

UNIT-III: ***SEMICONDUCTORS & OPTOELECTRONIC DEVICES***

Syllabus: Introduction - Intrinsic semiconductors - Density of electrons in intrinsic semiconductor - Density of holes in intrinsic semiconductor (qualitative) - Intrinsic carrier concentration - Fermi energy - Electrical conductivity of intrinsic semiconductors - Extrinsic semiconductors - Density of charge carriers in Extrinsic semiconductors (qualitative) - Drift and Diffusion currents - Direct and Indirect bandgap semiconductors - Hall effect, Hall coefficient, and Applications - pn junction

Optoelectronic devices: Light Emitting Diode (LED), Photodiode, and Semiconductor diode laser.

Introduction:

Based on the band theory of solids, solid materials are classified into 3 types.

i.e. Conductors, Semiconductors, and Insulators.

Conductors have a large number of free electrons, Insulators have no free electrons, and Semiconductors have intermediate properties between conductors and insulators. Semiconductors are having high resistance at low temperatures and low resistance at high temperatures. Semiconductor devices play a vital role in Electrical and Electronics Engineering. The field of electronics becomes more popular after the discovery of transistors in 1948. In general, semiconductors are less weight, low cost, have less power consumption, and are available from the earth's crust, hence they are used in many applications.

- * In semiconductors, the charge carriers are electrons and holes.
- * When a suitable form of energy is supplied to a semiconductor, the electron moves from the valance band to the conduction band, this phenomenon is called *electron-hole pair generation*.
- * When a free electron in the conduction band moves back to the valance band and combines with a hole is called *recombination*.
- * The missing electron in the valance band is said to be a hole. "*In absence of an electron in the valance band of semiconductor is called HOLE*".
- * The number of charge carriers per unit volume is defined as carrier concentrations.
- * In the periodic table 11 elements are semiconductors.

In a solid material, if the forbidden gap is relatively small such material is known as a semiconductor.

(or) The electrical properties of solid materials in between conductors and insulators are called semiconductors. The semiconductors are classified into 2 types.

1. Intrinsic semiconductor 2. Extrinsic semiconductor

**** Intrinsic semiconductor:** A pure form of semiconductor is called an intrinsic semiconductor.

Ex. Pure Germanium (0.72 eV), Pure Silicon (1.1 eV)

In intrinsic semiconductors, at 0 K the total valence electrons are present in the valance band and zero electrons in the conduction band, hence it behaves as an insulator. With the increase in temperature, electrons move from the valance band to the conduction band, this phenomenon is called electron-hole pair generation. Now the electrons in the conduction band are called free electrons and holes in the valance band are called free holes. *In intrinsic semiconductors, the number of electrons in the conduction band is equal to the number of holes in the valance band*. Here E_V is maximum valance band energy, E_C is minimum conduction band energy, and E_F Fermi energy level. In intrinsic semiconductors, the Fermi energy level is located midway between the valance band max. and conduction band min.

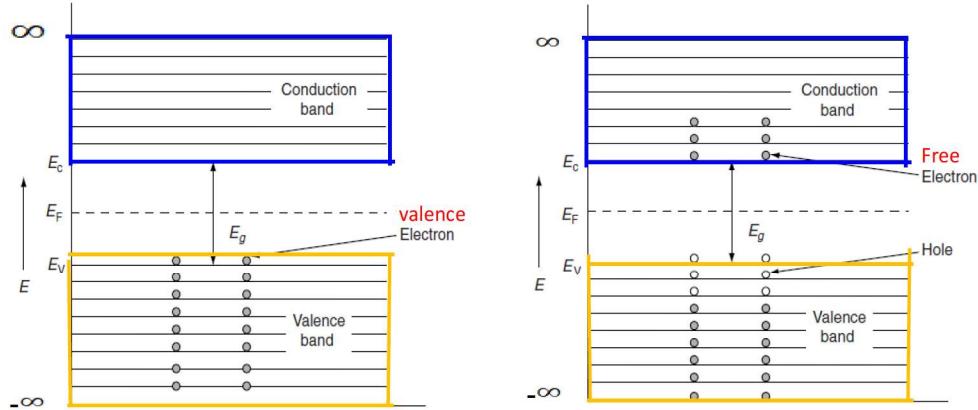


Fig. Band structure of intrinsic semiconductor at 0 K

at T K

**** Density of electrons in intrinsic semiconductor (or)**

Concentration of electrons in the conduction band of intrinsic semiconductor:

At 0 K, in intrinsic semiconductor valence electrons are present in the valance band and the conduction band is empty. As temperature increases, electrons move from the valance band to the conduction band (*covalent bonds will break and lead to the generation of electron-hole pair*). In intrinsic semiconductors, the number of electrons (n) in the conduction band (CB) is equal to the number of holes (p) in the valance band (VB). The electrons in the conduction band are called *free electrons* and the holes in the valance band are called *free holes*.

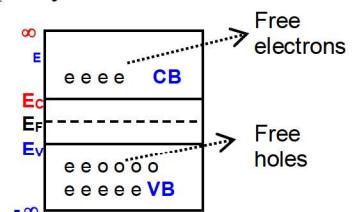
Number of electrons in conduction band = Density of states times the occupancy of electrons

$$n = \rho(E) F(E)$$

where $\rho(E)$ = density of states with energy in the conduction band

$F(E)$ = Probability of electron occupancy

$$\therefore \text{Total no. of electrons in CB is } \int_{E_C}^{\infty} dn = \int_{E_C}^{\infty} \rho(E) F(E) dE \quad \text{--- (1)}$$



$$\text{But } \rho(E) = \text{density of states between } E \text{ & } E_C \text{ levels is } = \frac{4\pi}{h^3} (2m_e^*)^{3/2} (E - E_C)^{1/2} \quad \text{--- (2)}$$

$$\text{Probability of electron occupancy is } F(E) = \frac{1}{1 + \exp\left[\frac{E - E_F}{KT}\right]} \quad \text{--- (3)}$$

Where m_e^* = effective mass of electron E_c = min. the energy of the conduction band

E = energy level in CB h = Planck's constant K = Boltzman's constant

Substituting Eq. (2) & (3) in Eq.(1)

$$\int_{E_C}^{\infty} dn = \int_{E_C}^{\infty} \frac{4\pi}{h^3} (2m_e^*)^{\frac{3}{2}} (E - E_C)^{\frac{1}{2}} \frac{1}{1 + \exp\left[\frac{E - E_F}{KT}\right]} dE$$

Here $\frac{E - E_F}{KT} \gg 1$, $\therefore \exp\left(\frac{E - E_F}{KT}\right)$ is very large and '1' can be neglected in the denominator.

$$n = \frac{4\pi}{h^3} (2m_e^*)^{\frac{3}{2}} \int_{E_C}^{\infty} (E - E_C)^{\frac{1}{2}} \exp\left(-\frac{[E - E_F]}{KT}\right) dE$$

$$n = \frac{4\pi}{h^3} (2m_e^*)^{\frac{3}{2}} \int_{E_C}^{\infty} (E - E_C)^{\frac{1}{2}} \exp\left(-\frac{[E - E_C + E_C - E_F]}{KT}\right) dE$$

$$n = \frac{4\pi}{h^3} (2m_e^*)^{\frac{3}{2}} \int_{E_C}^{\infty} (E - E_C)^{\frac{1}{2}} \exp\left(-\frac{[E - E_C]}{KT}\right) \exp\left(\frac{E_F - E_C}{KT}\right) dE$$

$$n = \frac{4\pi}{h^3} (2m_e^*)^{\frac{3}{2}} \exp\left(\frac{E_F - E_C}{KT}\right) \int_{E_C}^{\infty} (E - E_C)^{\frac{1}{2}} \exp\left(-\frac{[E - E_C]}{KT}\right) dE$$

$$\text{Let } \frac{E - E_C}{KT} = x \quad \rightarrow \quad E - E_C = KT x$$

Differentiating above Eq.

$$dE = KT dx \quad \text{Limits } E_C \text{ to } \infty \text{ becomes } 0 \text{ to } \infty$$

$$\therefore n = \frac{4\pi}{h^3} (2m_e^*)^{\frac{3}{2}} \exp\left(\frac{E_F - E_C}{KT}\right) \int_0^{\infty} (KT x)^{\frac{1}{2}} \exp(-x) KT dx$$

$$n = \frac{4\pi}{h^3} (2m_e^* KT)^{\frac{3}{2}} \exp\left(\frac{E_F - E_C}{KT}\right) \int_0^{\infty} (x)^{\frac{1}{2}} \exp(-x) dx$$

$$n = \frac{4\pi}{h^3} (2m_e^* KT)^{\frac{3}{2}} \exp\left(\frac{E_F - E_C}{KT}\right) \left(\frac{\sqrt{\pi}}{2}\right)$$

$$n = \frac{2}{h^3} (2m_e^* KT \pi)^{\frac{3}{2}} \exp\left(\frac{E_F - E_C}{KT}\right)$$

$$n = 2 \left(\frac{2m_e^* KT \pi}{h^2} \right)^{\frac{3}{2}} \exp\left(\frac{E_F - E_C}{KT}\right)$$

No. of electrons in the conduction band

$$n = N_c \exp\left(\frac{E_F - E_C}{KT}\right)$$

$$\text{where } N_c = 2 \left(\frac{2m_e^* KT \pi}{h^2} \right)^{\frac{3}{2}}$$

**** Density of holes in intrinsic semiconductor:** (or)

Concentration of holes in valance band of intrinsic semiconductor: (qualitative)

At 0 K, in intrinsic semiconductor valence electrons are present in the valance band and the conduction band is empty. As temperature increases, electrons move from the valance band to the conduction band (*electron-hole pair generation takes place*). Now the number of electrons (n) in the conduction band (CB) is equal to the number of holes (p) in the valance band (VB). The electrons in the conduction band are called *free electrons* and the holes in the valance band are called *free holes*.

