Unit. 2 Semiconductors.

* Syllabus : ① intrinsic and Extrinsic semiconducters.

② Dependance 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-semiconducter 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 extrinsie 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
ependency of electrical conduetivity	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), Galium (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 dopping 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.

(1) 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, transister, LED, photodiodes etc.

Extrinsic are further devided 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 creat a vacancy behind. It is know an Hole.

for intrinsic semiconducter for every excited electron, moving to C_b there is a hole created in V_b.

So $n_e = n_h$

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

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

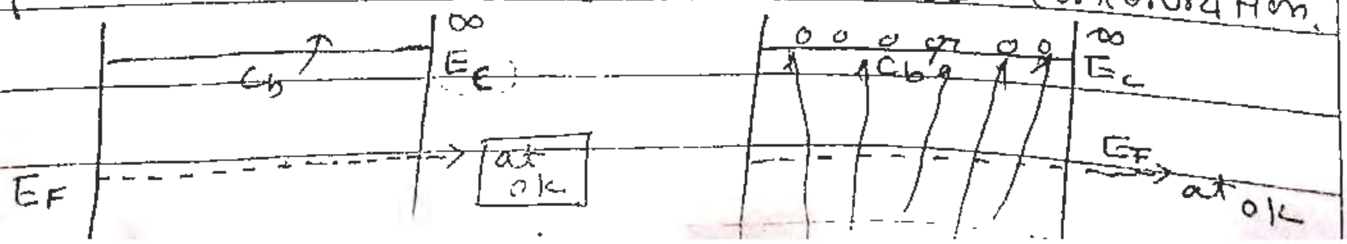
where

$n_e = n_h = n_i$ = intrinsic carrier concentration

μ_e, μ_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 is completely empty.

→ Expression :

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

Intrinsic carrier concentration $\therefore n_e = \int_{E=0}^{E=max} Z(E)\,dE \cdot f(E)$ → ①

Integrating eqn ① wrt bottom of C_b E_c and top of C_b ∞

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

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

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

The energy for electron in C_b becomes $E-E_c$ so eqn ③ can be written as

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

Substituting ④ into ②

$$n_e = \frac{\pi}{2}\left(\frac{8m_e^*}{h^2}\right)^{3/2}\int_{E_c}^{\infty} (E-E_c)^{1/2}\,dE \ldots$$

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

$$f(E) = \frac{1}{1 + e^{((E-E_F)/KT)}} \rightarrow (6)$$

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

So, $E - E_f >> K_B T$

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

$$\therefore f(E) = \frac{1}{e^{(E-E_f)/K_B T}} \quad \text{or}$$

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

Now, substituting eqn (7) into (5)

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

To solve the above eqn

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

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

differentiating $\quad dE = dx \cdot K_B T \rightarrow (11)$

The limit will change based on assumption

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

$E = \infty \Rightarrow x = \infty$ (upper limit)

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

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

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

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

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

simplifying

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

or

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

$\pi^{3/2}$

density of ele. in C_b for intrinsic semiconductor

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,

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

probability of absence = 1 - probability of presence

$\therefore$ hole probability = 1 - Electron probability

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

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

with $x = e^{(E-E_f)/k_BT}$ and ingnoring higher powers

$$1 - f(E) = 1 - \left[1 - e^{(E-E_f)/k_BT}\right]$$

$$\therefore \quad 1 - f(E) = e^{(E-E_f)/k_BT} \longrightarrow (2)$$

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

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

substituting eqn (2) (3) into (1)

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

To solve the above eqn

$$E_v - E = x \cdot k_BT \longrightarrow (5)$$

$$\therefore E = E_v - xk_BT \longrightarrow (6)$$

differentiating the eqn (6)

$$dE = -dx \cdot k_BT \longrightarrow (7)$$

Limit will changed

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

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

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

$$n_h = \frac{\pi}{2}\left(\frac{8m_h^*}{h^2}\right)^{3/2} \int_{\infty}^{0} (xk_BT)^{1/2} \cdot e^{(E_v - xk_BT - E_f)/k_BT} (-dx\, k_BT)$$

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

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

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

$$\frac{1}{4} \times (4)^{3/2} \Rightarrow 4^{\frac{3}{2}-1}$$

$$4^{\frac{3-2}{2}} = 4^{1/2} = 2^{2/2} \Rightarrow \boxed{2}$$

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

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

~~Exper~~ Expression for density of holes in V_b for intrinsic semiconductor

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_b = density of holes in V_b

so we can write

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

$$\therefore (m_e^*)^{3/2} \cdot e^{(E_f - E_c)/k_B T} = (m_h^*)^{3/2} \cdot e^{(E_v - E_f)/k_B T} \longrightarrow (1)$$

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

$$\therefore \left(\frac{m_h^*}{m_e^*}\right)^{3/2} = e^{(2E_f - (E_c + E_v))/k_B T}$$

$$\therefore \left(\frac{m_h^*}{m_e^*}\right)^{3/2} \cdot e^{(E_c + E_v) k_B T} = e^{2E_f / k_B T} \longrightarrow (2)$$

