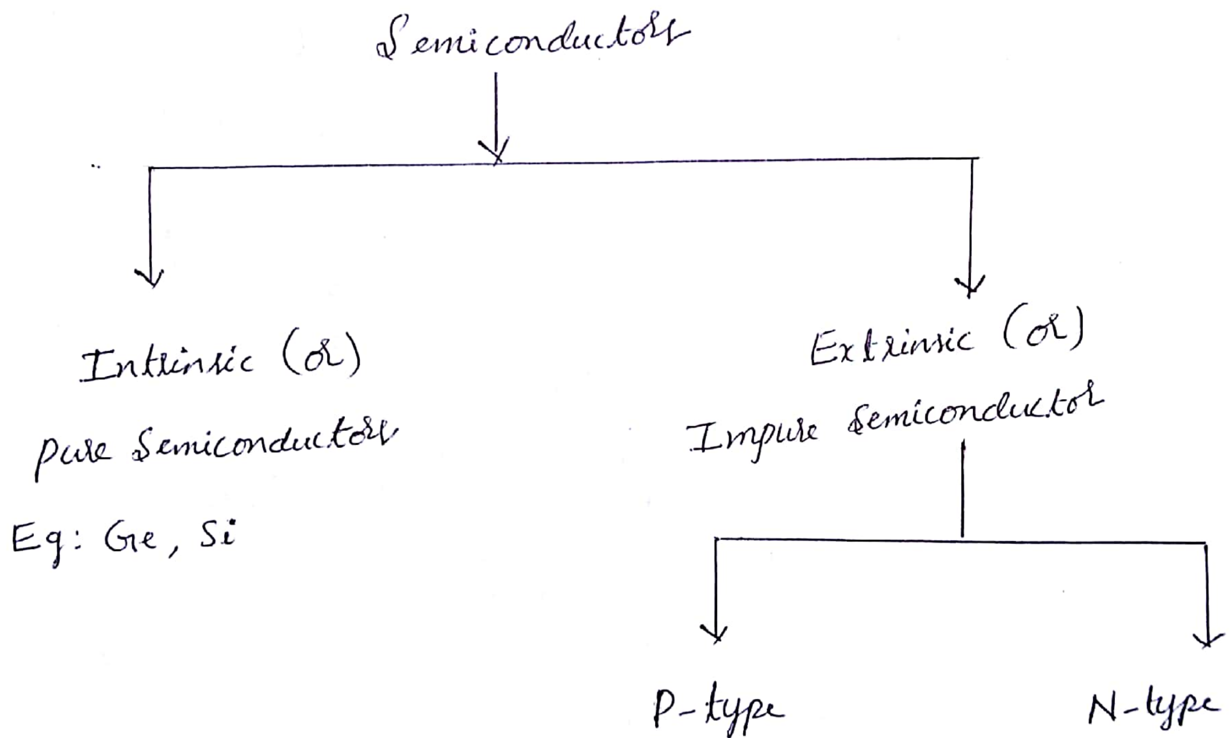
UNIT - II

SEMICONDUCTOR PHYSICS

Introduction :-

A substance which has resistivity in between conductors and insulators is known as "semiconductor".

Semiconductors may be classified as :



Semiconductors have the following properties :-

(i). They have resistivity less than insulators and more than conductors.

(ii). The resistance of semiconductor decreases with the

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increase in temperature and vice versa.

i.e., they have negative temperature coefficient of resistance.

Eg:- Ge is an insulator at low temperatures while it becomes a good conductor at high temperatures.

(iii). When suitable impurity like arsenic, boron etc., is added to a semiconductor, its conductivity increases appreciably.

§ Intrinsic Semiconductors :-

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A Semiconductor in the purest, uncontaminated with any other material is called an "Intrinsic Semiconductor".

Eg:- Germanium $(Z=32)$ $1s^2, 2s^2 2p^6, 3s^2 3p^6 3d^{10}, \underline{4s^2 4p^2}$;

& Silicon $(Z=14)$ $1s^2, 2s^2 2p^6, \underline{3s^2 3p^2}$;

Covalent Bonding :-

'Ge' has 32 electrons and 'Si' has 14 electrons in their atomic structures. Since each of them have 4 valence electrons in their outermost shell hence they are tetravalent atoms (i.e., their valency is 4).

The neighbouring atoms form covalent bonds by sharing 4 electrons with each other.

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This covalent bond is shown in fig (a).

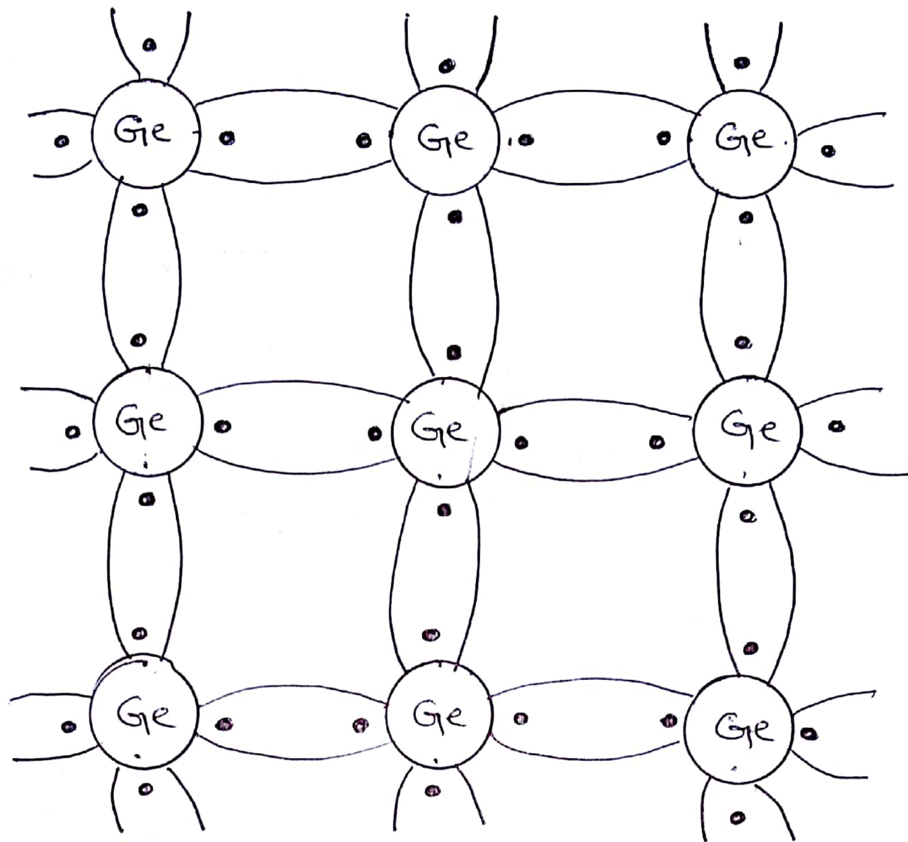

Fig (a): Germanium crystal structure, showing covalent bond

Since all the bonds are intact strongly and hence (no free electrons for conductivity) the crystal acts as a perfect insulator at 0K.

In order to provide electrical conduction, covalent bonds are to be broken. The energy required to break such a covalent bond is about 0.72 eV for Ge and 1.1 eV for Silicon.

At room temp. the thermal energy is sufficient to break covalent bonds. Hence, semiconductors will conduct

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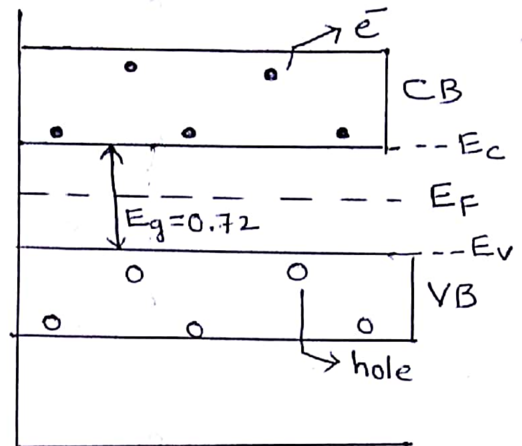
electric current even at room temperatures. When a covalent bond is broken the electron becomes free and it escapes from VB to conduction band. As a result a vacancy is formed in the VB. This vacancy is called a "hole".

At any temp (other than 0K) in an intrinsic semiconductor, the no. of free $\bar{e}$'s in the CB will be always equal to the no. of holes in the VB. This is shown in fig(b) for Ge.



Fig(b): Ge crystal at room temperature

Thus, in a pure semiconductor both holes and electrons are charge carriers.

In an intrinsic semiconductor the Fermi energy level (E_F) lies midway in the forbidden gap (E_g).

Carrier Concentration in Intrinsic Semiconductor :—

We know that an intrinsic semiconductors the charge carriers are nothing but electrons in the CB and holes in the VB.

Since, these carriers are generated due to the

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breaking of covalent bonds, we have equal no. of electrons and holes. At 0K temp, since all the bonds are strongly intact, the semiconductor acts as an insulator (as there is no free $\bar{e}$).

With increase of thermal energy the covalent bonds are broken and electron-hole pairs are created.

Now, we have to calculate the carrier concentration,

i.e., No. of $\bar{e}$'s in the CB per unit volume (n) of the material (i.e., density of electrons) as well as

No. of holes in the VB per unit volume (p) of the material (i.e., density of holes).

Calculation of density of electrons (n):-

Let dn be the no. of electrons available between energy level E and $E+dE$ in the CB.

$$dn = Z(E).F(E).dE \longrightarrow (1)$$

where, $Z(E)dE \rightarrow$ is the density of states in the energy interval E & $E+dE$ (i.e., the no. of energy states per unit volume)

& $F(E) \rightarrow$ is the electron occupancy probability (i.e., probability of an $\bar{e}$, occupying an energy state E)

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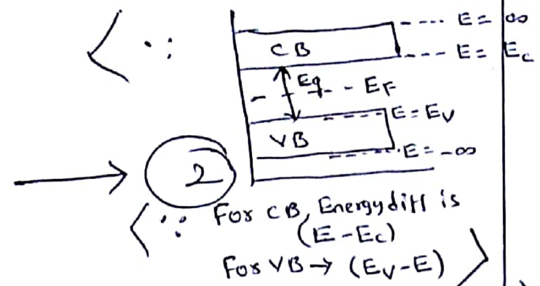
Integrating eq^n ① we get the total no. of $\bar{e}$'s in the CB,



$\because$ For CB, Energy diff is $(E-E_c)$
For VB → $(E_v - E)$
$(E_g = E_c - E_v)$

i.e,
$$n = \int_{E_c}^{\infty} Z(E).F(E).dE \rightarrow ②$$

where, $E_c \rightarrow$ is the energy corresponding to the bottom of the CB.

The density of states $Z(E)dE$ is given by,

$$Z(E)\,dE = \frac{4\pi}{h^3}(2m)^{3/2} . E^{1/2} . dE \rightarrow ③$$

Since, the $\bar{e}$ is moving in a periodic potential, its mass has to be replaced by its effective mass m_e^*.

Hence, eq^n ③ becomes,

$$Z(E)dE = \frac{4\pi}{h^3}(2m_e^*)^{3/2} . E^{1/2} . dE \rightarrow ④$$

Since, the energy E starts at the bottom of the CB' E_c,

$$\therefore Z(E)dE = \frac{4\pi}{h^3}(2m_e^*)^{3/2} . (E-E_c)^{1/2} . dE \rightarrow ⑤$$

Electron occupancy probability $F(E)$ is given by,

$$F(E) = \frac{1}{1+e^{\left(\frac{E-E_F}{KT}\right)}} \rightarrow ⑥$$

where, $E_F \rightarrow$ is the energy of the Fermi level, which is

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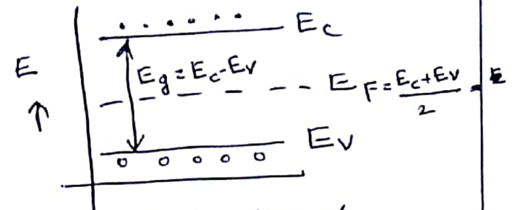
exactly at the centre of the forbidden energy gap in the case of intrinsic semiconductor.

i.e., $E_F = \frac{E_c + E_v}{2}$ → (7)



where, E_v → is the energy corresponding to the top of the VB

& E_c → is the energy corresponding to the bottom of the CB

Eq^n (6) can also be expressed as,

$$F(E) = \left[1 + e^{E-E_F/kT}\right]^{-1} \rightarrow (8)$$

On solving eq^n (8), for all possible temperatures $E - E_F \gg kT$, we get

$$F(E) = e^{-\left(\frac{E-E_F}{kT}\right)} \quad \text{(or)}$$

$$\therefore \boxed{F(E) = e^{\left(\frac{E_F-E}{kT}\right)}} \rightarrow (9)$$

Now, substituting eq^n's (5) & (9) in eq^n (2), we get

$$n = \int_{E_c}^{\infty} e^{\left(\frac{E_F-E}{kT}\right)} \cdot \frac{4\pi}{h^3}(2m_e^*)^{3/2} \cdot (E-E_c)^{1/2} \cdot dE \quad \text{(or)}$$

$$= \frac{4\pi}{h^3}(2m_e^*)^{3/2} \int_{E_c}^{\infty} (E-E_c)^{1/2} \cdot e^{\frac{E_F-E}{kT}} \cdot dE \quad \text{(or)}$$

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$$\therefore n = \frac{4\pi}{h^3}(2m_e^*)^{3/2} \cdot e^{\frac{E_F}{kT}} \int_{E=E_c}^{\infty=E} (E-E_c)^{1/2} \cdot e^{-E/kT} \cdot dE \rightarrow (10)$$

To solve this integral, let us put

$$E - E_c = x$$

$$\therefore E = E_c + x \longrightarrow 10(a)$$

$$dE = 0 + dx = dx$$

⟨∵ Upper limit: $E = \infty \Rightarrow x + E_c = \infty$ (∵ 10(a))
$\Rightarrow x = \infty - E_c$
$\therefore x = \infty$

Lower limit: $E = E_c \Rightarrow E_c + x = E_c$
$\Rightarrow x = 0$ ⟩

$$\therefore n = \frac{4\pi}{h^3}(2m_e^*)^{3/2} \cdot e^{E_F/kT} \int_{x=0}^{\infty} x^{1/2} \cdot e^{-(E_c+x)/kT} \cdot dx \quad (\text{or})$$

$$\therefore n = \frac{4\pi}{h^3}(2m_e^*)^{3/2} \cdot e^{\frac{E_F-E_c}{kT}} \cdot \int_0^{\infty} x^{1/2} \cdot e^{-x/kT} \cdot dx \longrightarrow (11)$$

But, using gamma function it can be shown that

$$\int_0^{\infty} x^{1/2} \cdot e^{\frac{-x}{kT}} \cdot dx = (kT)^{3/2} \cdot \frac{\pi^{1/2}}{2} \longrightarrow (12)$$

Hence,

$$n = \frac{\overset{2}{\cancel{4}}\pi}{h^3}(2m_e^*)^{3/2} \cdot e^{\frac{E_F-E_c}{kT}} \cdot (kT)^{3/2} \cdot \frac{\pi^{1/2}}{\cancel{2}}$$

$$n = \frac{2\pi^{3/2}}{(h^2)^{3/2}} \cdot (2m_e^*)^{3/2} \cdot (kT)^{3/2} \cdot \exp\left[\frac{E_F - E_c}{kT}\right] \quad (\text{or})$$

$$** \therefore \boxed{n = 2\left(\frac{2\pi m_e^* kT}{h^2}\right)^{3/2} \cdot \exp\left[\frac{E_F - E_c}{kT}\right]} \longrightarrow (13)$$

The above eqn represents the no. of electrons per unit volume in the CB.