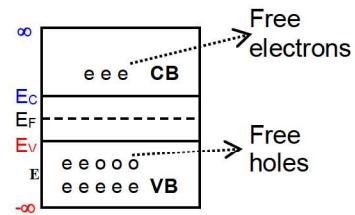
Number of holes = Density of states times the occupancy of holes

$$p = \rho(E) F_h(E)$$

where $\rho(E)$ = density of states with energy in the valance band

$F_h(E)$ = Probability of hole occupancy

$F_h(E) = 1 - F(E)$ (i.e. missing probability of electrons)



$$\therefore \text{Total no. of holes in VB is } \int_{-\infty}^{E_V} dp = \int_{-\infty}^{E_V} \rho(E) F_h(E) dE \quad \text{----- (1)}$$

$$\text{But } \rho(E) = \text{density of states between } E \text{ & } E_V \text{ levels is } = \frac{4\pi}{h^3} (2m_h^*)^{\frac{3}{2}} (E_V - E)^{\frac{1}{2}} \quad \text{----- (2)}$$

Where m_h^* = effective mass of hole

E_V = max. energy of the valance band

E = energy level in VB

h = Plancks constant

K = Boltzman's constant

$$F_h(E) = 1 - F(E) \rightarrow 1 - \frac{1}{1 + \exp\left[\frac{E - E_F}{KT}\right]} \quad \text{----- (3)}$$

Substituting Eq. (2) & (3) in Eq.(1) and solving we will get

$$p = 2 \left(\frac{2m_h^* K T \pi}{h^2} \right)^{\frac{3}{2}} \exp\left(\frac{E_V - E_F}{KT}\right)$$

No. of holes in the valance band

$$p = N_v \exp\left(\frac{E_V - E_F}{KT}\right)$$

$$\text{where } N_v = 2 \left(\frac{2m_h^* K T \pi}{h^2} \right)^{\frac{3}{2}}$$

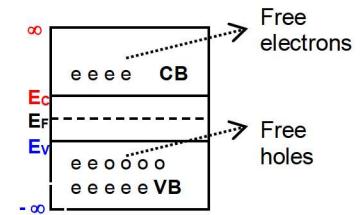
**** Intrinsic carrier concentration:**

At 0 K in an intrinsic semiconductor, valence electrons are present in the valance band and zero electrons in the conduction band. As temperature increases, electrons move from the valance band to the conduction band (*electron-hole pair generation takes place*). The electrons in the conduction band are called *free electrons* and holes in the valance band are called *free holes*. Let 'n' be the number of

electrons in the conduction band and ‘p’ be the number of holes in the valance band. The number of electrons in the conduction band is equal to the number of holes in the valance band.

$$\text{No. of an electron in the conduction band is } n = N_c \exp\left[\frac{E_F - E_C}{KT}\right] \quad \dots\dots (1)$$

$$\text{No. of holes in the valance band is } p = N_v \exp\left(\frac{E_V - E_F}{KT}\right) \quad \dots\dots (2)$$



where E_F is the Fermi energy level, E_V is the top energy level in the valance band,

E_c is the bottom energy level in the conduction band,

N_c & N_v are constants and depends on temperature

$$\text{Here } N_c = 2 \left(\frac{2 m_e^* K T \pi}{h^2} \right)^{\frac{3}{2}} \quad \text{and} \quad N_v = 2 \left(\frac{2 m_h^* K T \pi}{h^2} \right)^{\frac{3}{2}}$$

For any given semiconductor the product of electron (n) and hole (p) concentration remains constant at a given temperature and equal to the square of intrinsic carrier concentration.

In intrinsic semiconductor $n = p = n_i$

$$n \cdot p = n_i^2$$

$$[\text{Eq. (1)}] \times [\text{Eq. (2)}] \rightarrow n \cdot p = N_c \exp\left[\frac{E_F - E_C}{KT}\right] N_v \exp\left[\frac{E_V - E_F}{KT}\right]$$

$$n_i^2 = N_c N_v \exp\left[\frac{E_V - E_C}{KT}\right]$$

$$n_i = (N_c N_v)^{\frac{1}{2}} \exp\left[\frac{-E_g}{KT}\right]^{\frac{1}{2}} \quad (\because E_C - E_V = E_g)$$

$$n_i = (N_c N_v)^{\frac{1}{2}} \exp\left[\frac{-E_g}{2KT}\right]$$

From the above equation, it is clear that,

Intrinsic carrier concentration is independent of the Fermi level (E_F).

Intrinsic carrier concentration is a function of the bandgap (E_g).

Intrinsic carrier concentration depends on the temperature (T).

**** Fermi Energy Level:**

In intrinsic semiconductors, the Fermi energy level is located mid-way between the valance band and conduction band. It depends upon temperature. Let ‘n’ be the number of free electrons in the conduction band and ‘p’ be the number of free holes in the valance band.

$$\text{No. of electrons in the conduction band is } n = N_c \exp\left[\frac{E_F - E_C}{KT}\right] \quad \dots \quad (1)$$

$$\text{No. of holes in the valance band is } p = N_v \exp\left[\frac{E_V - E_F}{KT}\right] \quad \dots \quad (2)$$

where E_F is Fermi energy, E_V is the top energy level in the valance band,

E_c is the bottom energy level in the conduction band,

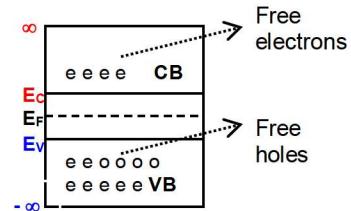
N_c & N_v are constants and depends on temperature

$$\text{Here } N_c = 2\left(\frac{2m_e^* KT \pi}{h^2}\right)^{\frac{3}{2}}, \quad N_v = 2\left(\frac{2m_h^* KT \pi}{h^2}\right)^{\frac{3}{2}}$$

In an intrinsic semiconductor, the number of electrons in the conduction band they are equal to the number of holes in the valance band ($n = p$)

$$\text{i.e. Eq.(1) = Eq.(2)} \quad N_c \exp\left[\frac{E_F - E_C}{KT}\right] = N_v \exp\left[\frac{E_V - E_F}{KT}\right]$$

$$\frac{N_v}{N_c} = \frac{\exp\left(\frac{E_F - E_C}{KT}\right)}{\exp\left(\frac{E_V - E_F}{KT}\right)}$$



$$\frac{N_v}{N_c} = \exp\left(\frac{2E_F - E_C - E_V}{KT}\right)$$

Taking log on both sides

$$\ln\left(\frac{N_v}{N_c}\right) = \left(\frac{2E_F - E_C - E_V}{KT}\right)$$

$$2E_F - E_C - E_V = KT \ln\left(\frac{N_v}{N_c}\right)$$

$$2E_F = E_C + E_V + KT \ln\left(\frac{N_v}{N_c}\right)$$

$$E_F = \frac{E_C + E_V}{2} + \frac{KT}{2} \ln\left(\frac{N_v}{N_c}\right)$$

Let us assume that the effective mass of the electron (m_e^*) is equal to the effective mass of hole (m_h^*)
then $N_c = N_v$

$$\therefore \text{Fermi energy level } (E_F) = \frac{E_C + E_V}{2}$$

The Fermi energy level in intrinsic semiconductors may be considered as independent of temperature and it is midway between E_C and E_V .

**** Electrical conductivity of intrinsic semiconductor (or) Intrinsic conductivity:**

Electrical conductivity is mainly due to two factors.

i.e. Availability of charges & Mobility (μ) of the charge

An empty band doesn't contribute to conduction, since there are no charges. If the band is full also doesn't contribute to conduction, since they cannot move. In an intrinsic semiconductor, the valence band is partly empty and the conduction band is partly filled. (i.e. No. of holes in the valence band equal to No. of electrons in the conduction band). Let 'v' be pd applied to the semiconductor, the charge carriers are forced to move in a particular direction, this phenomenon is known as drift.

