

## UNIT IV

### CHAPTER 1

## SEMICONDUCTORS

### Semiconductors:

A Semiconductor is a substance whose conductivity or resistivity ( $10^{-4}$  to  $0.5 \text{ ohm-m}$ ) lies in between conductors and insulators.

Examples: Si, Ge, GaAs, AlAs and InP etc.

### Properties:

- They have crystalline structure.
- They are formed by covalent bonds.
- They have negative temperature of coefficient of resistance.
- At  $T=0\text{K}$ , they behaves as insulators.
- When the impurities (III group or V group elements) added to the pure semiconductor, then electrical conductivity increases.

### Direct Band Gap And Indirect Band Semi Conductors:

Based on the type of energy emission the semiconductors can be of two groups.

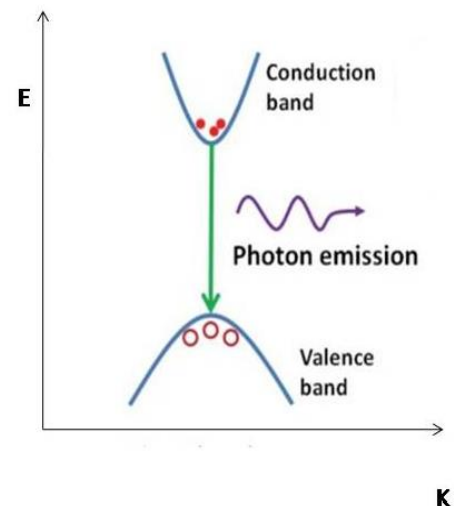
1. Direct band gap semiconductors
2. Indirect band gap semiconductors

### Direct Band Gap Semi Conductors:

- The semiconductor, in which the minimum of the conduction band lies directly above the maximum of the valance band in the E-K space diagram (as shown in fig), is known as direct band gap semiconductor.
- In a direct band gap semiconductor such as GaAs, AlAs and InP, when an excited electron falls back into the valence band, the electrons and holes recombine to produce light energy.

*i.e.,  $\bar{e} + \text{hole} \longrightarrow h\nu \text{ (photon)}$*

- This process is known as radiative recombination and also called spontaneous emission.
- These direct band gap semiconductors are used to make LED's and lasers of different colours.

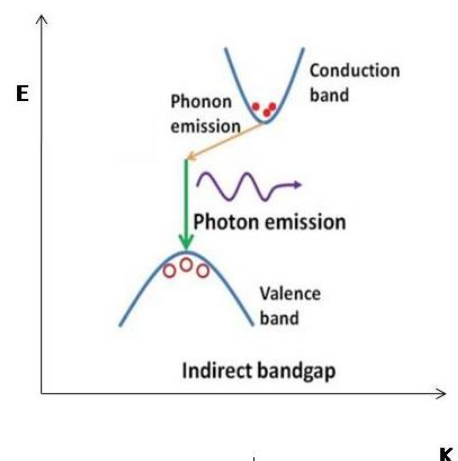


### Indirect Band Gap Semi Conductors:

- The semiconductor, in which the minimum of the conduction band does not lies directly above the maximum of the valance band in the E-K space diagram( as shown in fig), is known as indirect band gap semiconductor.
- In an indirect gap semiconductor such as Si, Ge and Gap, when an excited electron falls back into the valence band, the electrons and holes recombine to generate heat and is dissipated within the material.

*i.e.,  $\bar{e} + \text{hole} \longrightarrow \text{phonon}$*

- This process is known as non-radiative recombination.