Taking logarithm on both sides

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

$$\therefore \quad E_f = \frac{3}{4} K_B T \ln\left(\frac{m_h^*}{m_e^*}\right) + \frac{E_V + E_C}{2} \longrightarrow (3)$$

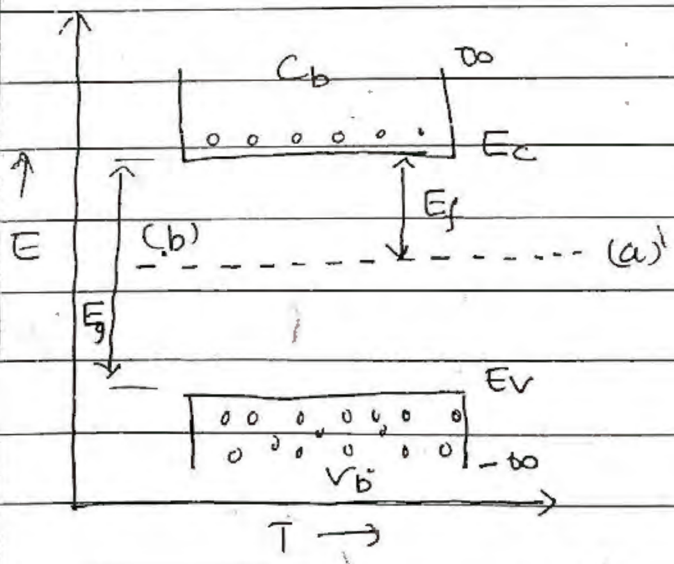
when $m_e^* = m_h^*$

eqn (3) reduced to

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

So we can say fermi level is in the middle of Vb and Cb.

* Dependence of fermi level (E_f) on temperature



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

→ As the temp. increases slightly, the term $\ln\left(\frac{m_h^*}{m_e^*}\right)$ begin to contribute slightly as practically $m_e^* > m_h^*$

→ 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

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

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

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

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

$$\therefore n_i = 2\left(\frac{2\pi K_B T}{h^2}\right)^{3/2} (m_e^* \cdot m_h^*)^{3/4} e^{(E_V - E_C)/2K_B T} \longrightarrow (2)$$

we know that $E_c - E_v = E_g$

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

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 stea~~ 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 semiconductor

For an intrinsic, electron holes both are change carrier

conductivity is $\sigma = n \cdot e \cdot \mu$

for electron. $\therefore \sigma_e = n_e \cdot e \cdot \mu_e$

(μ_e = mobility of ele.

$\therefore \mu_e = V_d / E$)

for holes

~~σ_h~~ $\sigma_h = n_h \cdot e \cdot \mu_h$

μ_h = mobility of hole

$\because$ 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

$$\sigma_i = 2e \left(\frac{2\pi K_B T}{h^2} \right)^{3/2} \cdot (m_e^* \cdot m_h^*)^{3/4} \cdot e^{(-E_g / 2K_B T)} (\mu_e + \mu_h) \rightarrow (1)$$

$$\therefore \boxed{\sigma_i = C \cdot e^{(-E_g / 2K_B T)}} \longrightarrow (2)$$

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 (2) we can say that σ_i depends on negative exponential of E_g, temp & mobilities

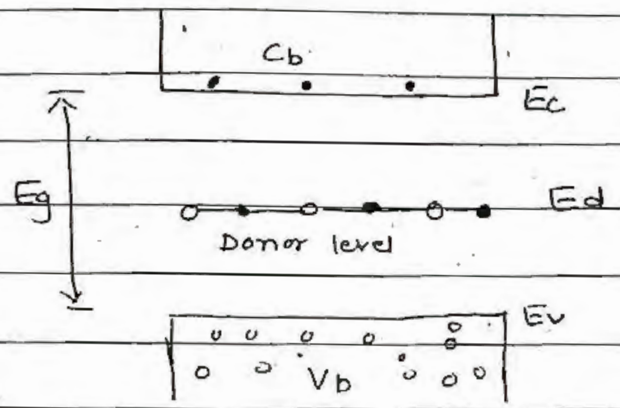
taking log on both sides

$$\boxed{\ln \sigma_i = \ln C - \frac{E_g}{2K_B T}}$$

This shows that conductivity increases with

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

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



let Nd be donor concentration (no. of atom per unit volume) and Ed be donor energy level. For N-type material. Assume that $E_c - E_f > k_BT$, then the density will be

$$n_e = 2\left(\frac{2\pi m_e^* k_BT}{h^2}\right) e^{\left(\frac{E_F - E_c}{k_BT}\right)} \longrightarrow (1)$$

at T = 0K the E_f lies between E_c & E_d

Assume E_f ~~the~~ lies more than a few k_BT above Ed., then density of ionised donor atom N_d^+ must be equal to product of donor atoms Nd and probability function $[1 - f(E_d)]$.

