

# Unit-6

## Semiconductors

### Syllabus:

Crystalline and Amorphous solids, Band theory of solids, mobility and carrier concentrations, properties of P-N junction, Energy bands, hall effect, VI characteristics of photodiode, Zener diode and photovoltaic cell

## Crystalline and amorphous solids:

Solids can be broadly classified in to following three types-

- 1) Crystalline solids
- 2) Amorphous solids or non-crystalline solids
- 3) Polly crystalline solids

### Crystalline solids

If the atoms or the molecules in a solid are arrange in some regular fashion then it is known as crystalline solids. Hence in a crystalline solid the atoms are arranged in an orderly three dimensional array that is repeated throughout the structure. This is shown in the figure (1-a). The metallic crystal are *Cu, Ag, Al* etc. the non-metallic crystals are *C, Si, Ge* etc.

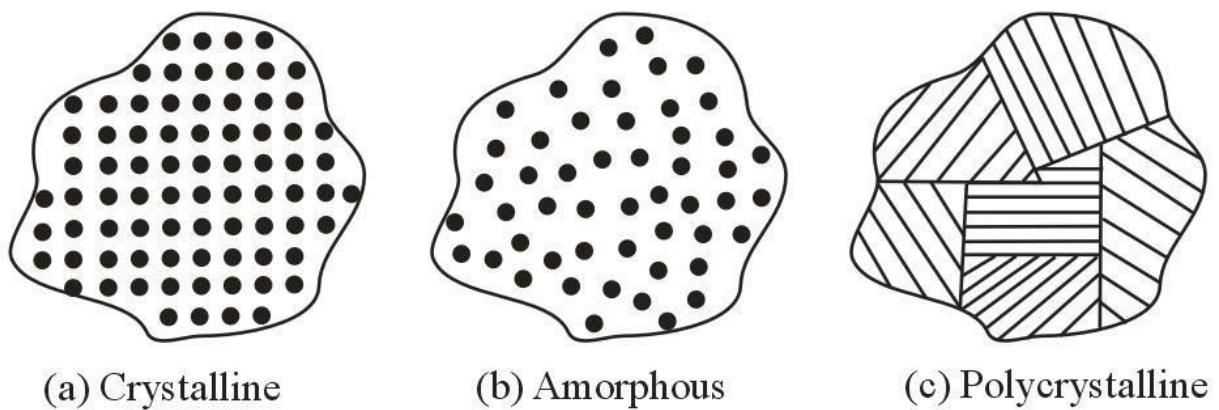


Figure (1)

### Amorphous solids or non-crystalline solids:

Amorphous means without form. When the atoms or molecules in a solid are arrange in an irregular fashion then it is known as amorphous solids which is shown in the figure (1-b). The examples are *Glass, Plastic, Rubber* etc.

### Polly crystalline solids

There are some solids which are composed of many small regions of single crystal material and are called polycrystalline solid. Hence the atoms in polycrystalline solids are so arranged that within certain sections some short of pattern of the atoms exists but the various sections are randomly arranged with respect to each other as shown in the figure.

### Difference between amorphous and crystalline solids:

	Amorphous Solids		Crystalline Solids
1.	Solid those don't have definite geo shape.	1.	Crystalline solids have the characteristic geometrical shape.
2.	Amorphous solids do not have particular melting point. They melt over a wide range of temperature.	2.	They have sharp melting point.
3.	Physical properties of amorphous solids are same in different direction. i.e. those solids are isotropic.	3.	Physical properties of crystalline solids are different in different directions. This phenomenon is known as anisotropy.
4.	Amorphous solids are unsymmetrical.	4.	When crystalline solids are rotated about an axis there appearance does not changes. This shows that they are symmetrical.
5.	Amorphous solids do not break at fixed cleavage planes.	5.	Crystalline solids cleavage along particular direction at fixed cleavage planes.