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Calculation of density of holes (p):-

Let dp be the number of holes available between energy level E and E+dE in the VB,

$$dp = Z(E)\,[1-F(E)]\,dE \rightarrow (14)$$

where, $Z(E)\,dE \rightarrow$ is the density of states in the energy interval E & E+dE (i.e., the no. of energy states per unit volume)

& $1-F(E) \rightarrow$ is the probability of existence of a hole (i.e., probability of an $\bar{e}$ not occupying the state)

Integrating eqn (14) we get the total no. of holes in the VB,

i.e.,

$$p = \int_{E=-\infty}^{E_V} Z(E) \cdot [1-F(E)] \cdot dE \rightarrow (15)$$

(see page No. 6)

where, $E_V \rightarrow$ is the energy of the top of the VB.

The density of states $Z(E)dE$ is given by,

$$Z(E)\,dE = \frac{4\pi}{h^3}\,(2m_h^*)^{3/2}\,E^{1/2} \cdot dE \rightarrow (16)$$

Since E_V is the energy of the top of the VB,

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$$\therefore \boxed{Z(E)\,dE = \frac{4\pi}{h^3}(2m_h^*)^{3/2}\cdot(E_v - E)^{1/2}\cdot dE} \longrightarrow (17)$$

Now, the probability of existance of a hole $1-F(E)$ is given by,

$$1-F(E) = 1 - \left[\frac{1}{1+e^{E-E_F/kT}}\right] \longrightarrow (18)$$

On solving eq^n (18), for all possible temperatures $E - E_F >> kT$, we get

$$\therefore \boxed{1-F(E) = e^{\left(\frac{E-E_F}{kT}\right)}} \longrightarrow (19)$$

Now, substituting eq^n's (17) & (19) in eq^n (15), we get

$$p = \int_{-\infty}^{E_v} e^{\left(\frac{E-E_F}{kT}\right)} \cdot \frac{4\pi}{h^3}(2m_h^*)^{3/2}\cdot(E_v-E)^{1/2}\cdot dE \quad \text{(or)}$$

$$p = \frac{4\pi}{h^3}(2m_h^*)^{3/2}\cdot e^{\left(-\frac{E_F}{kT}\right)} \int_{-\infty}^{E_v} (E_v-E)^{1/2}\cdot e^{\left(\frac{E}{kT}\right)}\cdot dE \longrightarrow (20)$$

To solve this, let us take

$E_v - E = x$ (or)

$E = E_v - x$

$\therefore dE = -dx \longrightarrow (21)$

$\because$ upperlimit:- $E = E_v \Rightarrow E_v - x = E_v$
$\Rightarrow E_v - E_v = x$
$\Rightarrow x = 0$

Lowerlimit:- $E = -\infty \Rightarrow E_v - x = -\infty$
$\Rightarrow E_v + \infty = x$
$\Rightarrow x = \infty$

$$\therefore p = \frac{4\pi}{h^3}(2m_h^*)^{3/2}\cdot e^{\left(-\frac{E_F}{kT}\right)}\cdot \int_{x=\infty}^{x=0} x^{1/2}\cdot e^{\frac{E_v-x}{kT}}\cdot(-dx)$$

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$$p = \frac{4\pi}{h^3}(2m_h^*)^{3/2} \cdot e^{\frac{-E_F}{kT}} \cdot e^{\frac{E_V}{kT}} \cdot \int_0^\infty x^{1/2} \cdot e^{-x/kT} \cdot dx \quad (or)$$

$$\therefore p = \frac{4\pi}{h^3}(2m_h^*)^{3/2} \cdot e^{\frac{E_V-E_F}{kT}} \cdot \left\{ (kT)^{3/2} \cdot \frac{\pi^{1/2}}{2} \right\} \quad (\because \text{Using gamma fun})$$

$$p = \frac{\overset{2}{\cancel{4}}\pi}{h^3} \cdot (2m_h^*)^{3/2} \cdot e^{\frac{E_V-E_F}{kT}} \cdot (kT)^{3/2} \cdot \frac{\pi^{1/2}}{\cancel{2}}$$

$$= \frac{2\pi^{3/2}}{(h^2)^{3/2}} \cdot (2m_h^*)^{3/2} \cdot (kT)^{3/2} \exp\left[\frac{E_V-E_F}{kT}\right]$$

$$** \therefore \boxed{p = 2\left(\frac{2\pi m_h^* kT}{h^2}\right)^{3/2} \cdot \exp\left(\frac{E_V-E_F}{kT}\right)} \longrightarrow (22)$$

The above eq^n represents, the no. of holes per unit volume in the VB.

Intrinsic Carrier concentration :-

In intrinsic semiconductors, we have

$$n = p$$

Hence, $n = p = n_i$ is called intrinsic carrier concentration

Therefore,

$$n_i^2 = np = \left\{2\left(\frac{2\pi m_e^* kT}{h^2}\right)^{3/2} \cdot \exp\left(\frac{E_F-E_c}{kT}\right)\right\}\left\{2\left(\frac{2\pi m_h^* kT}{h^2}\right)^{3/2} \cdot \exp\left(\frac{E_V-E_F}{kT}\right)\right\}$$

$$= 4\left(\frac{2\pi kT}{h^2}\right)^3 \cdot (m_e^* m_h^*)^{3/2} \cdot \exp\left(\frac{\cancel{E_F}-E_c+E_V-\cancel{E_F}}{kT}\right)$$

$$= 4\left(\frac{2\pi kT}{h^2}\right)^3 \cdot (m_e^* m_h^*)^{3/2} \cdot \exp\left(\frac{E_V-E_c}{kT}\right) \quad (or)$$

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$$n_i^2 = 4\left(\frac{2\pi kT}{h^2}\right)^3 \cdot (m_e^* m_h^*)^{3/2} \cdot e^{-E_g/kT} \longrightarrow (23)$$

where, $E_g = E_c - E_v$ is the forbidden energy gap.

Hence,

$$n_i = \left\{4\left(\frac{2\pi kT}{h^2}\right)^3 \cdot (m_e^* \cdot m_h^*)^{3/2} \cdot e^{-E_g/kT}\right\}^{1/2} \quad \text{(or)}$$

** $\therefore$

$$\boxed{n_i = 2\left(\frac{2\pi kT}{h^2}\right)^{3/2} \cdot (m_e^* \cdot m_h^*)^{3/4} \cdot \exp\left(\frac{-E_g}{2kT}\right)} \longrightarrow (24)$$

Fermi level in Intrinsic Semiconductors :-

Since $n = p$

in intrinsic semiconductors,

$$\cancel{2}\left(\frac{2\pi m_e^* kT}{h^2}\right)^{3/2} \cdot \exp\left(\frac{E_F - E_c}{kT}\right) = \cancel{2}\left(\frac{2\pi m_h^* kT}{h^2}\right)^{3/2} \cdot \exp\left(\frac{E_v - E_F}{kT}\right) \quad \text{(or)}$$

$$\cancel{\left(\frac{2\pi kT}{h^2}\right)^{3/2}} \cdot (m_e^*)^{3/2} \cdot \exp\left(\frac{E_F - E_c}{kT}\right) = \cancel{\left(\frac{2\pi kT}{h^2}\right)^{3/2}} \cdot (m_h^*)^{3/2} \cdot \exp\left(\frac{E_v - E_F}{kT}\right) \quad \text{(or)}$$

$$(m_e^*)^{3/2} \cdot \exp\left(\frac{E_F - E_c}{kT}\right) = (m_h^*)^{3/2} \cdot \exp\left(\frac{E_v - E_F}{kT}\right) \quad \text{(or)}$$

$$e^{\frac{E_F}{kT}} \cdot e^{-\frac{E_c}{kT}} = \left(\frac{m_h^*}{m_e^*}\right)^{3/2} \cdot e^{\frac{E_v}{kT}} \cdot e^{-E_F/kT} \quad \text{(or)}$$

$$e^{\frac{2E_F}{kT}} = \left(\frac{m_h^*}{m_e^*}\right)^{3/2} \cdot \exp\left(\frac{E_v + E_c}{kT}\right) \longrightarrow (25)$$

Taking logarithms on both sides, we get

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$$\log_e e^{\frac{2E_F}{kT}} = \log_e \left(\frac{m_h^*}{m_e^*}\right)^{3/2} \cdot \exp\left(\frac{E_V+E_C}{kT}\right) \quad \text{(or)}$$

$$\frac{2E_F}{kT} = \frac{3}{2}\log_e\left(\frac{m_h^*}{m_e^*}\right) + \log_e e^{\left(\frac{E_V+E_C}{kT}\right)} \quad \text{(or)} \quad (\because \log_e AB = \log_e A + \log_e B)$$

$$(\because \log_e e^x = x)$$

$$\frac{2E_F}{kT} = \frac{3}{2}\log_e \frac{m_h^*}{m_e^*} + \left(\frac{E_V+E_C}{kT}\right) \quad \text{(or)}$$

$$E_F = \frac{kT}{2}\cdot\frac{3}{2}\cdot\log_e\left(\frac{m_h^*}{m_e^*}\right) + \left(\frac{E_V+E_C}{kT}\right)\frac{kT}{2}$$

$$\therefore E_F = \frac{3kT}{4}\log_e\left(\frac{m_h^*}{m_e^*}\right) + \left(\frac{E_V+E_C}{\cancel{kT}}\right)\frac{\cancel{kT}}{2} \longrightarrow (26)$$

If we assume that $m_e^* = m_h^*$, then

$$\log_e \frac{m_h^*}{m_e^*} = \log_e 1 = 0$$

$$\therefore E_F = 0 + \frac{E_V+E_C}{2}$$

$$\boxed{E_F = \frac{E_V+E_C}{2}} \longrightarrow (27)$$

Thus, Fermi level is located half way between the VB and CB. Since m_h^* is greater than m_e^*, E_F is just above the middle, and rises slightly with increasing temp.

Position of fermilevel in an intrinsic semiconductor at various temperatures is shown in fig(1).

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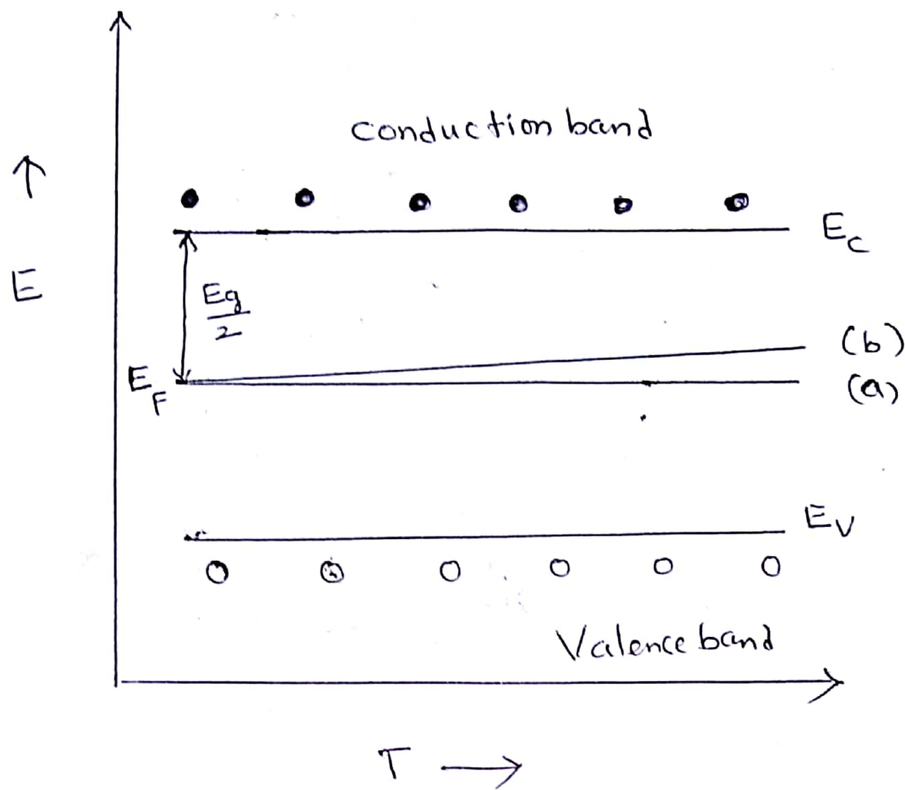

Fig (1)(a):- at T = 0K the Fermilevel is in the middle of the forbidden band

(b). as temp. rises it shifts upward since $m_h^* > m_e^*$

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§ EXTRINSIC SEMICONDUCTORS :-

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We already knew that at absolute zero (0K) an intrinsic semiconductor behaves like a perfect insulator. But, as temp is increased, $\bar{e}$-hole pairs are generated & the conductivity increases with increase of temp.

But, at room temp, the conductivity of an intrinsic semiconductor is very low. To increase the electrical conductivity, certain specified types of impurities are added to the pure semiconductor during the crystallization process.

The process of adding impurities to a pure semiconductor material is called "doping". A doped semiconductor is called an " Extrinsic Semiconductor".