$$\therefore N_d^+ = N_d\,[1 - f(E_d)] \longrightarrow (2)$$

we know that

$$f(E_d) = \frac{1}{1 + e^{(E_d - E_f)/k_BT}}$$

$$\therefore \quad 1 - f(E_d) = 1 - \frac{1}{1 + e^{(E_d - E_f)/k_BT}}$$

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

$$\therefore \quad 1 - f(E_d) = 1 - \left[1 - e^{(E_d - E_f)/k_BT}\right]$$

$$\therefore \quad 1 - f(E_d) = e^{(E_d - E_f)/k_BT} \longrightarrow (3)$$

substituting eqn (3) into (2) we get

$$N_d^+ = N_d \, e^{\frac{(E_d - E_f)}{k_BT}} \longrightarrow (4)$$

At very low temp no ele-hole pair is generated. so density of n_e in C_b = density of positive donor atoms

$$\therefore \quad n_e = N_d^+$$

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

taking logarithm on both sides

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

rearranging the above eqn

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

multiplying by $k_B \cdot T$ and simplifying the eqn

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

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

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

$$\therefore E_f = \left(\frac{E_d + E_c}{2}\right) + \frac{K_BT}{2} \ln\left(\frac{N_d}{2\left(\frac{2\pi m_e^* K_BT}{h^2}\right)^{3/2}}\right) \rightarrow (5)$$

at T=0 the eqn (5) reduced to

$$\boxed{E_f = \frac{E_d + E_c}{2}} \rightarrow \text{eqn for fermilevel.}$$

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)

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

putting the values of E_f from eqn (5)

before that simplifying term $E_f - E_c$ for the above eqn

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

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

deviding the above eqn by K_BT

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

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

Now substituting the above eqn in the eqn for n_e

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

we know

$$e^{a+b} = e^a . e^b$$

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

Simplifying the above eqn

$$\boxed{n_e = (2N_d)^{1/2}\left(\frac{2\pi m_e^* k_BT}{h^2}\right) e^{\left(\frac{E_d - E_c}{2k_BT}\right)}} \quad (8)$$

From above eqn it is clear that density of electron in Cb is equal to sq. root of donor concentration Nd.

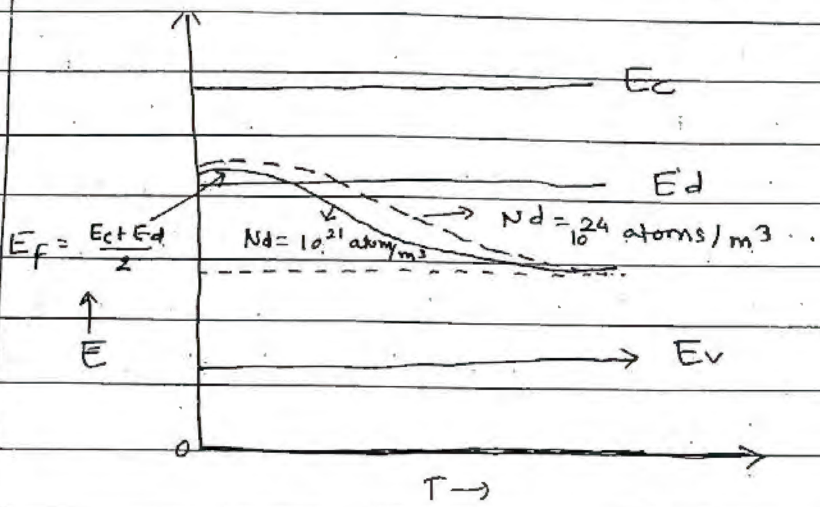
2.7 variation of fermilevel with temperature and impurity concentration in N-type semiconductors.

we know

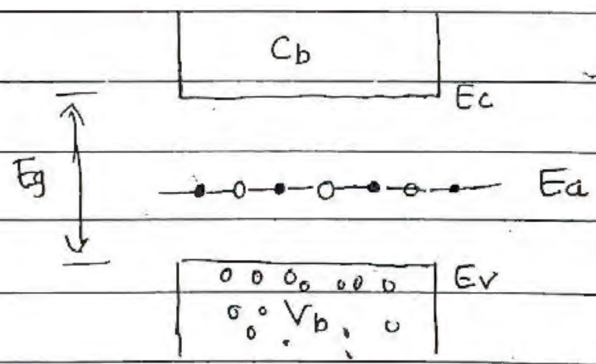
$$E_F = \left(\frac{E_d + E_c}{2}\right) + \frac{k_BT}{2} \ln\left[\frac{N_d}{2\left(\frac{2\pi m_e^* k_BT}{h^2}\right)^{3/2}}\right]$$

- 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 Cb and Fermi level lies between Ec and Ed.

- 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

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

at 0 K Fermi level lies betn E_V 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 from V_b

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.

$$\therefore \quad N_a^- = N_a \cdot f(E_a) \longrightarrow ②$$

we know

$$f(E_a) = \frac{1}{1 + e^{(E_a - E_f)/k_BT}} \longrightarrow ③$$

Fermi level lies between E_a and E_v so $(E_a - E_f)$ is positive and greater than k_BT. so ignoring 1 in denominator

$$\therefore \quad f(E_a) = \frac{1}{e^{(E_a - E_f)/k_BT}}$$

$$\therefore \quad f(E_a) = e^{(E_f - E_a)/k_BT} \longrightarrow ④$$

Substituting eqn ④ into ②

$$N_a^- = N_a \cdot e^{(E_f - E_a)/k_BT} \longrightarrow ⑤$$

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

$$\therefore \quad n_h = N_a^-$$

$$\therefore \quad 2\left(\frac{2\pi m_h^* k_BT}{h^2}\right)^{3/2} \cdot e^{\left(\frac{E_v - E_F}{k_BT}\right)} = N_a \cdot e^{\left(\frac{E_f - E_a}{k_BT}\right)}$$