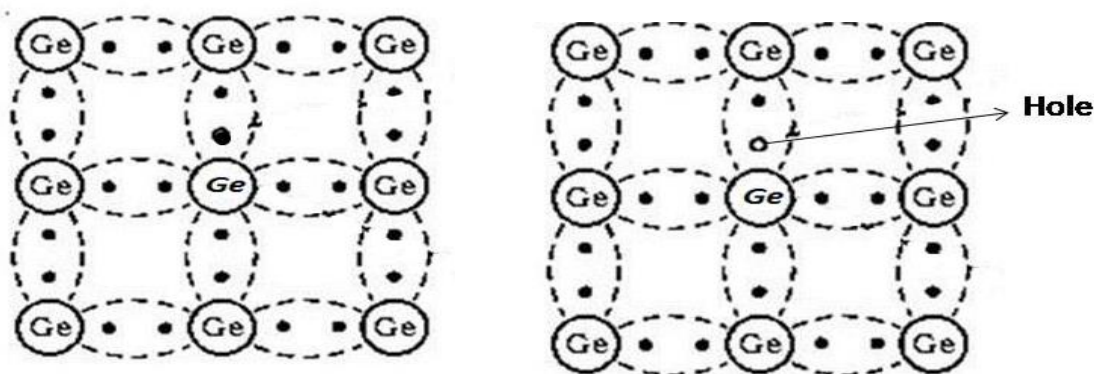


**Based on purity semiconductors are classified into types,**

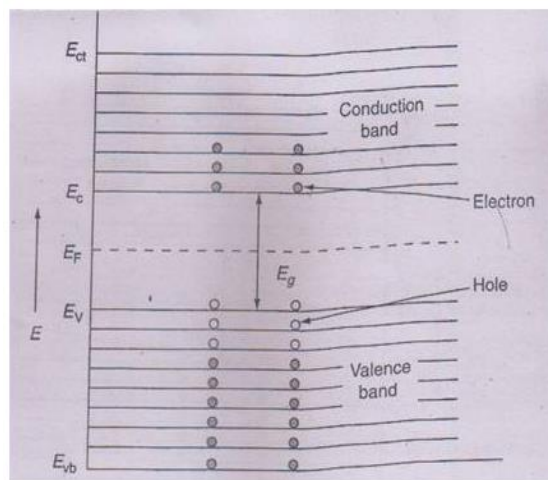
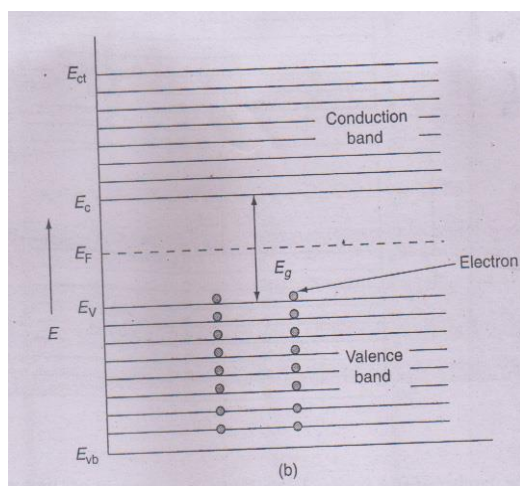
- ### Intrinsic semiconductor:

Examples: Si, Ge etc.

- Consider a pure (semi conductor) Si or Ge Crystal. We know that Ge is a fourth group element, i.e., it has four valence electrons; to get stability each silicon atom will make four covalent bonds with neighboring Silicon atoms as shown in fig.
- **At absolute zero temperature (0K):** all the electrons are tightly bound by the semi conductor atoms and the covalent bonds are very strong. So there are no free electrons. *Therefore, the semi conductor crystal behaves as a perfect insulator at absolute zero temperature.*



- a) At  $T=0K$
- b) At  $T > 0K$
- **Above absolute zero ( $> 0 K$ ):** When the temperature is raised, some of the covalent bonds in the semi conductor break due to the thermal energy supplied.
- The breaking of bonds set those electrons free, at the same time vacant site produced in the covalent bond called “hole”.
- The result is that a few free electrons exist in the semi conductor. These free electrons can constitute a tiny electric current if potential difference is applied across the semi conductor as shown in fig(c)
- **Energy band description:** Fig (d) shows the energy band diagram. As the temperature is raised, some of the valence electrons acquire sufficient energy to enter into the conduction band and thus become free electrons.
- Under the influence of electric field, these free electrons will constitute electric current. It may be noted that each time a valence electron enters into the conduction band; a hole is created in the valence band, which acts a positive charge.
- For one electron set free one hole is created. Therefore, thermal energy creates hole-electron pairs;
- In an intrinsic semi conductor, even at room temperature electron-hole pairs are created. Every free electron creates one hole in the valence band.
- *Therefore the number of electrons in the conduction band and the number of holes in the valence band become equal.*



- a) At  $T=0K$  b) At  $T > 0K$
- When electric field is applied across an intrinsic semiconductor, the current conduction takes place by two processes namely: by free electrons and holes.
  - Therefore the total current inside the semiconductor is the sum of currents due to free electrons and holes

$$I = I_{\text{Electron}} + I_{\text{Hole}}$$

### Extrinsic Semi Conductor:

The electrical conductivity of a pure semiconductor is very small. To increase the conductivity, impurities are added. The impurity added semiconductor is called “**Extrinsic Semi Conductor**”. (OR)

The conductivity of intrinsic semiconductor can be increased enormously by adding small amounts of impurity atoms [such as III or V group atoms]. This impure semiconductor is called “**Extrinsic Semi Conductor**”.

### Doping:

The process of adding impurities to a semiconductor is called doping and the impurity added is called “**Dopant**”.

Depending upon the type of impurity added, Extrinsic Semiconductors are classified into two types.

1. N - Type Semi Conductor.
2. P - Type Semi Conductor

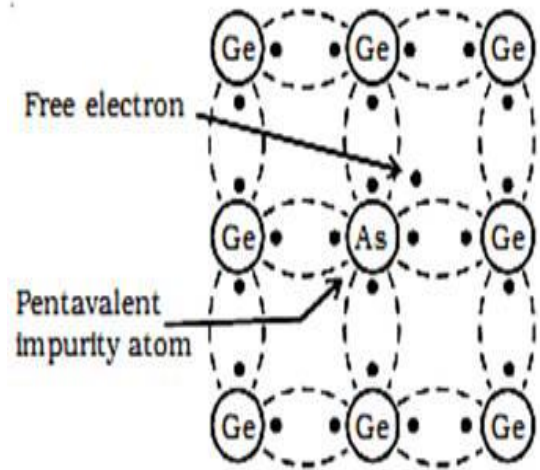
### N – Type Semi Conductor:

When a small quantity of pentavalent impurity is added to a pure semiconductor, it is known as ‘n – type semiconductor’.

