

## Unit - 2 Semiconductors.

- \* Syllabus : -
- (1) Intrinsic and Extrinsic semiconductors.
  - (2) Dependence of Fermi level on carrier concentration and temp. (equilibrium carrier statistics)
  - (3) carrier generation and recombination, carrier transport, diffusion, drift, p-n-junction.
  - (4) metal-semiconductor junction (ohmic & Schottky)  
Semiconductor material of interest for optoelectronic devices.

# Difference Between Intrinsic and Extrinsic Semiconductor

The **Intrinsic** and **Extrinsic semiconductors** are distinguished from each other considering various factors such as doping or the addition of the impurity, density of electrons and holes in the semiconductor material, electrical conductivity and its dependency on various other factors.

The difference between the two types of the semiconductor is given below in detail.

BASIS OF DIFFERENCE	INTRINSIC SEMICONDUCTOR	EXTRINSIC SEMICONDUCTOR
Doping of impurity	Doping or addition of impurity does not take place in intrinsic semiconductor.	A small amount of impurity is dopped in a pure semiconductor for preparing extrinsic semiconductor.
Density of electrons and holes	The number of free electrons in the conduction band is equal to the number of holes in the valence band.	The number of electrons and holes are not equal.
Electrical conductivity	Electrical conductivity is low.	Electrical conductivity is high
Dependency of electrical conductivity	Electrical conductivity is a function of temperature alone.	Electrical conductivity depends on temperature as well as on the amount of impurity doping in the pure semiconductor.
Example	Crystalline form of pure Silicon and Germanium.	Impurity like As, Sb, P, In, Bi, Al etc. are dopped with Germanium and Silicon atom.

**Intrinsic Semiconductor** is a pure form of the semiconductor as there is no addition of impurity takes place. An example of intrinsic semiconductors is Silicon (Si) and Germanium (Ge).

On the other hand, when a small quantity of Tetravalent or Pentavalent impurity like Arsenic (As), Aluminium (Al), Phosphorus (P), Gallium (Ga), Indium (In), Antimony (Sb) etc. is added in pure semiconductor, an **Extrinsic Semiconductor** is obtained.

## Difference Between Intrinsic and Extrinsic Semiconductor

- In an intrinsic semiconductor, the addition of impurity with a pure semiconductor does not take place, whereas the extrinsic semiconductor is formed by doping of impurity in a pure semiconductor.
- The density of electrons and holes in the intrinsic semiconductor is same, i.e. the number of free electrons present in the conduction band is equal to the number of holes in the valence band. but in the case of extrinsic semiconductor the number of electrons and holes are not equal. In a p-type semiconductor, the holes are in excess and n-type semiconductor the number of electrons is greater than the number of holes.
- The electrical conductivity of an intrinsic semiconductor is low, whereas in extrinsic semiconductor the electrical conductivity is high.
- The impurity like arsenic, antimony, phosphorus, aluminium indium, etc. is added to the pure form of silicon and germanium to form an extrinsic semiconductor. The pure form of silicon and germanium crystal is used in an intrinsic semiconductor.
- Electrical conductivity in intrinsic semiconductor is a function of temperature alone, but in extrinsic semiconductor the electrical conductivity depends upon the temperature and the amount of impurity doping in the pure semiconductor.

## Intrinsic and Extrinsic Semiconductors :-

### ① Intrinsic :-

Pure semiconductors are known as intrinsic semiconductors. or a semiconductor in which electrons and holes are solely created by thermal excitation is pure or intrinsic semiconductors.

Chemically pure with less than one impurity atom in a billion host atom.

Electrical conductivity is low.

Not useful for device manufacturing because of low conductivity.

### ② Extrinsic :-

The semiconductors in which impurities are added is called extrinsic semiconductors.

Large quantity of impurity atoms present  
The impurity produced carriers are not temperature dependent but voltage dependent and amount of impurity added.

Electrical conductivity is high.

Useful for semiconductor devices as diodes, transistor, LED, photodiodes etc.

Extrinsic are further divided into 2 types. (i) P-type semiconductors  
(ii) N-type semiconductors.

(2) Dependence of Fermi level on carrier concentration and temp (equilibrium carrier statistics)

\* Intrinsic semiconductors - carrier concentration.

The energy gap between  $V_b$  and  $C_b$  is very small. So at room temp few electron can go to  $C_b$  and create a vacancy behind. It is known as Hole. For intrinsic semiconductor for every excited electron, moving to  $C_b$  there is a hole created in  $V_b$ .

$$so \quad n_e = n_h$$

density of ele = density of hole

- when voltage is applied, electron in  $C_b$  moves toward +ve terminal and hole in  $V_b$  moves toward -ve terminal.

The conductivity

$$\sigma_i = n_e \cdot e \cdot \mu_e + n_h \cdot e \cdot \mu_h$$

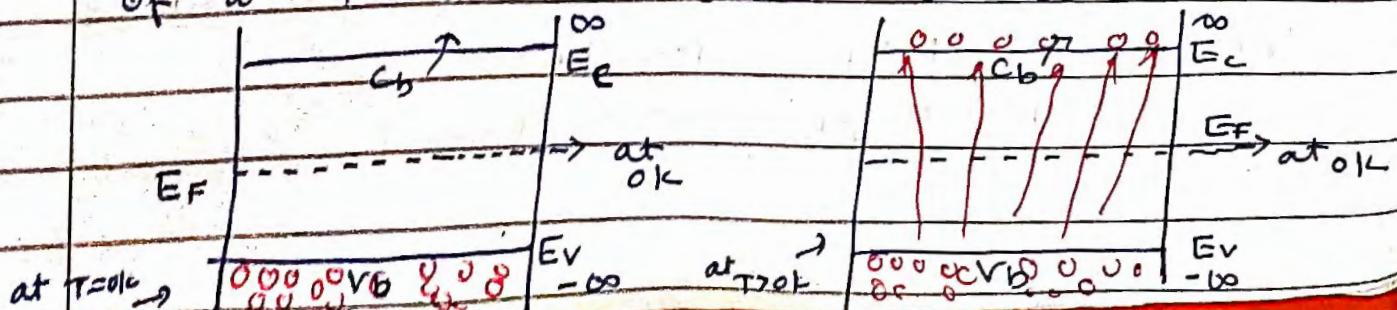
where

$n_e = n_h = n_i$  = intrinsic carriers concentration

$\mu_e, \mu_h$  = mobility of ele and hole respectively

2.1 Density of Electron in conduction band for Intrinsic Semiconductors.

No. of charge carrier per unit volume of a material is called carrier concentration.



where  $E_F$  = Fermi energy level.

$E_C$  = Bottom of  $C_b$

$E_V$  = top of  $V_b$

as seen in figure at  $T=0$   $V_b$  is completely filled and  $C_{b,eq}$  is completely empty.

→ Expression:

carrier density can be obtained by integrating the density of states  $Z(E) dE$  and probability function  $f(E)$

$$\therefore n_e = \int_{E=0}^{E=\max} Z(E) dE \cdot f(E) \quad \rightarrow (1)$$

Integration eqn (1) wrt bottom of  $C_b$   $E_C$  and top of  $V_b$   $E_V$

$$\therefore n_e = \int_{E_C}^{\infty} Z(E) dE \cdot f(E) \quad \rightarrow (2)$$

density of state for an ele. with effective mass  $m^*$  is

$$Z(E) dE = \frac{\pi}{2} \left( \frac{8m_e^*}{\hbar^2} \right)^{3/2} E^{1/2} dE \quad \rightarrow (3)$$

The energy for electron in  $C_b$  becomes  $E - E_C$

so eqn (3) can be written as

$$Z(E) dE = \frac{\pi}{2} \left( \frac{8m_e^*}{\hbar^2} \right)^{3/2} (E - E_C)^{1/2} dE \quad \rightarrow (4)$$

Substituting (4) into (2)

$$n_e = \frac{\pi}{2} \left( \frac{8m_e^*}{\hbar^2} \right)^{3/2} \int_{E_C}^{\infty} (E - E_C)^{1/2} dE f(E) \quad \rightarrow (5)$$

The probability function  $f(E)$  is given by

$$f(E) = \frac{1}{1 + e^{(E-E_f)/k_B T}} \rightarrow (6)$$

at any temp energy required by an electron to move in  $C_b$  is greater than  $k_B T$

$$\text{So, } E - E_f \gg k_B T$$

$\therefore 1$  in denominator in eqn (6) can be ignored.

$$\therefore f(E) = \frac{1}{e^{(E-E_f)/k_B T}} \propto$$

$$f(E) = e^{(E_f - E)/k_B T} \rightarrow (7)$$

Now, substituting eqn (7) into (5)

$$n_e = \frac{\pi}{2} \left( \frac{8m_e^*}{h^2} \right)^{3/2} \int_{E_c}^{\infty} (E - E_c)^{1/2} \cdot e^{(E_f - E)/k_B T} \cdot dE \quad (8)$$