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 side 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 side with $\frac{k_B T}{2}$

$$\therefore E_F = \frac{E_V + E_a}{2} - \frac{k_B T}{2} \ln\left[\frac{N_a}{2\left(\frac{2\pi m_h^* k_B T}{h^2}\right)^{3/2}}\right] \quad (6)$$

at $T=0$ above eqn reduced to

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

fermi level eqn for p-type semiconductors

* Expression for density of holes in valence band:

from eqn (1)

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

Substituting the value of E_F from above in eqn (6)

$$E_v - E_f = E_v - \frac{E_v - E_a}{2} + \frac{k_BT}{2} \ln\left[\frac{N_a}{2\left(\frac{2\pi m_h^* k_BT}{h^2}\right)^{3/2}}\right]$$

$$E_v - E_f = \frac{E_v - E_a}{2} + \frac{k_BT}{2} \ln\left[\frac{N_a}{2\left(\frac{2\pi m_h k_BT}{h^2}\right)^{3/2}}\right]$$

deviding both side by k_BT

$$\frac{E_v - E_f}{k_BT} = \frac{E_v - E_a}{2k_BT} + \frac{1}{2} \ln\left[\frac{N_a.}{2\left(\frac{2\pi m_h^* k_BT}{h^2}\right)^{3/2}}\right]$$

$$\therefore \frac{E_v - E_f}{k_BT} = \frac{E_v - E_a}{2k_BT} + \log\left[\frac{(N_a)^{1/2}}{\left\{2\left(\frac{2\pi m_h^* k_BT}{h^2}\right)^{3/2}\right\}}\right] \rightarrow ⑧$$

Substituting eqn ⑧ in expression n_h

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

$$\therefore n_h = 2\left(\frac{2\pi m_h^* k_BT}{h^2}\right)^{3/2} \cdot e^{\frac{E_v - E_a}{k_BT}} \frac{N_a^{1/2}}{\left(2\left(\frac{2\pi m_h^* k_BT}{h^2}\right)^{3/2}\right)^{1/2}}$$

on simplifying we get

$$\boxed{n_h = (2N_a)^{1/2} \cdot \left(\frac{2\pi m_h^* k_BT}{h^2}\right)^{3/4} \cdot e^{\frac{E_v - E_a}{k_BT}}} \rightarrow ⑨$$

eqn for density of holes in V_b for P-type semiconductors.

2.9 Variation of E_F with temp and impurities in p-type semiconducters.

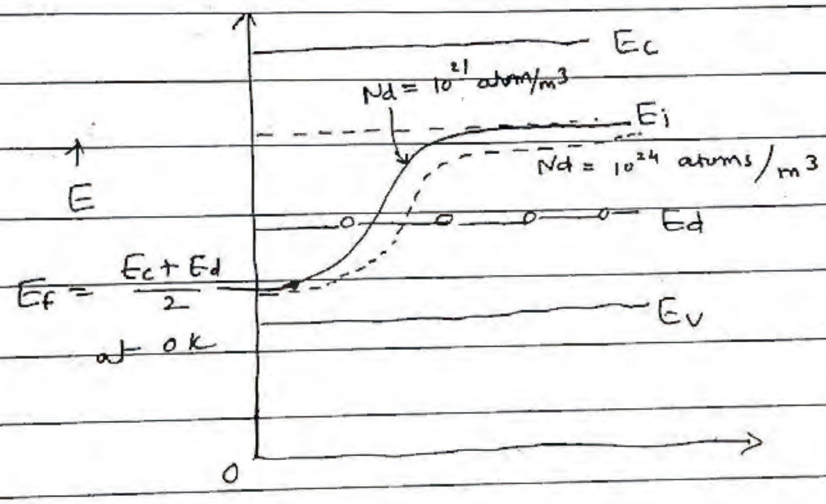
we know that

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

from the
increased
negatively

from the eqn we can say temp gets slowly increased. more and more accepter atom gets negatively ionised due to transfer of ele from V_b and fermi level lies between E_v and E_a.

At a perticular temp. all accepter 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.



$T \rightarrow$

2.10 Electrical conductivity for Extrinsic semiconductors

for pure N-type semiconductor

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

where μ_e = mobility of ele.

n_e = density of ele.

and

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

For a pure p-type semiconductor

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

where μ_h = mobility of holes.

n_h = density of holes

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

(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 state 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.

