_n = 0) + I_n(x_p = 0)$$

$$= I_p \text{ diff } (x_n = 0) + I_n \text{ diff } (x_p = 0) \quad \text{--- (2)}$$

for a p-n junction under thermal equilibrium

$$\frac{I_{p0}}{I_{n0}} = e^{qV_0/kT} \quad \text{--- (3)}$$

with bias  $V_a$  applied,  $V_o \rightarrow V_o - V_a$

$$\therefore \frac{P_p(x_p=0)}{P_n(x_n=0)} = e^{q(V_o-V_a)/kT} \quad \text{--- (4)}$$

For low level injection majority carrier concentration is unchanged

$$\text{i.e., } P_p(x_p=0) = P_{p0}$$

$$\text{eqn (3)} \div \text{eqn (4)}$$

$$\frac{P_n(x_n=0)}{P_{n0}} = e^{qV_a/kT} \quad \text{--- (5)}$$

$$\text{i.e., } P_n(x_n=0) = P_{n0} \cdot e^{qV_a/kT}$$

$$P_n(x_n=0) = P_{n0} + \Delta P_n$$

$$\Delta P_n = P_n(x_n=0) - P_{n0}$$

$$= P_n e^{qV_a/kT} - P_{n0}$$

$$\Delta P_n = P_{n0} (e^{qV_a/kT} - 1),$$

excess hole conc.

11) excess electron conc. at  $x_p=0$  is given

by

$$\Delta n_p = n_{p0} (e^{qV_A/kT} - 1)$$

ii, the injected excess minority carrier concentrations increases exponentially with increase in forward bias

By approximation ② and ③

Assume that the minority carrier current is by diffusion only,

$$\text{ii, } \frac{d^2 \delta p(x_n)}{dx_n^2} = \frac{\delta p(x_n)}{L_p^2}$$

Solution ~~of~~ to the above eqn is given

by

$$\delta p(x_n) = C_1 e^{-x_n/L_p} + C_2 e^{x_n/L_p}$$

Apply the boundary conditions,

1)  $x_n = 0, \delta p(x_n) = \Delta p_n$

2) at  $x_n = \infty, \delta p(x_n) = 0$

$$\therefore \Delta p_n = C_1 + C_2$$

at  $x_n = \infty$ ,

$$0 = C_1 \times 0 + C_2 e^{\infty}$$

$$C_2 = 0$$

$$\therefore C_1 = \Delta p_n$$

$$\therefore \text{solution to } \delta p(x_n) = \Delta p_n e^{-x_n/L_p}$$

Hole diffusion current on the n side is given by,

$$I_{p \text{ diff}}(x_n) = -qA D_p \frac{d}{dx_n} \delta p(x_n)$$

$$= -qA D_p \frac{d}{dx_n} (\Delta p_n e^{-x_n/L_p})$$

$$I_{p \text{ diff}} = qA \frac{D_p}{L_p} \Delta p_n e^{-x_n/L_p}$$

$$III^4 I_{n \text{ diff}}(x_p) = -qA \frac{D_n}{L_n} \Delta n_p e^{-x_p/L_n}$$

$\therefore$  Total current through the diode is given by

$$I = I_{p \text{ diff}}(x_n=0) + I_{n \text{ diff}}(x_p=0)$$

$$T = qA \frac{D_p}{L_p} \Delta p_n + qA \frac{D_n}{L_n} \Delta n_p$$

Sub:  $\Delta p_n \text{ in } \Delta n_p$

$$T = qA \left[ \frac{D_p}{L_p} p_{no} \left( e^{qV_a/kT} - 1 \right) + \frac{D_n}{L_n} n_{po} \left( e^{qV_a/kT} - 1 \right) \right]$$

$$T = qA \left[ \frac{D_p}{L_p} p_{no} + \frac{D_n}{L_n} n_{po} \right] \left( e^{qV_a/kT} - 1 \right)$$

$$T = I_s \left( e^{qV_a/kT} - 1 \right)$$

where,

$$I_s = qA \left[ \frac{D_p}{L_p} p_{no} + \frac{D_n}{L_n} n_{po} \right]$$

It is reverse saturation current.

## Metal - Semiconductor contacts

When a junction between a metal-semiconductor is created it is called metal-semiconductor contact.

## Types of Metal - Semiconductor contacts

There are two-types of metal semiconductor contacts.

1. Ohmic contact
  2. Rectifying

The behaviour of an ideal metal semiconductor contact depends on the relative value of the work function of metal ( $\phi_m$ ) and semiconductor ( $\phi_c$ ).