### Explanation:

- To explain the formation of n-type semiconductor, consider a pure (semiconductor) Germanium Crystal.
- We know that germanium atom has four valence electrons, when a small amount of pentavalent impurities like arsenic (As) is added to a germanium crystal, a large number of free electrons available in the crystal.

- The reason is simple. Arsenic is pentavalent i.e., its atom has five valence electrons. The four of the five valence electrons of Arsenic will make covalent bonds with four germanium atoms. The fifth valence electron of arsenic atom finds no place in covalent bonds and is thus free as shown in fig.
- Therefore for each arsenic atom is added, one free electron will be available in the germanium crystal.
- Thus, a small amount of arsenic impurities (As) are added to a germanium crystal, a large number of free electrons available in the crystal.
- Pentavalent impurities are also known as donor impurities because they donate free electrons to semi conductor crystal.



### Energy Band Description:

- Fig (2) shows the energy band description of n-type semi conductor.
- The addition of donor impurity to an intrinsic semi conductor creates extra energy level (called donor energy level) just below the bottom of conduction band.
- **At Absolute Zero:** At absolute zero temperature the fifth electrons of arsenic atoms occupy the donor level (represented by dashed lines) as shown in fig.
- **At above Absolute Zero:** Even room temperature provides enough thermal energy to push the electrons sitting at donor energy level to conduction band. (The result is that at room temperature, there are a large number of free electrons in the conduction band as shown in fig) and also few of the covalent bonds in the semi conductor break due to the thermal energy applied.
- Due to the breaking of covalent bond, there will be a few holes formed in the valance band at this temperature. The result is that at room temperature, there are a large number of free electrons in the conduction band compared to the holes in valence band, i.e., Electrons are majority carriers and holes are minority carriers. So this material is called n-type semi conductor.

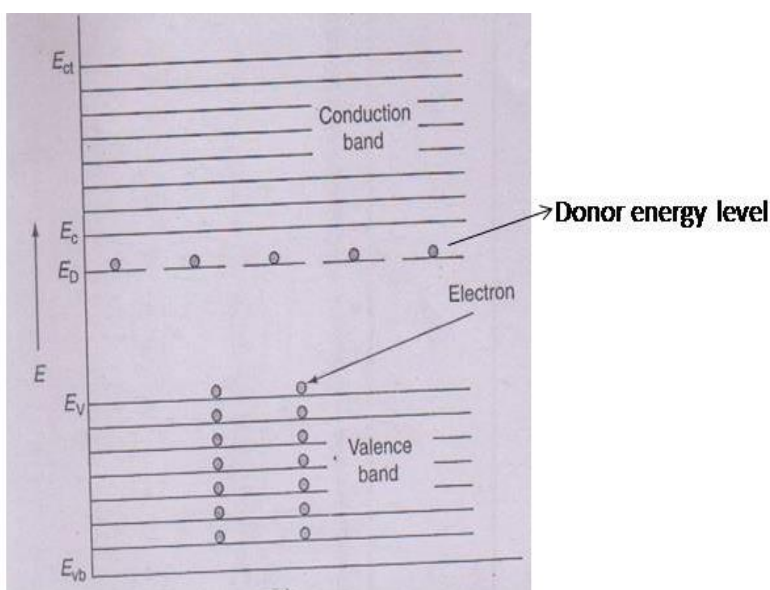
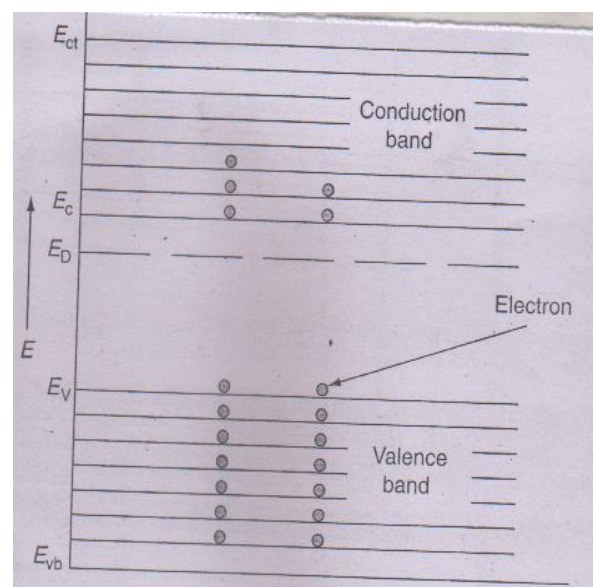