To solve the above eqn

$$E - E_c = x k_B T \rightarrow (9)$$

$$E = E_c + x k_B T \rightarrow (10)$$

$$\text{differentiating } dE = dx \cdot k_B T \rightarrow (11)$$

The limit will change based on assumption

$$E = E_c \Rightarrow x = 0 \text{ (lower limit)}$$

$$E = \infty \Rightarrow x = \infty \text{ (upper limit)}$$

So eqn (8) will become after (9) (10) (11) putting

$$n_e = \frac{\pi}{2} \left( \frac{8m_e^*}{h^2} \right)^{3/2} \int_0^{\infty} (x k_B T)^{1/2} \cdot e^{(E_f - x k_B T - E_c)/k_B T} \cdot k_B T \cdot dx$$

$$\therefore n_e = \frac{\pi}{2} \left( \frac{8m_e^*}{h^2} \right)^{3/2} \cdot (K_B T) \cdot e^{(E_f - E_c)/k_B T} \int_0^{\infty} x^{1/2} e^{-x} \cdot dx$$

$$\text{Now } \int_0^{\infty} x^{1/2} e^{-x} \cdot dx = \sqrt{\frac{\pi}{2}} \text{ (gamma function)}$$

$$n_e = \frac{\pi}{2} \left( \frac{8m_e^* k_B T}{h^2} \right)^{3/2} e^{(E_f - E_v)/k_B T} \sqrt{\frac{\pi}{2}}$$

simplifying

$$n_e = \frac{1}{4} \left( \frac{8m_e^* k_B T}{h^2} \right)^{3/2} e^{(E_f - E_v)/k_B T}$$

or

$$n_e = \frac{2}{\pi} \left( \frac{2\pi m_e^* k_B T}{h^2} \right)^{3/2} e^{(E_f - E_v)/k_B T}$$



density of ele. in  $C_b$  for intrinsic

semiconductors

## 2.2 Density of holes in Valence band for intrinsic semiconductors

The density of holes can be calculated by density of states  $Z(E)dE$  and probability function  $f(E)$  for a hole  $[1 - f(E)]$  between the limits from the bottom of valence band  $(-\infty)$  to top of valence band  $E_v$

which is,

$$n_h = \int_{-\infty}^{E_v} Z(E) dE [1 - f(E)] \rightarrow ①$$

probability of absence = 1 - probability of presence  
 $\therefore$  hole probability = 1 - Electron probability

$$\text{So } 1 - f(E) = 1 - \left[ \frac{1}{1 + e^{(E - E_f)/k_B T}} \right]$$

$$= 1 - \left[ 1 + e^{-(E - E_f)/k_B T} \right]^{-1}$$

Using binomial series

$$(1+x)^{-1} = 1-x+x^2-x^3+\dots$$

with  $x = e^{(E-E_f)/k_B T}$  and ignoring higher p

$$1 - f(E) = 1 - [1 - e^{(E-E_f)/k_B T}]$$

$$\therefore 1 - f(E) = e^{(E-E_f)/k_B T} \rightarrow (2)$$

expression for  $Z(E)dE$  for holes (assuming them to be free particle of mass  $m_h^*$ ) can be

given

$$Z(E)dE = \frac{\pi}{2} \left( \frac{8m_h^*}{h^2} \right)^{3/2} (E_v - E)^{1/2} \cdot dE \quad (3)$$

Substituting eqn (2)(3) into (1)

$$n_h = \frac{\pi}{2} \left( \frac{8m_h^*}{h^2} \right)^{3/2} \int_{-E_f}^{E_v} (E_v - E)^{1/2} \cdot e^{(E-E_f)/k_B T} \cdot dE \quad (4)$$

To solve the above eqn.

$$E_v - E = x \cdot k_B T \rightarrow (5)$$

$$\therefore E = E_v - x \cdot k_B T \rightarrow (6)$$

Differentiating the eqn (6)

$$dE = -dx \cdot k_B T \rightarrow (7)$$

Limit will change

$$E = E_v \Rightarrow x = 0$$

$$E = E_f \Rightarrow x = \infty$$

Substituting eqn (5)(6)(7) into eqn (4)

$$n_h = \frac{\pi}{2} \left( \frac{8m_h^*}{h^2} \right)^{3/2} \int_0^\infty (x k_B T)^{1/2} \cdot e^{(E_v - x k_B T - E_f)/k_B T} \cdot (-dx \cdot k_B T)$$

$$\therefore n_h = \frac{\pi}{2} \left( \frac{8m_h^*}{h^2} \right)^{3/2} (k_B T)^{3/2} \cdot e^{(E_v - E_f)/k_B T} \int_0^\infty x^{1/2} \cdot e^{-x} dx$$

$$\therefore n_h = \frac{\pi}{2} \left( \frac{8m_h^* k_B T}{h^2} \right)^{3/2} \cdot e^{(E_v - E_f)/k_B T} \times \sqrt{\pi}$$

$$(\because \text{gamma function } \frac{\sqrt{\pi}}{2} = \int_0^\infty x^{1/2} e^{-x} dx)$$

$$\therefore n_h = \frac{1}{4} \left( \frac{8\pi m_h^* k_B T}{h^2} \right)^{3/2} e^{(E_V - E_F)/k_B T}$$

$$\therefore n_h = 2 \left( \frac{2\pi m_h^* k_B T}{h^2} \right)^{3/2} e^{(E_V - E_F)/k_B T}$$

↓

Express Expression for density of holes in V<sub>b</sub> for  
Intrinsic Semiconductors

### 2.3 Fermi level and its variation with temperature for Intrinsic Semiconductors.

for an intrinsic semiconductor

$$n_e = n_h$$

density of ele in C<sub>b</sub> = density of holes in V<sub>b</sub>

so we can write

$$2 \left( \frac{2\pi m_e^* k_B T}{h^2} \right)^{3/2} e^{(E_F - E_C)/k_B T} = 2 \left( \frac{2\pi m_h^* k_B T}{h^2} \right)^{3/2} e^{(E_V - E_F)/k_B T}$$

$$\therefore (m_e^*)^{3/2} e^{(E_F - E_C)/k_B T} = (m_h^*)^{3/2} e^{(E_V - E_F)/k_B T} \rightarrow ①$$

$$\therefore \left( \frac{m_h^*}{m_e^*} \right)^{3/2} = \frac{e^{(E_F - E_C)/k_B T}}{e^{(E_V - E_F)/k_B T}}$$

$$\therefore \left( \frac{m_h^*}{m_e^*} \right)^{3/2} = e^{(2E_F - (E_C + E_V))/k_B T}$$

$$\therefore \left( \frac{m_h^*}{m_e^*} \right)^{3/2} e^{(E_C + E_V)/k_B T} = e^{2E_F/k_B T} \rightarrow ②$$

Taking logarithm on both sides.

$$\frac{2E_f}{k_B T} = \frac{3}{2} \ln \left( \frac{m_n^*}{m_e^*} \right) + \left( \frac{E_V + E_C}{k_B T} \right)$$

$$\therefore E_f = \frac{3}{4} k_B T \ln \left( \frac{m_n^*}{m_e^*} \right) + \frac{E_V + E_C}{2} \quad \text{--- (3)}$$

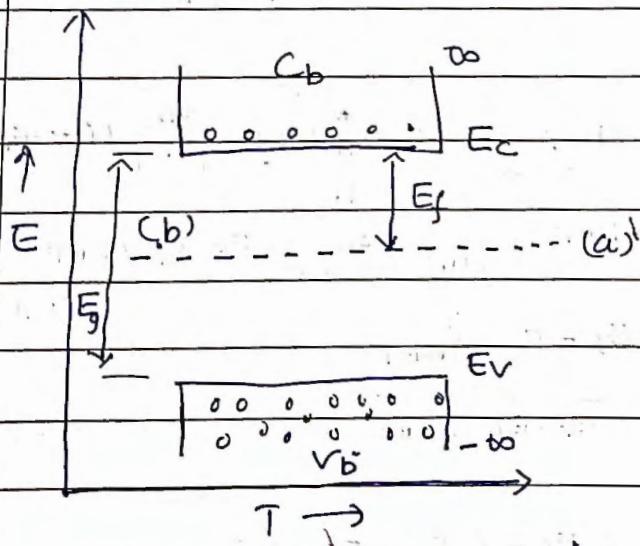
when  $m_e^* = m_n^*$

eqn (3) reduced to

$$E_f = \frac{E_V + E_C}{2} \quad (\because \ln(1) = 0)$$

So we can say fermi level is in the middle of  $V_b$  and  $C_b$ .

\* Dependence of fermi level ( $E_f$ ) on temperature



→ at  $T = 0 \text{ K}$  Fermi level lies exactly in the middle of forbidden gap as shown in (a).