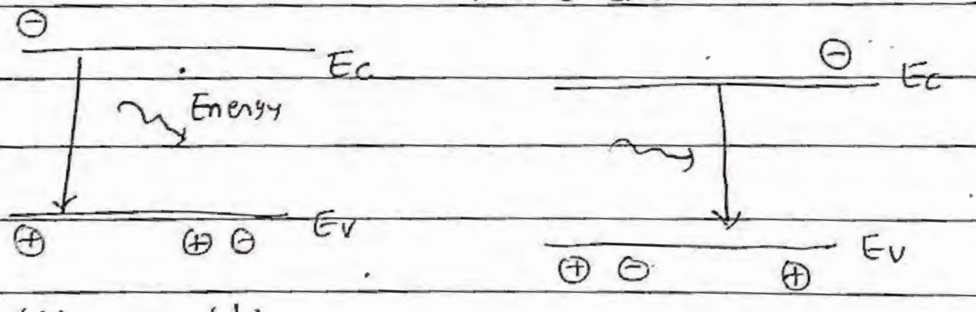
The reverse process (generation) is achived by giving energy to atoms in which ~~ato~~ electron transfer ~~to~~ from V_b to C_b and creating a hole in V_b.

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 conserved.

energy $E = h\nu$ → freq of photon

h → Planks Const.



(a) (b)

(Recombination) (Generation)

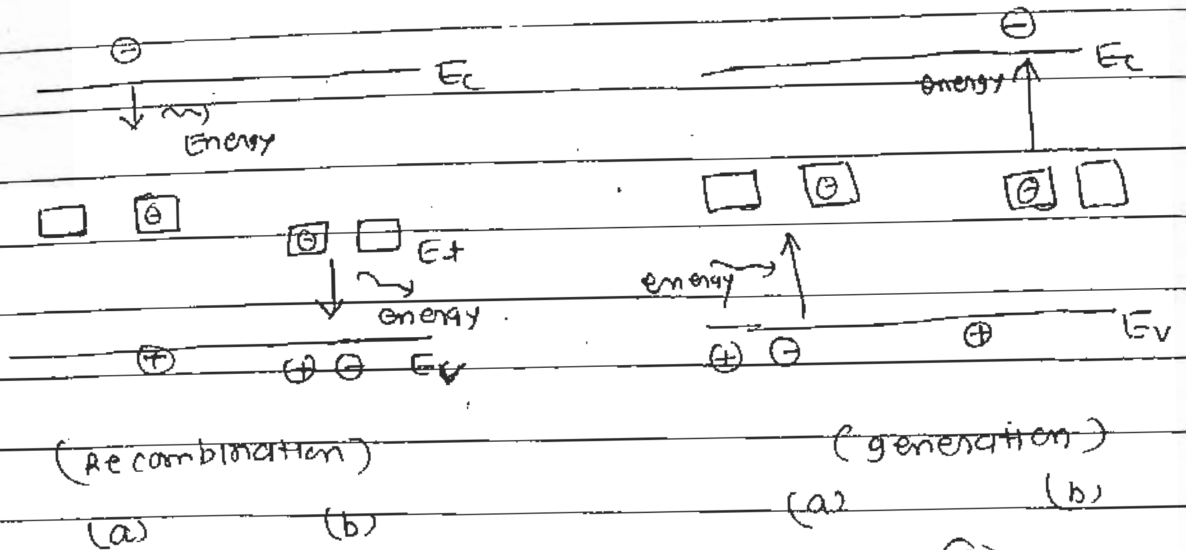
The process of Recombination is directly proportional to available holes and electrons.

(2) Phonon transition :- (SRH)

Also known as indirect or trap assisted recombination.

It is a trap assisted, Passing through a

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



① ②

* Electron capture :- an ele from Cb is captured by an empty trap in band gap. This excess energy is $(E_c - E_t)$ is transferred to crystal lattice. (Phonon emission)
* Hole capture :- The trapped ele. moves to Vb and neutralize a hole (the hole is captured by a trap). A Phonon with energy $(E_t - E_v)$ is generated.
* Hole emission :- An ele from Vb is trapped, leaving a hole in the Vb (hole is omitted from empty trap to Vb) energy required is $(E_t - E_v)$
* Electron emission :- A trapped electron moves from the trap energy level to Cb. The hole and ele emission rates are proportional to concentration of empty traps and filled trapes respectively.

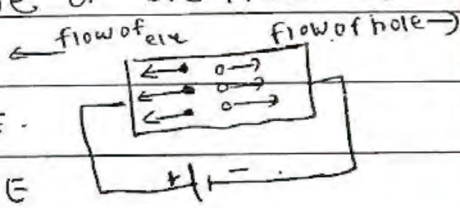
The ele capture and hole capture rate is proportional to concentration in Cb and Vb respectively.

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 semiconducter 2 types of carriers, ele. and hole when voltage is applied to a semiconducter, free ele moves towards +ve terminal of battery and holes moves towards -ve terminal. Generally in semiconducter 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 elecron 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.



drift velocity of ele. $V_e = \mu_e E$.