Fig: a) At  $T=0K$



b) At  $T > 0K$

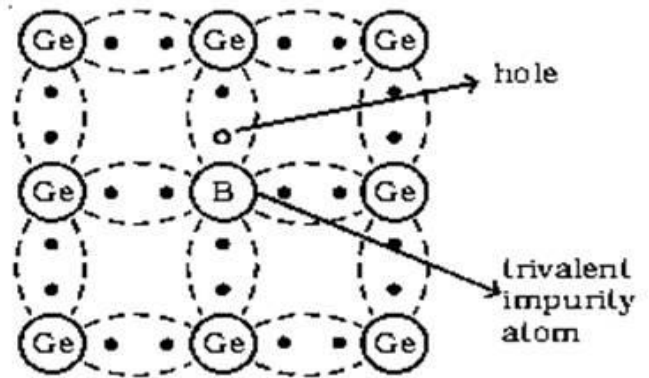


### **P-Type Semi Conductor:**

When a small quantity of trivalent impurity (such as indium (In) Boron (B), aluminum (Al) etc. is added to a pure semi conductor, it is called P-type semi conductor.

#### **Explanation:**

- To explain the formation of p-type semi conductor, consider a pure (semi conductor) Germanium Crystal.
- We know that germanium atom has four valence electrons, when a small amount of trivalent impurities like boron atoms (B) are added to a germanium crystal, a large number of holes available in the crystal.
- The reason is simple. Boron is trivalent i.e., its atom has three valence electrons. The three valence electrons of Boron atom will make three covalent bonds with surrounding Ge atoms.
- The fourth bond is incomplete because short of one electron. This missing electron is called a “hole”.
- Therefore, for each boron atom is added, one hole will be available in the germanium crystal.



- Thus, a small amount of boron impurities (B) are added to a germanium crystal, a large number of free holes available in the crystal.
- Trivalent dopant impurities also called acceptors. Because they have need of extra electrons to complete their fourth covalent bonds formation with Ge atoms.
- **Energy Band Description:** Fig (2) shows the energy band description of p-type semi conductor. The addition of acceptor impurity to an intrinsic semi conductor creates extra energy level (called acceptor energy level) just above the top of the valence band [see fig].
- Since the energy difference between acceptor level and valence band energy level is very small so even at low temperature the valence band electrons gain sufficient thermal energy to occupy the acceptor energy level states as shown in fig.
- After receiving an electron the, Boron atom becomes a negative ion.
- But at room temperature provides enough thermal energy to push the electrons in the valence band to the acceptor energy level and also due to thermal agitation a few electrons jumps from V.B to C.B.
- The result is that at room temperature there are a large number of holes in the V.B compared to the electrons in the C.B. i.e., holes are majority carriers and electrons are minority carries. So, this material is called P-type semi conductors.

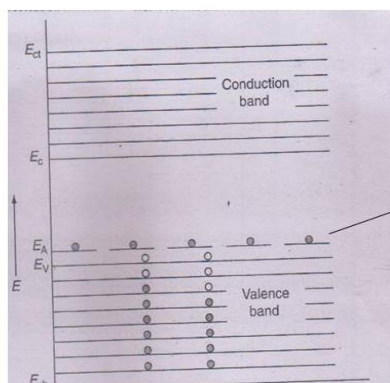
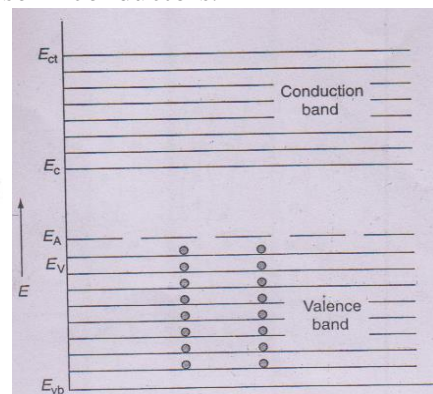


Fig: a) At  $T=0K$



b) At  $T > 0K$

## Electrical conduction in semiconductors

In the semiconductors electrical conduction arises due to two processes namely

1. Drift and
2. Diffusion

### Drift:

#### Definition:-

Under an applied electric field both the charge carriers i.e., electrons and holes acquire an average velocity called the drift velocity ( $V_d$ ) and this process is called drift.

The drift velocity  $V_d$  is small. It is directly proportional to the electrical field  $E$ .

$$\text{i.e., } V_d \propto E$$

$$V_d = \mu E \longrightarrow (1)$$

Where  $\mu$  is a constant and is called the mobility of charge carriers.

If  $\mu_n$  and  $\mu_p$  are the electron mobility and hole mobility respectively, then

$$V_n = \mu_n E \text{ and } \longrightarrow (2)$$

$$V_p = \mu_p E \longrightarrow (3)$$

1. We know that, Current  $I = neAV_d$ .

But in a semi conductor, the total current is the sum of electrons current and holes current.

Let  $n$  be the electron concentration and  $p$  be the hole concentration.