Extrinsic Semiconductors are of two types :-

(i). N- type Semiconductors &

(ii). P- type Semiconductors.

①. N-Type Semiconductor :-

When a small quantity of a pentavalent material (such as Phosphorous, Arsenic, Antimony, Bismuth having a valency of 5) is added as an impurity to a pure semiconductor

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during the process of crystallization, the resulting extrinsic semiconductor formed is "N-type extrinsic semiconductor".

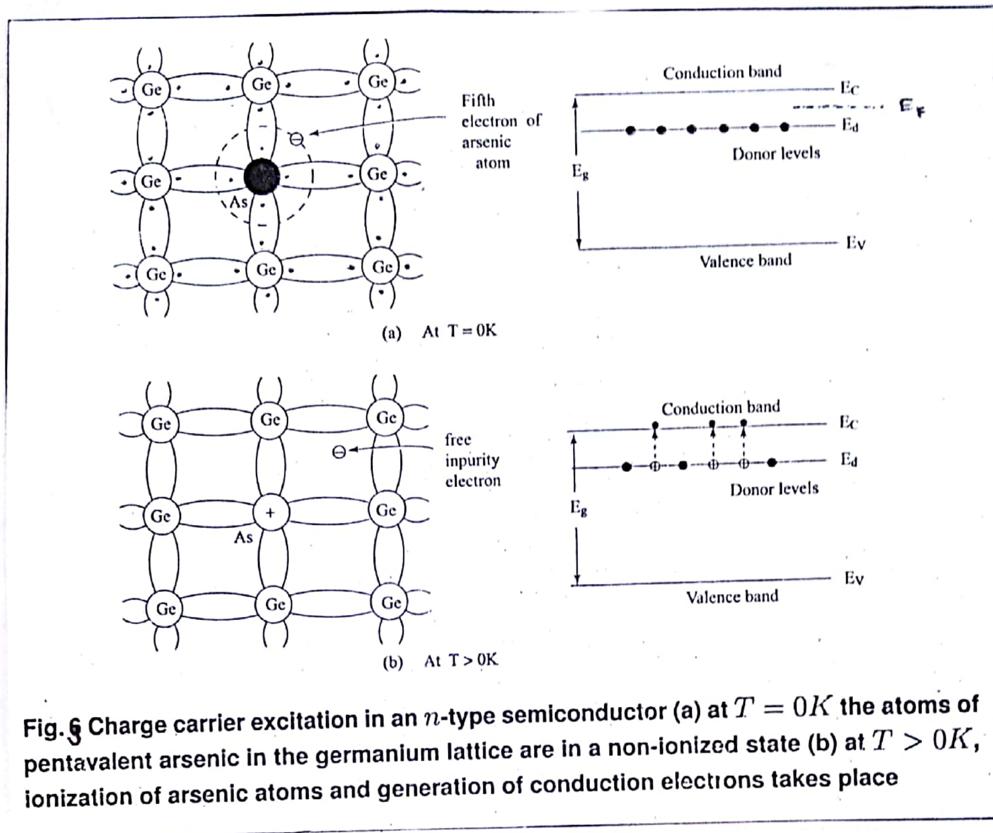

Fig. 5 Charge carrier excitation in an n-type semiconductor (a) at $T = 0K$ the atoms of pentavalent arsenic in the germanium lattice are in a non-ionized state (b) at $T > 0K$, ionization of arsenic atoms and generation of conduction electrons takes place

Fig (1)

Pentavalent elements such as phosphorous (P), Arsenic (As), Antimony (Sb) or Bismuth (Bi) have 5 electrons in their outermost orbits.

When any one (say As) such impurity is added to the intrinsic semiconductor (say Ge) during the crystallization process, four electrons are engaged in covalent bonding with 4 neighbouring pure Ge atoms. The 5th e^- is weakly bound to the parent (As) atom.

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Even for lesser thermal energy this 5th $\bar{e}$ is released leaving the parent atom positively ionised (As^+). During this process no hole is generated.

Since, these pentavalent elements donate negative charges ($\bar{e}$'s), they are called " Donor impurities " and the semiconductor doped with pentavalent impurities are called " N-type semiconductor ".

In the energy level diagram the energy level of the fifth electron is called " Donar level (E_d) ". The donor level is so close to the bottom of the CB as shown in fig (1).

Most of the donor level electrons are excited into the CB at room temp and become the majority charge carrier. If the thermal energy is sufficiently high, in addition to the As^+ atoms, breaking of covalent bonds may also occur (at VB) there by giving rise to generation of electron - hole pairs.

Hence, in N-type semiconductors electrons are majority carriers and holes are minority carriers.

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(2). P-Type Semiconductor :-

When a small quantity of a trivalent material (such as Boron, Aluminium, Gallium, Indium, thallium having a valency of 3) is added as an impurity to a pure semiconductor during the process of crystallization, the resulting extrinsic semiconductor formed is "P-type semiconductor".

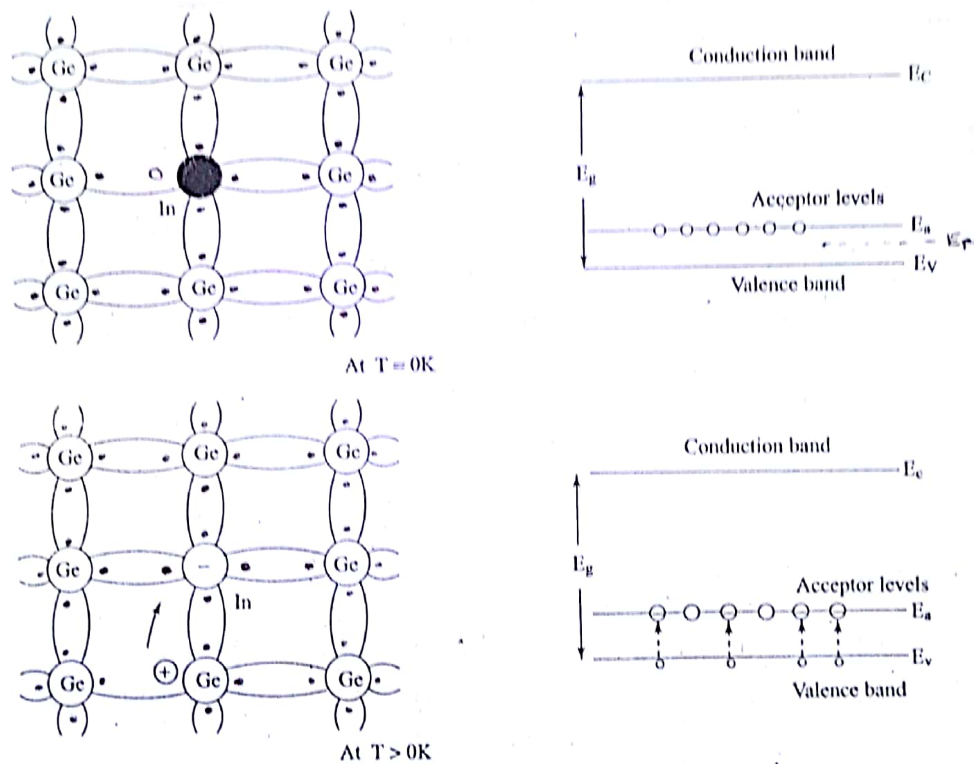

Fig. 2 Charge carrier excitation in a p-type semiconductor. a) Atoms of trivalent indium in the germanium lattice at $T = 0K$ (the fourth band of the indium atom is unpaired) b) At $T > 0K$, the electrons can go over to unpaired bonds of impurity atoms creating an indium ion and a vacant level (hole) in the valence band of germanium

Trivalent elements such as Boron (B), Aluminium (Al), Gallium (Ga), Indium (In) or Thallium (Tl) have 3 ē's in their outermost orbits.

When any one such impurity (say In) is added

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to the pure semiconductor (say Ge) during the crystallization process, all the 3 $\bar{e}$'s of In are engaged in covalent bonding with 3 neighbouring Ge atoms. In needs one more $\bar{e}$ to complete its bond. This $\bar{e}$ may be supplied by neighbouring Ge, there by creating a hole on the semiconductor atom.

Since, In accepts one extra $\bar{e}$, the energy level of this impurity atom is called "Acceptor level". This acceptor level lies just above the VB as shown in fig(2). These type of impurities are called "Acceptor impurities" and the semiconductors doped with acceptor impurities are called "p-type semiconductors".

Even at relatively low temperatures, these acceptor atoms get ionized taking $\bar{e}$'s from VB and thus giving rise to holes in VB for conduction.

If the temp. is sufficiently high, in addition to this process, electron-hole pairs are generated due to breaking of covalent bonds.

Thus, holes are more in number than electrons & hence holes are majority carriers and electrons are minority carriers in p-type semiconductors.

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Carrier concentration in N-type semiconductors :-

We have the density of electrons in conduction band is given by eq^n (13),

$$n = 2\left(\frac{2\pi m_e^* kT}{h^2}\right)^{3/2} \cdot \exp\left[\frac{E_F - E_c}{kT}\right] \longrightarrow (28)$$

Let N_d be the donor concentration i.e., the no. of donor atoms per unit volume of the material and E_d is the donor energy level, then the density of ionised donors is given by,

$$N_d\left[1 - F(E_d)\right] \approx N_d \exp\left[\frac{E_d - E_F}{kT}\right] \longrightarrow (29)$$

At very low temperatures, when electron-hole pairs are not generated due to breaking of covalent bonds, the no. of $\bar{e}$'s in the CB must be equal to the no. of ionised donors (As^+) (i.e., +ve immobile ions)

i.e.,
$$n = N_d \exp\left(\frac{E_d - E_F}{kT}\right) \text{ (or)}$$

$$2\left(\frac{2\pi m_e^* kT}{h^2}\right)^{3/2} \cdot \exp\left(\frac{E_F - E_c}{kT}\right) = N_d \exp\left(\frac{E_d - E_F}{kT}\right)$$

Taking logarithm and rearranging, we get

$$\ln\left\{2\left(\frac{2\pi m_e^* kT}{h^2}\right)^{3/2}\right\} + \ln \exp\left(\frac{E_F - E_c}{kT}\right) = \ln N_d + \ln \exp\left(\frac{E_d - E_F}{kT}\right) \text{ (or)}$$

$\langle \because \log A \cdot B = \log A + \log B \rangle$

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

$\langle \because \log_e e^x = x \rangle$

$$\left(\frac{E_F - E_c}{kT}\right) - \left(\frac{E_d - E_F}{kT}\right) = \ln N_d - \ln 2\left(\frac{2\pi m_e^* kT}{h^2}\right)^{3/2} \quad \text{(or)}$$

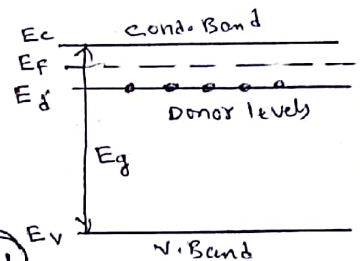
$$\frac{1}{kT}\left[E_F - E_c - E_d + E_F\right] = \ln \frac{N_d}{2\left(\frac{2\pi m_e^* kT}{h^2}\right)^{3/2}}$$

$\langle \because \log A - \log B = \log \frac{A}{B} \rangle$

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

$$2E_F = (E_c + E_d) + kT \ln \frac{N_d}{2\left(\frac{2\pi m_e^* kT}{h^2}\right)^{3/2}} \quad \text{(or)}$$

$$\therefore \boxed{E_F = \frac{(E_c + E_d)}{2} + \frac{kT}{2} \ln \frac{N_d}{2\left(\frac{2\pi m_e^* kT}{h^2}\right)^{3/2}}} \longrightarrow (30)$$



At 0K, (i.e., T=0K)

$$\therefore \boxed{E_F = \frac{E_c + E_d}{2}} \longrightarrow (31)$$

i.e., At 0K, Fermi level lies exactly at the middle of the donor level E_d and the bottom of the conduction band E_c as shown in fig (3)(a).

Density of electrons in the Conduction band :- (n)

From eq^n (28) density of electrons in the CB (for intrinsic semiconductor) is given by

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$$n = 2\left(\frac{2\pi m_e^* kT}{h^2}\right)^{3/2} \cdot \exp\left(\frac{E_F - E_c}{kT}\right)$$

by putting eq^n (30) in the above eq^n, we get the density of $\bar{e}$'s in the CB for N-type semiconductor,

$$\text{i.e., } n = 2\left(\frac{2\pi m_e^* kT}{h^2}\right)^{3/2} \cdot \exp\left\{\frac{1}{kT}\left[\frac{(E_d+E_c)}{2} + \frac{kT}{2}\ln\frac{N_d}{2\left(\frac{2\pi m_e^* kT}{h^2}\right)^{3/2}} - E_c\right]\right\}$$

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

$$= 2\left(\frac{2\pi m_e^* kT}{h^2}\right)^{3/2} \cdot \exp\left\{\left(\frac{E_d - E_c}{2kT}\right) + \ln\frac{N_d^{1/2}}{\left[2\left(\frac{2\pi m_e^* kT}{h^2}\right)^{3/2}\right]^{1/2}}\right\} \quad \left\langle \because \tfrac{1}{2}\log x = \log x^{1/2}\right\rangle$$

$$= 2\left(\frac{2\pi m_e^* kT}{h^2}\right)^{3/2} \cdot \exp\left(\frac{E_d - E_c}{2kT}\right) \cdot \exp\left(\ln\frac{N_d^{1/2}}{\left[2\left(\frac{2\pi m_e^* kT}{h^2}\right)^{3/2}\right]^{1/2}}\right)$$

$$\left\langle \because e^{x+y} = e^x \cdot e^y \right\rangle$$

$$\therefore n = 2\left(\frac{2\pi m_e^* kT}{h^2}\right)^{3/2} \cdot \exp\left(\frac{E_d - E_c}{2kT}\right) \cdot \frac{N_d^{1/2}}{\left[2\left(\frac{2\pi m_e^* kT}{h^2}\right)^{3/2}\right]^{1/2}} \longrightarrow (32)$$

$$\left\langle \because e^{\log_e x} = x \right\rangle$$

$$n = \frac{\sqrt{2}\sqrt{2}}{(2)^{1/2}}\left(\frac{2\pi m_e^* kT}{h^2}\right)^{3/2} \cdot \exp\left(\frac{E_d - E_c}{2kT}\right) \cdot \left(\frac{2\pi m_e^* kT}{h^2}\right)^{-3/4} \cdot N_d^{1/2} \text{ (or)}$$

$$\therefore n = (2N_d)^{1/2} \cdot \left(\frac{2\pi m_e^* kT}{h^2}\right)^{\frac{3}{2}-\frac{3}{4}} \cdot \exp\left(\frac{E_d - E_c}{2kT}\right)$$

$$^{**}\therefore \boxed{n = (2N_d)^{1/2} \cdot \left(\frac{2\pi m_e^* kT}{h^2}\right)^{3/4} \cdot \exp\left(\frac{E_d - E_c}{2kT}\right)} \longrightarrow (33)$$

(or)

$$^{*}\therefore \boxed{n \propto \sqrt{N_d}} \longrightarrow (34)$$

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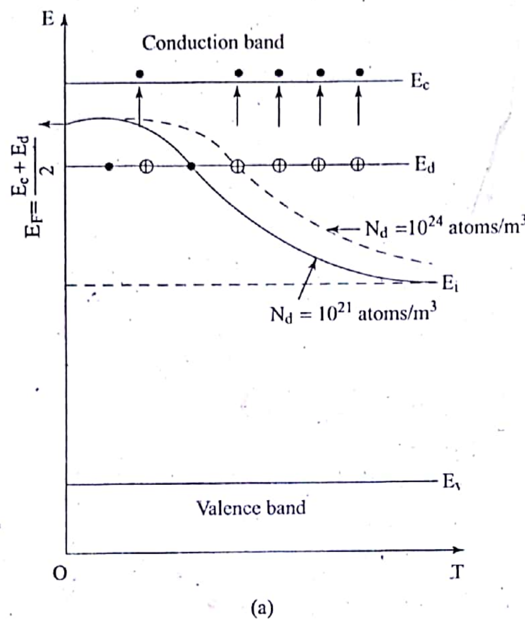
Thus, we find that the density of electrons in the CB is proportional to the square root of the donor concentration (N_d) at moderately low temperatures.