### How does the band forms in the solids:

We know that the atoms are arranged in a periodic manner in a solid and they formed the crystal. In an atom the electron revolves in different orbits according to their energy. If we take each individual atom and find the energy of electron then this energy becomes identical for each corresponding atom for every electron. But as in solids the atoms are not free but they interact one-another so the energy becomes slightly more or less for some of the electrons and if we plot the energies we get an energy band in solids. There may be a number of energy bands in a solid but two of them are of our interest

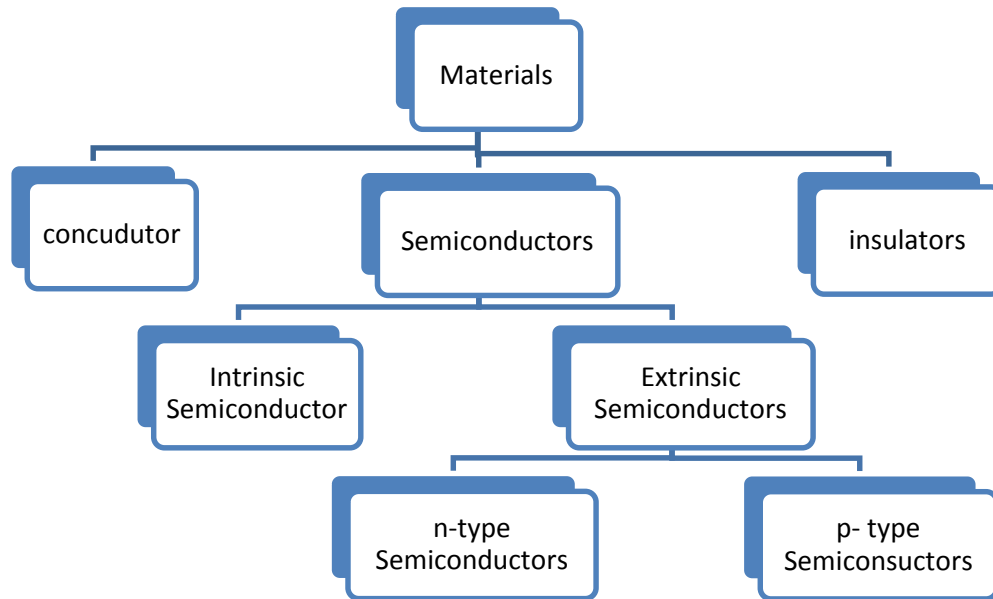
- 1) **Valance band:** The energy band plotted by energy of the electrons those are revolving in the outermost orbit is called the valance band.
- 2) **Conduction band:** The electrons those are revolving in the outermost orbit are loosely bounded and can be separated by giving some energy to those electrons. Now those electrons are free to move inside the crystal and they are not concerned to any individual atom.

The energy band plotted by the energy levels of the free electrons is called the conduction band. Since these electrons are free to move inside the crystal and are responsible for conduction of electricity is known as conduction band. There is a gap in between the upper most energy level of valance band and lowest energy level of conduction band is known as forbidden energy gap. Because these energy levels cannot be occupied by

any electron. On the basis of this band theory we can classify the conductors, insulators and semiconductor.

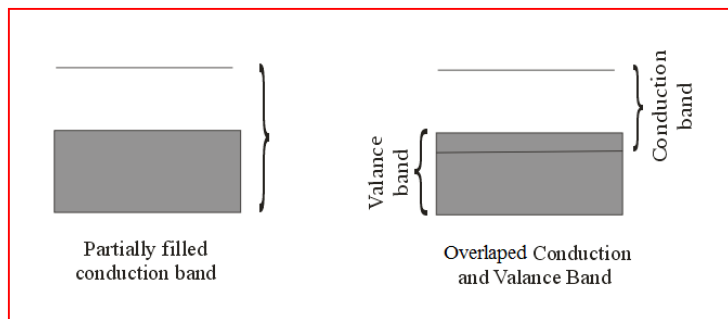
### Types of materials on the basis of the electrical conduction:

Materials can be classified into three different categories on the basis of their electrical conductivity.