Therefore  $I = I_n + I_p$

$$= neAV_n + pAV_p$$

$$= eA (nV_n + pV_p) \quad [\text{From equations (2) \&(3)}]$$

$$= eA(n\mu_n E + p\mu_p E)$$

$$= eA(n\mu_n + p\mu_p)E$$

**2. Current density  $J = \frac{I}{A}$**

$$J_n = \frac{neA\mu_n E}{A} \text{ and}$$

$$J_p = \frac{peA\mu_p E}{A}$$

Therefore, total current density  $J = J_n + J_p$

$$= \frac{eA(n\mu_n + P\mu_p)E}{A} = e(n\mu_n + P\mu_p)E$$

$$\text{Conductivity } \sigma = \frac{J}{E} = \frac{e(n\mu_n + P\mu_p)E}{E} = e(n\mu_n + P\mu_p)$$

### **NOTE:-**

1. For an intrinsic semiconductor:  $n=p=n_i$

Where  $n_i$  is the carrier concentration of the intrinsic semiconductor.

$$I_{inc} = eA(n_i\mu_n + n_i\mu_p)E$$

$$= eAn_i(\mu_n + \mu_p)E$$

$$\therefore \text{Current density } J_{in} = \frac{I_{in}}{A} = \frac{eAn_i(\mu_n + \mu_p)E}{A} = en_i(\mu_n + \mu_p)E$$

$$\text{Conductivity } \sigma_{in} = \frac{J_{in}}{E} = \frac{en_i(\mu_n + \mu_p)E}{E} = en_i(\mu_n + \mu_p)$$

### **FOR AN EXTRINSIC SEMICONDUCTOR:-**

a) **For n-type semiconductor :-** The hole current is neglected, as the holes are minority carriers and the electrons are the majority carriers.

$n \simeq N_d$  is the donor electron concentration

[ $\therefore$  Where  $N_a$  can be neglected]

$$I = eA V_n N_d$$

$$= eA\mu_n EN_d$$

$$J = \frac{I}{A} = e\mu_n EN_d$$

$$\sigma = \frac{J}{E} = e\mu_n EN_d$$

b) **For P-type semiconductor :-** The electron current is neglected and  $P=N_{ai}$ , where  $N_a$  is the acceptor hole concentration. [ $\therefore$  When  $N_d$  can be neglected].

$$I = eA V_p N_a$$

$$= eA\mu_p E N_a$$

$$J = \frac{I}{A} = e\mu_p E N_a$$

$$\sigma = \frac{J}{E} = e\mu_p N_a$$

## **DIFFUSION :-**

Diffusion takes place due to existence of non-uniform concentration of charge carriers.

### **Definition:-**

Due to non –uniform carrier concentration in a semiconductor, the charge carrier's moves from a region of higher concentration to a region of lower concentration. This process is known as diffusion of charge carriers.

- According to Fick's law, the diffusion flux  $F$  is directly proportional to concentration gradient <i.e. carrier concentration per unit length > of the particles and is in the opposite direction.i.e;

$$F \propto \frac{-\partial(\Delta N)}{\partial X}$$
$$F = -D \frac{\partial(\Delta N)}{\partial X} \quad \longrightarrow \quad (1)$$

Where  $D$  is diffusion constant.

And  $\Delta N$  is the excess carrier concentration.

Let  $\Delta n$  and  $\Delta p$  be the excess concentration in a semiconductor material.

Then Fick's

$$F \propto \frac{-\partial(\Delta N)}{\partial X} \quad (\text{For electrons})$$
$$F = -D_n \frac{\partial(\Delta N)}{\partial X} \quad \longrightarrow \quad (2)$$

and

$$F \propto \frac{-\partial(\Delta P)}{\partial X} \quad (\text{For electrons})$$
$$F = -D_p \frac{\partial(\Delta P)}{\partial X} \quad \longrightarrow \quad (3)$$

- But the current density due to diffusion depends on charge of particle and rate of diffusion.

∴ Current density ( $J$ ) = Charge of particle × Rate of diffusion  $\longrightarrow (4)$

- The diffusion flux density due to electron is given by

$$J_{n(\text{Diff})} = -e \left[ -D_n \frac{\partial(\Delta N)}{\partial X} \right] \quad \therefore \text{from (4)}$$

$$J_{n(\text{Diff})} = e D_n \frac{\partial(\Delta N)}{\partial X} \quad \longrightarrow \quad (5)$$

The diffusion flux density due to hole is given by

$$J_{p(\text{Diff})} = +e \left[ D_p \frac{\partial(\Delta P)}{\partial X} \right] \quad \longrightarrow \quad (6)$$

Where  $+e$  and  $-e$  are charge of the hole and electron respectively.

∴ The total current density due to diffusion is given by

$$J_{\text{TOTAL(DIFF)}} = J_{n(\text{diff})} + J_{p(\text{diff})}$$
$$J_{\text{TOTAL(DIFF)}} = e D_n \frac{\partial(\Delta N)}{\partial X} - e D_p \frac{\partial(\Delta P)}{\partial X} \quad \longrightarrow \quad (7)$$

**NOTE:-** The total current density due to excess electrons is the sum of the current densities due to drift and diffusion of electrons.

$$J_n = J_{n(\text{drift})} + J_{n(\text{diff})}$$
$$= \Delta n \mu_n E + e D_n \frac{\partial(\Delta N)}{\partial X} \quad \longrightarrow \quad (8)$$

Similarly,

The total current density due to excess holes is the sum of the holes densities due to drift and diffusion of holes.

$$J_p = \Delta p e \mu_p E - e D_p \frac{\partial(\Delta P)}{\partial X} \quad \longrightarrow \quad (9)$$



### EINSTEIN'S RELATION:-

Einstein showed the direct relation between the mobility ( $\mu$ ) and diffusion coefficient (D) of a semiconductor. This relation is called Einstein relation.