→ As the temp.

increases slightly, here the term  $\ln \left( \frac{m_n^*}{m_e^*} \right)$  begin to contribute slightly as practically  $m_e^* > m_n^*$

→ This results in small magnitude of  $E_f$ .

→ Thus we can say Fermi level increases slightly as  $T$  increases as shown in (b)

## 2.4 Law of mass action. (

This law states that for a given semiconductor (intrinsic or extrinsic) product of charge carrier concentration remains a constant at any given temperature even if doping is varied.

$$n_e \cdot n_h = n_i^2 = \text{constant}$$

$n_i$  = carrier concentration for intrinsic

Based on mass action law

$$n_i^2 = n_e \times n_h \rightarrow (1)$$

$$n_i^2 = 2 \left( \frac{2\pi m_e^* k_B T}{h^2} \right)^{1/2} e^{(E_f - E_c)/k_B T}$$

$$\times 2 \left( \frac{\pi^* k_B T}{2m_h^* h^2} \right)^{3/2} e^{(E_V - E_f)/k_B T}$$

$$\therefore n_i^2 = 2^2 \left( \frac{2\pi k_B T}{h^2} \right)^3 (m_e^* m_h^*)^{3/2} e^{(E_V - E_c)/k_B T}$$

$$\therefore n_i = 2 \left( \frac{2\pi k_B T}{h^2} \right)^{3/2} (m_e^* m_h^*)^{3/4} e^{(E_V - E_c)/2k_B T} \quad (2)$$

We know that  $E_c - E_V = E_g$

$$\therefore n_i = 2 \left( \frac{2\pi k_B T}{h^2} \right)^{3/2} (m_e^* m_h^*)^{3/4} e^{(-E_g/2k_B T)}$$

From Above eqn it is clear that product of  $n_e \cdot n_h$  does not depend on  $E_f$  but remain const. at a given temp. and above eqn gives carrier concentration for an intrinsic semiconductor

$$n_e = n_h = n_i$$

## 2.5 Mobility and conductivity for intrinsic Semiconductors

For an intrinsic, electron holes holes are charge carrier

$$\text{conductivity is } \sigma = n \cdot e \cdot \mu_e$$

$$\text{for electron, } \therefore \sigma_e = n_e \cdot e \cdot \mu_e$$

( $\mu_e$  = mobility of ele.

$$\mu_e = v_d / E$$

for holes

$$\leftarrow \sigma_h = n_h \cdot e \cdot \mu_h$$

$\mu_h$  = mobility of hole

∴ total conductivity

$$\sigma_i = \sigma_e + \sigma_h$$

$$= n_e \cdot e \cdot \mu_e + n_h \cdot e \cdot \mu_h$$

$$\therefore \sigma_i = n_i e (\mu_e + \mu_h) \quad (\because n_e = n_h = n_i)$$

putting values of  $n_i$

$$\sigma_i = 2e \left( \frac{2\pi k_B T}{h^2} \right)^{3/2} \cdot (m_e \cdot m_h)^{3/4} \cdot e^{-Eg/2k_B T} \cdot (\mu_e + \mu_h)$$

$$\boxed{\sigma_i = C \cdot e^{-Eg/2k_B T}} \quad \rightarrow (1)$$

where

$$C = e \left( \frac{2\pi k_B T}{h^2} \right)^{3/2} \cdot (m_e^* m_h^*)^{3/4} (\mu_e + \mu_h)$$

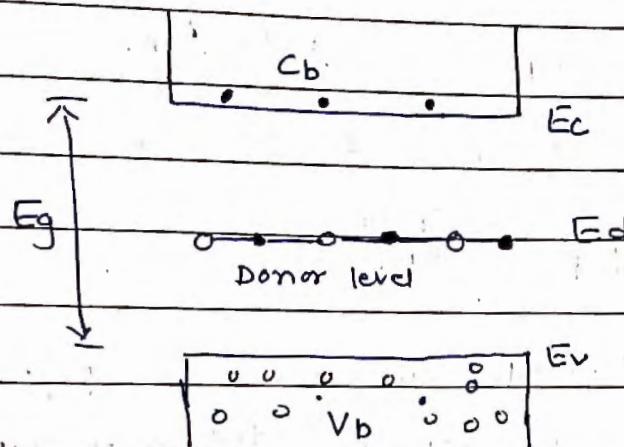
From eqn (1) we can say that  $\sigma_i$  depends on negative exponential of  $E_g$ , temp & mobilities taking log on both sides

$$\ln \sigma_i = \ln C - \frac{Eg}{2k_B T}$$

This shows that conductivity increases with increase in temp.

## 2.6 Expression for carrier concentration in N-type semiconductor (Extrinsic)

first we will derive eqn for Fermi level  
then carrier concentration.



Let  $N_d$  be donor concentration (no. of atom per unit volume)  
and  $E_d$  be donor energy level. For N-type material.

Assume that  $E_c - E_f > k_B T$ , then the density  
will be

$$n_e = 2 \left( \frac{2\pi m_e k_B T}{h^2} \right)^{\frac{1}{2}} e^{-\frac{(E_F - E_c)}{k_B T}} \quad \rightarrow ①$$

at  $T=0K$  the  $E_F$  lies between  $E_c$  &  $E_d$

Assume  $E_F$  lies more than a few  $k_B T$   
above  $E_d$ , then density of ionised donor atoms

~~$N_d^+$~~  must be equal to product of donor atoms  
 $N_d$  and probability function  $[1 - f(E_d)]$ .

$$N_d^+ = N_d [1 - f(E_d)] \quad \rightarrow ②$$

we know that

$$f(E_d) = \frac{1}{1 + e^{(E_d - E_F)/k_B T}}$$

$$\therefore 1 - f(E_d) = 1 - \frac{(E_d - E_f)/k_B T}{1 + e}$$

$$= 1 - \left[ 1 + e^{\frac{(E_d - E_f)k_B T}{}} \right]^{-1}$$

$$\therefore 1 - f(E_d) = 1 - \left[ 1 - e^{\frac{(E_d - E_f)k_B T}{}} \right]$$

$$\therefore 1 - f(E_d) = e^{\frac{(E_d - E_f)k_B T}{}} \rightarrow (3)$$

Substituting eqn (3) into (2) we get

$$N_{d^+} = N_d e^{\frac{(E_d - E_f)k_B T}{}} \rightarrow (4)$$

At very low temp no ele-hole pair is generated.

so density of  $n_e$  in  $C_b$  = density of positive donor atoms

$$\therefore n_e = N_{d^+}$$

$$\therefore 2 \left( \frac{2\pi m_e^* k_B T}{h^2} \right)^{3/2} e^{\left( \frac{E_f - E_c}{k_B T} \right)} = N_d e^{\left( \frac{E_f - E_c}{k_B T} \right)}$$

taking logarithm on both sides

$$\ln \left[ 2 \left( \frac{2\pi m_e^* k_B T}{h^2} \right)^{3/2} \right] + \frac{E_f - E_c}{k_B T} = \ln N_d + \frac{E_d - E_f}{k_B T}$$

rearranging the above eqn

$$\frac{E_f - E_c}{k_B T} - \frac{(E_d - E_f)}{k_B T} = \ln N_d - \ln \left[ 2 \left( \frac{2\pi m_e^* k_B T}{h^2} \right)^{3/2} \right]$$

multiplying by  $k_B T$  and simplifying the eqn

$$E_f - E_c - E_d + E_f = k_B T \cdot \ln \left[ \frac{N_d}{2 \left( \frac{2\pi m_e^* k_B T}{h^2} \right)^{3/2}} \right]$$

$$\left( \because \ln a - \ln b = \ln \left( \frac{a}{b} \right) \right)$$

$$\therefore 2E_f = (E_d + E_c) + k_B T \cdot \ln \left[ \frac{N_d}{2 \left( \frac{2\pi m_e^* k_B T}{h^2} \right)^{3/2}} \right]$$

$$\therefore E_f = \left( \frac{E_d + E_c}{2} \right) + \frac{k_B T}{2} \ln \left( \frac{N_d}{2 \left( \frac{2\pi m_e^* k_B T}{h^2} \right)^{3/2}} \right)$$

at  $T=0$  the eqn ⑤ reduced to 6(5)

$$E_f = \frac{E_d + E_c}{2}$$

→ eqn for Fermi level.

Fermi level lies exactly in the middle of donor level and bottom of conduction band.