drift velocity of holes $V_h = \mu_h E$

drift current density of ele. $J_e = n_e \mu_e \cdot E$

drift current density due to hole $J_h = n_e \mu_h E$

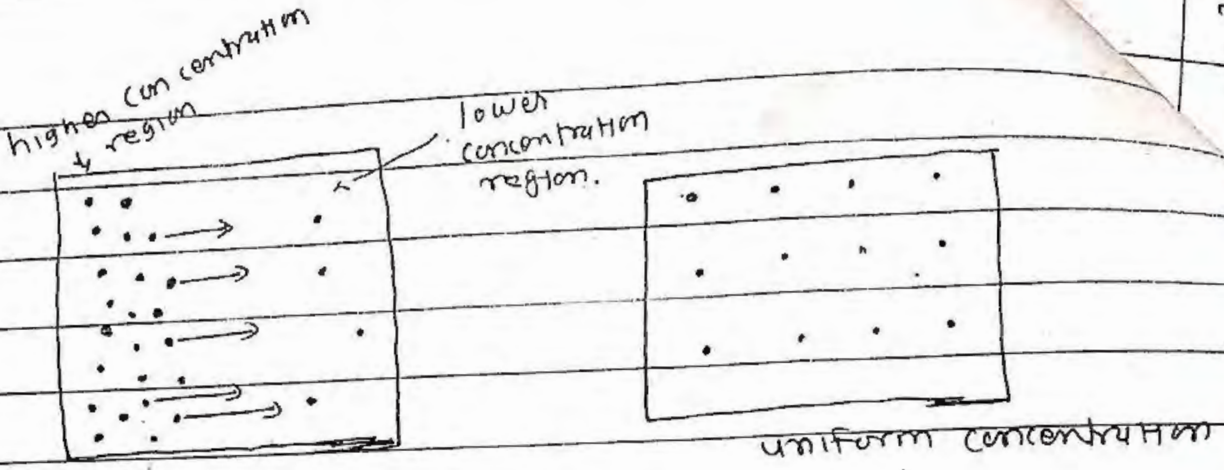
Total drift current density $J = J_e + J_h$

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

$$\boxed{J = n_e E(\mu_e + \mu_h)}$$

* Diffusion current :

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



Non uniform concentration

The Above process occure in semiconducters that are non-uniformly dopes.

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 ~~experiece~~ 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 semiconducters.

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

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

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

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

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

$$\therefore J_e = e n_e \mu_e . E + e D_e \frac{dn_e}{dx}$$

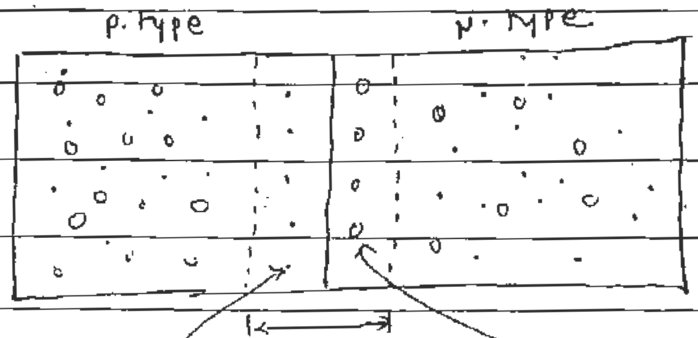
Total current density due to hole = Drift current + Diffusion current

$$\therefore J_h = n_h . e . \mu_h E - e D_h \frac{dn_h}{}$$

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.

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.

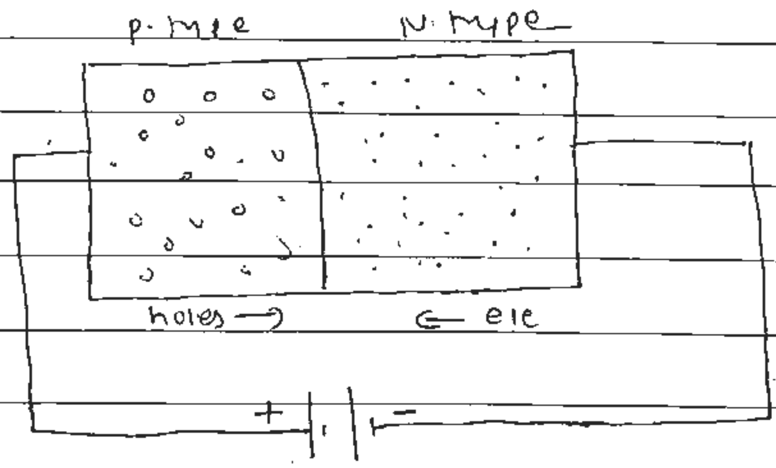
The potential ~~difference~~ difference across the

* **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.