At any disturbance in equilibrium, the drift and diffusion current densities due to carrier concentration are equal.

$$\begin{aligned} \text{i.e.; } J_{n(\text{drift})} &= J_{n(\text{diff})} \\ (\Delta n) e E \mu_n &= D_n e \frac{\partial(\Delta n)}{\partial X} \longrightarrow (1) \end{aligned}$$

The force on excess electrons ( $\Delta n$ ) to restore equilibrium is given by the product of  $\Delta n$  and electric forces  $eE$  on each electron. Thus,

$$F = (\Delta n) e E \longrightarrow (2)$$

Equation (1) can be written as

$$\begin{aligned} F \cdot \mu_n &= D_n e \frac{\partial(\Delta n)}{\partial X} \\ F &= \frac{D_n}{\mu_n} e \frac{\partial(\Delta n)}{\partial X} \longrightarrow (3) \end{aligned}$$

From the kinetic theory of gases, the force on gas molecules (charge carriers) is given by

$$F = K_B T \frac{\partial(\Delta n)}{\partial X} \longrightarrow (4)$$

Comparing (3) and (4), we get

$$\begin{aligned} K_B T \frac{\partial(\Delta n)}{\partial X} &= \frac{D_n}{\mu_n} e \frac{\partial(\Delta n)}{\partial X} \\ K_B T &= \frac{D_n}{\mu_n} e \\ D_n &= \frac{\mu_n K_B T}{e} \\ \frac{D_n}{\mu_n} &= \frac{k_B T}{e} \longrightarrow (5) \end{aligned}$$

Similarly for holes,

$$\frac{D_p}{\mu_p} = \frac{k_B T}{e} \longrightarrow (6)$$

From equations (5) and (6)

$$\begin{aligned} \frac{D_n}{\mu_n} &= \frac{D_p}{\mu_p} \\ \frac{D_n}{D_p} &= \frac{\mu_n}{\mu_p} \end{aligned}$$

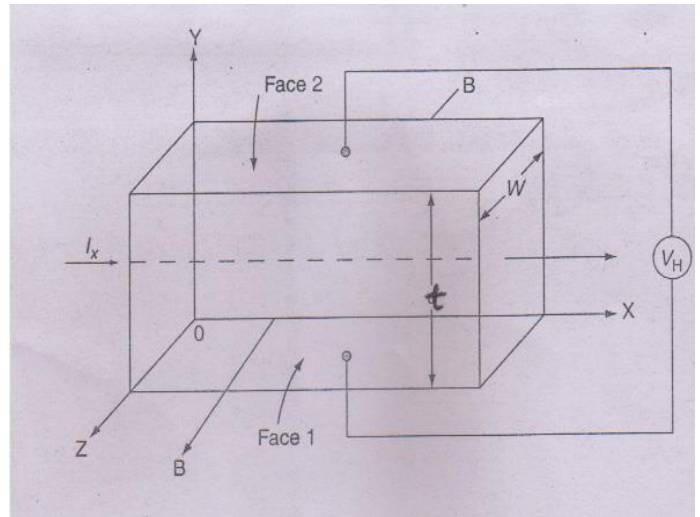
The above relation is known as Einstein's relation.

### Hall Effect:

When a current carrying semiconductor is placed in the magnetic field, then a potential difference (voltage) or electric field is developed in the material perpendicular to both the current and the applied magnetic field. This effect is known as Hall Effect and the developed potential difference (voltage) is known as Hall voltage.

### Explanation:

- Consider a semiconductor slab of thickness ' $t$ ' and width ' $w$ ' in which current ( $I$ ) flowing along X-direction and magnetic field is applied along Z-direction as shown in fig.
- The charge carriers inside the semiconductor experience a force due to the applied magnetic field called Lorentz force.
- As a result, electrons move (drift) towards downward direction with velocity ' $V_d$ ' and accumulate at bottom surface (face 1) and the corresponding positive charge on upper surface (face 2) of the material as shown in fig.
- Thus a potential difference and electric field developed across the surface. This developed electric field along Y-direction exerts a force ( $F_e = eE_H$ ) on the electrons to prevent further accumulation at the bottom surface.
- Therefore, the force due to potential difference  $F_e = eE_H$   
the force due to magnetic field  $F_L = BeV_d$



At steady state

$$F_e = F_L$$

$$eE_H = Bev_d$$

$$E_H = Bv_d \longrightarrow (1)$$

### For n-type:

If ' $n$ ' is the electrons carrier concentration in the semiconductor, then current density

$$J = -neV_d$$
$$V_d = \frac{J}{-ne} \longrightarrow (2)$$

Substituting eq (2) in eq(1)

$$E_H = \frac{BJ}{-ne}$$

$$\boxed{E_H = R_H BJ} \longrightarrow (3)$$

Where  $R_H = \frac{1}{-ne}$  is known as Hall coefficient.