Metal n type S.C rectifying  $\rightarrow \phi_m > \phi_{sc}$   
 Ohmic  $\rightarrow \phi_m < \phi_{sc}$

Metal p type sc ohmic  $\rightarrow \phi_m > \phi_{sc}$   
 Rectifying  $\rightarrow \phi_m < \phi_{sc}$

## Metal n type Semiconductor Schottky contact

When a contact is made between metal and

n-type semiconductor with  $\phi_m > \phi_{sc}$ , the fermi-level in semiconductor is above that in metal. So that electrons move from semiconductor metal until the fermi-level align and equilibrium condition is attained. As electron move away from n-type sc, the semiconductor near the metal get depleted of mobile charge carriers.

The energy barrier for electron movement from semiconductor to metal is  $qV_0$  is given by

$$qV_0 = q\phi_m - q\phi_{sc}$$

$$qV_0 = q(\phi_m - \phi_{sc})$$

This energy barrier from metal to semiconductor called schottky barrier, it is independent of bias voltage.

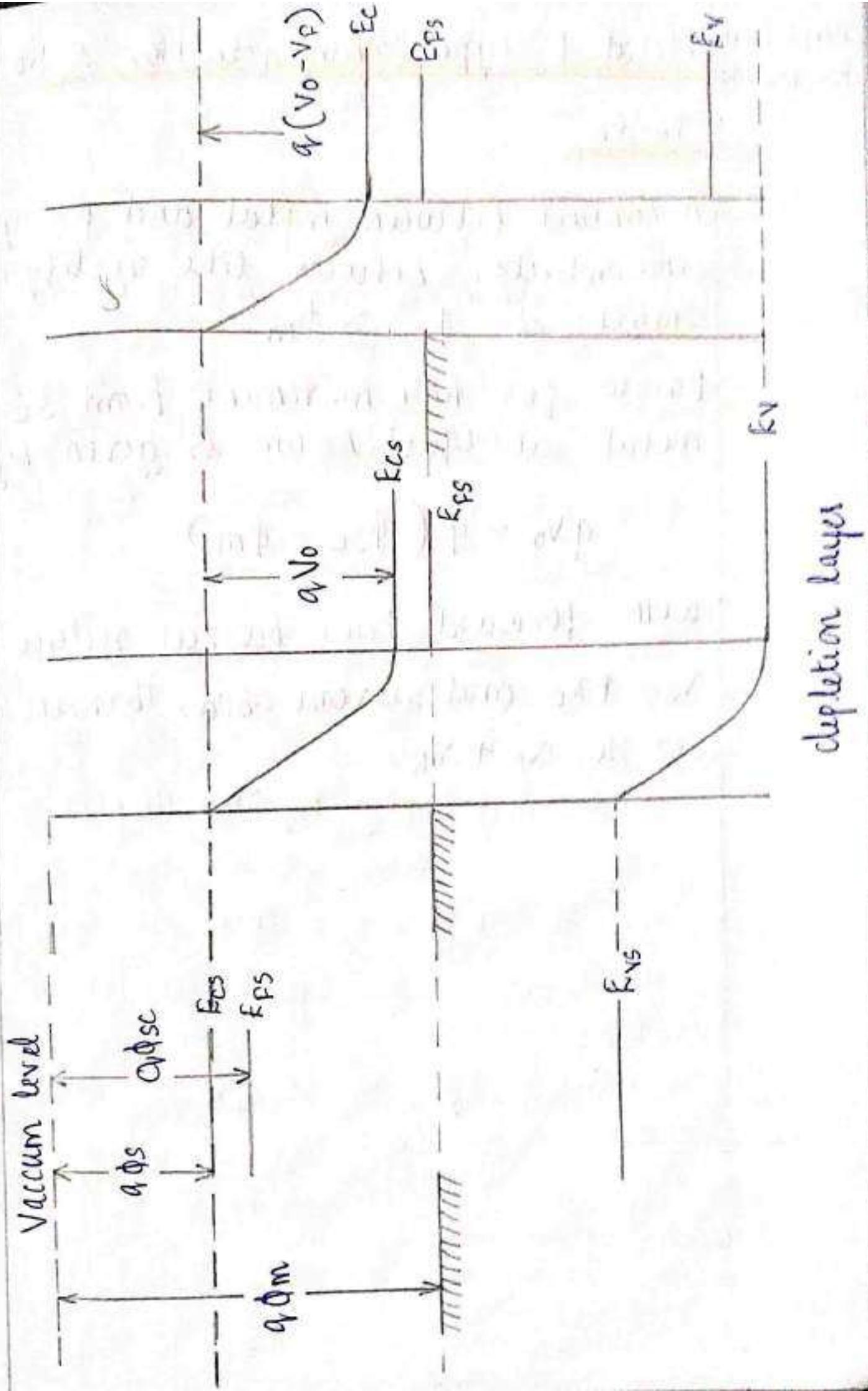
Width of the depletion layer is given by,

$$w_0 = \sqrt{\frac{2\epsilon V_0}{qN_0}}$$

Potential drop across the depletion layer

$$V_0 = \frac{1}{\alpha} \sum_m w_0$$

$$\left\{ \sum_m = \frac{2V_0}{w_0} \right\}$$



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## Metal P-type Semiconductor Schottky diode

A contact between metal and p-type semiconductor between like rectifying contact if  $\phi_{sc} > \phi_m$ .