Figure(7): Classification of the materials

### Conductors:

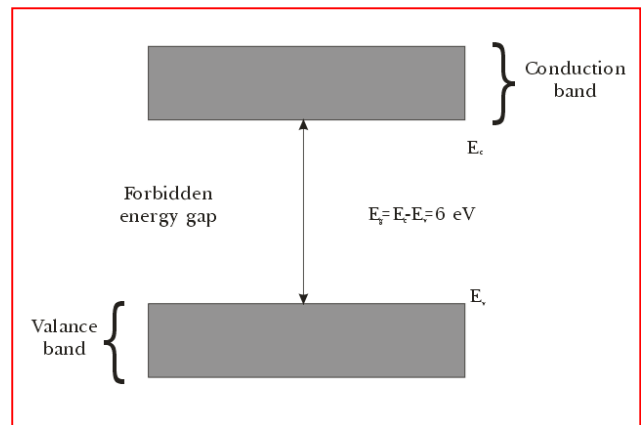


Figure(8): Conductors

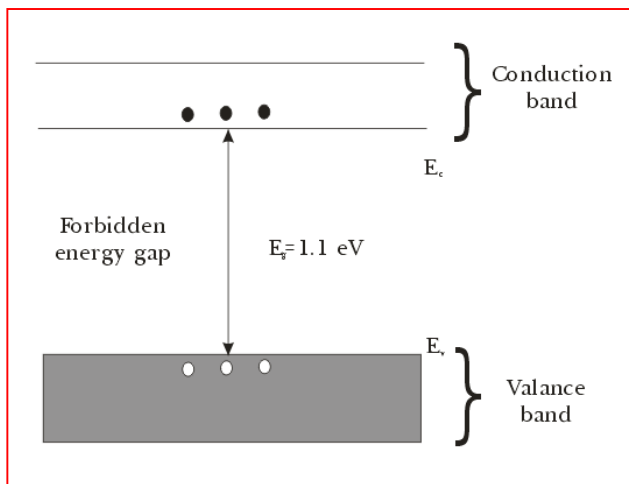
Conductors are those materials which have completely or partially filled conduction band and the forbidden energy gap between the conduction band and valance band is zero. So the electrons those are in valance band also available in conduction band to flow the current.

**Insulator:**

The materials which does not allows to flow the current from them, are called the insulator. In case of insulator there is a large energy gap between the conduction band and valance band of about  $6\sim 10\text{ eV}$  so it is impossible to lift the electron from valance band by giving some energy to the conduction band. Therefore materials are insulators.



Figure(9): Insulator

**Semiconductor:**

Figure(10):

Semiconductors are those materials which has there electrical conductivity somewhere between conductors and insulators. It means these materials behave as an insulator at low temperature while at the elevated temperature they shows some electrical conductivity.

The semiconductor has totally empty conduction band at absolute zero, but at elevated temperature some of the electrons jumps from the valance band to

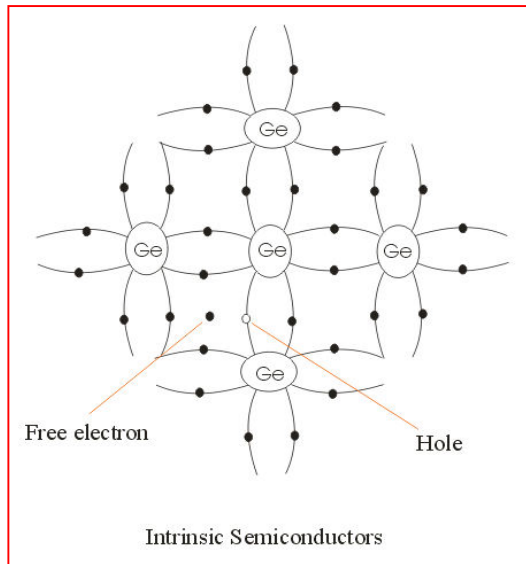
conduction band as the forbidden energy gap between the semiconductors is of moderate size of about  $0.1\sim 2.0\text{ eV}$  and this much amount of energy can be provided easily to the valance band electrons so the current can flow in this type of material.

Semiconductors are of two types:

- 1) Intrinsic semiconductors
- 2) Extrinsic semiconductors

**Intrinsic semiconductors:**

Intrinsic semiconductors are pure semiconductor as *Ge* and *Si*. These materials have four electrons in their outermost orbit. To complete the octal an *Ge/Si* atom form the covalent bonds with four other neighbouring *Ge/Si* atoms as shown in the figure.



Figure(11): Intrinsic semiconductor

Due to this, no electron is available in conduction band at low temperature and therefore it behaves as an insulator, but at elevated temperature, due to some thermal agitation some of the covalent bonds in the semiconductor material break, due to which an electron-hole pair is created. The electron is now available in the conduction band even at room temperature and the hole is available in the valence band. The hole is a vacancy created in the valence band, which is filled by the neighbouring electron, and thus the electron and hole start flowing in the valence band, and due to both electrons and holes, the electric conduction in the material is now possible.

### Extrinsic Semiconductors:

In intrinsic semiconductors only  $10^6$  electrons per cubic meter contribute to the conduction of electric current; hence these are of no particular use.

If a small amount ( $\sim 1 \text{ PPM}$ ) of pentavalent or trivalent impurity is introduced into a pure *Ge/Si* crystal, then the conductivity of the crystal increases appreciably and the crystal becomes an extrinsic semiconductor.