\* Expression for carrier concentration in conduction band for N-type semiconductors

from eqn ①

$$n_e = 2 \left( \frac{2\pi m_e^* k_B T}{h^2} \right)^{3/2} e^{(E_f - E_c)/k_B T}$$

putting the values of  $E_f$  from eqn ⑤

before that simplifying term  $E_f - E_c$  for the

above eqn

$$E_f - E_c = \left( \frac{E_d + E_c}{2} \right) + \frac{k_B T}{2} \ln \left[ \frac{N_d}{2 \left( \frac{2\pi m_e^* k_B T}{h^2} \right)^{3/2}} \right] - E_c$$

$$\therefore E_f - E_c = \frac{E_d - E_c}{2} + \frac{k_B T}{2} \ln \left[ \frac{\frac{N_d}{2}}{\left( \frac{2\pi m_e^* k_B T}{h^2} \right)^{3/2}} \right] \rightarrow (6)$$

dividing the above eqn by  $k_B T$

$$\frac{E_f - E_c}{k_B T} = \frac{E_d - E_c}{2k_B T} + \frac{1}{2} \ln \left[ \frac{\frac{N_d}{2}}{\left( \frac{2\pi m_e^* k_B T}{h^2} \right)^{3/2}} \right]$$

$$\therefore \frac{E_f - E_c}{k_B T} = \frac{E_d - E_c}{2k_B T} + \ln \left[ \frac{\frac{N_d}{2}}{\left( \frac{2\pi m_e^* k_B T}{h^2} \right)^{3/2}} \right]^{1/2} \rightarrow (7)$$

$$\left( \because x \ln \left( \frac{a}{b} \right) = \ln \left( \frac{a^x}{b^x} \right) \right)$$

Now substituting the above eqn in the eqn for  $n_e$

$$n_e = 2 \left( \frac{2\pi m_e^* k_B T}{h^2} \right)^{3/2} \exp \left( \frac{E_d - E_c}{2k_B T} + \ln \frac{N_d^{1/2}}{\left( 2 \left( \frac{2\pi m_e^* k_B T}{h^2} \right)^{3/2} \right)^{1/2}} \right)$$

we know

$$e^{a+b} = e^a \cdot e^b$$

$$\therefore n_e = 2 \left( \frac{2\pi m_e^* k_B T}{h^2} \right)^{3/2} e^{\left( \frac{E_d - E_c}{2k_B T} \right)} \cdot \left( \frac{N_d^{1/2}}{\left( 2 \left( \frac{2\pi m_e^* k_B T}{h^2} \right)^{3/2} \right)^{1/2}} \right)$$

Simplifying the eqn above we get

$$n_e = (2N_d)^{1/2} \left( \frac{2\pi m_e^* k_B T}{h^2} \right)^{1/2} e^{\left( \frac{E_d - E_c}{2k_B T} \right)}$$

(8)

From above eqn it is clear that density of electrons in  $C_b$  is equal to sq. root of donor concentration  $N_d$ .

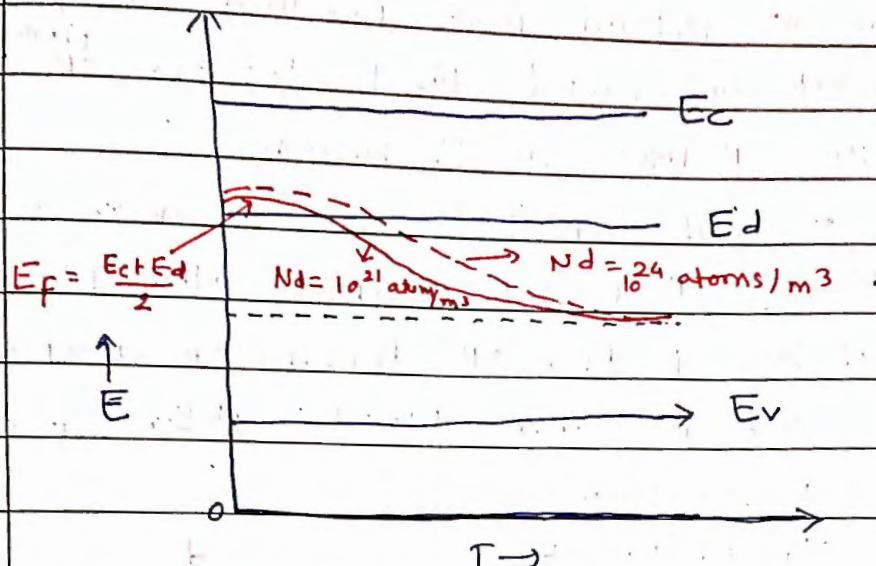
## 2.7 variation of Fermilevel with temperature and impurity concentration in N-type semiconductors.

We know

$$E_F = \left( \frac{E_d + E_c}{2} \right) + \frac{k_B T}{2} \ln \left[ \frac{N_d}{2 \left( \frac{2\pi m_e^* k_B T}{h^2} \right)^{3/2}} \right]$$

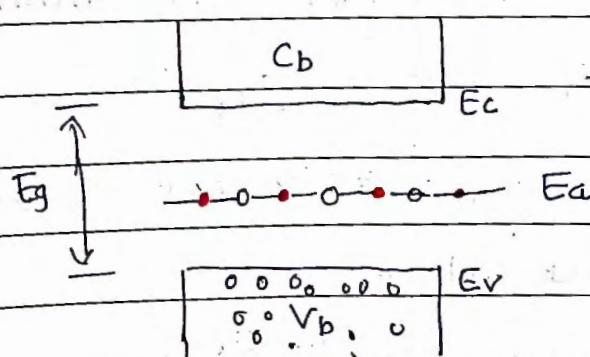
- we can say that Fermi level increases with increase in temperature.
- Now as temp increases more donor atoms get positively ionised due to donation of electron in  $C_b$  and Fermi level lies between  $E_c$  and  $E_d$ .

- In the figure variation of Fermi level with high and low donor concentration is indicated.



## 2.8 Expression for carrier concentration (hole concentration)

In P-type semiconductors.



Let  $N_a$  be acceptor concentration

$E_a$  = acceptor energy level

Let's assume that  $E_a - E_F > k_B T$

so density of holes in  $V_b$  is given by

$$n_h = \left( \frac{2\pi m_h^* k_B T}{h^2} \right)^{3/2} e^{\left( \frac{E_v - E_c}{k_B T} \right)} \rightarrow (1)$$

at 0 K Fermi level lies betw.  $E_F$  and  $E_A$

At very low temp all acceptor level remain empty.

With increase in temp more and more acceptor atom get negatively ionised due to transfer of  $V_b$  from atom.

so density of holes in  $V_b$  increases.

If we say that  $E_F$  lies below acceptor level then the density of ionised acceptor atom  $N_A^-$  must be equal to product of density of acceptor atom  $N_A$  and probability function  $f(E_A)$  for occupancy of an electron.

$$\therefore N_A^- = N_A \cdot f(E_A) \rightarrow (2)$$

We know

$$f(E_A) = \frac{1}{1 + e^{(E_A - E_F)/k_B T}} \rightarrow (3)$$

Fermi level lies between  $E_A$  and  $E_V$ . So  $(E_A - E_F)$  is positive and greater than  $k_B T$ . So ignoring 1 in denominator.

$$\therefore f(E_A) = \frac{1}{e^{(E_A - E_F)/k_B T}}$$

$$\therefore f(E_A) = e^{-(E_F - E_A)/k_B T} \rightarrow (4)$$

Substituting eqn (4) into (2)

$$N_A^- = N_A \cdot N_A \cdot e^{-(E_F - E_A)/k_B T} \rightarrow (5)$$

At lower temp covalent bonds not broken so density of holes in  $V_b$  = density of ionised acceptors atom

$$\therefore n_h = N_A^-$$

$$\therefore 2 \left( \frac{2\pi m_h^* k_B T}{h^2} \right)^{3/2} e^{-(E_F - E_A)/k_B T} = N_A^- \cdot e^{-(E_F - E_A)/k_B T}$$

• Taking logarithm on both sides

$$\ln \left[ 2 \left( \frac{2\pi m_h^* k_B T}{h^2} \right)^{3/2} \right] + \frac{E_V - E_F}{k_B T} = \ln N_a + \frac{E_F - E_a}{k_B T}$$

Rearranging the above eqn

$$\frac{E_V - E_F}{k_B T} - \frac{E_F - E_a}{k_B T} = \ln N_a - \ln \left[ 2 \left( \frac{2\pi m_h^* k_B T}{h^2} \right)^{3/2} \right]$$

$$\therefore -\frac{2E_F}{k_B T} + \frac{E_V + E_a}{k_B T} = \ln \left[ \frac{N_a}{2 \left( \frac{2\pi m_h^* k_B T}{h^2} \right)^{3/2}} \right]$$

$$\left( \because \ln a - \ln b = \ln \left( \frac{a}{b} \right) \right)$$

Multiplying both sides by (-ve) and rearranging

$$\frac{2E_F}{k_B T} = \frac{E_V + E_a}{k_B T} - \ln \left[ \frac{N_a}{2 \left( \frac{2\pi m_h^* k_B T}{h^2} \right)^{3/2}} \right]$$