**For p-type:**

If 'p' is the electrons carrier concentration in the semiconductor, then current density

$$J = peV_d$$

$$V_d = \frac{J}{pe} \longrightarrow (2)$$

Substituting eq (2) in eq(1)

$$E_H = \frac{BJ}{pe}$$

$E_H = R_H BJ$

 $\longrightarrow (3)$

Where  $R_H = \frac{1}{pe}$  is known as Hall coefficient

**Hall coefficient in terms of hall voltage:**

If the thickness of the sample is 't' and the developed voltage is  $V_H$ , then the Hall voltage

$$V_H = E_H \cdot t \longrightarrow (4)$$

Substituting eq (3) in eq(4);

$$V_H = R_H BJ t \longrightarrow (5)$$

If 'w' is the width of the semiconductor,

then area of the sample  $A = w \cdot t$

But current density  $J = \frac{I}{A} = \frac{I}{w t} \longrightarrow (6)$

Substituting eq (8) in eq(7); we get

$$V_H = \frac{R_H IB}{w}$$

$$R_H = \frac{V_H w}{IB}$$

$$R_H = \frac{V_H w}{IB}$$

This is the relation between Hall coefficient and hall voltage.

- The electrical conductivity in a semiconductor is given by

$$\sigma = ne\mu$$

$$\mu = \frac{\sigma}{ne}$$

$$\mu = R_H \sigma$$

**APPLICATIONS:**

- Knowing  $R_H$  and  $\sigma$ , the mobility of charge carriers can be measured. i.e.,  $\mu = R_H \sigma$
- It is used to find the carrier concentration

$$n = -\frac{1}{eR_H} \quad \text{and} \quad p = \frac{1}{eR_H}$$

- It is used to determine whether the material is p-type or n-type semiconductor.  
i.e., if  $R_H$  is negative then the material is n-type.  
if  $R_H$  is positive then the material is p-type.

### P-n junction:

When a p-type semiconductor is suitably joined to n-type semiconductor, the contact surface is established between them, is called p-n junction.

### Formation of p-n junction:

- The formation of p-n junction as shown in fig
- Let us consider the formation of a junction when two separate semiconductors of p and n-types are brought together.
- We know that, in a p-type semiconductor holes are the majority carriers and electrons are the minority carriers and in a n-type semiconductor free electrons are the majority carriers and holes are minority carriers.
- When they are joined, due to non-uniform carrier concentration, free electrons diffuse from n-region to p-region and recombine with holes and holes diffuse from p-region to n-region and recombine with electrons.
- As result, a net negative charge is created on the p-side and a net positive charge is created on the n-side. These charges produce the potential difference, is called potential barrier and this region is called depletion region because it opposes the further flow of electrons from n-region to p-region.
- The potential barrier is the order of 0.1 to 0.3 volt.

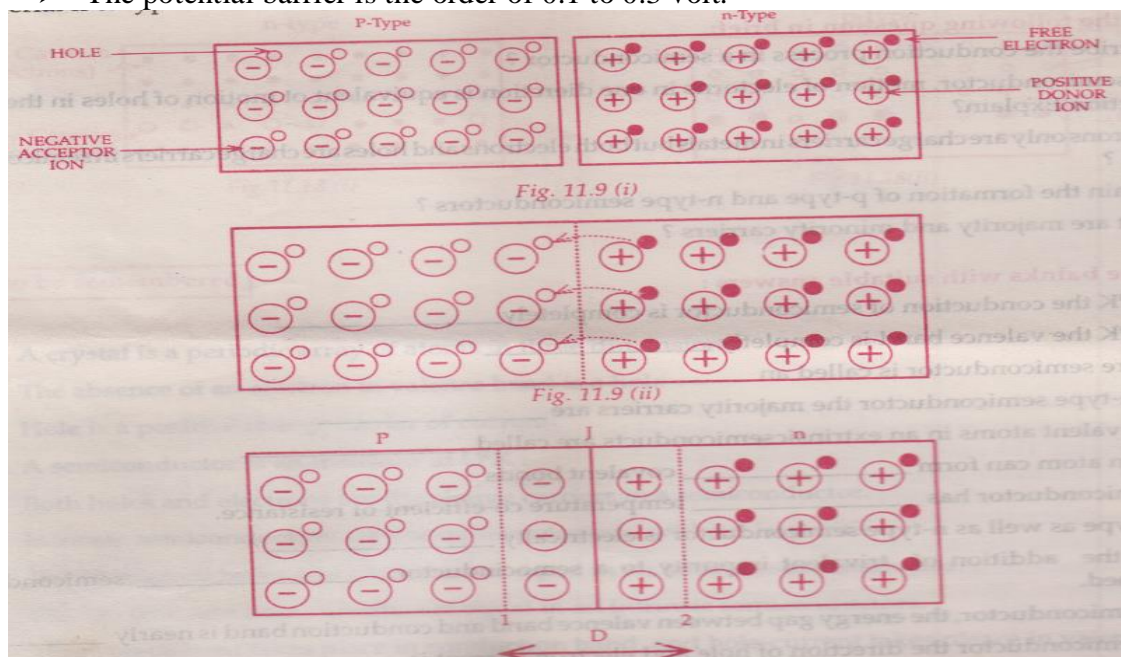
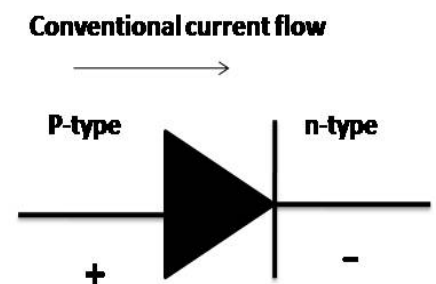