Barrier for hole movement from sc to metal at equilibrium is given by

$$qV_0 = q(\phi_{sc} - \phi_m)$$

With forward bias barrier reduces to  $V_0 - \Phi V_F$  and reverse bias barrier increases to  $V_0 + V_R$ .

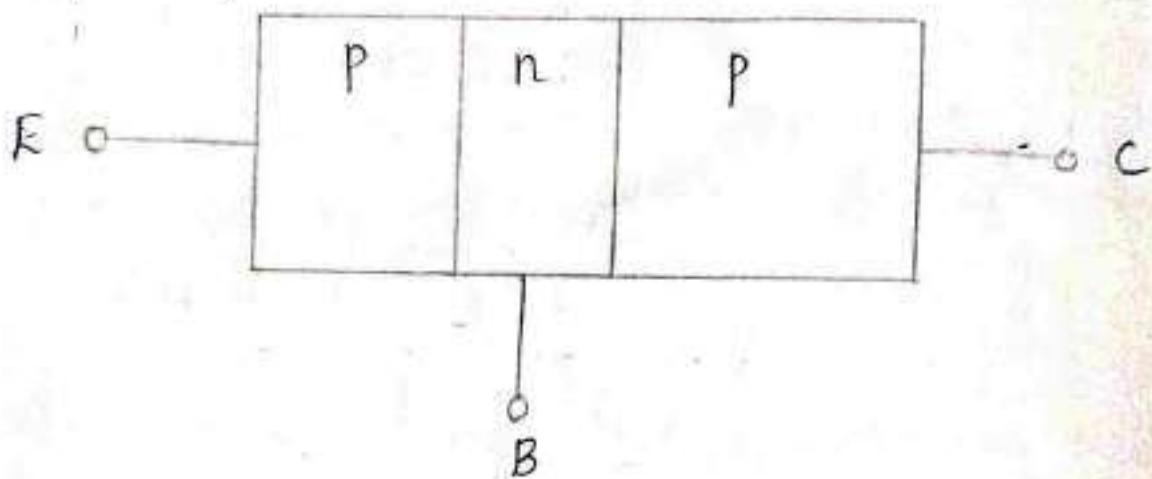
## Comparison between schottky diode and p-n junction diode

1. The reverse saturation current of schottky diode is many orders higher than that of p-n junction of same material. Therefore, the forward voltage drop for a given current is much less than that of p-n junction diode. Hence, schottky diode is preferred in low voltage high current rectifiers.
2. There is no storage capacitance as there is no storage of minority carriers in Schottky diode. Its reverse recovery time is decided only by the depletion layer capacitance and series resistance of the diode ( $C_{jR}$ ). Thus, it can be used for high speed switching.

The disadvantage is its high reverse saturation current and poor reproducibility.

## Bipolar Junction Transistor [BJT]

A bipolar junction transistor [BJT] consists of two p-regions separated by an n-region. ~~or~~ or two n-regions separated by a p-region.



A schematic simplified schematic  
of pnp transistor .

The former is called p-n-p transistor  
and the latter n-p-n transistor.

A BJT consists of 3 terminals - Emitter, base and collector and 2 p-n junctions - emitter base junction, collector base junction.