Let 'n' be the number of electrons in a semiconductor with charge 'e' then the current density due to electrons is $J_n = neV_d$

$$J_n = ne \mu_n E \quad \text{-----(1)} \quad (\because V_d = \mu_n E)$$

Where V_d is the drift velocity of the electron, μ_n is the mobility of electrons, E is the Electric field

Similarly, the current density due to holes is $J_p = peV_d$

$$J_p = pe \mu_p E \quad \text{----- (2)}$$

Net current density $J = J_n + J_p$

$$J = ne \mu_n E + pe \mu_p E$$

$$J = eE(n \mu_n + p \mu_p) \quad \text{----- (3)}$$

But we know that current density $J = \sigma E$ where σ is conductivity ----- (4)

From Eq.(3) & (4) $\sigma E = eE(n \mu_n + p \mu_p)$

$$\sigma = e(n \mu_n + p \mu_p)$$

But in intrinsic semiconductor $n = p = n_i$

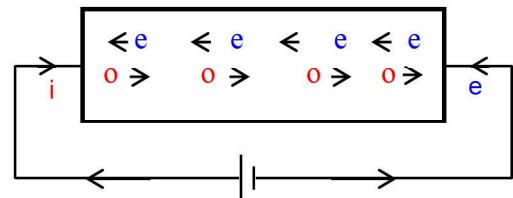
$$\sigma = e n_i (\mu_n + \mu_p) \quad \text{----- (5)}$$

$$\text{But } n_i = (N_c N_v)^{\frac{1}{2}} \exp\left[\frac{-E_g}{2KT}\right]$$

$$\text{Substituting above Eq. in Eq.(5)} \quad \sigma = e (N_c N_v)^{\frac{1}{2}} \exp\left[\frac{-E_g}{2KT}\right] (\mu_n + \mu_p)$$

$$\text{Conductivity } (\sigma) = A \exp\left[\frac{-E_g}{2KT}\right]$$

$$\text{where } A = e (N_c N_v)^{\frac{1}{2}} (\mu_n + \mu_p)$$



**** Extrinsic Semiconductor:**

Because of low conductivity and strong temperature dependence, intrinsic semiconductors are not useful for device applications. With a small number of selected impurities added to the intrinsic semiconductor, we will get extrinsic semiconductors. The process of adding impurities to the host material (intrinsic semiconductors) is called *doping*.

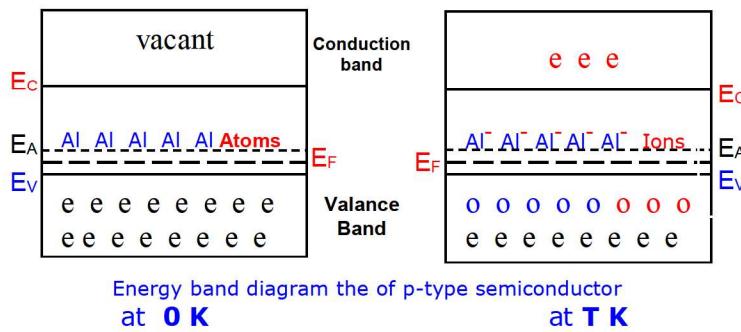
Extrinsic semiconductors are divided into 2 types.

i.e. p-type semiconductor & n-type semiconductor

p - type semiconductor:

Whenever trivalent impurity is added to an intrinsic semiconductor, the p-type semiconductor is formed. (**or**) when a small quantity of acceptor impurity is added to an intrinsic semiconductor, a p-type semiconductor is formed.

Trivalent atoms (III group) such as Gallium (Ga) / Indium (In) / Aluminium (Al) / Boron (B) adding to an intrinsic semiconductor (Ge, Si), then the p-type semiconductor is formed. Si / Ge consists of 4 valence electrons, but the trivalent impurity provides only 3 valance electrons, as a result, a bond takes place between Si & trivalent atom (Al) with a shortage of one electron. To attain stability, it completes 4 covalent bonds by accepting a stray electron from in its vicinity. This stray electron belongs to the Si atom and the Si atom acquires a hole.



In the energy band diagram, E_v is the maximum energy of the valance band, E_c is the minimum energy of the conduction band and E_a is the acceptor energy level (*it is just above the valance band energy level*). In a p-type semiconductor, the Fermi energy (E_f) lies between the acceptor level (E_a) and the valance band energy (E_v).

At '0' K the valance electrons are present in the valance band and trivalent impurity atoms at the E_a level (*CB is empty*), hence at '0' K, p-type semiconductor behaves as insulators. With a small increase in temperature, the electrons move from the valance band to acceptor level (E_a) up to saturation level [*Now impurity atoms (Al) at E_a level become impurity ions (Al⁻)*]. With a further increase in temperature, the electrons move from the valance band to the conduction band.

In a p-type semiconductor, the holes are the majority charge carriers and the electrons are the minority charge carriers. *In a p-type semiconductor, the total number of holes in the valance band is equal to the number of impurity ions in the acceptor level and electrons in the conduction band.*

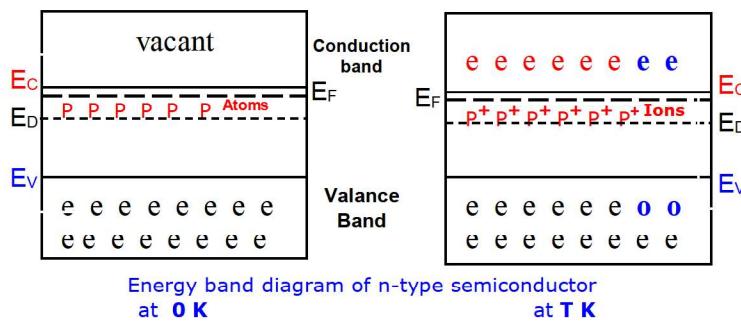
n-type semiconductor:

Whenever pentavalent impurity is added to an intrinsic semiconductor, the n-type semiconductor is formed (**or**) when a small quantity of donor impurity is added to the intrinsic semiconductor n-type semiconductor is formed.

Pentavalent (V group) atoms such as Phosphorus (P)/ Arsenic (As)/ Antimony (Sb)/ Bismuth (Bi) adding to the intrinsic semiconductor (Ge, Si), then the n-type semiconductor is formed. Si / Ge consist of 4 valence electrons, but the pentavalent impurity provides 5 electrons, as a result, 4 covalent bond takes place between Si & P (with an excess of 1 electron). At '0' K the 5th electron is closely bound with the phosphorus atom. With a small increase in temperature phosphorus atom loses its 5th electron and becomes a phosphorus ion, this 5th electron entering into the conduction band.

In the energy band diagram (n-type), E_v is the maximum energy of the valence band, E_c is the minimum energy of the conduction band, and the donor energy level (E_d) is just below the conduction band energy level (E_c). In an n-type semiconductor, the Fermi energy (E_F) level lies between donor level (E_d) and conduction band energy (E_c).

At '0' K the valance electrons are present in the valance band and the pentavalent impurity atoms at E_d level (conduction band is vacant), hence at '0' K the n-type semiconductor behaves as insulators. With a small increase in temperature, the electrons move from the E_d level to the conduction band. This process is continued up to saturation level [*Now impurity atoms (p) at E_d level become impurity ions (p^+)*]. With a further increase in temperature, electrons move from the valance band to the conduction band.



In an n-type semiconductor, the electrons are majority charge carriers and the holes are minority charge carriers. *In an n-type semiconductor, the total number of electrons in the conduction band is equal to the total number of impurity ions in the donor level and the holes in the valance band.*

**** Density of charge carriers in n-type: (or)**

**** Concentration of electrons in n-type semiconductor (or)**

Concentration of electrons in extrinsic semiconductor

(qualitative)

A small percentage of the pentavalent impurity atoms added to the intrinsic semiconductors (such as Ge, Si), then n-type semiconductor is formed. In an extrinsic semiconductor, carrier concentration varies with temperature and impurity concentration. At '0' K the valance electrons are present in the

valence band and pentavalent impurity atoms at the donor energy level [E_D] (at '0' K, the conduction band is vacant). With a further increase in temperature the donor atoms get ionized (*i.e. the impurity atom electron moves to the conduction band*). With the further increase in temperature, now the electrons move from the valence band to the conduction band.

Let 'N_d' be the concentration of donor atoms in donor energy level. In an n-type semiconductor, the electrons are majority charge carriers and the holes are minority charge carriers.

$$\text{We know that the no. of electrons in the conduction band is } (n) = N_c \exp\left[\frac{E_F - E_C}{KT}\right] \quad \text{--- (1)}$$

where *E_F* is the Fermi energy, *E_C* is min. the energy of the conduction band

N_c is constant & depends on temperature

In the n-type semiconductor, the total number of electrons in the conduction band is equal to the sum of ionized donor atoms (N_d⁺) and the number of holes in the valence band. i.e. $n = N_d^+ + p$

At moderate temperatures, concentration holes (p) in the valence band are extremely less

$$\therefore n = N_d^+ \quad \text{--- (2)}$$

{Concentration of ionized donors (N_d⁺) = N_d [1 - F(E_d)]}

where [1 - F(E_d)] is the missing probability of electrons in donor energy level,

$$N_d^+ = N_d \left[1 - \frac{1}{1 + \exp\left(\frac{E_d - E_F}{KT}\right)} \right] \rightarrow N_d^+ = N_d \left[1 - \left\{ 1 + \exp\left(\frac{E_d - E_F}{KT}\right) \right\}^{-1} \right]$$

$$N_d^+ = N_d \left[1 - 1 + \exp\left(\frac{E_d - E_F}{KT}\right) \right]$$

$$\text{Eq.(2)} \rightarrow n = N_d^+ = N_d \left[\exp\left(\frac{E_d - E_F}{KT}\right) \right] \quad \text{--- (3)}$$

But Eq.(1), (3) represents the number of electron in the conduction band

$\therefore \text{Eq.(1)} = \text{Eq.(3)}$

$$n = N_c \exp\left[\frac{E_F - E_C}{KT}\right] = N_d \left[\exp\left(\frac{E_d - E_F}{KT}\right) \right] \rightarrow \exp\left[\frac{2E_F - E_C - E_d}{KT}\right] = \frac{N_d}{N_c}$$

taking Log on both sides

$$\left[\frac{2E_F - E_C - E_d}{KT} \right] = \ln\left(\frac{N_d}{N_c}\right)$$

$$2E_F - E_C - E_d = KT \ln\left(\frac{N_d}{N_c}\right) \rightarrow 2E_F = E_C + E_d + KT \ln\left(\frac{N_d}{N_c}\right)$$

$$E_F = \frac{E_C + E_d}{2} + \frac{KT}{2} \ln\left(\frac{N_d}{N_c}\right) \quad \text{--- (4)}$$

This equation gives position of Fermi level in n-type semiconductor.