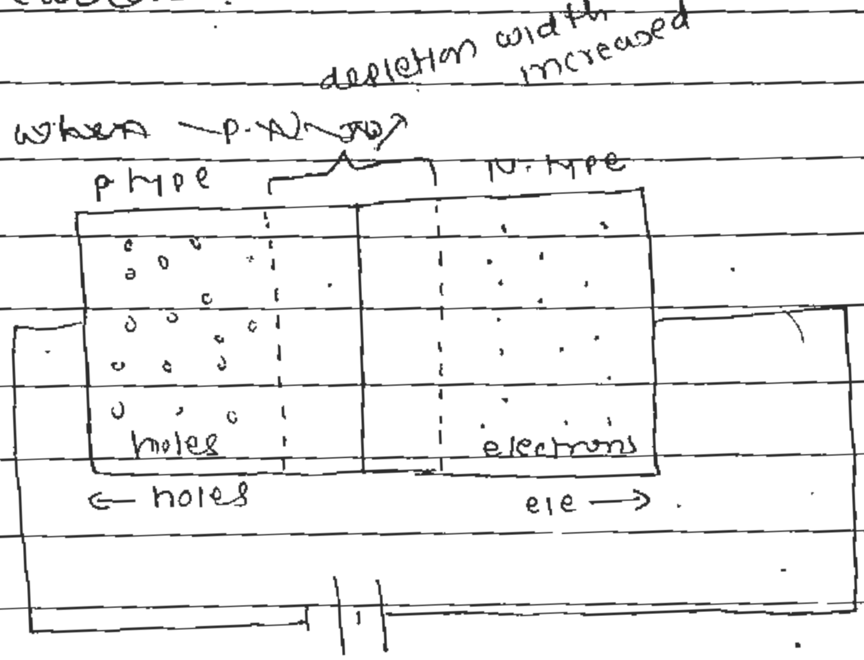
② **Reverse bias :-**

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

The applied reverse voltage creates an ele 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.



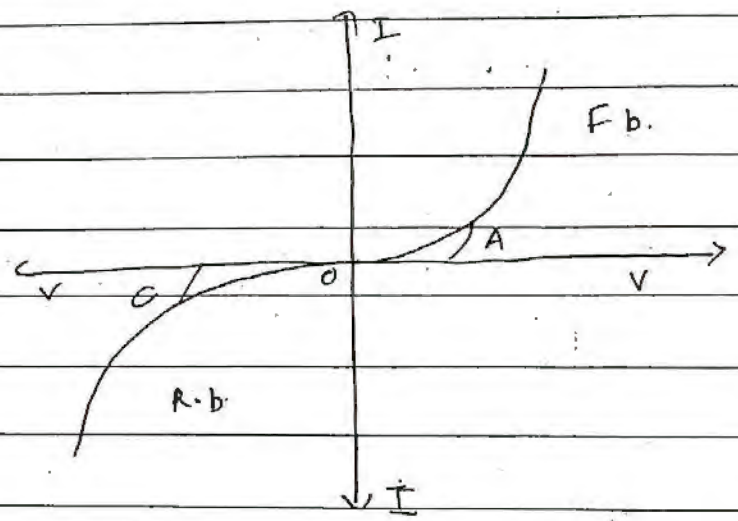
→ when a P-N junction diode is forward biased low resistance path and current flows.

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, clamper 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 thresold voltage (V_{th}) or knee voltage. (0.3 V for Ge 0.7 V for Si)

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

(V_b = barrier potential)

Forward bias resistence

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

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 (μA) for Ge and (nA) for Si.

Resistance of diode

is $R_f = \frac{\Delta V_R}{\Delta I_R}$.

(4) Metal-semiconductor junction (ohmic & schottky) and semiconducting material of interest of optoelectronic devices.

4.1 Metal semiconductor junction (ohmic & schottky)

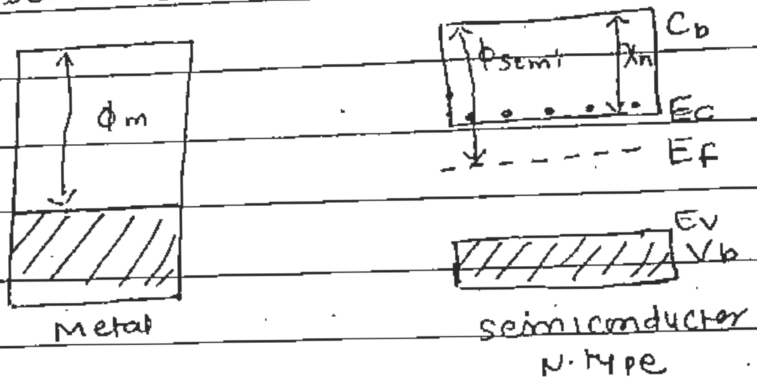
* work function (ϕ) :- It's the minimum energy required to transfer an ele. from a point within a solid to a point outside its surface.
* Electron affinity (χ_n) :- It is defined as the energy released or spent when ele is added to a neutral atom or molecules.

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

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

$\phi_m < \phi_{semi}$ → 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 semiconducter.

The fermi level lines up and a +ve potential is created on semiconducter 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.