## Modes of operation

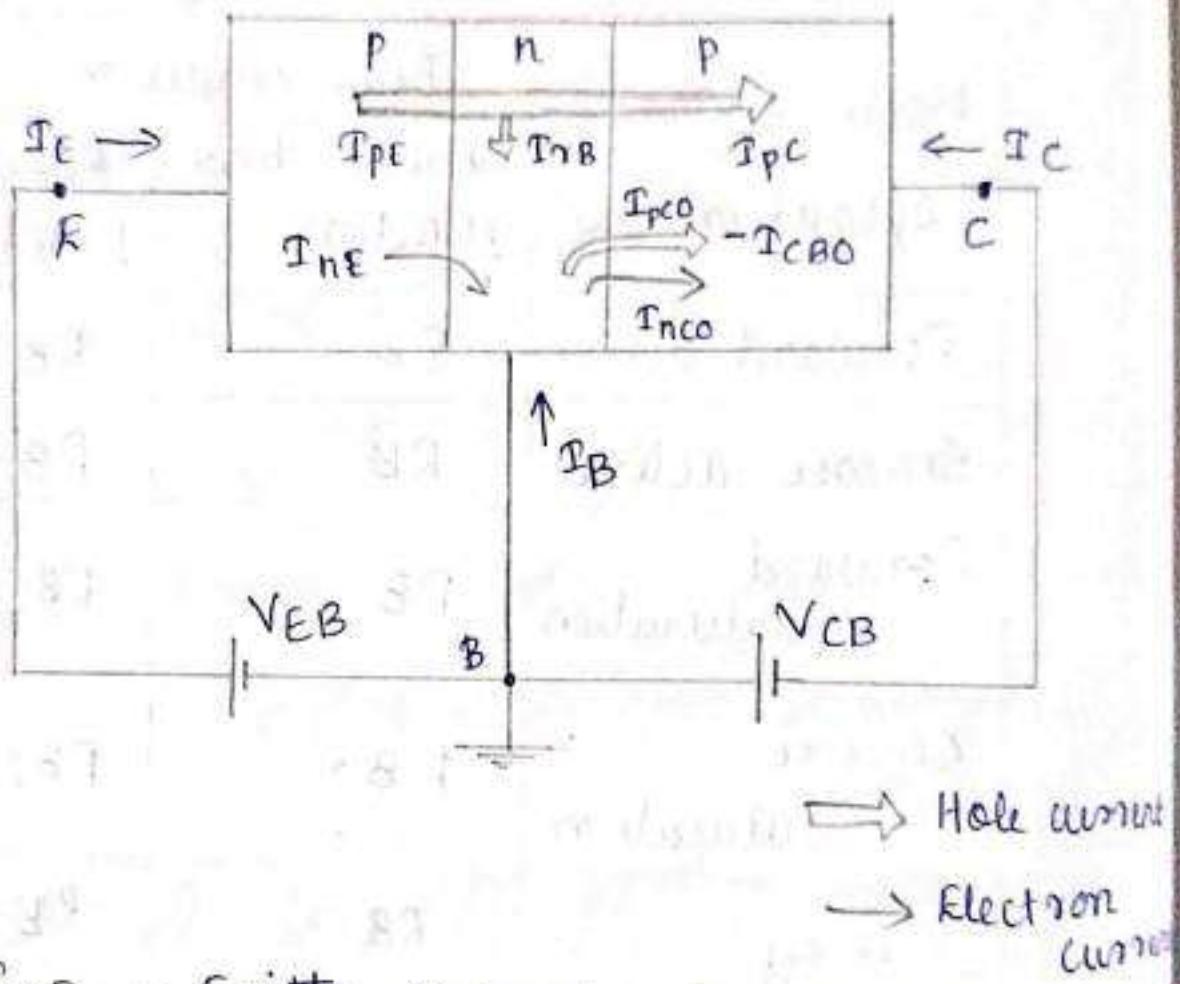
Depending on the bias conditions of the emitter-base junction and collector-base junction, there are different modes of operations for a transistor.

Mode of operation	Bias condition	
	Emitter - base junction	Collector - base junction
Forward active	FB	RB
Inverse active	RB	FB
Forward saturation	FB	FB; $V_{EB} > V_{CB}$
Inverse saturation	FB	FB; $V_{EB} < V_{CB}$
Cut off	RB	RB

## Current Components

In normal active mode of operation, emitter-base junction is forward biased and collector-base junction is reverse-biased. Holes are injected from emitter to base.

and electrons from base to emitter. A portion of holes injected into the base recombine with electrons in the base region, and the remaining portion reaches the collector. Minority carrier current  $I_{CBO}$  flows across the base collector junction.



$I_{PE}$  - Emitter current due to holes injected from emitter to base.

$I_{nE}$  - Emitter current due to electrons injected from base to emitter.

$I_{rB}$  - Base current due to recombination.

$I_{PC}$  - collector current due to holes reaching

the collector which are injected from the emitter.

$I_{CBO}$  - Reverse saturation current of CB junction with emitter open. This current is constituted by the minority carriers crossing the junction. It is also known as leakage current of CB junction.

### Terminal currents

Emitter current ( $I_E$ ), collector current ( $I_c$ ) and base current ( $I_B$ ) are the terminal currents of a BPT.