Eq.(4) shows that at '0' K Fermi level is in between E_C & E_d and as temperature increases the Fermi level moves down words and crosses the donor level. At high temperature n-type semiconductor loses its extrinsic character and behaves as intrinsic semiconductor.

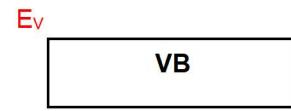
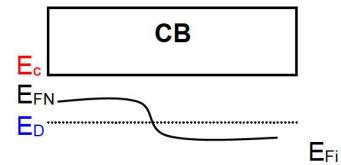
Substituting Eq. (4) in Eq.(1)

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$$n = N_c \exp \left[\frac{\left\{ \frac{E_d + E_c}{2} + \frac{KT}{2} \ln \left(\frac{N_d}{N_c} \right) \right\} - E_c}{KT} \right]$$

$$n = N_c \exp \left[\frac{E_d - E_c}{2KT} + \frac{1}{2} \ln \left(\frac{N_d}{N_c} \right) \right] \rightarrow n = N_c \exp \left[\frac{E_d - E_c}{2KT} + \ln \left(\frac{N_d}{N_c} \right)^{\frac{1}{2}} \right]$$

$$n = N_c \exp \left(\frac{E_d - E_c}{2KT} \right) \left(\frac{N_d}{N_c} \right)^{\frac{1}{2}}$$



On solving (1) & (2) we get

$$n = (N_c N_d)^{\frac{1}{2}} \exp \left(\frac{E_d - E_c}{2 K T} \right)$$

This equation gives the concentration of electrons in an n-type semiconductor.

From the above equation, the number of electrons in CB of n-type semiconductors is directly proportional to the square root of donor concentration. i.e. $n \propto (N_d)^{\frac{1}{2}}$

**** Density of charge carriers in p-type: (or)**

**** Concentration of holes in p-type semiconductor (or)
Concentration of holes in extrinsic semiconductor**

(qualitative)

A small percentage of trivalent impurity atoms added to intrinsic semiconductors (such as Ge, Si), the p-type semiconductor is formed. In an extrinsic semiconductor, carrier concentration varies with temperature and impurity concentration. At '0' K the valance electrons are present in the valance band and trivalent impurity atoms at E_A level (*CB is empty*). With a small increase in temperature, the electrons move from valance band to acceptor level (E_A) up to saturation level [*Now impurity atoms (Al) at E_A level become impurity ions (Al⁺)*]. With a further increase in temperature, now the electrons move from the valance band to the conduction band. In a p-type semiconductor, the holes are majority charge carriers and electrons are minority charge carriers.

We know that the no. of holes in the valance band is $(p) = N_v \exp \left[\frac{E_v - E_F}{K T} \right]$ ----- (1)

where *E_F is the Fermi energy, E_v is top energy of the conduction band,*

N_v is constants & depends on temperature,

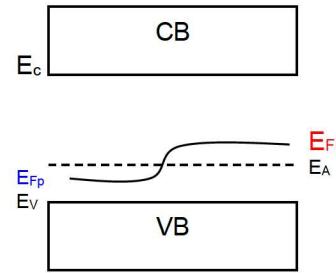
In p-type semiconductor, the total number of holes in valance band is equal to number of impurity ions in acceptor level and electron in conduction band. i.e. $p = N_A^- + n$

At moderate temperature, concentration electrons (p) in conduction band are extremely less

$$\therefore p = N_A^- \quad \text{----- (2)}$$

On solving Eq. (1) & (2), we get

$$p = (N_A N_V)^{\frac{1}{2}} \exp\left(\frac{E_V - E_A}{2 K T}\right)$$



This equation gives the concentration of holes in a p-type semiconductor.

From the above equation, several holes in the valance band of the p-type semiconductor are directly proportional to the square root of acceptor concentration. i.e. $p \propto \sqrt{N_A}$

**** Equation for drift & Diffusion currents:**

Equation for drift currents:

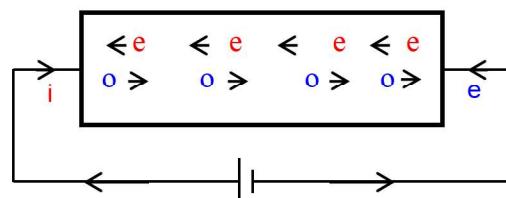
In semiconductors, the free electron was present in the conduction band and holes were present in the valance band. These electrons and holes were responsible for electrical conduction of semiconductors.

[Electrical conductivity is mainly due to 2 factors. i.e. availability of charges & Mobility (μ) of the charge]

Under the influence of an external electric field,

the charge carriers in the semiconductor are forced to move in a particular direction and give electric current.

This phenomenon is known as *drift*.



Let n & p be the number of free electrons & free holes present in the semiconductor. Let 'E' be the applied electric field then force exerts on the charge carrier [$F = eE$], resulting in electrons moving in opposition to the electric field direction and holes moving in the direction of the field. The velocity of carriers is called drift velocity (V_d). As long as temperature constant, V_d of electrons/holes constant. The drift velocity of electrons and holes produces a drift current in the material.

$$\text{Current density of due to electrons is } J_n = n e V_d \quad \text{----- (1)}$$

$$\text{But the drift velocity } V_d = \mu_n E \quad \text{where } \mu_n \text{ is mobility of electrons}$$

$$\therefore J_n = n e \mu_n E \quad \text{----- (2)}$$

Similarly, current density due to holes is $J_p = p e \mu_p E$ ----- (3)

Net current density $J_{\text{drift}} = J_n + J_p$

$$J_{\text{drift}} = n e \mu_n E + p e \mu_p E \quad (\text{Eq. 1 + Eq. 2})$$

$$J_{\text{drift}} = e E (n \mu_n + p \mu_p) \quad \text{----- (4)}$$

Equation for Diffusion current:

Due to non-uniform carrier concentration in semiconductors, the charge carriers move from higher concentration region to lower concentration region and lead to current is called *diffusion current*.

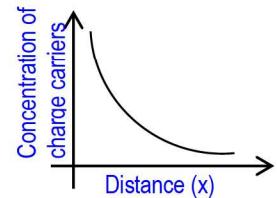
Let $\Delta n, \Delta p$ is the excess in the concentration of electrons and holes in the material.

From *Fick's law*, the rate of diffusion is proportional to concentration gradient

$$\text{Rate of flow of holes through unit area} \propto -\frac{\partial \Delta p}{\partial x}$$

$$\text{Rate of flow of holes through unit area} = -D_p \frac{\partial \Delta p}{\partial x}$$

Where D_p is *diffusion coefficient*



$$\text{Current density due to diffusion hole } (J_p) = e \left[-D_p \frac{\partial \Delta p}{\partial x} \right] \quad \text{----- (5)}$$

$$\text{Similarly current density due to diffusion electrons is } J_n = -e \left[-D_n \frac{\partial \Delta n}{\partial x} \right] \quad \text{----- (6)}$$

Current density due to diffusion is $(J_{\text{diffusion}}) = J_p + J_n$

$$(\text{Eq. 5}) + (\text{Eq. 6}) \rightarrow J_{\text{diffusion}} = e \left[-D_p \frac{\partial \Delta p}{\partial x} \right] + e \left[D_n \frac{\partial \Delta n}{\partial x} \right] \quad \text{----- (7)}$$

$$\text{Net Current density } (J) = J_{\text{drift}} + J_{\text{diffusion}} \quad (\text{i.e. Eq. 4 + Eq. 7})$$

$$J = E e (n \mu_n + p \mu_p) + e \left[-D_p \frac{\partial \Delta p}{\partial x} \right] + e \left[D_n \frac{\partial \Delta n}{\partial x} \right]$$

$$J = e \left[\left(E n \mu_n + D_n \frac{\partial \Delta n}{\partial x} \right) + \left(E p \mu_p - D_p \frac{\partial \Delta p}{\partial x} \right) \right]$$

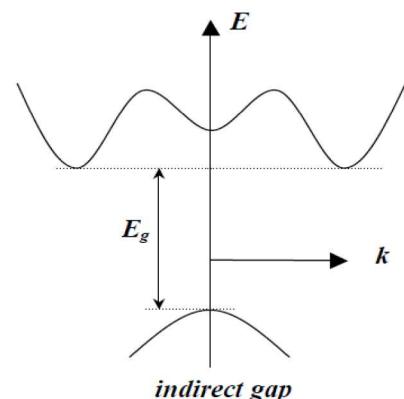
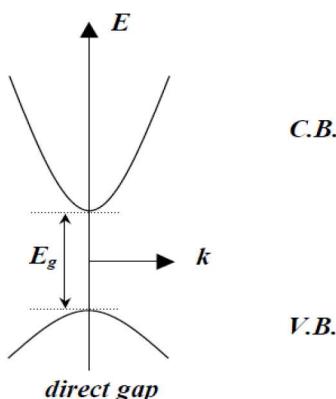
**** Direct & Indirect bandgap semiconductors:**

Semiconductors are available in elemental form (Ge, Si) and compound form (GaAs, InP,).