$$\phi_m - \phi_{semi} = eV_0$$

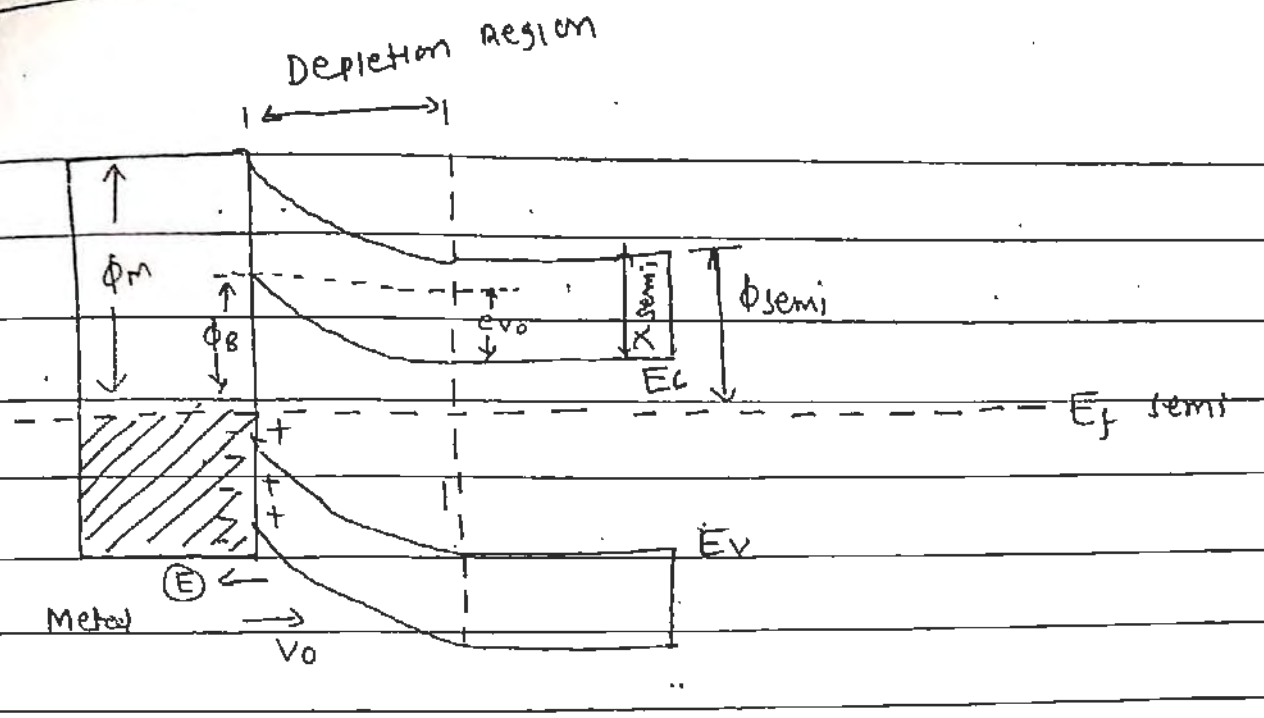
This contact potential work as barrier for electrons to move from semiconducter to metal.

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

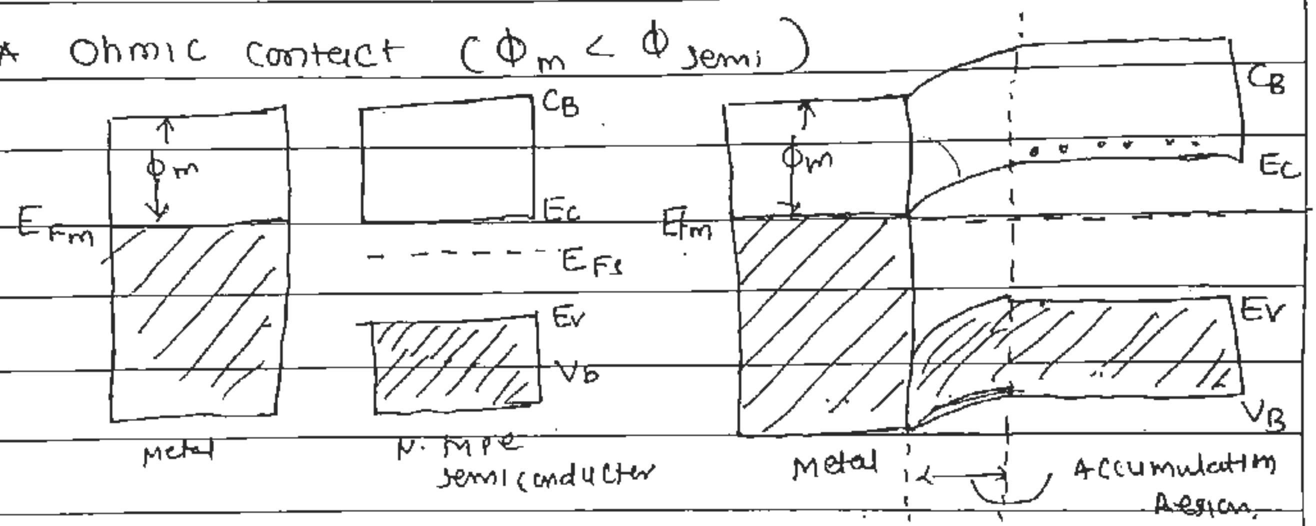
$$\phi_B = (\phi_m - \phi_{conti}) + (E_c - E_{fn})$$

$$\phi_B = (\phi_m - \chi_n) \quad (\chi_n \text{ is ele affinity of}$$



Applications: Rectifiers, voltage clampers, RF mixer, detector, Rectifying high freq. signals.

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



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

At equilibrium the fermi levels line up. The ele 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 resister.

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 creat 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) Photoluminsecence :

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

sub process $\left\{ \begin{array}{l} \text{Phosphorescence} \\ \text{fluorescence.} \end{array} \right\}$ used in fluorescent lamp

(2.2) cathodoluminescence:

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

Examples: 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 devided into two categories.

optoelectronic devices

- convert ele. current into EM Radiation (light)
  Ex. LED
- Convert light into electric current
  Ex. photodiode.

* * * * *.