Variation of Fermi level with temperature :-



The energy level diagram of a N-type semiconductor is shown in fig 3(a). Here, N_d is the donor concentration, and E_d is the donor energy level.

At very low temp.'s donor energy level E_d is filled with electrons.

Fig 3(a):- Variation of Fermi level position with temp in N-type semiconductors

If we increase the temperature (T), Fermi level (E_F) increases slightly. As the temp. is increased more and more, donor atoms are ionised. For a particular temp. all the donor atoms are ionised. Further increase in temp. results in generation of electron-hole pairs due to breaking of covalent bonds and the material tends to behave in intrinsic manner. The Fermi level gradually moves towards the intrinsic Fermi level (E_i) as shown in fig 3(a).

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Variation of Fermi level with donor concentration :-

Fig 3 (a). explains the behaviour of a N-type semiconductor of higher donor concentration (i.e., $N_d = 10^{24}$ atoms/m^3) with a lower one (i.e., $N_d = 10^{21}$ atoms/m^3).

In the case of higher donor concentration material, if we rise the temp., we find that lowering of Fermi level (E_F) from $E_F = \frac{E_d + E_c}{2}$ to intrinsic fermi level (E_i) is very slow than the lower one.

Naturally highly doped semiconductor will behave in intrinsic manner only after all the donor atoms are ionised.

Carrier concentration in P-type Semiconductors :-

We have the density of holes in VB is given by eq^n (22).

$$p = 2\left(\frac{2\pi m_h^* kT}{h^2}\right)^{3/2} \cdot \exp\left(\frac{E_V - E_F}{kT}\right) \longrightarrow (35)$$

Let N_a be the acceptor concentration i.e., the no. of acceptor atoms per unit volume of the material and E_a is the acceptor energy level, then the density of ionised acceptors is given by

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** $$N_a \cdot F(E_a) = N_a \cdot \exp\left(\frac{E_F - E_a}{kT}\right) \longrightarrow (36)$$

Since the density of holes in the VB is equal to the density of ionised acceptors,

i.e., $p = N_a . F(E_a)$ (or)

$$2\left(\frac{2\pi m_h^* kT}{h^2}\right)^{3/2} \cdot \exp\left(\frac{E_V - E_F}{kT}\right) = N_a \cdot \exp\left(\frac{E_F - E_a}{kT}\right) \quad \text{(or)}$$

$$\exp\left(\frac{E_V - E_F}{kT} - \frac{E_F - E_a}{kT}\right) = \frac{N_a}{2\left(\frac{2\pi m_h^* kT}{h^2}\right)^{3/2}} \quad \text{(or)}$$

$$\therefore \exp\left(\frac{E_V + E_a - 2E_F}{kT}\right) = \frac{N_a}{2\left(\frac{2\pi m_h^* kT}{h^2}\right)^{3/2}} \longrightarrow (37)$$

Taking logarithm, we get

$$\ln \exp\left(\frac{E_V + E_a - 2E_F}{kT}\right) = \ln \frac{N_a}{2\left(\frac{2\pi m_h^* kT}{h^2}\right)^{3/2}} \quad \text{(or)}$$

$$\frac{E_V + E_a - 2E_F}{kT} = \text{'' \quad ''} \quad \langle \because \log_e e^x = x \rangle$$

(or)

$$(E_V + E_a) - 2E_F = kT \cdot \ln \frac{N_a}{2\left(\frac{2\pi m_h^* kT}{h^2}\right)^{3/2}} \quad \text{(or)}$$

$$(E_V + E_a) - kT \ln \frac{N_a}{2\left(\frac{2\pi m_h^* kT}{h^2}\right)^{3/2}} = 2E_F \quad \text{(or)}$$

$$\therefore \boxed{E_F = \frac{(E_V + E_a)}{2} - \frac{kT}{2} \ln \frac{N_a}{2\left(\frac{2\pi m_h^* kT}{h^2}\right)^{3/2}}} \longrightarrow (38)$$

***

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At 0K, (i.e., at T = 0 K),

** $\therefore$ $$E_F = \frac{E_v + E_a}{2} \longrightarrow (39)$$

i.e., At 0K, Fermi level lies exactly at the middle of the acceptor level (E_a) and the top of the VB (E_v) as shown in fig 3(b).

Density of holes in the Valence Band :-

From eq^n (35) density of holes in the VB (for pure semiconductors) is given by

$$p = 2\left(\frac{2\pi m_h^* kT}{h^2}\right)^{3/2} \cdot \exp\left(\frac{E_v - E_F}{kT}\right)$$

By putting eq^n (38) in the above eq^n, we get the density of holes in the VB for p-type semiconductors,

i.e., $$p = 2\left(\frac{2\pi m_h^* kT}{h^2}\right)^{3/2} \cdot \exp\left\{\frac{1}{kT}\left[E_v - \frac{(E_v+E_a)}{2} + \frac{kT}{2}\ln\frac{N_a}{2\left(\frac{2\pi m_h^* kT}{h^2}\right)^{3/2}}\right]\right\}$$

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

$$= 2\left(\frac{2\pi m_h^* kT}{h^2}\right)^{3/2} \cdot \exp\left\{\frac{(E_v - E_a)}{2kT} + \ln\frac{N_a^{1/2}}{\left[2\left(\frac{2\pi m_h^* kT}{h^2}\right)^{3/2}\right]^{1/2}}\right\} \quad \left(\because \tfrac{1}{2}\log x = \log x^{1/2}\right)$$

$$p = 2\left(\frac{2\pi m_h^* kT}{h^2}\right)^{3/2} \cdot \exp\left(\frac{E_v - E_a}{2kT}\right)\frac{N_a^{1/2}}{\left[2\left(\frac{2\pi m_h^* kT}{h^2}\right)^{3/2}\right]^{1/2}} \quad \langle \because e^{x+y} = e^x \cdot e^y \rangle \text{ (or) } \langle \because e^{\log_e x} = x \rangle$$

$$= \frac{\sqrt{2}\sqrt{2}}{\sqrt{2}} \cdot \left(\frac{2\pi m_h^* kT}{h^2}\right)^{3/2} \sqrt{N_a} \cdot \exp\left(\frac{E_v - E_a}{2kT}\right) \cdot \left(\frac{2\pi m_h^* kT}{h^2}\right)^{-3/4} \quad \text{(or)}$$

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$$\therefore\ p = (2N_a)^{1/2}\left(\frac{2\pi m_h^* kT}{h^2}\right)^{3/4} \cdot \exp\left(\frac{E_v - E_a}{2kT}\right) \longrightarrow (40)$$

Thus, we find that the density of holes in the VB is proportional to the square root of the acceptor concentration at moderately low temperatures.

$$\text{i.e.,}\quad p \propto \sqrt{N_a} \longrightarrow (41)$$

Variation of Fermi level with temperature :-

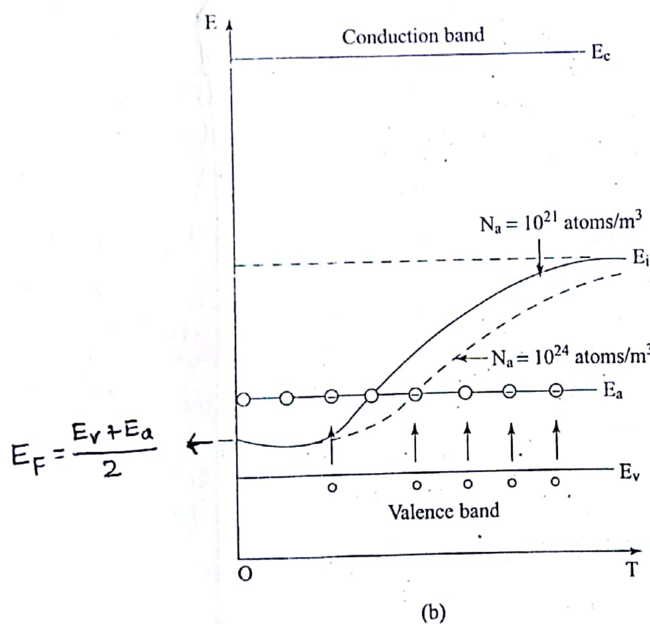

Fig 3(b):- Variation of Fermi level position with temp. in p-type semiconductor

The energy level diagram of a P-type semiconductor is shown in fig 3(b). Here, N_a is the acceptor concentration and E_a is the acceptor energy level. At very low temperatures the acceptor level E_a is empty.

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If we increase the temp (T), Fermi level (E_F) decreases slightly. As the temp. is increased, more & more, acceptor atoms are ionised. For a particular temp. all the acceptor atoms are ionised. Further increase of temp. results in generation of electron-hole pairs due to breaking of covalent bonds and the material tends to behave in intrinsic manner.

The Fermi level gradually moves towards the intrinsic Fermi level E_i as shown in fig 3(b).

Variation of Fermi level with Acceptor Concentration:-

Fig 3(b) explains the behaviour of a p-type semiconductor for two different acceptor concentrations.

⟨ i.e., (i). higher acceptor concentration $N_a = 10^{24}$ atoms/m^3
(ii). lower acceptor " " $N_a = 10^{21}$ atoms/m^3 ⟩

In the case of higher acceptor concentration material, if we rise the temp., we find that raising of Fermi level from $E_F = \frac{E_v + E_a}{2}$ to intrinsic fermi level E_i is very slow than the lower one.

This is because, the highly doped semiconductor will behave in intrinsic manner only after all the acceptor atoms are ionised.

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§ P-N JUNCTION DIODE :

* * * * *

Actually a P-N junction diode is device consisting of a P-N junction and having two terminals that are usually to be connected to the two terminals of a battery.

Schematic symbol of a P-N Junction Diode :-

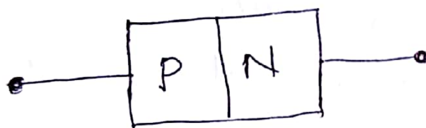

Fig (a)

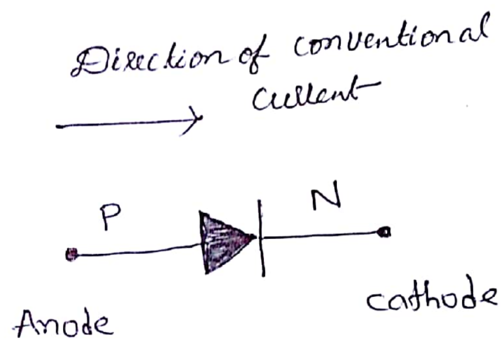

Fig (b)

Fig (1)

The P-N Junction diode having two terminals is represented in fig1(a).

The schematic symbol of a P-N Junction diode is shown in fig1(b). The P-region of the diode is called the "Anode" and the N-region is called the "Cathode". The symbol is an arrow pointing from P-region to the N-Region. This indicates the fact that, through the diode, the conventional current flows from P-region to the N-Region.

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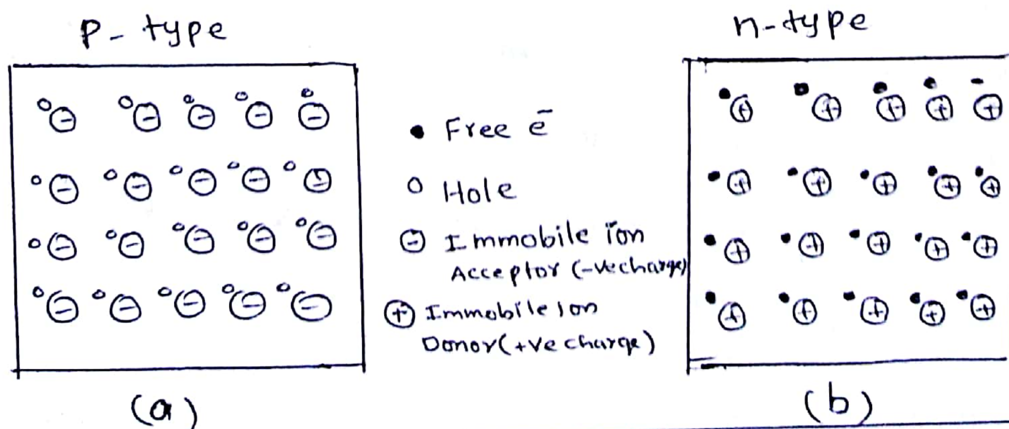
Formation of P-N Junction :-

A P-N junction is formed when a p-type extrinsic semiconductor is intimately joined with a N-type extrinsic semiconductor.