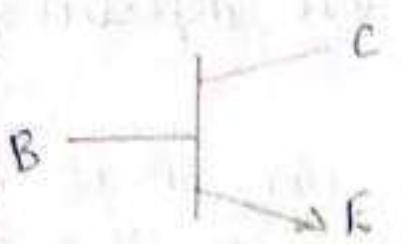
$$I_E = I_{pE} + I_{nE}$$

$$I_c = -(I_{pC} - I_{CBO})$$

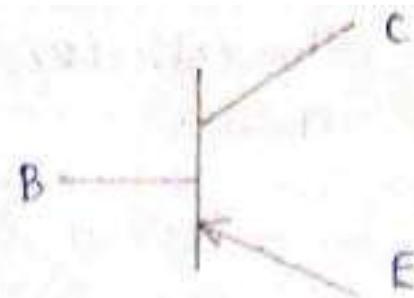
$$I_B = -(I_{pB} + I_{nE} + I_{CBO})$$

For a transistor, the current flowing into the device is taken as positive.

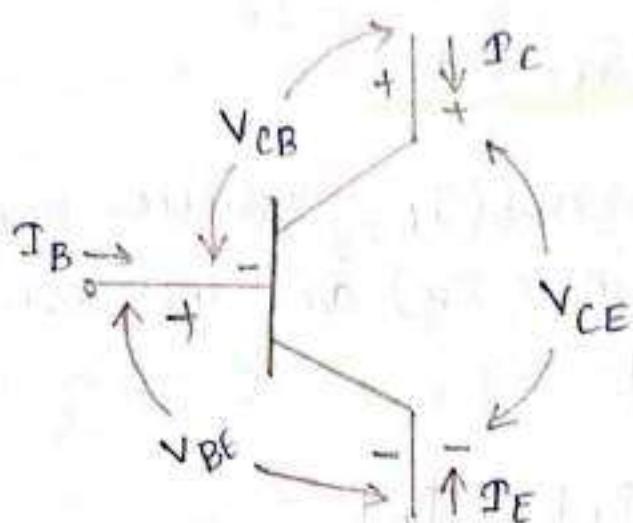
Therefore for a pnp transistor, emitter current is +ve. For npn transistor,  $I_E$  is -ve and  $I_c$  and  $I_B$  are +ve.



Circuit symbol  
of NPN transistor



Circuit symbol  
of PNP transistor



currents and voltages of a BJT

### Basic Performance Parameters

1. Emitter injection efficiency
2. Base transport factor
3. Common emitter current gain
4. Common base current gain

## 1. Injection efficiency ( $\gamma^e$ )

Emitter injection efficiency is the effectiveness in injecting charge carriers from emitter to base rather than that from base to emitter.

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

$$\gamma^e = \frac{1}{1 + \frac{I_{nE}}{I_{pE}}}$$

## 2. Base Transport factor ( $\alpha_p$ )

The base transport factor of a BJT is the effectiveness of the base in transporting charge carriers injected from emitter to the collector through the base.

$$\alpha_p = \frac{I_{pC}}{I_{pE}} = \frac{I_{pC}}{I_{pC} + I_{nB}}$$

$$\alpha_p = \frac{1}{1 + \frac{I_{nB}}{I_{pC}}}$$

### 3. Common Emitter current gain ( $\beta$ )

Current gain in common emitter configuration.

$$\beta = \frac{I_C}{I_B}$$
 [output current  
input current]

### 4. Common Base current gain ( $\alpha$ )

Current gain in common base configuration.

$$\alpha = \frac{I_C}{I_E}$$

### Derivation of terminal currents

Terminal currents of a transistor are derived with the following assumptions

1. The area of cross-section is same for emitter, base and collector regions.

2. The junctions are abrupt. no charge carriers
3. Doping is uniform in all regions
4. The minority carrier currents in the neutral regions are by diffusion only. This type of transistor is called diffusion transistor.
5. Low-level injection condition exists in all regions.
6. The transistor is in steady-state condition.
7. Current flow is one dimensional.
8. No generation or recombination in depletion regions.

The major components of currents in a BJT are obtained from slope of minority carrier distribution in the base region under steady-state condition, with current by diffusion only the continuity equation for holes in the base region reduces to

$$\frac{d^2 \delta p(x)}{dx^2} = -\frac{\delta p(x)}{L_p^2} \quad \text{--- (1)}$$

Solution of this equation is of the form

$$\delta p(x) = C_1 e^{-x/L_p} + C_2 e^{x/L_p} \quad \text{--- (2)}$$

The boundary conditions are

$$\text{at } x = 0 ; \Delta p(x) = \Delta p_E$$

$$x = W_B ; \Delta p(x) = \Delta p_C$$

Applying boundary conditions to eqn ②

$$\Delta p_E = c_1 + c_2 \quad \dots \quad ③$$

$$\Delta p_C = c_1 e^{-W_B/L_P} + c_2 (e^{W_B/L_P}) \quad \dots \quad ④$$

[eqn 3  $\times e^{-W_B/L_P}$ ] - [eqn 4] gives

$$\Delta p_E e^{-W_B/L_P} - \Delta p_C = c_2 (e^{-W_B/L_P} - e^{W_B/L_P})$$

$$\therefore c_2 = \frac{\Delta p_E (e^{-W_B/L_P}) - \Delta p_C}{(e^{W_B/L_P} - e^{-W_B/L_P})}$$