Multiplying both sides with  $\frac{k_B T}{2}$

$$\therefore E_F = \frac{E_V + E_a}{2} - \frac{k_B T}{2} \ln \left[ \frac{N_a}{2 \left( \frac{2\pi m_h^* k_B T}{h^2} \right)^{3/2}} \right]$$

at  $T=0$  above eqn reduced to

$$E_F = \frac{E_V + E_a}{2}$$

(6)  
fermi level eqn for p-type  
semiconductor

\* Expression for density of holes in valence band:

from eqn ①

$$n_h = 2 \left( \frac{2\pi m_h^* k_B T}{h^2} \right)^{3/2} \cdot e^{(E_V - E_F)/k_B T}$$

Substituting the value of  $E_F$  from above in eqn ⑥  
but before simplifying the term  $(E_V - E_F)$

$$E_V - E_F = E_V - \frac{E_V - E_a}{2} + \frac{k_B T}{2} \ln \left[ \frac{N_a}{2 \left( \frac{2\pi m_n^* k_B T}{h^2} \right)^{3/2}} \right]$$

$$E_V - E_F = \frac{E_V - E_a}{2} + \frac{k_B T}{2} \ln \left[ \frac{N_a}{2 \left( \frac{2\pi m_n^* k_B T}{h^2} \right)^{3/2}} \right]$$

dividing both sides by  $k_B T$

$$\frac{E_V - E_F}{k_B T} = \frac{E_V - E_a}{2 k_B T} + \frac{1}{2} \ln \left[ \frac{N_a}{2 \left( \frac{2\pi m_n^* k_B T}{h^2} \right)^{3/2}} \right]$$

$$\therefore \frac{E_V - E_F}{k_B T} = \frac{E_V - E_a}{2 k_B T} + \log \left[ \frac{(N_a)^{1/2}}{\left\{ 2 \left( \frac{2\pi m_n^* k_B T}{h^2} \right)^{3/2} \right\}} \right]$$

Substituting eqn ⑧ in expression  $n_h$  ⑨

$$n_h = 2 \left( \frac{2\pi m_n^* k_B T}{h^2} \right)^{3/2} \cdot \exp \left[ \frac{E_V - E_a}{2 k_B T} + \ln \left[ \frac{N_a^{1/2}}{\left\{ 2 \left( \frac{2\pi m_n^* k_B T}{h^2} \right)^{3/2} \right\}} \right] \right]$$

$$\therefore n_h = 2 \left( \frac{2\pi m_n^* k_B T}{h^2} \right)^{3/2} \cdot e^{\frac{E_V - E_a}{k_B T}} \cdot \frac{N_a^{1/2}}{\left( 2 \left( \frac{2\pi m_n^* k_B T}{h^2} \right)^{3/2} \right)^{1/2}}$$

on simplifying we get

$$n_h = (2 N_a)^{1/2} \cdot \left( \frac{2\pi m_n^* k_B T}{h^2} \right)^{3/4} \cdot e^{\frac{E_V - E_a}{k_B T}}$$
⑩

eqn for density of holes in  $V_b$  for p-type semiconductor.

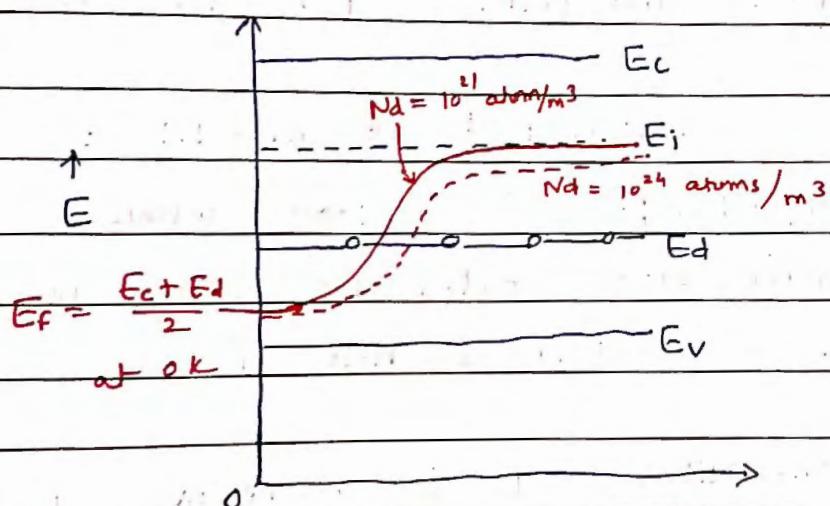
## 2.9 Variation of $E_F$ with temp and impurities in p-type semiconductors.

we know that

$$E_F = \frac{E_V + E_a}{2} - \frac{k_B T}{e} \ln \left[ \frac{N_a}{2 \left( \frac{2\pi m_n^* k_B T}{h^2} \right)^{3/2}} \right]$$

from the eqn we can say temp gets slowly increased more and more acceptor atom gets negatively ionised due to transfer of ele from V<sub>b</sub> and fermi level lies between E<sub>V</sub> and E<sub>A</sub>.

At a particular temp all acceptor atoms are ionised. beyond this temp ele-hole pair are generated due to breaking of covalent bond. and the material will behave like intrinsic semiconductor.



## 2.10 Electrical conductivity for Extrinsic Semiconductors

for pure N-type semiconductor

$$\sigma = n_e \cdot e \cdot \mu_e$$

where  $\mu_e$  = mobility of ele.

$n_e$  = density of ele.

and

$$n_e = (2Nd)^{1/2} \cdot \left( \frac{2\pi m_e^* k_B T}{h^2} \right)^{3/4} \cdot e^{\left( \frac{E_d - E_c}{2k_B T} \right)}$$

for a pure p-type semiconductor

$$\sigma = n_h \cdot e \cdot \mu_h$$

where  $\mu_h$  = mobility of holes

$n_h$  = density of holes

$$n_h = (2 N_A)^{1/2} \cdot \left( \frac{2\pi m_h k_B T}{h^2} \right)^{3/4} \cdot e^{\left( \frac{E_V - E_A}{k_B T} \right)}.$$

(3) carrier generation and recombination, carrier-transport: diffusion and drift, p-n junction.

### 3.1 carrier generation and recombination:

\* carrier generation :- it is a process where electron-hole pairs are created by exciting an electron from  $V_b$  to  $C_b$ . So creating a hole in  $V_b$ .

\* Carrier recombination :- It is a reverse process where electrons and holes from  $C_b$  and  $V_b$  respectively recombine and are annihilated (destroyed).

In the above process both the carriers are eventually disappear. The energy difference of first and final stage is given off as Phonon and photons.

In semiconductors many process are lead to generation and recombination which are

- (1) Photon transition. (optical generation, Recombination)
- (2) Phonon transition (Shockley-Read-Hall (SRH) recombination).

## (1) Photon transition.

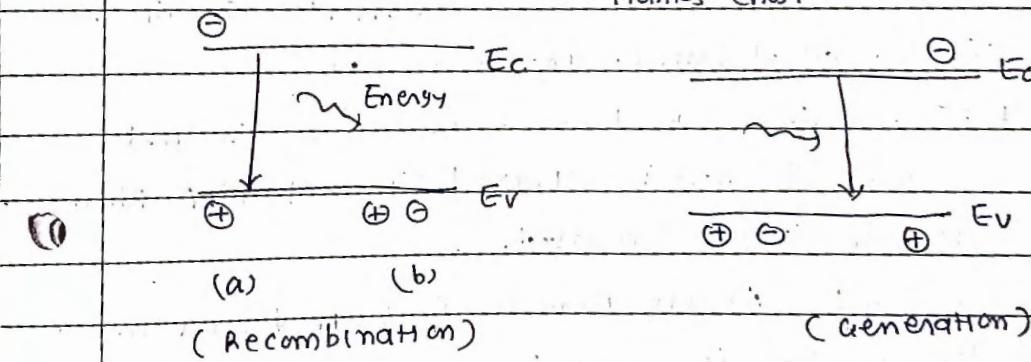
It is known as 'direct' recombination.  
here an electron from  $C_b$  falls back to  $V_b$  and release energy in the form of photon.

The reverse process (generation) is achieved by giving energy to atoms in which electron transfer is from  $V_b$  to  $C_b$  and creating a hole in  $V_b$ .

The energy of incident photon has to be atleast of the magnitude of bandgap energy.