The gap between the valance band and conduction band is called the bandgap of the material. The bandgap of semiconductors is divided into two types.

i.e. Direct bandgap & Indirect bandgap.

<i>Direct bandgap semiconductor</i>	<i>Indirect band gap semiconductor</i>
<ol style="list-style-type: none"> 1. The minimum energy of the conduction band & maximum energy of the valance band is having the same value of a wave vector (k) is called a direct bandgap semiconductor. 2. The minimum energy of the conduction band is just above the maximum energy of the valance band is called the direct bandgap semiconductor. 3. The electron in the conduction band can recombine with a hole in the valance band directly. 4. Recombination time off is very less 5. Here photons (Light) are emitted during recombination 6. These are used in the fabrication of LED, Laser diode, solar cell, IC 7. These are mostly from the compound semiconductors. 8. Current amplification is less <p><i>Ex:</i> CdS, $GaAs$, ZnS, $CdTe$, SnS_2, GaP, ...</p>	<ol style="list-style-type: none"> 1. The minimum energy of the conduction band & maximum energy of the valance band is not having the same value of a wave vector is called an indirect bandgap semiconductor. 2. The minimum energy of the conduction band is not above the maximum energy of the valance band is called the indirect bandgap semiconductor. 3. The electron in the conduction band can recombine with a hole in the valance band indirectly through taps. 4. Recombination time is more 5. Here phonons (Heat) are emitted during recombination. 6. These are used to amplify signals in the case of diodes, transistors, etc. 7. These are mostly from the elemental semiconductors. 8. Current amplification is more. <p><i>Ex:</i> Si, Ge, SnS,</p>



**** Hall Effect:**

"When a current-carrying specimen is kept in a uniform magnetic field in a perpendicular direction, then a voltage is developed perpendicular to both the current and the magnetic field directions."

Let 'i' be the current passing through the specimen (along X-axis) and 'B' be the applied magnetic field (along Z-axis) then the force experienced on the electron is ' $eV_d B$ '. Due to this force, electrons move downward direction and cause -ve charges to accumulate on the bottom of the specimen, and the corresponding positive charges on the upper surface of the specimen. As result potential difference is established from the top to bottom surface of the specimen and causes an electric field along Y-axis. The developed electric field is called **Hall electric field** (E_H) and the voltage is called **Hall voltage** (V_H).

Due to magnetic field, force acting on electron $F = e V_d B$ ----- (1)

$$\text{Electrostatic force } F = e E_H \quad \text{----- (2)}$$

At equilibrium Eq.(1) = (2) $e V_d B = e E_H$

$$E_H = V_d B \quad \text{----- (3)}$$

We have current density (J) = $n e V_d$ ----- (4)

where 'n' is no. charge carriers

' V_d ' is drift velocity of electrons

$$\text{From Eq. (4)} \quad V_d = \frac{J}{ne}$$

$$\text{Substituting above Eq. in Eq. (3), then } E_H = \frac{J B}{ne} \quad \text{----- (5)}$$

But Hall electric filed is proportional to current density (J) and magnetic field (B)

$$E_H \propto J B$$

$$E_H = R_H J B \quad \text{----- (6)}$$

where ' R_H ' is Hall coefficient

$$\text{From Eq. (5) \& (6)} \quad R_H J B = \frac{J B}{ne}$$

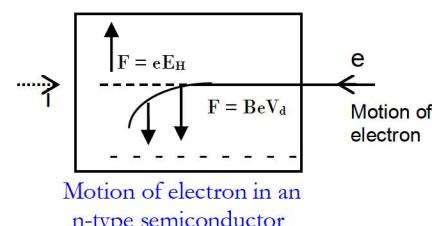
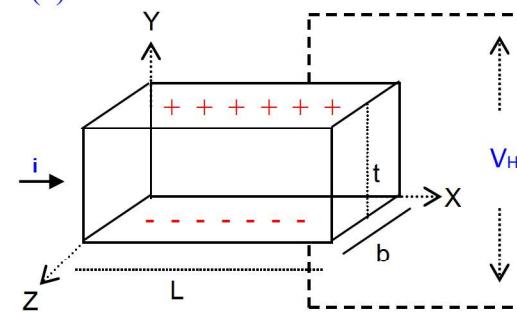
$$R_H = \frac{1}{ne}$$

For n-type semiconductors, the hall coefficient is $-\frac{1}{ne}$

For p-type semiconductors, the hall coefficient is $+\frac{1}{ne}$

Let 'L, b, t' be the length, breadth and thick ness of sample, then we have $E_H = \frac{V_H}{b}$

$$\text{From Eq. (6)} \quad R_H = \frac{E_H}{J B}, \text{ substituting } E_H \text{ in this equation}$$



$$R_H = \frac{V_H}{J B b} \quad \rightarrow \quad V_H = R_H J B b$$

But current density (J) = $\frac{\text{current } (i)}{\text{area } (a)} = \frac{i}{b t}$

$$\therefore V_H = R_H \frac{i}{b t} B b$$

$$V_H = \frac{R_H i B}{t}$$

or

$$R_H = \frac{V_H t}{i B}$$

Applications of Hall Effect:

- 1) Determination of the type of semiconductor.
- 2) To calculate carrier concentrations.
- 3) To find the hall mobility.
- 4) To find the resistivity of the material.
- 5) To study the electrical properties of the material at various temperatures.
- 6) Used in sensors to sense a magnetic field.
- 7) Used in magnetically activated electronic switches.

**** p-n Junction:**

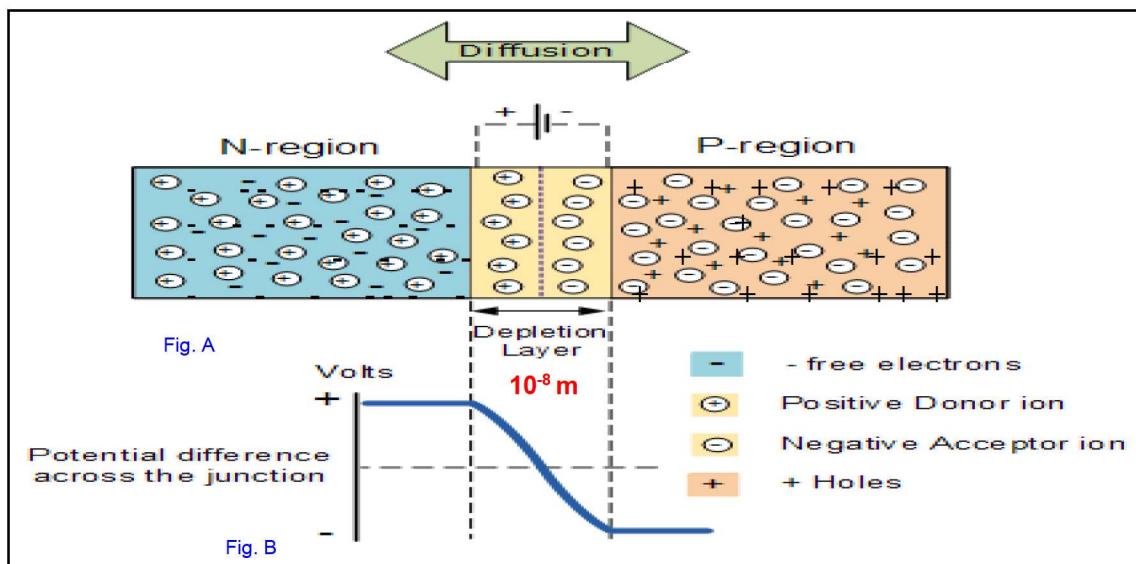
A piece of semiconductor, if one half is doped with trivalent impurity & other half is doped with a pentavalent impurity, as a result, $p\text{n}$ junction diode is formed. The plane dividing the two zones is called $p\text{n}$ Junction. *In a p-type semiconductor, the total number of holes in the valance band is equal to the number of impurity ions in the acceptor level and free-electron in the conduction band. In an n-type semiconductor, the total number of electrons in the conduction band is equal to the number of impurity ions at donor level and free holes in the valance band.*

When p & n-type semiconductors are kept close together and by supplying thermal energy, the diffusion process takes place at the junction. i.e. The free electrons in the 'n' region begin to diffuse across the junction and combine with the holes in the 'p' region near the junction. This makes the 'n' region lose free electrons and creates a layer of positive charges (*immobile charges*) near the junction. As the free electrons combine with the holes in the 'p' region, the 'p' region also loses holes and creates a layer of negative charges (*immobile charges*) near the junction. As result the p-region surface occupied with -ve ions and the n-region surface occupied with +ve ions, this region is called the *depletion region*. The width of depletion regions is about 10^{-8} m.

Ex. At room temperature, the potential barrier of Ge is about 0.3 V and Si is about 0.7 V.