$$= \frac{\Delta p_C - \Delta p_E (e^{-W_B/L_P})}{e^{W_B/L_P} - e^{-W_B/L_P}} \quad \dots \quad ⑤$$

$$c_1 = \Delta p_E - c_2$$

$$= \Delta p_E - \left( \frac{\Delta p_C - \Delta p_E e^{-W_B/L_P}}{e^{W_B/L_P} - e^{-W_B/L_P}} \right)$$

$$= \frac{\Delta p E e^{WB/l_p} - \Delta p C}{e^{WB/l_p} - e^{-WB/l_p}} \quad \text{--- (6)}$$

Sub. the values of  $c_1$  and  $c_2$  in eqn ②

$$\begin{aligned} \delta p(x) &= \frac{\Delta p E e^{WB/l_p} - \Delta p C}{e^{WB/l_p} - e^{-WB/l_p}} \times e^{-x/l_p} \\ &\quad + \frac{\Delta p C - \Delta p E e^{-WB/l_p}}{e^{WB/l_p} - e^{-WB/l_p}} \times e^x/l_p \\ &= \frac{(\Delta p E e^{WB/l_p} - \Delta p C) e^{-x/l_p} + (\Delta p C - \Delta p E e^{-WB/l_p}) \times e^x/l_p}{e^{WB/l_p} - e^{-WB/l_p}} \\ &= \frac{\Delta p E \left[ e^{\left(\frac{WB-x}{l_p}\right)} - e^{-\left(\frac{WB-x}{l_p}\right)} \right] + \Delta p C (e^x/l_p - e^{-x/l_p})}{e^{WB/l_p} - e^{-WB/l_p}} \\ &= \frac{\Delta p E \sinh \left( \frac{WB-x}{l_p} \right) + \Delta p C \sinh \left( \frac{x}{l_p} \right)}{\sinh \left( \frac{WB}{l_p} \right)} \quad \text{--- (7)} \end{aligned}$$

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The hole diffusion current on the basis

$$T_p(x) = -q \Lambda D_p \cdot \frac{d}{dx} \delta p(x)$$

$$= q \Lambda \frac{D_p}{L_p} (c_1 e^{-x/L_p} - c_2 e^{x/L_p}) \quad \text{--- (1)}$$

$T_{pE}$  =  $T_p(x)$  at  $x=0$  in above eqn

$$\therefore T_{pE} = q \Lambda \frac{D_p}{L_p} (c_1 - c_2)$$

$$= q \Lambda \frac{D_p}{L_p} \left[ \frac{\Delta p E e^{W_B/L_p} - \Delta p C - \Delta p C}{e^{W_B/L_p} - e^{-W_B/L_p}} + \Delta p E e^{-W_B/L_p} \right]$$

$$= q \Lambda \frac{D_p}{L_p} \left[ \frac{2 \Delta p E \cosh(\frac{W_B}{L_p}) - 2 \Delta p C}{2 \sinh(\frac{W_B}{L_p})} \right]$$

$$= q \Lambda \frac{D_p}{L_p} \left[ \Delta p E \coth(\frac{W_B}{L_p}) - \Delta p C \operatorname{csch}(\frac{W_B}{L_p}) \right]$$

$$T_{pC} = T_p(x) \text{ at } x = W_B \quad \text{--- (2)}$$

$$= q \Lambda \frac{D_p}{L_p} (c_1 e^{-W_B/L_p} - c_2 e^{W_B/L_p})$$

$$= q \Lambda \frac{D_p}{L_p} \left[ \frac{\Delta p E - \Delta p C e^{-W_B/L_p} - \Delta p C e^{-W_B/L_p} + \Delta p E}{e^{W_B/L_p} - e^{-W_B/L_p}} \right]$$

$$= qA \frac{D_p}{L_p} \left[ \frac{\Delta p_E - \Delta p_C \coth(\frac{W_B}{L_p})}{\sinh(\frac{W_B}{L_p})} \right]$$

$$= qA \frac{D_p}{L_p} \left[ \Delta p_E \operatorname{cosech}(\frac{W_B}{L_p}) - \Delta p_C \coth(\frac{W_B}{L_p}) \right] \quad \text{--- (10)}$$

III<sup>4</sup> by solving continuity eqn in the emitter region for minority carrier distribution, the current due to electrons injected from base to emitter may be evaluated as

$$I_{nE} = qA \frac{D_{nE}}{L_{nE}} \Delta_{nE} \coth\left(\frac{W_E}{L_{nE}}\right) \quad \text{--- (11)}$$