From transition from excited states to lower state, momentum has to be conserved.

$$\text{energy } E = \frac{h\nu}{\text{freq of photon}} \text{ Planck's Law}$$



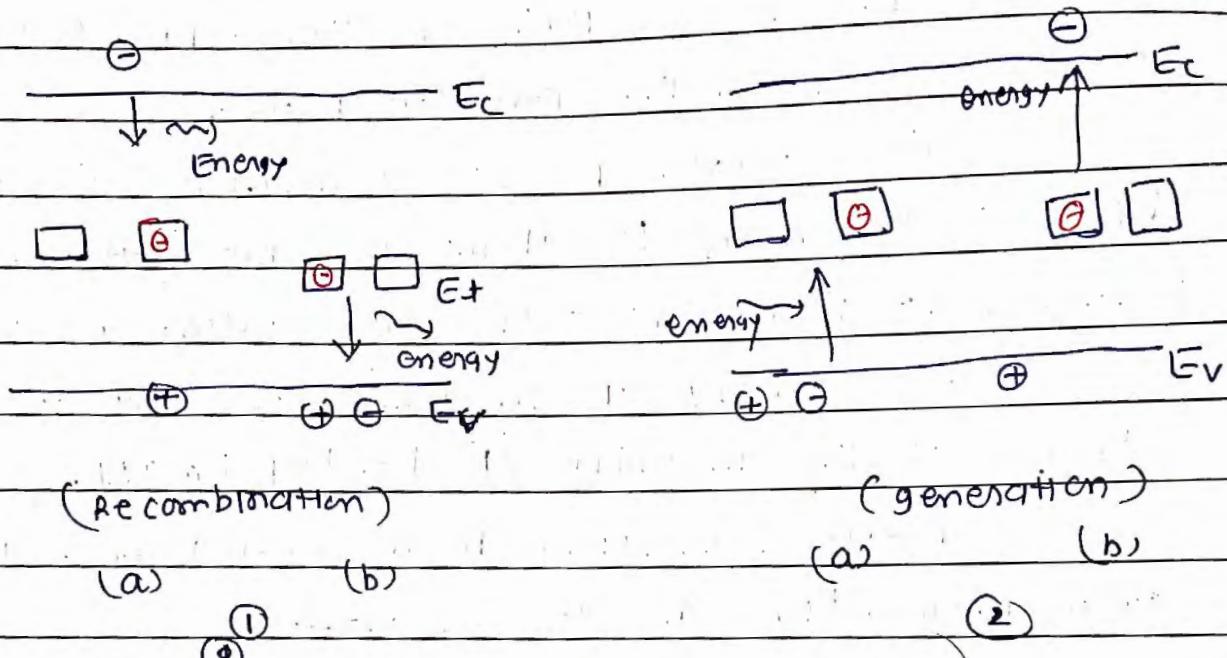
The process of recombination is directly proportional to available holes and electrons.

## (2) phonon transition :- (SRH)

Also known as indirect or trap assisted recombination.

It is a trap assisted, passing through a lattice defect at Energy level  $E_F$  within the bandgap.

The trap can be caused by presence of any foreign p atom.



\* Electron capture :- an ele from  $C_b$  is captured by an empty trap in band gap. This excess energy is  $(E_c - E_F)$  is transferred to crystal lattice. (phonon emission)

\* Hole capture :- the trapped ele. moves to  $V_b$  and neutralize a hole (the hole is captured by a trap). A phonon with energy  $(E_F - E_v)$  is generated.

\* Hole emission :- An ele from  $V_b$  is trapped, leaving a hole in the  $V_b$  (hole is emitted from empty trap to  $V_b$ ) energy required is  $(E_F - E_v)$

\* Electron emission :- A trapped electron moves from the trap energy level to  $C_b$ . The hole and ele emission rates are proportional to concentration of empty traps and filled traps respectively.

The ele capture and hole capture rate is proportional to concentration in  $C_b$  and  $V_b$  respectively.

### 3.2 Carrier transport: Diffusion and drift

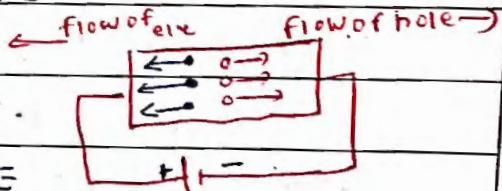
\* **Drift current:** The flow of charge carrier which is due to applied voltage or electrical field is called drift current.

In a semiconductor 2 types of carriers, ele. and hole. When voltage is applied to a semiconductor, free ele moves towards +ve terminal of battery and holes moves towards -ve terminal. Generally in semiconductor ele tends to travel in straight direction but due to collisions they change direction. With every collision they bounce back in random direction. The applied voltage does not stop collisions but causes the electron to drift towards the positive terminal.

The average velocity that an electron or hole achieve due to applied voltage or ele field is called drift velocity.

$$\text{drift velocity of ele. } V_e = \mu_e E$$

$$\text{drift velocity of holes } V_h = \mu_h E$$



$$\text{drift current density of ele. } J_e = n_e \mu_e E$$

$$\text{drift current density due to hole } J_h = n_h \mu_h E$$

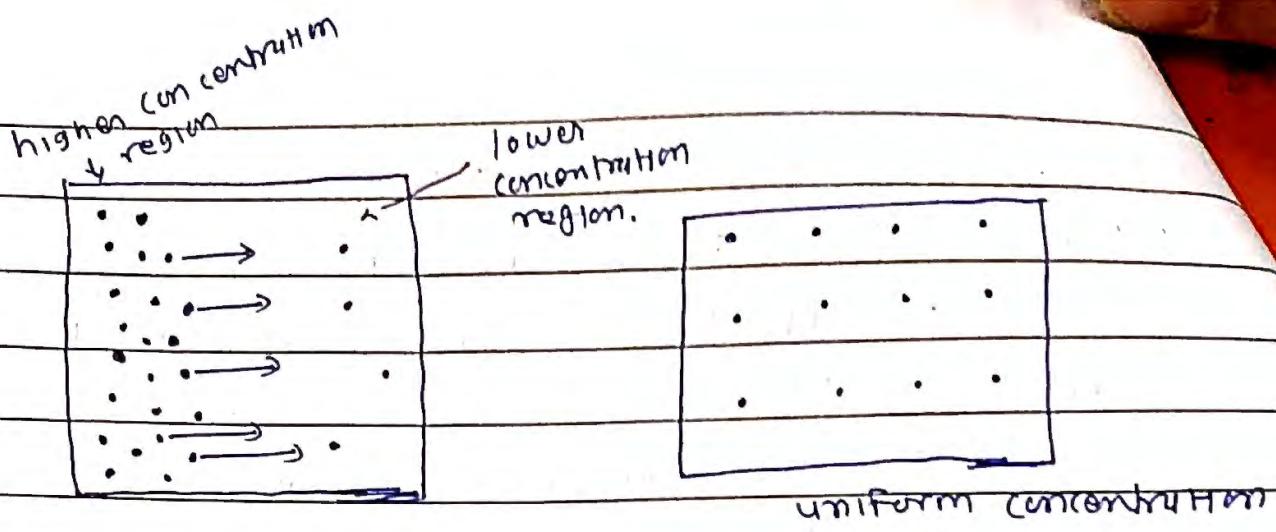
$$\text{Total drift current density } J = J_e + J_h$$

$$= n_e \mu_e E + n_h \mu_h E$$

$$J = n_e E (\mu_e + \mu_h)$$

#### \* Diffusion current:

current produced due to motion of charge carriers from a higher concentration to lower concentration region is called diffusion current.



Non uniform concentration

The above process occurs in semiconductors that are non-uniformly doped.

As seen in the above figure in Non-uniform doping case there will be 2 regions called higher con and lower concentration area. The ele from higher concentration region will experience repulsive force and tend to move in lower concentration area and will produce current. This current is known as diffusion current.

Both drift and diffusion current occurs in Semiconductors.

Diffusion current occurs without an external voltage or ele field applied.

Diffusion current density due to ele.  $J_e = e D_e \frac{dn}{dx}$

Diffusion current density due to hole  $J_h = -e D_h \frac{dn}{dx}$

where  $D_e$  &  $D_h$  = diffusion coefficient of ele. and hole.

Total current density due to ele. is = drift current + Diffusion current

$$\therefore J_e = e n \mu_e E + e D_e \frac{dn}{dx}$$

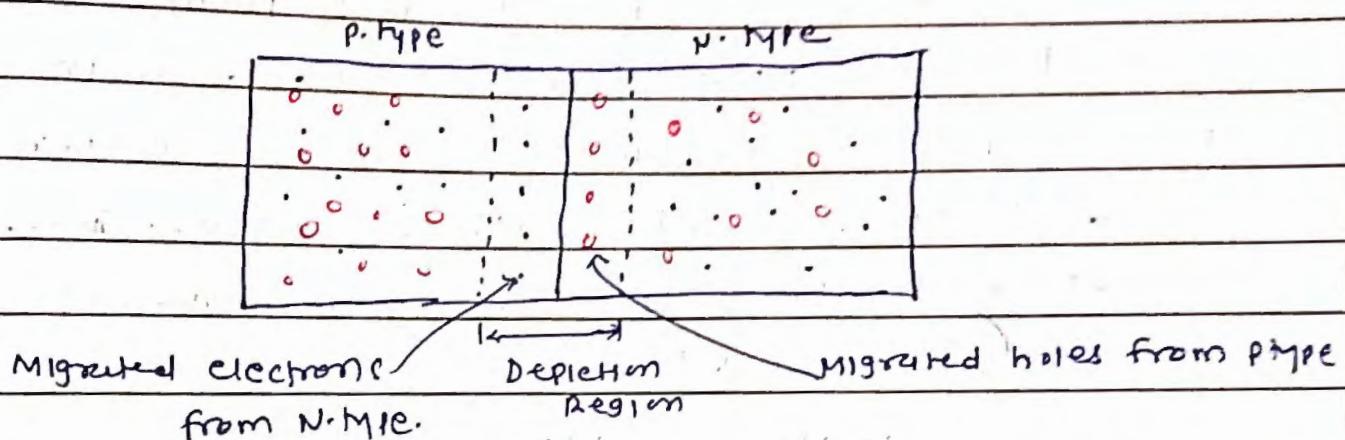
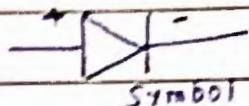
Total current density due to hole = drift current + diffusion current

$$\therefore J_h = n_h \cdot e \cdot \mu_h \cdot E - e D_h \frac{dn}{dx}$$

### 3.3 P-N Junction.

When a P-type semiconductor is fused (joined) to an N-type semiconductor, a P-N junction is formed. It is fabricated by special processes like alloying and diffusion methods.