A P-N junction is formed from a single piece of a semiconducting material like Ge or Si by special fabrication techniques, such that one half will be P-type and the other half N-type.

The plane dividing the two regions is called the "P-N junction". The most important characteristic of a P-N junction is that it allows current to flow through in one direction only. If the current direction is reversed, the P-N junction offers very high resistance.

The Formation of P-N junction is shown in fig (2).



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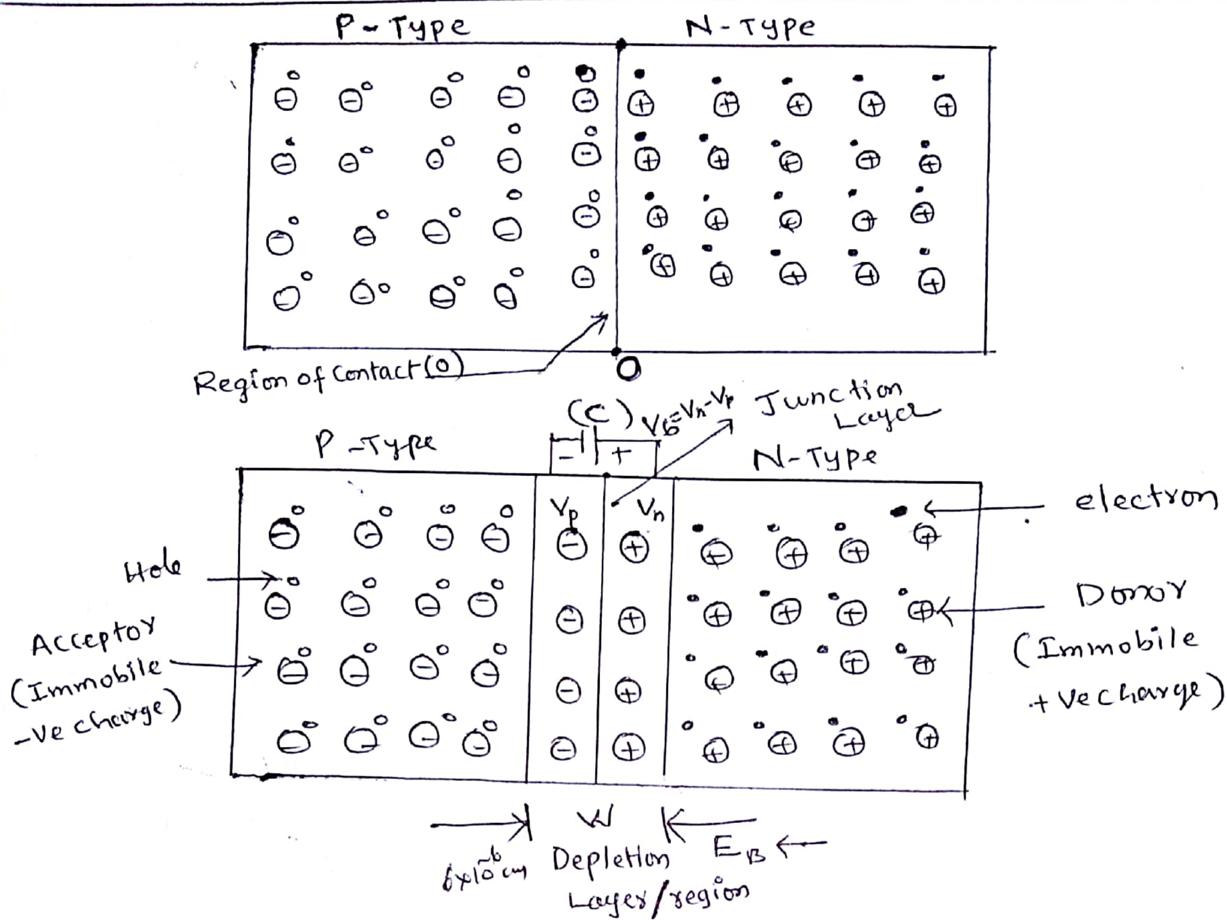

(d)

Fig (2) Formation of P-N Junction

Let us consider the formation of a sharp junction (O) when two seperate semiconductors of P and N-type are brought together.

The P-type has holes as majority carriers and electrons as minority carriers and the negative immobile ions (impurity).

The N region will be having electrons as majority carriers, holes as minority carriers and the positive immobile ions (impurity).

<Note:- For simplicity, the minority charge carriers are not shown in fig 2>

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When they are joined, in the region of contact the free electrons diffuse from n- region and combine with holes in p- region.

As a result n- region near the boundary +vely charged and p- region -vely charged. Hence, an electric field E_B appears in a small region "W" on either side of the junction "O" as shown in fig 2(d). This region is called " Depletion Region". The thickness of (W) this region is in the order of 6×10^{-6} cm.

Due to the electric field E_B, potential difference appears across the depletion region and this potential V_B is called "Contact potential" (or) " Barrier Potential" (or) 'Junction Barrier". It is of the order of 0.7V for a silicon P-N junction and of 0.3V for a Ge P-N junction.

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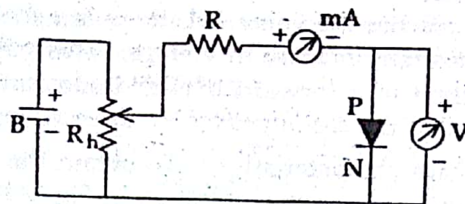
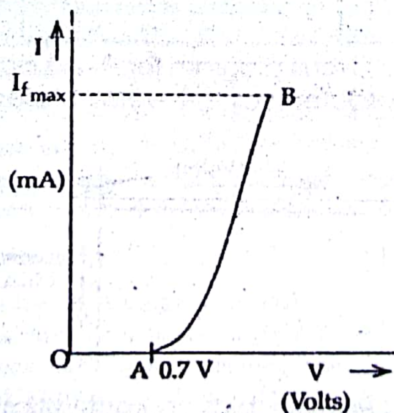
V-I Characteristics of a PN-Junction Diode :-

(a). Forward - bias characteristics :



14 (a) : Circuit diagram for PN junction diode characteristics – Forward biased

A dc battery 'B' is connected to a PN diode through rheostat R_h, a resistance R and a mA as shown in fig. A voltmeter V is connected in parallel to the P-N junction diode. The rheostat helps in varying the voltage across the diode. The voltmeter measures this voltage. The milliammeter measures the corresponding current in the forward-bias.



14 (b) : Forward characteristics of a diode

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A graph is drawn with voltage applied (V) on x-axis and the corresponding current (I) on y-axis. From this V-I characteristics we observe that, I is quite small upto the point A (OA = 0.7V for Si diode, & 0.3V for Ge diode). After the voltage reaches the value OA, there is a sharp increase in current even for a slight increase in voltage. This voltage OA = V_0 at which the current in a F.Biased diode starts to increase very rapidly is called the "Cut-in-Voltage" (or) "knee voltage (V_0)".

(b). Reverse-Bias characteristics :-

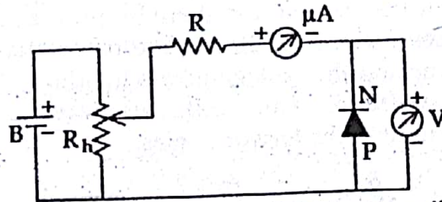

Fig. 9·14 (c) : Circuit diagram for P- N junction diode characteristics - Reverse-biased

In this case the terminals of the diode are reversed and the mA is replaced by a μA, because the currents through the reverse-biased diode will be very very small. The modified ckt is shown in fig ( ). Again by adjusting the Rh, the voltage is changed and the corresponding μA

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readings are noted. The graph between V and I will be as shown in fig ( ).

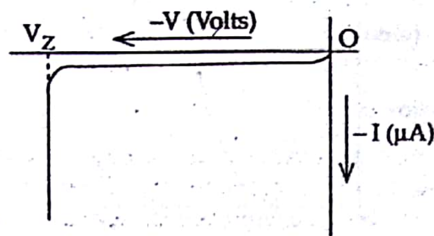
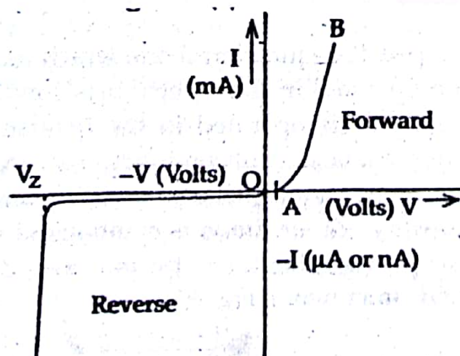


Fig. 9·14 (d) : Revere - bias characteristics of a diode

From this characteristics, we observe that in the RB, the diode current (I) is very very small (μA for Ge, nA for Si diode). It is also noticed that the reverse current remains small (almost const) for voltages upto the breakdown voltage V_Z. At the breakdown voltage (V_Z), the current increases abruptly for a small voltage increase.

The two graphs - for FB and RB are combined together to get the V-I characteristics of the PN junction diode which looks like fig ( ).



(e) : V-I Characteristics of a PN-junction diode

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Energy diagram of P-N diode :-

The contact potential V_B across the junction is due to the potentials of depletion regions on n-side denoted by V_n and p-side denoted by V_p.

i.e., $$V_B = V_n - V_p \longrightarrow (1)$$

The energy levels of VB, CB and Fermi level (E_F) of both p-type and n-type semiconductors are shown in fig 3 (a) and (b).

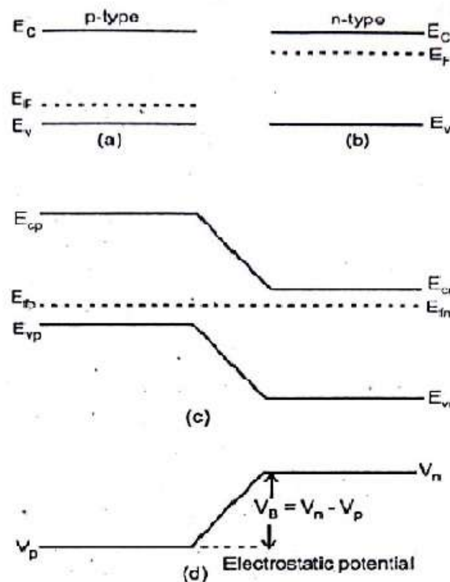

Fig. 3 (a) and (b) Energy level diagram of p-type semiconductors respectively (c) Energy level diagram of PN junction and (d) formation of potential barrier across the junction

When P-N junction is formed, the Fermi levels (E_{fp} & E_{fn}) become common for both the types as shown in fig 3 (C). Formation of potential barrier (V_B) across the junction is represented in fig 3 (d).

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The Hall Effect :-

The Hall effect was discovered in 1879 by Edwin H. Hall. This effect relates to the generation of a voltage when a current carrying conductor is placed in a magnetic field.

According to this Hall effect, "When a magnetic field is applied perpendicular to a current carrying conductor, a potential difference is developed between the opposite sides of the conductor".

Let us consider a uniform thick metal strip placed with its length parallel to the X-axis. Let a current i_x be passed in the conductor along the X-axis. The conductor is now placed in a magnetic field, applied along the Y-direction and $\perp^r$ to

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the length of the metal strip. This is shown in fig (a).

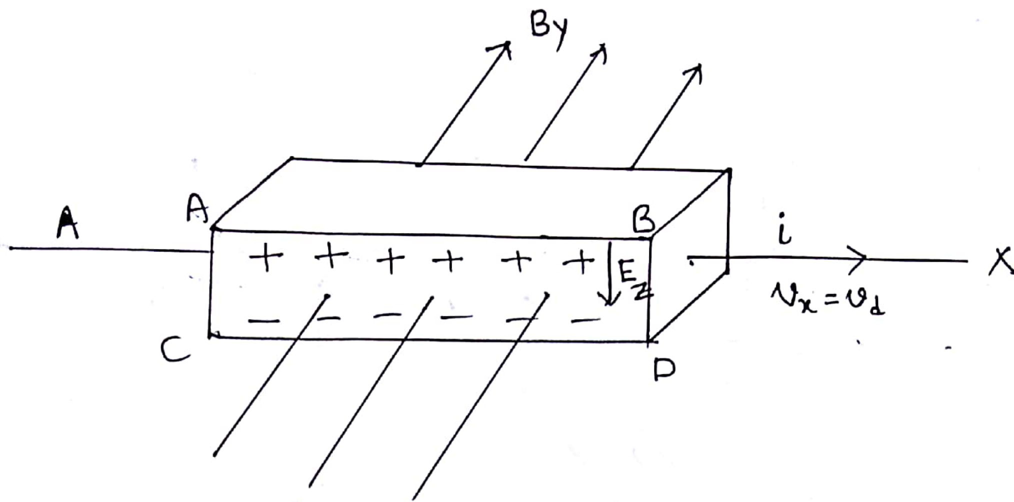

Fig (a)

Case (i) :- Now, let us suppose the charge carriers inside the conductor are positive. Their drift velocity v_d will be along the +ve X-direction. $v_x = v_d$. Because of the magnetic field B_y, the +ve particle (hole) will experience a magnetic force

$$F_B = q\left[v_x \times B\right] \longrightarrow (1)$$

along +ve Z direction. That is, the +vely charged particles will move upwards, towards the face AB, leaving -ve charges on the face CD below. This gives rise to a potential difference V_H across AB and CD and an electric field E_z directed along the -ve Z direction, downwards. This is shown in fig (a).