The current due to electron injected from base to collector is given by,

$$I_{nC} = -qA \frac{D_{nC}}{L_{nC}} \cdot \Delta_{nC} \coth\left(\frac{W_C}{L_{nC}}\right) \quad \text{--- (12)}$$

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

$$= qA \frac{D_p}{L_p} \left[ \Delta p_E \coth\left(\frac{W_B}{L_p}\right) - \Delta p_C \operatorname{cosech}\left(\frac{W_B}{L_p}\right) \right]$$

$$+ qA \frac{D_{nE}}{L_{nE}} \cdot \Delta_{nE} \coth\left(\frac{W_E}{L_{nE}}\right) \quad \text{--- (13)}$$

Sus. for  $\Delta p_E$ ,  $\Delta p_C$  and  $\Delta n_E$  from eqn.

$$T_E = q A n_i^2 \left[ \frac{D_p}{L_p} \frac{1}{N_D} \coth \left( \frac{W_B}{L_p} \right) + \frac{D_{NE}}{L_{NE}} \frac{1}{N_A} \right. \\ \left. \coth \left( \frac{W_F}{L_{NE}} \right) \right] (e^{V_{CE}/V_T} - 1) \\ - q A \frac{n_i^2}{N_D} \frac{D_p}{L_p} \operatorname{csch} \left( \frac{W_B}{L_p} \right) (e^{V_{CB}/V_T} - 1) \quad \text{--- (14)}$$

$$T_C = - (T_{pC} + T_{nC}) \\ = - q A \frac{D_p}{L_p} \left[ D_{pE} \operatorname{csch} \left( \frac{W_B}{L_p} \right) - \right. \\ \left. D_{pC} \coth \left( \frac{W_B}{L_p} \right) + q A \frac{D_{nC}}{L_{nC}} D_{nC} \right. \\ \left. \coth \left( \frac{W_C}{L_{nC}} \right) \right] \quad \text{--- (15)}$$

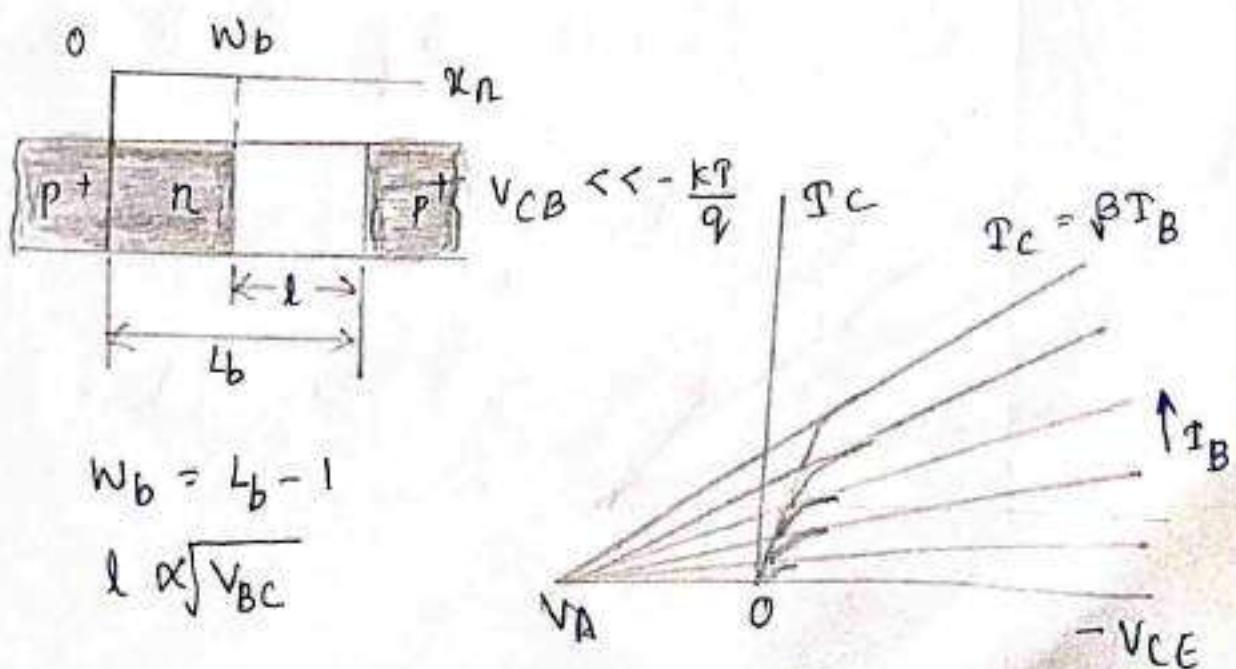
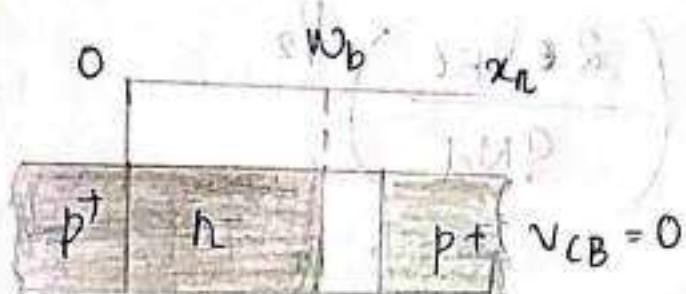
$$= q A n_i^2 \left[ \frac{D_{nC}}{L_{nC}} \times \frac{1}{N_A} \coth \left( \frac{W_C}{L_{nC}} \right) + \frac{D_p}{L_p} \right. \\ \left. \times \frac{1}{N_D} \coth \left( \frac{W_B}{L_p} \right) \right] (e^{V_{CA}/V_T} - 1) \\ - q A \frac{D_p}{L_p} \frac{n_i^2}{N_D} \operatorname{csch} \left( \frac{W_B}{L_p} \right) (e^{V_{EB}/V_T} - 1) \quad \text{--- (16)}$$