\* P-N Junction at zero bias



→ In P-type holes and in N-type ele. are majority charge carriers. along with majority charge carriers minority charge carriers are also present.

(1) The majority charge carrier near the junction diffuse across the junction and recombine. after few recombination the process stops. because of this there is a region created between P-type and N-type material which is having neutral charge. this region is known as Depletion region.

There is no current in this condition.

The thickness of the depletion region is of the order of  $10^{-6}$  m.

The potential difference between the depletion region is known as potential barrier.

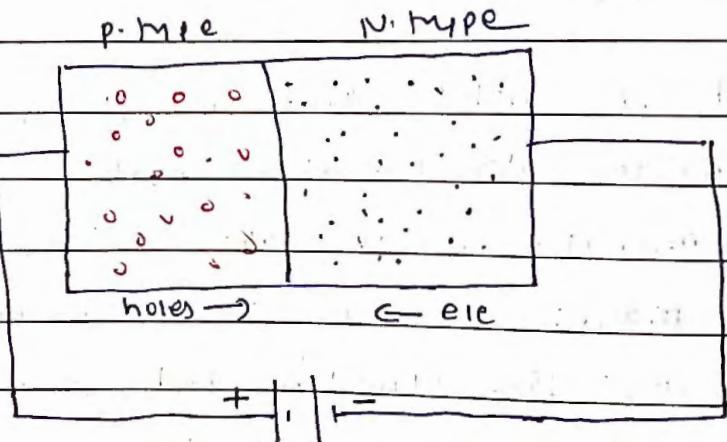
## \* Working of PN Junction :

### ① Forward bias :-

when +ve of battery is connected with +ve of diode and -ve of battery & with -ve of diode it is said to be forward bias.

when external voltage is applied the P-N

Junction cancels the barrier and permits the current. when forward bias is greater than potential barrier, the majority charge carrier moves towards junction and results in current. here current flows due to majority charge carriers and increase with forward bias.



### ② Reverse bias :-

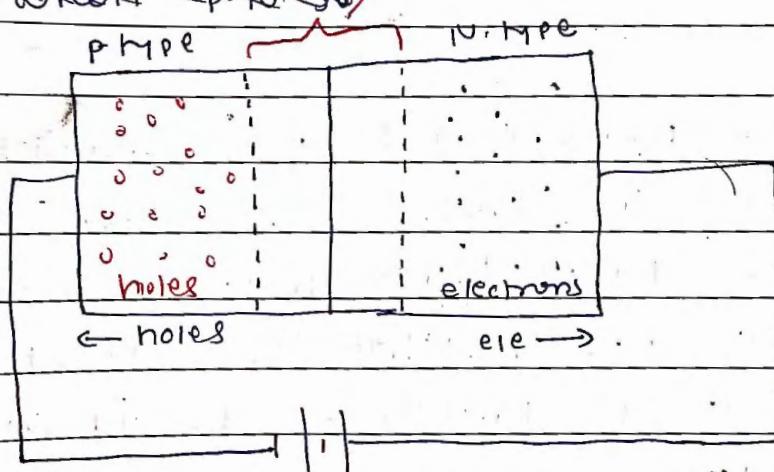
when +ve of battery is connected with -ve of diode and -ve of battery is connected with +ve of diode it is said to be reverse bias.

when external voltage is applied the P-N junction increases the potential barrier in reverse bias.

The applied reverse voltage creates an electric field which acts in the same direction of potential barrier. due to this potential barrier increases.

This barrier stops the flow of current across the junction. very small current flows in the circuit due to minority carriers called reverse current.

~~when p-N junction~~ <sup>depletion width increased</sup>



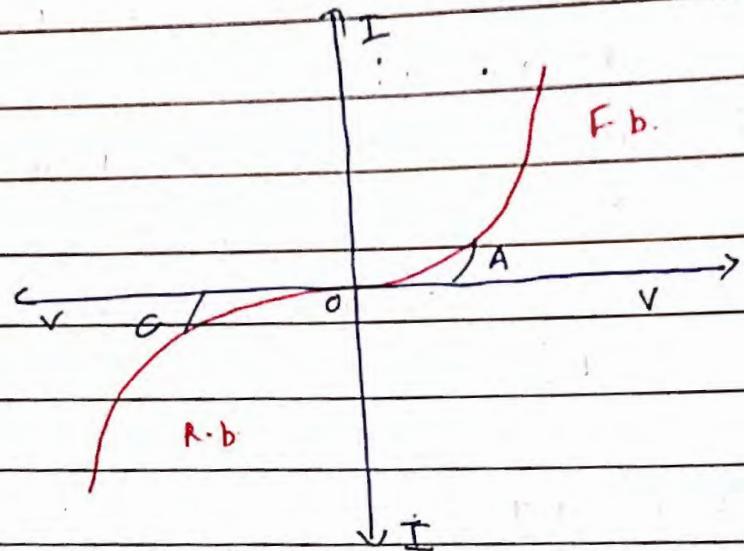
→ when a p-n junction diode is forward biased low resistance path and current flows.

When a p-n junction diode is reverse biased high resistance path and no current flows.

so diode can be used as a switch or rectifier.

It can also be used as clipper, clammer or in gates.

\* V-I characteristics of a P-N junction diode



→ The forward and reverse characteristics of a diode is shown in the above figure.

In forward bias if we increase the voltage at some value of voltage ( $V_f$ ) current start flowing this voltage is known as threshold voltage ( $V_{th}$ ) or knee voltage. (0.3 V for Ge 0.7 V for Si)

at point A,  $V_f = V_{th} = V_B$

forward bias

( $V_b$  = barrier potential)

resistance

$$R_f = \frac{\Delta V_f}{\Delta I_f}$$

If voltage increase beyond it diode may get damaged.

→ IN reverse bias condition majority charge carrier are blocked and only small current flows due to minority carriers

If we increase the reverse voltage slowly the reverse current will reach to maximum value this current is known as saturation current or leakage current.

The reverse current of the diode is of order of ( $\mu\text{A}$ ) for Ge and ( $\text{nA}$ ) for Si.

Resistance of diode

$$\text{Ans} \quad R_f = \frac{\Delta V_R}{\Delta I_R}$$

#### (4) metal-semiconductor junction (ohmic & schottky)

and semiconducting material of interest of optoelectronic devices.

##### 4.1 Metal Semiconductor Junction (ohmic & schottky)

\* work function ( $\phi$ ) :- it is the minimum energy required to transfer an ele. from a point within a solid to a point outside its surface.

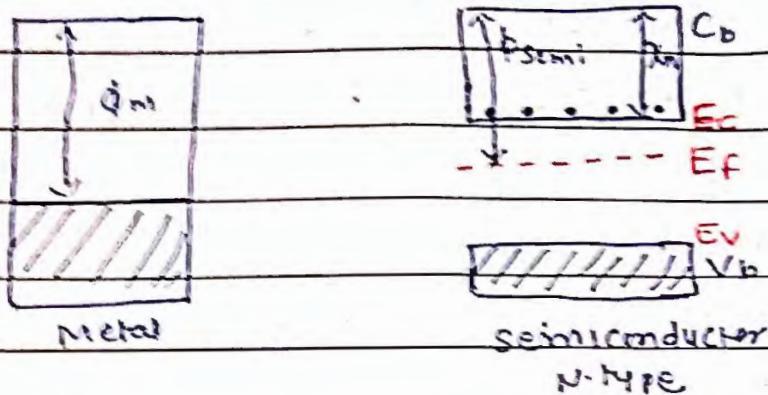
\* Electron affinity ( $X_n$ ) :- it is defined as the energy released or spent when ele. is added to a neutral atom or molecules.

→ when a metal and semiconductor brought into contact two types of junction can be formed.