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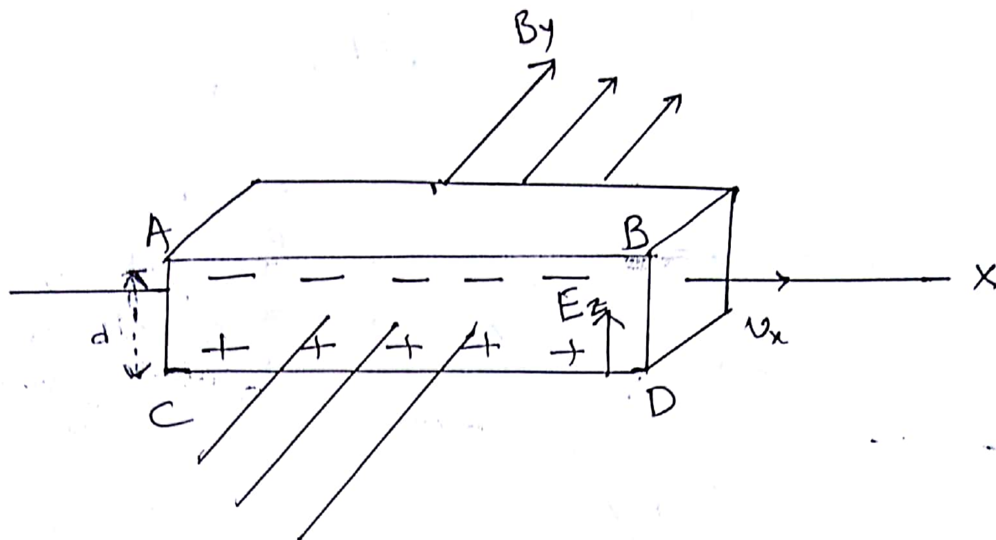

Fig (6)

Case (ii):- Now, let us suppose that the charge carriers inside the conductor are negative.
In this case, the drift velocity of these -ve charged particles will be along the -ve X-direction i.e., towards the left side.

$$v_d = -v_x$$

The magnetic force acting on these -vely charged particles is given by,

$$F_B = -q\left[-v_x \times B\right]$$

$$\therefore F_B = q\left[v_x \times B\right] \longrightarrow (2)$$

and is again along the +ve Z axis. i.e., upwards.
However, now the particles moving are -ve and hence, the -vely charged particles will be moving up towards the face AB, leaving +ve charges on the lower face CD. This again gives rise to a P.D 'V_H'

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-across AB and CD and an electric field E_z directed along the +ve Z direction, upwards. This is shown in fig (b).

The potential V_H is called Hall potential. From the polarity of this potential difference V_H, we can find whether the charge carriers are +ve or -ve.

If V_H is +ve → charge carriers are +vely charged holes

if V_H is -ve → charge carriers are -vely charged electrons.

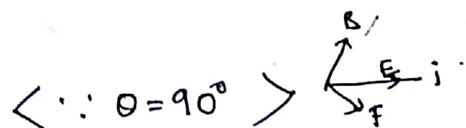
Experimentally it is found that for most of the metals the hall potential V_H is -ve. Thus, for most of the metals the charge carriers are -vely charged electrons.

Under equilibrium, we have

$$E_Z = \frac{V_H}{d} \longrightarrow (3)$$

where d → is the distance b/w AB & CD faces

& $qE_z = q[v_d \times B]$ (or)



$\langle \because \theta = 90^\circ \rangle$

$qE_z = qv_d B$ (or)

$$E_z = v_d B \longrightarrow (4)$$

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Now, if the current density (current per unit area of cross section) is J, the charge of the carrier is "q" and the density of charge-carriers (No. of charge carriers per unit volume) is "n" and the drift velocity is "v_d", then we have

$$J = nev_d \rightarrow (5)$$

(or)

$$v_d = \frac{J}{ne} \rightarrow (6)$$

From eqⁿ's (4) & (6),

$$E_z = \frac{J}{ne} \cdot B \quad \text{(or)}$$

$$\therefore \boxed{\frac{E_z}{JB} = \frac{1}{ne} = R_H \text{ (a const)}} \rightarrow (7)$$

This constant R_H is called the "Hall constant" (or) "Hall coefficient".

If R_H is -ve → the charge carriers will be -ve electrons, and

if R_H is +ve → the carriers will be +ve holes.

* * * *

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APPLICATIONS OF HALL EFFECT:

1. Hall effect gives information about the sign of charge carriers in electric conductor. It is found that most metals have negatively charged electrons.
2. Hall effect is quite helpful in understanding the electrical conduction in metals and semiconductors.
3. Hall effect can be used to measure the drift velocity of the chare carriers.

   i.e., $v_d = \frac{J}{ne}$ (∵ From eqn. 7)

4. Hall effect can be used to measure the carrier concentration.

If n be the carrier concentration (no of charge carriers per unit volume) and A be the face area of plate, then.

$$i = neAV_d \rightarrow (9) \quad (\because J = \frac{I}{A} = nev_d)$$

Also, from eqn (5)

$$v_d = \frac{Ez}{B} \qquad (\because E_z = v_d B \text{ from } 5)$$

Making this substitution in (9), we get

$$\therefore \quad i = neA\frac{Ez}{\boldsymbol{B}} \rightarrow (10)$$

Let b be the breadth and d be the width of face area of conductor, then A=bd So

$$i = nebd\frac{Ez}{\boldsymbol{B}} \qquad \text{(or)}$$

$$\therefore \quad \boxed{n = \frac{iB}{\boldsymbol{ebdEz}}} \rightarrow (11)$$

-oOo-

Bipolar Junction Transistor (BJT) :-

Construction :-

Bipolar Junction Transistor (BJT) consists of a silicon (or germanium) crystal in which a thin layer of N-type silicon is sandwiched between two layers of P-type silicon, to form the P-N-P junction transistor. Alternatively, a BJT may consist of a thin layer of P-type between two layers of N-type material to form the N-P-N structure.

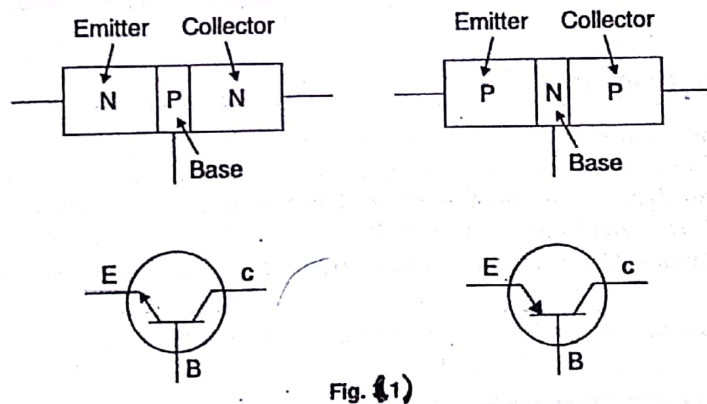

Fig. (1)

The central section is called the "base", one of the outer sections the 'emitter', and the other outer section the 'collector'. The base region usually very thin ($\approx 10^{-3}$ cm). The two end sections of the N-P-N transistor contain a no. of free electrons, while the central P-section possesses an excess of holes.

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Similarly the two outersections of the P-N-P transistor contain an excess of holes, while the central section contains an excess of electrons.

It may be seen from the circuit symbols of N-P-N and P-N-P transistors that the emitter (E) is distinguished from the collector (C) by an arrow which indicates the direction of conventional current flow.

Principle of Operation of a P-N-P Transistor :-

A circuit known as common-base ckt of a P-N-P transistor is shown in fig (2).

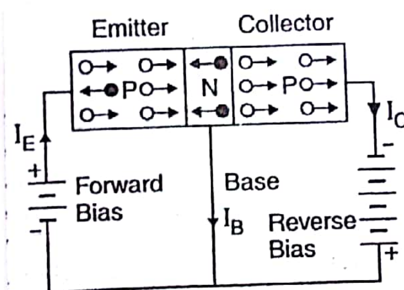

Fig. 1.2

It may be seen that the emitter (P-type) of P-N-P transistor is forward biased while the collector has a reverse bias. In fact, the emitter of transistor is always forward biased with respect to base while the collector is always reverse biased.

With the emitter voltage applied as shown in fig (2), holes are repelled from the +ve terminal and injected into

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the emitter junction. Since the base is only lightly doped and very thin, only few holes will recombine with electrons, probably not more than 5% of the total no. of holes leaving the emitter, and the remaining 95% of the holes will diffuse through the base and reach the collector junction. These holes cross over the collector junction into the collector region. They are rapidly drawn up by the -ve collector voltage.

For each hole flowing out of the collector & entering the -ve terminal of the battery, a hole from the +ve terminal of the emitter battery enters the emitter. This new hole then moves immediately towards the emitter-base junction and the process is thus repeated.

It should be noted that the charge carriers in the case of P-N-P transistor are predominantly holes. In P-N-P transistor, the collector current is always less than the emitter current ($I_C < I_E$), because of the recombination of holes & electrons occuring in the base region, and the current gain (α) is less than unity. < the current gain α is defined as the ratio of a small change in collector current to the small change in emitter current >.

Principle of Operation (N-P-N Transistor) :-

A ckt known as common-base ckt of a N-P-N transistor is shown in fig (3).

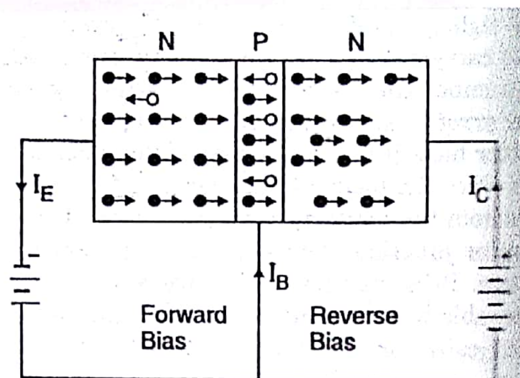

Fig. (3)

It may be seen that the emitter junction is biased in the forward direction while the collector junction is biased in reverse direction.

The operation of an N-P-N transistor is similar to that of P-N-P type, but the bias voltage polarities are reversed and the current carriers are electrons instead of holes.

With the emitter voltage applied as shown in fig (3) electrons are repelled from the -ve terminal and injected into the emitter junction. Since the base is only lightly doped and very thin, only few electrons will recombine with holes, probably not more than 5% of the total no. of ē's leaving the emitter, and the remaining 95% of the ē's will diffuse through the base, and reach the collector junction.

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These electrons cross over the collector junction into the collector region. They are rapidly drawn up by the +ve collector Voltage.

For each $\bar{e}$ flowing out of the collector & entering the +ve terminal of the battery, an $\bar{e}$ from the -ve terminal of the emitter battery enters the emitter. This new $\bar{e}$ then moves immediately towards the emitter-base junction and the process is then repeated.

It should be noted that the charge carriers in the case of N-P-N transistor are predominantly electrons. In N-P-N transistor, the collector current is always less than the emitter current ($I_c < I_E$), because of the recombination of electrons & holes occuring in the base region and the current gain (α) is less than unity.

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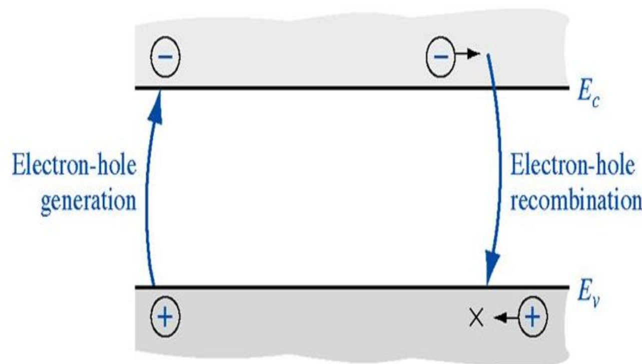
RADIATIVE AND NON-RADIATIVE RECOMBINATION MECHANISMS IN SEMICONDUCTORS:

Generation Process:

- In semiconductors a single event of covalent bond breaking leads to the generation of the charge carriers, an electron in the conduction band and a hole in the valence band.
- The electron and hole are produced simultaneously as a pair and the process is called **electron-hole pair generation**.



"Generation is a process whereby charge carriers electrons and holes are generated".

- The process may be represented as

Covalent bond + Thermal energy $\xrightarrow{\text{Rupture}}$ **(Electron + Hole) pair**

- Thermal energy is one of the agents which causes pair generation.
- Another agent is optical illumination.

Recombination Process:

- It is likely that the electron in CB may lose its energy due to collision with other particles in the lattice and fall into the VB.
- When a free electron falls into VB, it merges with a hole.

- This process is called Recombination.
- When a recombination event occurs, the free electron enters a ruptured covalent bond and re-bridges it. (i.e., electron-hole pair disappears/destroyed).
- In this process energy is released.

"Recombination is a reversed process of generation whereby charge carriers electrons and holes are destroyed and energy is released".

- The process may be represented as

Types of Recombination Process:

It is of two types such as,

1. Radiative Recombination:

- Radiative recombination occurs when an electron in the CB recombines with a hole in the VB and excess energy is emitted in the form of (light)**photon**.
- Semiconductors which obeys this mechanism are known as Direct bandgap(DBG) semiconductors.
- This mechanism occurs only in compound semiconductors such as GaAs, InP etc.

2. Non-Radiative Recombination:

- Non-Radiative recombination occurs when an electron in the CB recombines with a hole in the VB and excess energy is emitted in the form of (heat)**phonon**.
- Semiconductors which obeys this mechanism are known as Indirect bandgap(IBG) semiconductors.
- This mechanism occurs only in elemental semiconductors such as Si, Ge etc.

Direct bandgap and Indirect bandgap Semiconductors :- (Radiative & Non-Radiative Recombination Mechanisms in Semiconductors)

We know that the kinetic energy (E) of an $\bar{e}$ is dependent of wave vector "k" when it moves in a periodic potential, (∵ See Kronig-Penny Model)

i.e., $E = \frac{\hbar^2 k^2}{2m} \longrightarrow (1)$

We have seen how the energy spectrum of an electron moving in the presence of a periodic potential field, is divided into allowed and forbidden zones (refer topic E-K curve). E-K curve showed the relationship between energy and wave number (k) for an one-dimensional lattice.

But, in real crystals the E-K relationship is much more complicated. In crystals, E-K relationship and energy band formation depends on the orientation of the electron wave vector (k) to the crystallographic axes.

In few crystals like GaAs (gallium arsenide) the maximum of the valence band (VB) occurs at the same value of "k" as the minimum of the conduction band (CB) as shown in fig 4(a).

This is called "Direct Band gap" semiconductor or "Radiative semiconductor".

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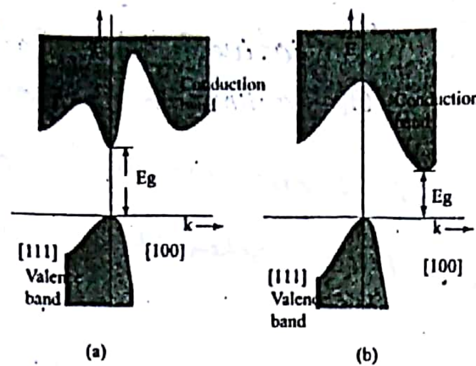

Fig. 4 Relationship of $E - k$ for (a) gallium arsenide (which has a direct bandgap) and (b) silicon (which has an indirect bandgap)

In few semiconductors like Silicon, GaP the maximum of the valence band does not always occur at the same k value as the minimum of the conduction band as shown in fig 4(b).