$p\text{n}$ junction is represented by 

From Fig. A, it is clear that electron concentration remains constant throughout the n-region the hole concentration remains constant throughout the p-region. In the depletion region, the n-side contains +ve ions and -ve ions on the p-side, hence n-region consists of higher potential (shown in Fig. B)



Energy band diagram of p-n Junction Diode:

The energy band diagram of individual p & n semiconductors is shown in Fig.(c) & (d). In a p-type semiconductor, the Fermi level is close to the valance band and in the n-type Fermi level is close to the conduction band. When the contact is made between p & n-type semiconductors, the electrons in the conduction band of n-type material travel across the junction, this process takes place until the Fermi level in both regions is adjusted to the same level (Fig. e). The conduction band of a p-type moves upwards by eV_B over the conduction band of an n-type. The immobile charges (ions) remain at the junction and they process as internal potential V_B .

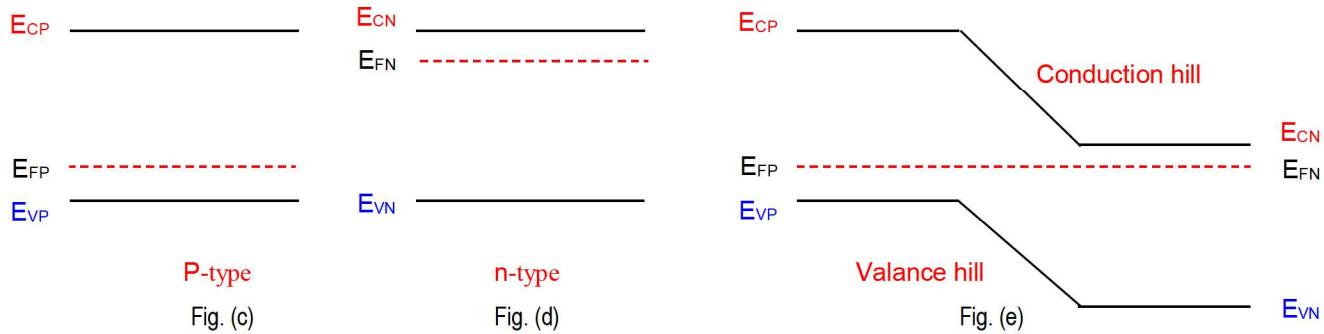


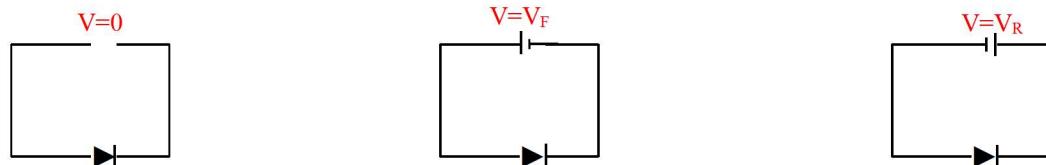
Fig. (c) Energy level diagram of the p-type semiconductor

Fig. (d) Energy level diagram of n-type semiconductor

Fig. (e) Energy level diagram of pn junction

Biased p-n junction:

p-n junction without battery connection is called an *unbiased condition*. Battery +Ve terminal is connected to p-region and -Ve terminal is connected to n-region, then p-n junction is said to be under *forward biased condition*. Battery +Ve terminal connected to n-region and -Ve terminal connected to p-region, then p-n junction is said to be under *reverse biased condition*.



The pn junction acts as a closed switch in forwarding bias condition and an open switch under reverse bias condition. This phenomenon is called rectifying action.

Optoelectronic devices

**** Light Emitting Diode (LED):**

LED is a specially made p-n junction diode that produces radiation (*Visible & IR*) under forward biased condition and this phenomenon is called electroluminescence. In the p-n junction, under forward bias condition the free electrons in n-regions move towards the p-region, and holes in the p-region move towards the n-region, as results increase the local minority carrier population than the normal value. This process is known as *minority carrier injection* (shown in Fig. B).

The excess minority electrons in the conduction band of the p-region recombine with the majority holes in the valance band of the p-region and emit photon energy ($h\nu$)/(light). Similar action (E_c to E_v) takes place in the n-region also. The brightness of the emitted light is proportional to the forward bias current.

$$E_c \sim E_v \rightarrow h\nu$$

To get a large photon emission/sec, a large number of electrons and holes recombine should take place/sec. *Hence doping concentration in p & n regions should be large*. In general the impurity concentration in n region $>$ p region.

As photons pass through the p-region, some of them get absorbed. This can be reduced by making the p-region very thin. For improving the efficiency of LED, the bottom electrode is coated with a reflective surface. *Under reverse bias conditions, no minority injection takes place hence there is no light.*

LED is represented by 

Due to recombination, emitted energy $E_c - E_v = h\nu$

$$E_g = h\nu \quad (\because E_g = E_c - E_v)$$

$$\text{But } c = \nu\lambda \quad \rightarrow \nu = \frac{c}{\lambda}$$

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$$\therefore E_g = \frac{hc}{\lambda}$$

$$\text{Wave length of emitted photon is } \lambda = \frac{hc}{E_g}$$

where h is Planck's constant ($6.626 \times 10^{-34} \text{ JS}$), c is the velocity of light, and E_g is the energy gap of the material.

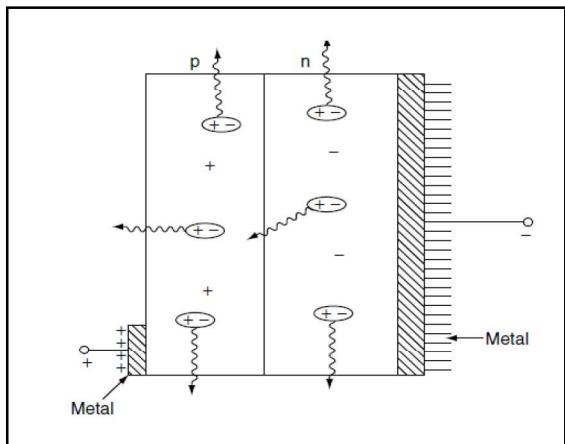


Fig. A

(or)

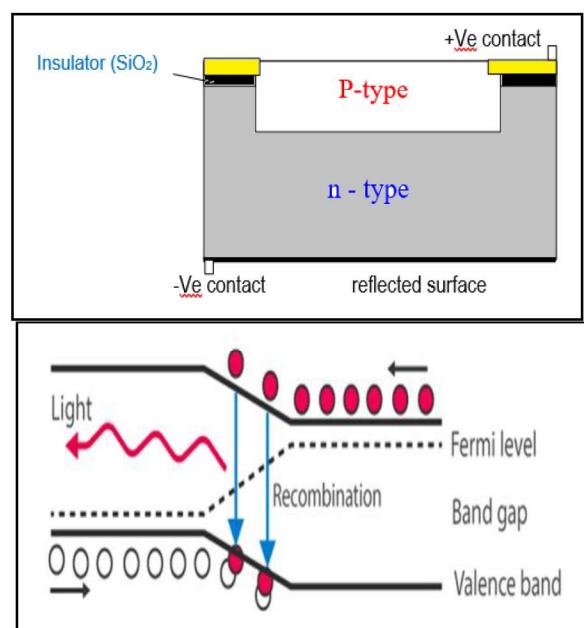


Fig. B

LED materials should have the following properties:

1. Both p and n-type must have low resistance.
2. The emitted color depends upon the bandgap of the material.
3. For visible radiation bandgap of a semiconductor is between 1.7 to 3.2 eV.
4. The refractive index of LED material is about 3.3 to 3.8.
5. Critical angle (θ_c) = $\text{Sin}^{-1}\left(\frac{n_1}{n_2}\right)$ where n_1, n_2 are refractive indices of air and semiconductor.

$$\theta_c = 15 \text{ to } 18^\circ$$

6. III-V group compound semiconductors are generally used for LEDs.
7. LED operation between 1.5 V & 10 mA.

Application of LED:

- 1) LED's are very fast response (n sec) hence they are used in fiber optical communication as a light source.
- 2) They have a long life (10^5 hrs.)
- 3) They can operate up to 0 to 70°C , hence suitable for all environments
- 4) Very small in size, viewing angle is not limited hence they have used multimeters, cell phones, digital watches, calculators, etc.
- 5) These are used in light indicators.
- 6) These are used in traffic signals.
- 7) These are used in the home light systems, street lights, floodlights, etc.
- 8) LED's arranged group of seven segments, used in the numeric display. These are also used in alpha numeric displays.
- 9) Very rugged, suitable for any environment hence used as sensors. (Counting missions)

Note:

* Different LED materials in the visible region

$$\begin{array}{lll} \text{GaP} \rightarrow \text{Green} & \text{GaN} \rightarrow \text{Blue} & \text{GaAs} \rightarrow \text{IR} \\ \text{SiC} \rightarrow \text{Blue} & \text{AlInGaP} \rightarrow \text{Yellow} & \text{GaAsP} \rightarrow \text{Yellow} \\ & & \text{AlGaAs} \rightarrow \text{Red} \end{array}$$

* White light LED is having high efficiency

* 16 W LED bulb was bright as 150 W halogen lamp.

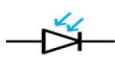
Threshold voltage: It is defined as the minimum forward voltage required for the LED to start glowing. i.e. the forward current starts flowing through the p-n junction of the LED.

**** Photodiode:**

The photodiode is a light-sensitive device, which converts light signals into electrical signals. These are also called photodetectors. The photodiode is a specially made p-n junction diode, which works under reverse biased conditions.