$$T_B = T_E - T_C \quad \text{--- (17)}$$

## Base width modulation / Early effect /

### Base narrowing

If the base region is lightly doped, the depletion region at the reverse-biased collector junction can extend significantly into the n-type base region. As the collector voltage increased, the space charge layer takes up more of the metallurgical width of the base  $L_b$ , and as a result, the effective base width  $w_b$  is decreased. This effect is variously called base narrowing, base width modulation and early effect.



The decrease in  $N_B$  cause  $\beta$  to increase. As a result, the collector current  $I_C$  increases with collector voltage rather than staying constant as predicted from simple treatment. The slope introduced by the Early effect is almost linear with  $I_C$  and CE characteristics extrapolate to an intersection with voltage axis at  $V_A$  called the Early voltage.

Approximate length  $l$  of collector junction depletion region in the n material

$$l = \left( \frac{2\epsilon V_{BC}}{qN_d} \right)^{1/2}$$

Module - 4 MOS CAPACITOR

MOS  $\rightarrow$  Metal oxide Semiconductor

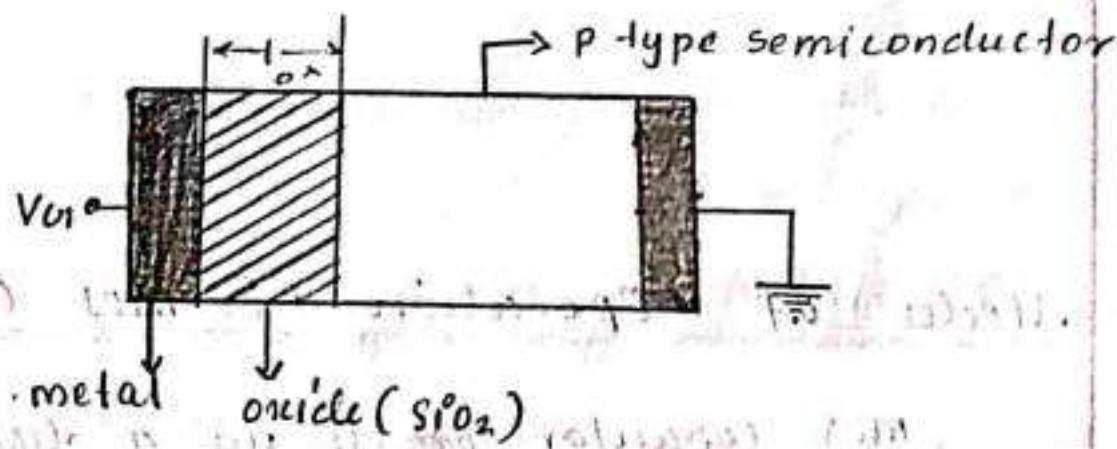
MOS Devices

Mos devices consist of 3 regions they are metal oxide and semiconductor.

e.g.: mos capacitor, mos fet

1. MOS Capacitor

Is a terminal metal oxide semiconductor is used as a mos capacitor (also known as mos diode). The structure of a metal (Al) oxide ( $\text{SiO}_2$ ) Semiconductor (P type si) capacitor is shown in fig below.

Ideal MOS Capacitor

A MOS capacitor is considered to be ideal if (1) the work function of the metal and semiconductor are equal & (2) oxide is a perfect insulator, with no trapped charges, no defects and no interface states.