This is called "Indirect Bandgap" semiconductor(s) "Non-Radiative" semiconductor.

In direct bandgap semiconductors the direction of motion of an $\bar{e}$ during a transition across the energy gap remains unchanged. Hence, the efficiency of transition of charge carriers across the bandgap is more in direct bandgap than in the indirect bandgap semiconductors.

* * *

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Light Emitting Diode (LED):-

Light emitting diode is a photoelectronic device which converts electrical energy into light energy.

It is a heavily doped p-n junction diode which under forward bias emits spontaneous radiation. The diode is covered with a transparent cover, so that the emitted light may come out.

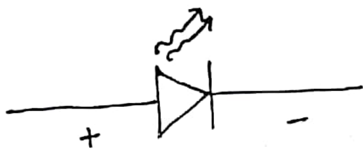
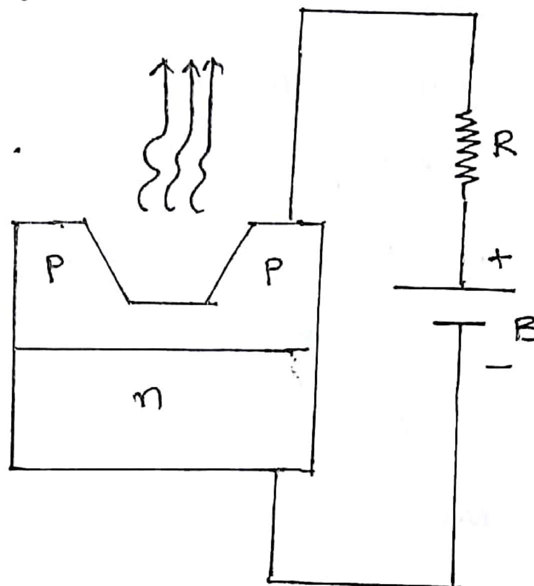


Fig (a): Symbol of LED



Fig(b): Construction & Working of LED

Working :-

→ When p-n junction is forward biased, the movement of majority charge carriers takes place across the junction.

→ The electrons move from n-side to p-side through the junction and holes move from p-side to n-side through the junction.

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→ As a result of it, the concentration of minority carriers increases rapidly at the junction boundary, as compared to the equilibrium concentration, when there is no bias across the junction.

→ Therefore, there are excess minority charge carriers on either side of the junction boundary, which recombine with majority carriers near the junction.

→ On recombination of electron and hole, the energy is given out in the form of heat and light. The photons with energy equal to or slightly less than the bandgap are formed.

→ When the forward current of the junction diode is small, the intensity of light emitting diode is small. As the forward current increases, intensity of light also increases and reaches a maximum value.

→ Beyond this stage, if forward current further increased the intensity of light starts decreasing.

V-I characteristics :-

→ The V-I characteristics of LED is similar to that of Si junction diode.

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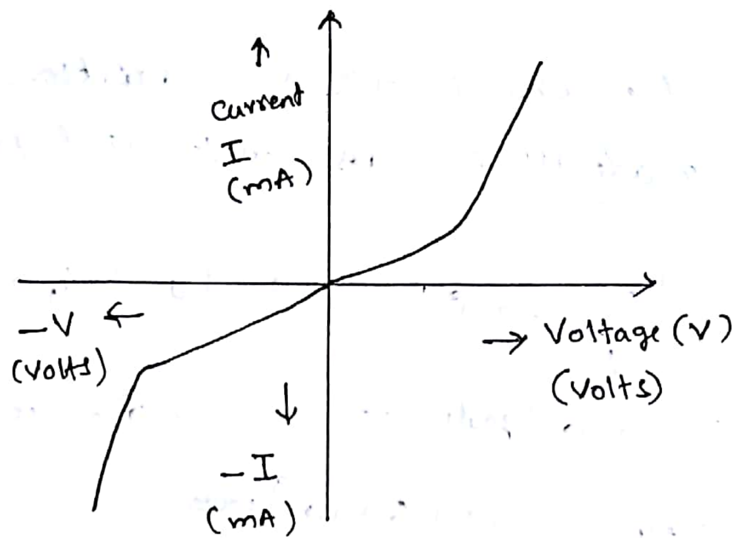

Fig (c): V-I characteristics of LED

→ For LED's the threshold voltages are much higher and slightly different for different colours.

→ The reverse breakdown voltages of LED's are low, generally around 5V. It is due to this reason, the care is taken that high reverse voltages donot appear across LED.

Applications of LED :-

→ In Burglar-alarm systems, infrared LED's are used.

→ In calculators and digital watches LED's are used.

→ LED's are used for numeric displays.

→ LED's are used in optical mouses for the computers

→ LED's are used in traffic signals and lighting technology.

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Problems:-

① Calculate the wavelength of radiation emitted by a LED made up of GaAs with band gap energy 1.43 eV.

Sol:- $\lambda = \frac{hc}{E_g}$ → ① ⟨∵ $E = h\nu = hc/\lambda$⟩

with $h = 6.62 \times 10^{-34}$ joule-sec ; $c = 3\times10^{8}$ m/sec

$E_g = 1.43\,eV = 1.43 \times 1.6 \times 10^{-19}$ joule

$\lambda = \frac{6.62\times10^{-34} \times 3\times10^{8}}{1.43\times1.6\times10^{-19}} = \frac{19.86}{2.288} \times 10^{-7} = 0.868\,\mu m$

∴ $\lambda = 0.868\,\mu m$ → ② ⟨Ans⟩

②. Calculate the energy gap when wavelength is 1.86 μm.

Sol:- Given $\lambda = 1.86\,\mu m$

$\lambda = 1.86\times10^{-6}$ m

we know, $E_g = \frac{hc}{\lambda} = \frac{6.626\times10^{-34} \times 3\times10^{8}}{1.86\times10^{-6}}$

∴ $E_g = 1.068\times10^{-19}$ J → ③ ⟨Ans⟩

③. Calculate the wavelength of emission from a laser whose energy band gap is 1.86 eV.

Sol:- $E_g = \frac{hc}{\lambda} \Rightarrow \lambda = \frac{hc}{E_g} = \frac{6.626\times10^{-34} \times 3\times10^{8}}{1.86\times1.6\times10^{-19}}$

∴ $\lambda = 6.679\times10^{-7}$ m

∴ $\lambda = 6679\,Å$ → ④ ⟨Ans⟩

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Semiconductor Photodetectors

Introduction:-

A photodetector is a device which absorbs light and converts the optical energy to electrical energy.

Detectors are classified as

(i). Thermal Detectors

(ii). photon Detectors

1). Thermal Detectors:-

When light falls on the device, it raises its temperature which in turn changes the electrical properties of material like electrical conductivity.

Eg:- Thermopile, Pyroelectric detectors etc

2). Photon Detectors:-

photon detectors work on the principle of conversion of photons to electrons.

Eg:- photomultipliers, photodiodes etc.,

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PIN DIODE :-

The PIN diode is a one type of photo detector used to convert optical signal into an electrical signal. The PIN diode comprises of three regions namely p-region I-region and N-region.

A diode obtained by sandwiching pure intrinsic material (i), between p-type and n-type extrinsic semiconductors is called a PIN diode. The PIN diode consists of p- and n-type heavily doped materials along with intrinsic material "i" between them.

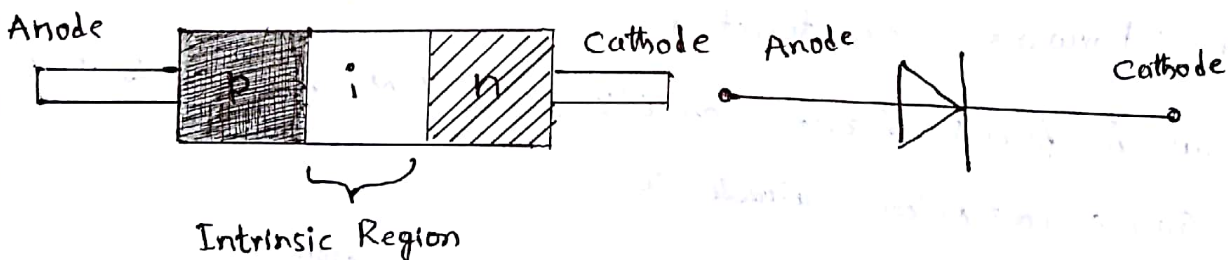

Fig (1). PIN Diode Construction

Fig (2): Symbol

The construction is shown in the fig (1) while its symbol is shown in the fig (2).

Working principle of PIN diode :-

The PIN diode behaves differently in forward biased and reverse biased conditions.

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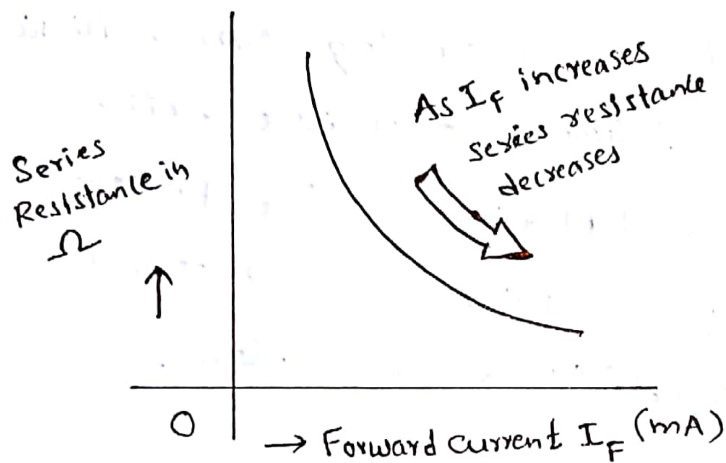
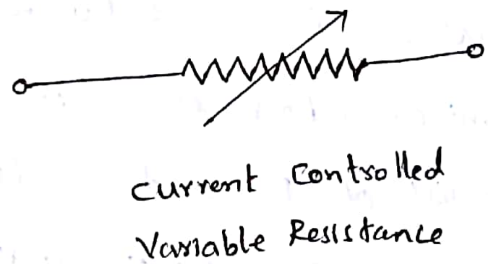
Forward biased operation:-

In FB, the holes from p-side and electrons from n-side are injected into i region. This increases carrier concentration of i-region. This decreases the resistivity and increases conductivity modulation of PIN diode.



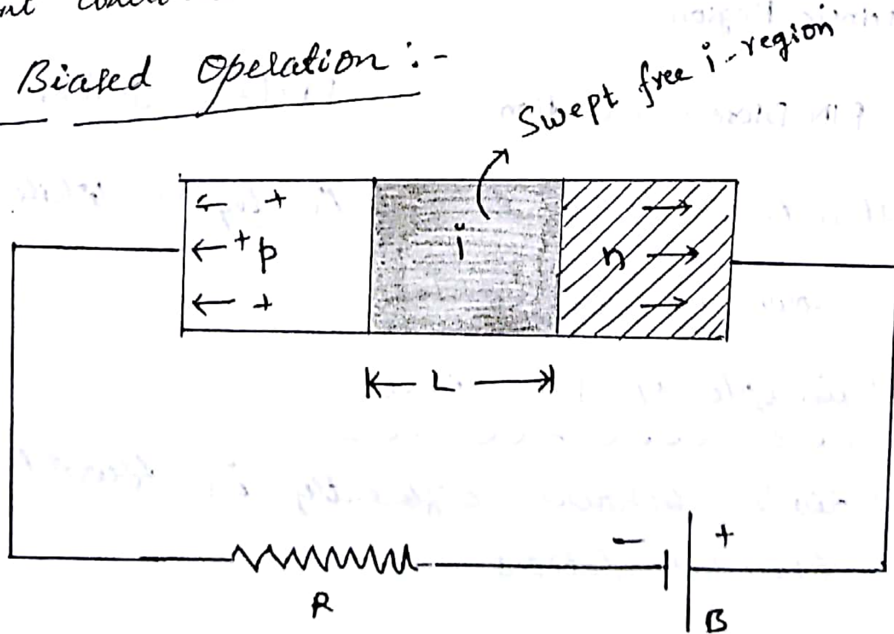
Fig(3): Forward Characteristics



Fig(4):- Forward Bias

Thus in forward biased condition, the PIN diode acts as a current controlled variable resistance.

Reverse Biased Operation:-



Fig(5): Reverse Biased PIN diode

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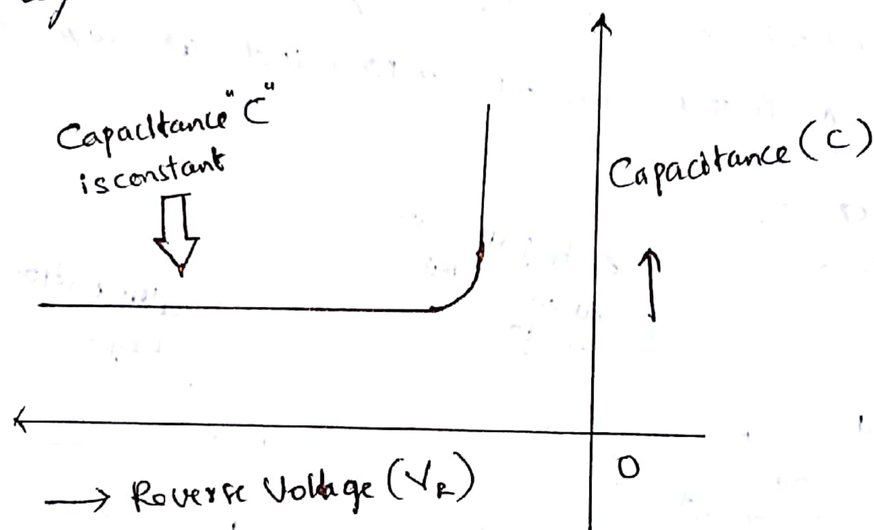
In reverse bias, the holes and electrons move in opposite directions and i-region becomes free from charge carriers. It acts as a depletion region E, which is shown in fig(5). is called swept free i region. The length of depletion region is almost equal to length L of i-region; which is constant. Hence, there exists a transition capacitance which remains constant.