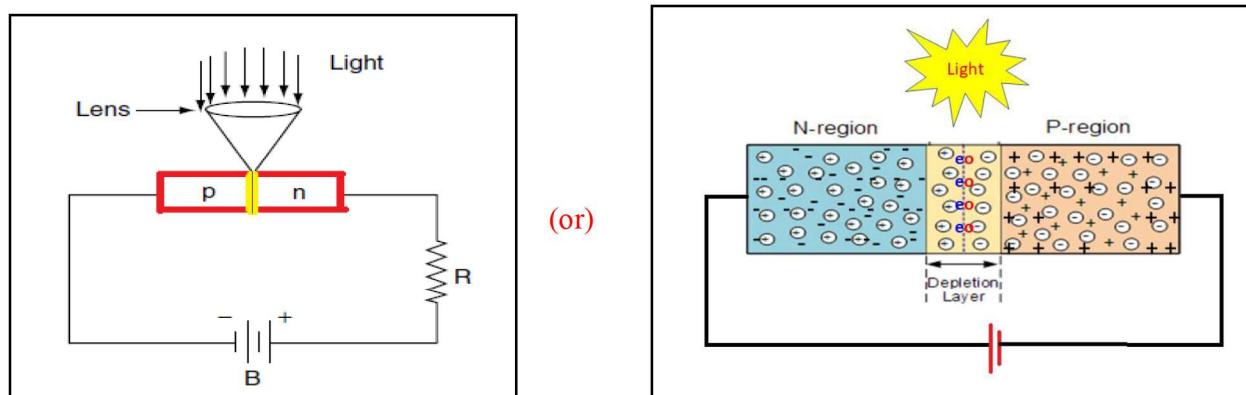
Photodiode which works under photoconductive mode. Photoconductivity is an optical and electrical phenomenon in which a material becomes more electrically conductive due to the absorption of electromagnetic radiation (i.e., visible light, ultraviolet light, infrared light, or gamma radiation.)

Photodiode is represented by



During the fabrication of the pn junction diode, a depletion region is formed at the junction region with the impurity ions. (The surface of the p-region consists of -ve ions & the surface of the n-region consists of +ve ions). These ions stop the motion of majority carriers but accelerate minority carriers across the junction. When photon energy (light) is incident in the junction region, electron-hole pairs are generated within the depletion region. The electric field (due to impurity ions) in the depletion region separates the generated electron-hole pair and these carriers are swept to their respective majority sides. This motion of minority carriers causes a reverse current. Even when no light is present, a small current exists, this current is called *dark current*. The dark current depends on the reverse bias voltage, the series resistance, and ambient temperature.

A photon of energy $h\nu \geq E_g$ incident in or near the depletion region of the diode, the photon can give up its energy and excite an electron from the valence band to the conduction band (*causes electron-hole pair generation*). These electron-hole pair is separated in the depletion region and drifts in opposite direction under the action of the electric field. The reverse current increases with an increase in the intensity of light incident on the photodiode. A reverse biased p-n junction (photodiode) is shown below.



The main disadvantage of this p-n photodiode is the depletion regions are relatively small when compared with diode volume, hence only a few photons are absorbed in the depletion region and cause a current. The photons absorbed in the bulk of the diode do not result in current. This problem is minimized in the p-i-n photodiode.

Note: p-i-n photodiode: In this device p-n region is separated by a wide intrinsic region (i). The first and most important feature of the p-i-n photodiode is that its depletion region extends well into the intrinsic region. When a photon of energy $h\nu \geq E_g$ incident in or near the depletion region of the diode, the photon can give up its energy and excite an electron from the valence band to the conduction band (*causing free electron-hole pair*). The impurity ions in the depletion region cause the free carriers to separate and be collected across the reverse bias junction. As the intrinsic layer is wide enough, most of the photons are absorbed and a large photocurrent is produced. Hence p-i-n photodiode is more sensitive than a p-n photodiode.

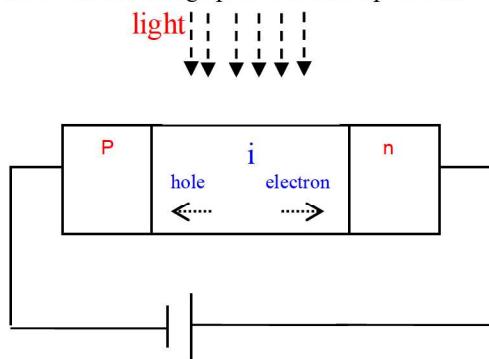


Fig. Reverse biased p-i-n junction (photodiode)

Applications:

1. Photodiodes are used in optical communications
2. Light operating switches
3. High speed counting's and switching circuits
4. Electronic control circuits
5. Which are used in light detectors, demodulators.
6. Used in light detectors.
7. These are used in speed guns / Sensor applications

**** Semiconductor diode laser:**

Hall and coworkers constructed semiconductor lasers (GaAs) in 1962. The semiconductor diode laser is “*a specially made pn junction diode, which emits coherent light under forward biased condition*”.

Construction:

The pn junction diode is extremely small in size (*about 1 mm³*). The top and bottom faces of the diode are metalized, these metal contacts are provided to pass current through the diode. The ends are polished, now they are parallel to each other and perpendicular to the junction. The entire structure is packed in a small case. To achieve population inversion p & n regions are heavily doped with impurities, the p-n junction serves as the active medium. The semiconductor laser is shown in Fig. A.

Working:

Heavily doped p and n regions are used in making laser diodes. Due to heavily doped impurities, the Fermi level in n-type is pushed into the conduction band and in p-type, E_F is pushed into the valence band. When the power is switched on, under the forward biased condition the electrons and holes are injected into the junction region and recombination of electron-hole takes place, as a result, the laser beam is emitted from the p-n junction region. Under the forward bias condition, the free electrons in the n-region move towards the p-region, and electron concentration increases therefore the condition of population inversion is established and causes a laser beam.

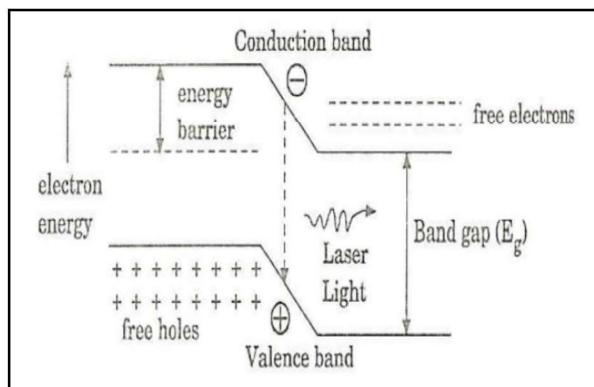


Fig. B

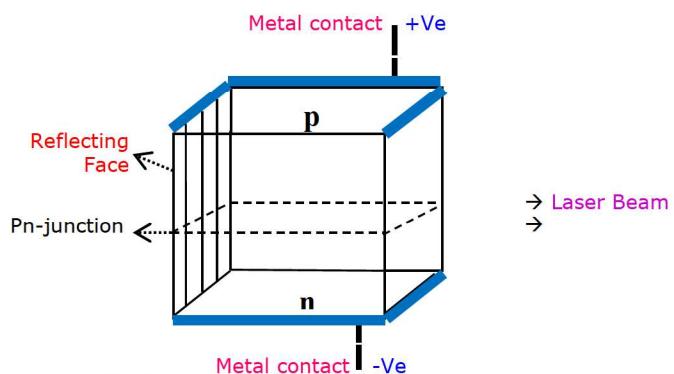


Fig. A

The bandgap of GaAs semiconductor is 1.4 eV and emits a laser beam of wavelength about **8874 Å**. GaAs lasers operated at low temperatures and emit wavelength in the infrared region (IR). Using pn junction we can produce anywhere in the spectrum from UV to IR. *The wavelength of the radiation depends on the energy gap of the semiconductor.*

$$\text{We have } E = E_g = hv \quad \dots \quad (1)$$

$$\text{But } c = v\lambda \rightarrow v = \frac{c}{\lambda}$$

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$$\text{Eq. (1)} \rightarrow E_g = \frac{hc}{\lambda}$$

$$\lambda = \frac{hc}{E_g}$$

where 'h' is Planck's constant (6.63×10^{-34} JS),

'c' is the velocity of light, 'v' is the frequency of radiation,
 E_g is the bandgap

Advantages:

- i. The efficiency of laser is approximately equal to He-Ne laser.
- ii. Mass production is possible
- iii. Suitable for optical communication
- iv. Diode lasers are less expensive.
- v. Continuously operate at room temperature.
- vi. Diode lasers are small in size, hence they are used in CD players, CD-Roms, high-speed laser printers, etc.

Note:

* In practice there is no necessity to polish the faces in semiconductor diode laser since GaAs has a high refractive index and ensure sufficient high reflection at the material.

* Direct band semiconductors are favorable for lasers

* If both pn are made up of the same material the junction is called homojunction semiconductor laser Ex. GaAs laser

* If pn is made up of different materials, the junction is a heterojunction semiconductor laser.

Ex. GaAs on one side and GaAlAs on the other side

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M.B. University
Tiruapti

Find the resistivity of an intrinsic semiconductor with intrinsic concentration of 2.5×10^{19} per m³. The mobilities of electrons and holes are 0.40 m²/V-s and 0.20 m²/V-s.