Fig: Formation of p-n junction

### P-n junction diode:

- A two electrode device is called diode.
- In the p-n junction, p-type semiconductor and n-type semiconductors behaves as electrodes.
- The symbol for the p-n junction diode is shown in fig.
- In fig, arrow of head indicates a p-type semiconductor and shows the direction of conventional current flow when the junction is forward biased, and the bar indicates a n-type semiconductor.



### **Bias:**

To apply an external voltage to the p-n junction is called bias.

Bias can be divided into two types

1. Forward bias
2. Reverse bias

#### **Forward bias:**

- When a p-type semiconductor is connected to the positive terminal of the battery and n-type semiconductor is connected to the negative terminal of the battery, then it is known as forward bias.
- When the junction is forward biased
  - a) The width of depletion region is decreased
  - b) The potential barrier is reduced
  - c) The Junction offers a very low resistance.
  - d) Electrons flows from n-region to p-region through the junction and this gives rise to forward current
  - e) Current is in the order of mA

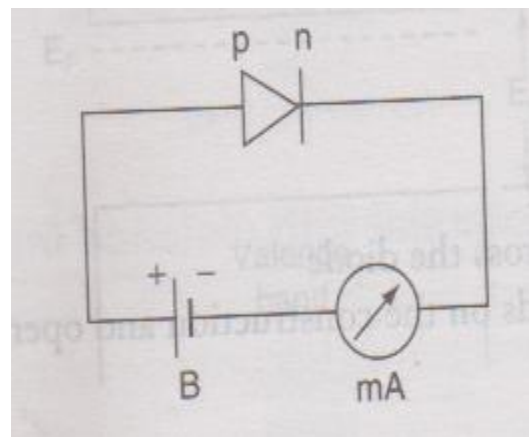
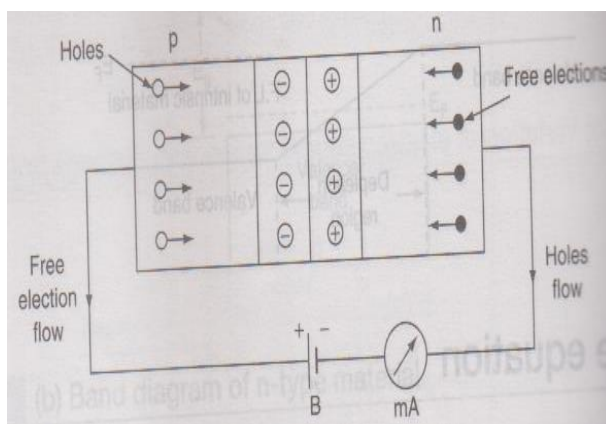


Fig: Forward bias p-n junction

#### **Reverse bias:**

When a p-type semiconductor is connected to the negative terminal of the battery and n-type semiconductor is connected to the positive terminal of the battery, then it is known as reverse bias.

When the junction is reverse biased

- a) The width of depletion region is increased
- b) The potential barrier is increased
- c) The Junction offers a very high resistance.
- d) Current is in the order of  $\mu\text{A}$

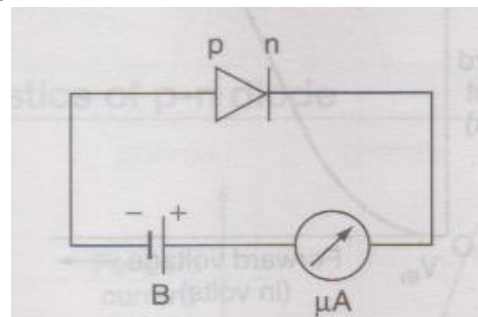
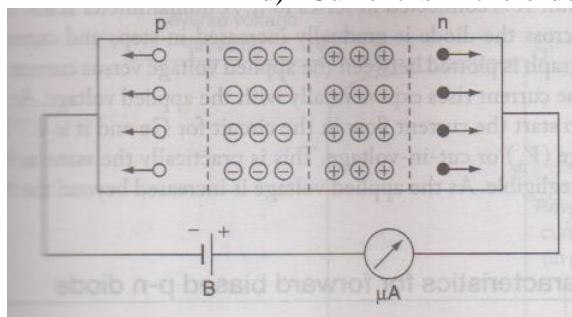


Fig: Reverse bias p-n junction