Fig(6): Reverse characteristics

Thus, in reverse biased condition, the PIN diode acts as a constant capacitance.

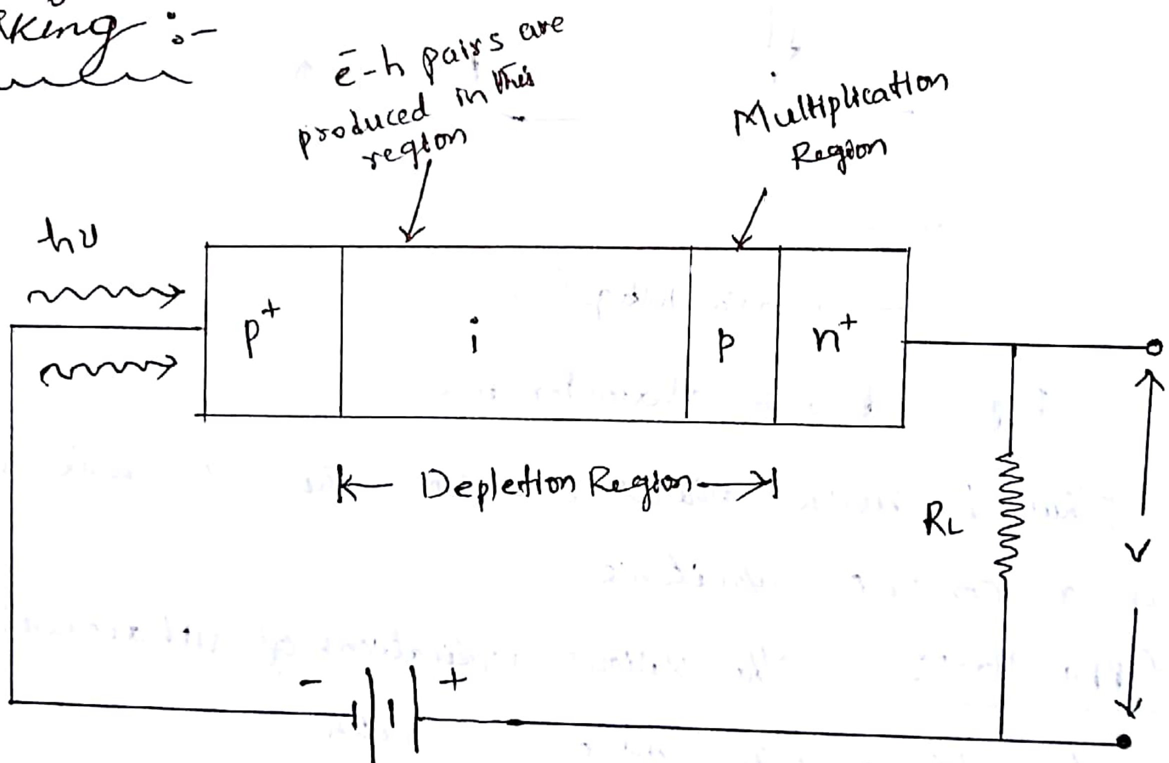
<u>Applications:-</u> The various applications of PIN diode are,

→ As a DC controlled microwave switch
→ Amplitude modulators at microwave frequencies
→ As a voltage variable attenuator in radio freq^n circuits
→ As a phase shifter in phased array radar systems.

Avalanche Photo Diode (APD) :-

Avalanche photodiodes are high sensitivity, high speed semi-conductor light sensors. Compared to regular PIN construction photodiodes, APD's have an internal region where electron multiplication occurs, by application of an external reverse voltage and the resultant gain in the output signal means that low light levels can be measured at high speed.

Working :-



Fig(1):- Circuit diagram of an Avalanche photo Diode

The ckt diagram of an APD is shown in fig(1). The device is essentially a reverse - biased p-n junction

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The n^+ and p^+ are heavily doped semiconductors and have very low resistance. The intrinsic region is lightly doped. Most of the incident light passes into intrinsic region through the thin p^+ region and electron-hole pairs are generated in the intrinsic region.

With increase in the reverse bias voltage, the depletion region across the p-n^+ junction becomes very high & the junction approaches the breakdown condition.

A photon that enters through the p^+ region is absorbed in the intrinsic region and the resulting electron-hole pair is seperated by the electric field in the intrinsic region. The hole drifts towards the p^+ and donot take part in the multiplication process.

The electron drifts through the intrinsic region to the p-n^+ junction. There the electric field due to high reverse bias accelerates the electron. The e^- acquires enough K.E to ionize neutral atoms in its path. Thus gaining enough energy to cause further impact ionization. Thus, the carriers no. increases exponentially and this effect is known as "avalanche effect."

As a result, one electron-hole pair will on an average produce large no. of e^--hole pairs in the process. Thus, there occurs a carrier multiplication & internal

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amplification. This internal amplification process enhances the responsivity of the detector.

Applications :-

Avalanche photo Diode are used in

- Data transmission
- Range finding
- High speed industrial inspection
- Distance measurement

Disadvantages :-

- Much higher operating voltage is be required
- Avalanche photo Diode produces higher level of noise.

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SOLAR CELLS

§ Introduction :

photosensitive device :-

A photo - sensitive device converts radiant energy directly into electrical energy. The photo - sensitive devices are classified into 3 types based on their construction.

(i). photo emissive cell (or) photo electric cell (or) photo cell

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(ii). photo conductive cell

(iii). photo Voltaic cell

1). <u>photo electric cell</u>:- when light is incident on the cathode it causes emission of electrons.

There are again 2 types :

a). Vacuum type

b). Gas filled type

2). <u>photo conductive cell</u> :- when light is incident on some semiconductors (selenium, lead sulphide) its, electrical resistance is reduced. It is rarely used.

** 3). <u>photo Voltaic cell</u>:- when light is incident on the oxide layer, electrons are emitted. An e.m.f is developed in this cell which is proportional to the intensity of light.

These, cells supply current without any external source of e.m.f (battery).

Eg:- Solar cell

SOLAR CELL :-

A solar cell (also called a photovoltaic cell) is basically a P-N junction diode which coverts solar energy into electrical energy.

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It is also called a "Solar Energy converter" and is simply a photo diode operated at zero bias voltage.

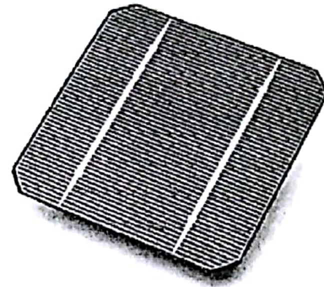
Fig. 1 Solar cells

The Solar cell works in 3 steps :-

1). photons in sunlight fall on the solar panel and are absorbed by semiconducting materials, such as silicon.

2). Electrons (-vely charged) are knocked loose from their atoms, causing an electric potential difference.

3). An array of solar cells converts solar energy into a usable amount of DC electricity.

Construction :-

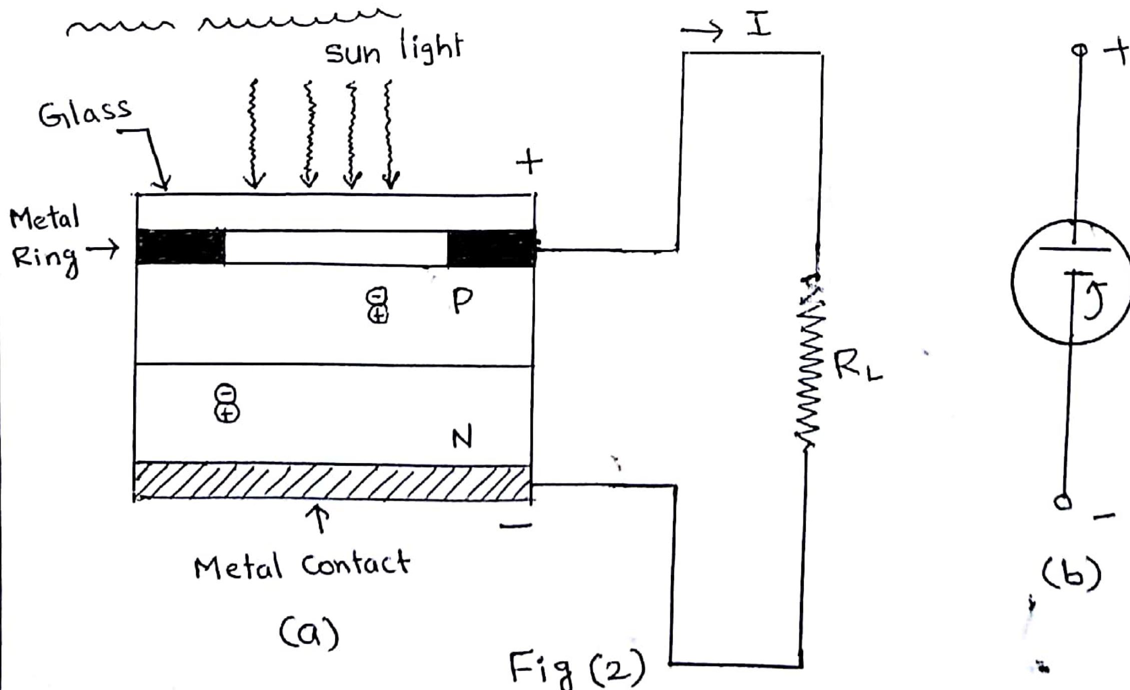

Fig (2)

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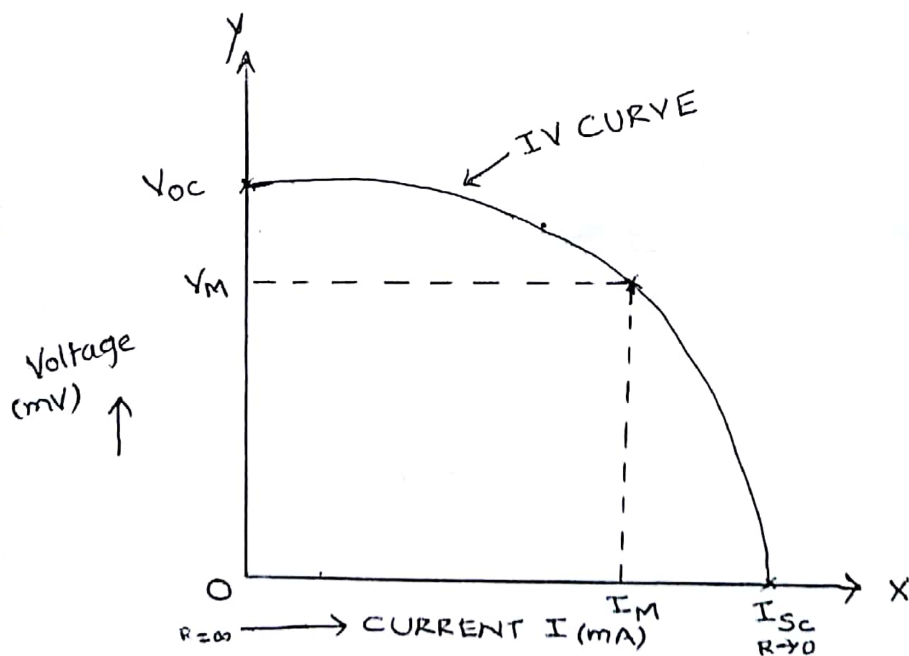
A solar cell consists of a P-N junction diode generally made of Ge or Si. It may also be constructed with many other semiconducting materials like Gallium Arsenide (GaAs), Indium Arsenide (InAs) and Cadmium Arsenide (CdAs).

The P-N diode so formed is packed in a can with glass window on top so that light may fall upon P & N type materials as shown in fig 2(a). A nickel plated ring is provided around the P-layer which acts as the +ve output terminal. A metal contact at the bottom serves as the -ve o/p terminal.

Fig 2(b) gives the schematic symbol of a solar cell. The inward arrow indicates the incoming light.

I-V Characteristics :-



Fig(3): V-I CHARACTERISTICS

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The e.m.f. generated by the photo-voltaic cell in the open ckt i.e., when no current is drawn from it is denoted by V_{OC} (Open ckt voltage). This is the max. value of e.m.f. when a high resistance ($R=\infty$) is introduced in the external ckt.

As the resistance in the external ckt is reduced, a small current flows through it and the voltage decreases. The voltage goes on falling and the current goes on increasing as the resistance in the external ckt is reduced. When the resistance is reduced to zero ($R \to 0$) the current rises to its maximum value known as saturation current and is denoted as I_{SC} (i.e., short ckt current), the voltage becomes zero. This is shown in fig (3).

The product of open ckt voltage V_{OC} & short ckt current I_{SC} is known as "an ideal power".

$$\therefore \text{Ideal power} = V_{OC} \times I_{SC} \longrightarrow (1)$$

The max. useful power (P_{MP}) is the area of the largest rectangle that can be formed under the V-I curve. If V_m (voltage at max. power) and I_m (current at max. power) are the values of voltage and current under this condition, then

$$\therefore \text{Max. useful power} (P_{MP}) = V_m \times I_m \longrightarrow (2)$$

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The ratio of the max. useful power to ideal power is called the fill factor.

$$\therefore \text{Fill Factor (FF)} = \frac{\text{Max. useful power } (P_{mp})}{\text{Ideal power}}$$

$$\therefore \boxed{FF = \frac{V_m \times I_m}{V_{oc} \times I_{sc}}} \rightarrow (3)$$

Energy conversion Efficiency (η):-

A solar cell energy conversion efficiency (η) is the percentage of power converted (from absorbed light to electrical energy) and collected, when a solar cell is connected to an electrical ckt.

It is the ratio of max. useful power (P_{mp}) to the product of input light irradiance and the surface area of the solar cell.

i.e., $$\boxed{\text{Efficiency } (\eta) = \frac{V_m \times I_m}{E \times A_c}} \rightarrow (4)$$

where, $E \rightarrow$ is the Input light irradiance in (W/m^2)

& $A_c \rightarrow$ is the surface area of the solar cell in (m^2)

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Applications:-

Solar cells are used in a wide variety of applications. Now a days solar cells are used in toys, watches, calculators, Electric fences, Remote lighting systems, water pumping, water treatment, Emergency power, portable power supplies, satellites etc.,

Solar cells are used extensively in satellites and space vehicles to supply power to electronic and other equipments and they also used to charge the storage batteries.

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