Intrinsic concentration (n_i) = $2.5 \times 10^{19}/\text{m}^3$

Mobility of electrons (μ_n) = 0.40 m²/V-s

The mobility of holes (μ_p) = 0.20 m²/V-s

Resistivity of an intrinsic semiconductor (ρ_i) = ?

$$\sigma_i = n_i e [\mu_n + \mu_p]$$

$$\text{The resistivity } (\rho_i) = \frac{1}{\sigma_i} = \frac{1}{n_i e [\mu_n + \mu_p]}$$

$$= \frac{1}{2.5 \times 10^{19} \times 1.6 \times 10^{-19} [0.40 + 0.20]}$$

$$= \frac{1}{2.5 \times 1.6 \times 0.6} = 0.4166 \Omega \cdot \text{m}.$$

The Hall coefficient of a semiconductor is 3.22×10^{-4} m³/C. Its resistivity is 8.50×10^{-3} Ω-m. Calculate the mobility and carrier concentration of the carriers.

R_H Semiconductor is 3.22×10^{-4} m³/C

Mobility = ?

Resistivity is 8.50×10^{-3} Ω-m

Carrier concentration = ?

$$R_H = \frac{1}{P e}$$

$$\text{Carrier concentration } (P) = \frac{1}{R_H e}$$

$$= \frac{1}{3.22 \times 10^{-4} \times 1.6 \times 10^{-19}}$$

$$= 19.4 \times 10^{21} \text{ m}^{-3}$$

$$\sigma = P e \mu_p$$

$$\mu_p = \frac{\sigma}{P e} \quad \rightarrow \quad \mu_p = \sigma R_H$$

$$\rightarrow \quad \mu_p = \frac{R_H}{P}$$

$$\mu_p = \frac{3.22 \times 10^{-4}}{8.50 \times 10^{-3}}$$

$$\text{Mobility of carriers: } = 0.0378 \text{ m}^2/\text{V-s}$$

Mobilities of electrons and holes in a sample of intrinsic germanium at 300 K are $0.36 \text{ m}^2/\text{V}\cdot\text{s}$ and $0.17 \text{ m}^2/\text{V}\cdot\text{s}$, respectively. If the resistivity of the specimen is $2.12 \Omega\cdot\text{m}$, compute the intrinsic concentration.

$$\begin{aligned}\mu_e &: 0.36 \text{ m}^2/\text{V}\cdot\text{s} & \text{Intrinsic concentration } (n_i) : ? \\ \mu_h &: 0.17 \text{ m}^2/\text{V}\cdot\text{s} \\ \rho &: 2.12 \Omega\cdot\text{m} & \sigma_i = n_i e [\mu_n + \mu_p] \\ T &: 300 \text{ K} & n = \frac{\sigma}{e[\mu_n + \mu_p]} \\ & & n = \frac{1}{\rho e [\mu_n + \mu_p]} \\ & & = \frac{1}{2.12 \times (1.6 \times 10^{-19}) \times (0.36 + 0.17)} = 556.25 \times 10^{16} / \text{m}^3\end{aligned}$$

A silicon plate of thickness 1 mm, breadth 10 mm and length 10 mm is placed in a magnetic field of 0.5 wb/m^2 acting perpendicular to its thickness. If 10^{-2} A current flows along its length, calculate the Hall voltage developed if the Hall coefficient it $3.66 \times 10^{-4} \text{ m}^3/\text{Coulomb}$.

$$\begin{aligned}t &= 1 \text{ mm} = 1 \times 10^{-3} \text{ m} & V_H : ? \\ b &= 10 \text{ mm} = 10 \times 10^{-3} \text{ m} \\ l &= 10 \text{ mm} = 10 \times 10^{-3} \text{ m} & V_H = \frac{R_H i B}{t} \\ B &= 0.5 \text{ wb/m}^2 \\ i &= 10^{-2} \text{ A} & V_H = \frac{(3.66 \times 10^{-4}) \times (10^{-2}) \times 0.5}{1 \times 10^{-3}} \\ R_H &= 3.66 \times 10^{-4} \text{ m}^3/\text{C} & V_H = 1.83 \times 10^{-3} \text{ V} \\ & & V_H = 1.83 \text{ mV}\end{aligned}$$

The Hall coefficient of certain silicon specimen was found to be $-7.35 \times 10^{-5} \text{ m}^3/\text{C}\cdot\text{K}$ from 100 to 400 K. Predict the nature of the semiconductor. If the conductivity was found to be $200 \text{ /}\Omega\text{m}$. Calculate the density and mobility of the charge carrier?

$$\begin{aligned}R_H &: -7.35 \times 10^{-5} \text{ m}^3/\text{C} \\ T &: 100 \text{ to } 400 \text{ K} & \text{Density charge carrier: ?} \\ \sigma &: 200 \text{ /}\Omega\text{m} & \text{Mobility of the charge carrier: ?} \\ & & \boxed{R_H : -Ve \rightarrow \text{it is n-type semiconductor}} \\ R_H &= \frac{1}{ne} & \text{Conductivity } (\sigma) = n e \mu_n \\ & & \text{Mobility } (\mu_n) = \frac{\sigma}{n e} \\ & & \text{Mobility } (\mu_n) = R_H \sigma \\ \text{Carrier concentration/} & & \mu_n = 7.35 \times 10^{-5} \times 200 \\ \text{Density of charge carrier } (n) &= \frac{1}{R_H e} & \mu_n = 14.7 \times 10^{-3} \text{ m}^2/\text{V}\cdot\text{s}^{-1} \\ n &= \frac{1}{(7.35 \times 10^{-5}) \times (1.6 \times 10^{-19})} = 8.503 \times 10^{22} \text{ m}^{-3}\end{aligned}$$

Calculate the wavelength of emitted radiation from GaAs which has a band gap of 1.44 eV.

$$\begin{aligned}E_g &: 1.44 \text{ eV} = 1.44 \times 1.6 \times 10^{-19} \text{ J} \\ \lambda &: ? \\ h &= \text{Planck's constant} = 6.63 \times 10^{-34} \text{ J}\cdot\text{s} \\ C &= 3 \times 10^8 \text{ m/s}\end{aligned}$$

$$\begin{aligned}\text{Wave length of emitted photon is } & \lambda = \frac{hc}{E_g} \\ & \lambda = \frac{(6.63 \times 10^{-34}) \times (3 \times 10^8)}{1.44 \times 1.6 \times 10^{-19}} \\ & = 8633 \times 10^{-10} \text{ m} \\ & = 8633 \text{ \AA}\end{aligned}$$

A current of 50 A is established in a slab of Cu 0.5 cm thick and 2 cm wide. The slab is placed in a magnetic field of 1.5 T. The magnetic field is perpendicular to the plane of the slab and to the current. The free electron concentration in copper is $8.48 \times 10^{28} \text{ e/m}^3$. What will be the magnitude of Hall voltage across the width of the slab.

$$i = 50 \text{ A}$$

$$t = 0.5 \text{ cm} = 0.5 \times 10^{-2} \text{ m}$$

$$V_H = ?$$

$$b = 2 \text{ cm} = 2 \times 10^{-2} \text{ m}$$

$$V_H = \frac{R_H i B}{t}$$

$$R_H = \frac{1}{ne}$$

$$B = 1.5 \text{ Tesla}$$

$$n = 8.48 \times 10^{28} \text{ e/m}^3$$

$$V_H = \frac{i B}{n e t}$$

$$V_H = \frac{50 \times 1.5}{(8.48 \times 10^{28}) \times (1.6 \times 10^{-19}) \times (0.5 \times 10^{-2})}$$

$$V_H = 1.116 \times 10^{-6} \text{ V}$$

A semiconductor diode laser has a peak emission wavelength of 1.55 μm . Find its band gap in eV.

$$\lambda : 1.55 \mu\text{m} = 1.55 \times 10^{-6} \text{ m}$$

$$h = \text{Planck's constant} = 6.63 \times 10^{-34} \text{ J-S}$$

$$E_g : ?$$

$$C = 3 \times 10^8 \text{ m/s}$$

$$\text{Wave length of emitted photon is } \lambda = \frac{hc}{E_g} \rightarrow E_g = \frac{h c}{\lambda}$$

$$E_g = \frac{(6.63 \times 10^{-34}) \times (3 \times 10^8)}{1.55 \times 10^{-6}} \text{ J}$$

$$E_g = \frac{(6.63 \times 10^{-34}) \times (3 \times 10^8)}{(1.55 \times 10^{-6}) \times (1.6 \times 10^{-19})} \text{ eV}$$

$$E_g = 0.8 \text{ eV}$$

Calculate the number of donor atoms per m^3 of n-type material having resistivity of 0.25 $\Omega\text{-m}$, the mobility of electrons is $0.3 \text{ m}^2/\text{V}\cdot\text{s}$.

Resistivity of n-type semiconductor is $0.25 \Omega\text{-m}$

Number of donor atoms per m^3 : ?

Mobility of electrons is $0.3 \text{ m}^2/\text{V}\cdot\text{s}$

$$\sigma = n e [\mu_n + \mu_p] \rightarrow \sigma = n e \mu_n$$

$$\rho = \frac{1}{n e \mu_n}$$

n = number of free electron per m^3 \approx number of donor atoms in n-type

$$n = \frac{1}{\rho e \mu_n} = \frac{1}{0.25 \times 1.6 \times 10^{-19} \times 0.3} = 8.333 \times 10^{19} \text{ per m}^3$$