$\phi_m > \phi_{semi} \rightarrow$  Schottky junction

$\phi_m < \phi_{semi} \rightarrow$  ohmic junction.

## \* Schottky contact ( $\Phi_m > \Phi_{semi}$ )



As seen in the figure Fermilevel of semiconductor is higher than metal. When the contact is made, Fermi level should line up at equilibrium. When the contact is formed there is formation of depletion region in semiconductor.

The Fermi level lines up and a positive potential is created on semiconductor side and a negative potential on metal side. Band bends up in the direction of electric field. There is built in potential in Schottky junction given by work function.

$$\Phi_m - \Phi_{semi} = eV_0$$

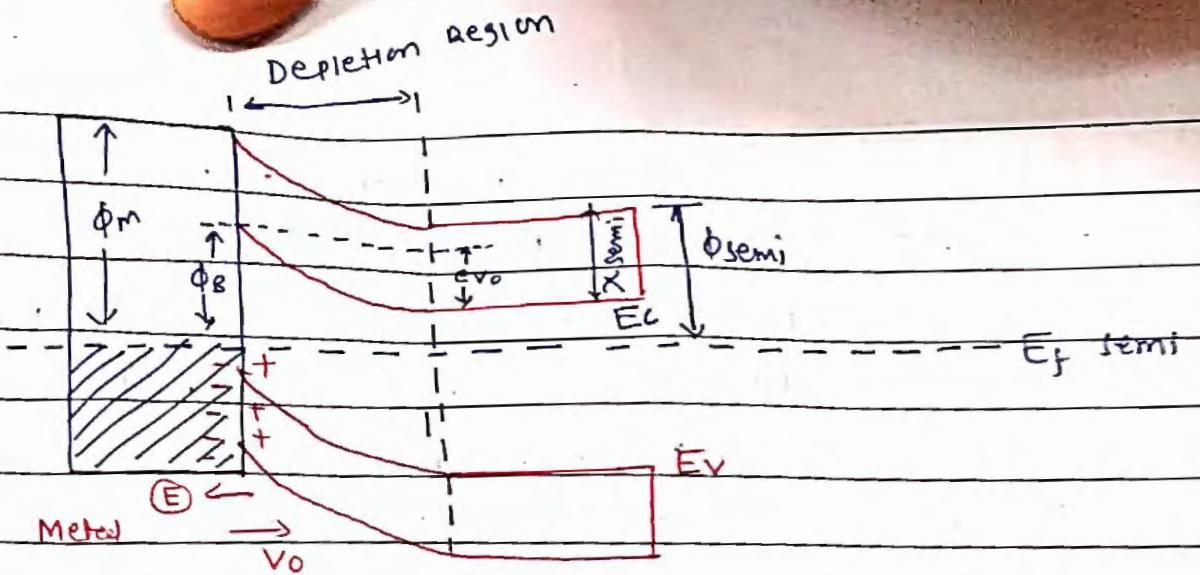
This contact potential works as barrier for electrons to move from semiconductor to metal.

When contact was made electrons moved to metal side and formed a depletion region which prevents further motion of electrons.

The Schottky barrier is given by

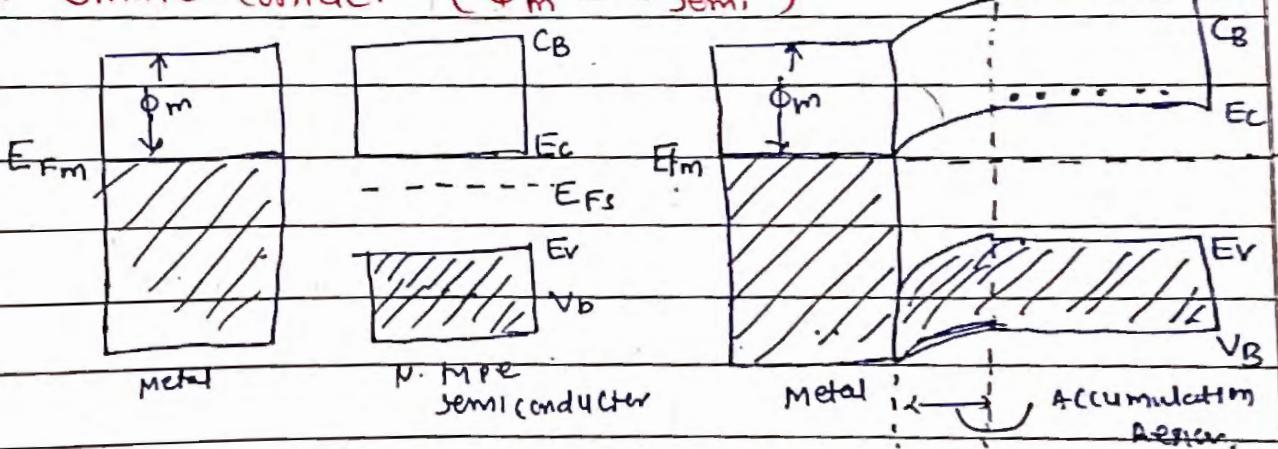
$$\Phi_B = (\Phi_m - \Phi_{semi}) + (E_C - E_{Fn})$$

$$\Phi_B = (\Phi_m - X_n) \quad (X_n \text{ is ele affinity of semi-conduc})$$



Applications: Rectifiers, voltage clamps, RF mixer, detector  
rectifying high freq. signals.

\* Ohmic contact ( $\phi_m < \phi_{\text{semi}}$ )



when the semiconductor has a higher work function than metal ohmic junction is formed.

At equilibrium the Fermi levels line up. The electrons move from metal to semiconductor and accumulation region near the interface. The accumulation region has higher conductivity due to high ele. concentration. so the ohmic junction work as a resistor.

Application:- used in thermoelectric devices

(cooling a small volume, by applying electric current).

## 4.2 Semiconducting material of interest for opto electronic devices.

When photons having energy equal to or higher than the band gap energy are incident on a semiconductor; electrons from the  $V_b$  are excited to  $C_b$  and create electron-hole pair.

### (1) Photoconductivity :-

The increase in conductivity of a material due to electron-hole pair arising from optical excitation is called photoconductivity used in photodiodes.

### (2) Luminescence :-

The property of light emission is called luminescence.

different types of luminescence are given below.

#### (2.1) Photoluminescence :

When photons electrons are excited by absorption of photons of suitable frequency and energy greater or equal to bond gap, the resultant radiation due to recombination of electron hole-pair is called photoluminescence.

Sub process { Phosphorescence }  
                          { fluorescence. }      used in fluorescent lamp

## (2.2) Cathodoluminescence:

(31)

When electron hole pair are generated by bombardment of highly energetic electrons into the material, the resulting radiation due to recombination of ele-hole pair is called cathodoluminescence.

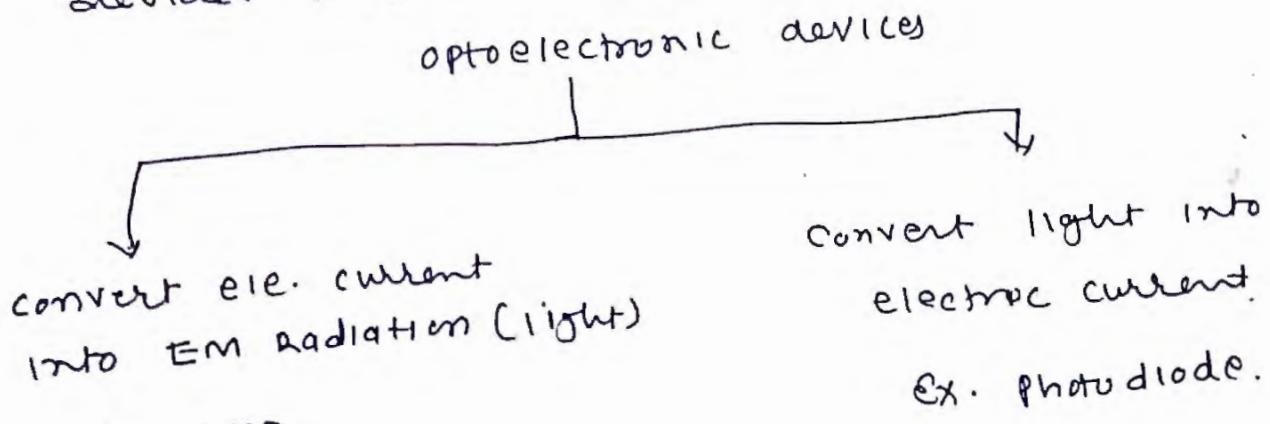
Ex: TV tubes, CRT's.

## (2.3) Electroluminescence (EL):

When the excitation of carriers (generation of electron-hole pair) is produced due to the introduction of forward current into the material, the resulting radiation due to recombination of ele-hole pair is called electroluminescence.

Ex: LED

Basically opto-det optoelectronic devices are divided into two categories.



Ex. photodiode.

Ex. LED