Again, extrinsic semiconductors are of two types

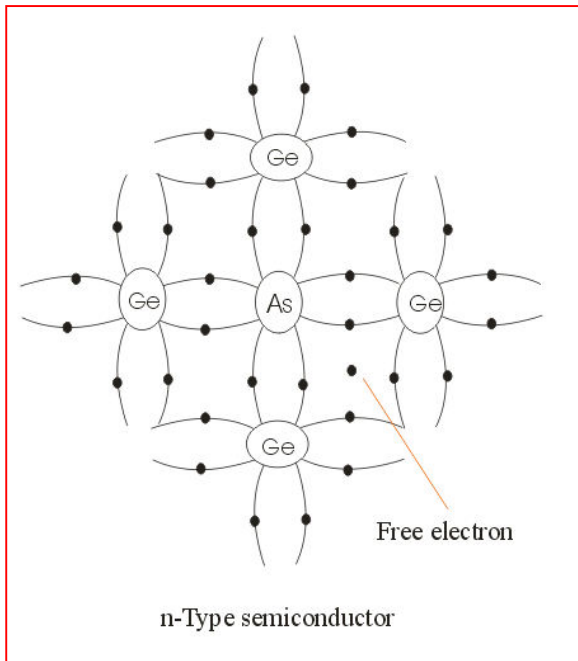
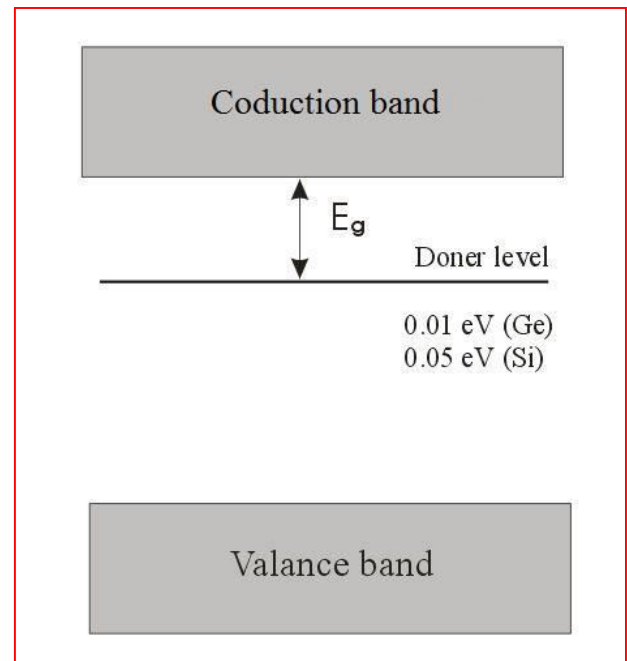
- 1) *N* – type extrinsic semiconductor
- 2) *P* – type extrinsic semiconductor

### *N* – type extrinsic semiconductor

If a pentavalent impurity such as (*Sb*, *P*, *As*) is added to *Ge/Si*, then four electrons of the outermost orbit of these atoms create covalent bonds, while the extra electron which is free in the crystal enhances the electrical conductivity of the materials.

In this type of the crystal, the current flows due to a negatively charged particle, i.e., electron, so the materials are known as *n* – type semiconductor materials.

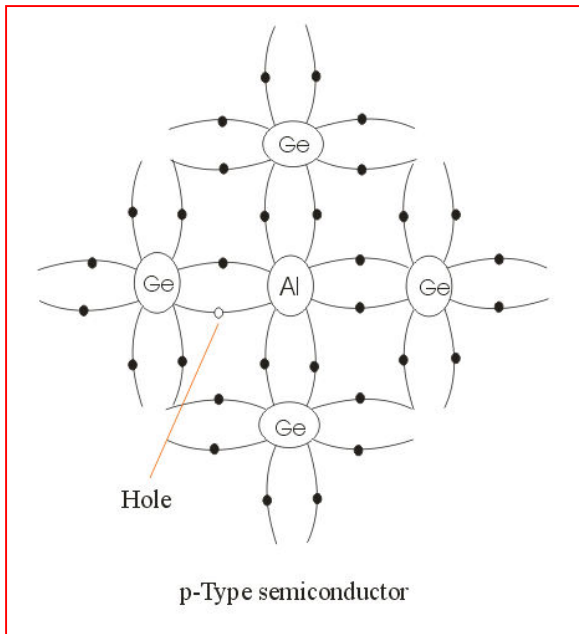
The impurity atom introduces a discrete energy level for the electron, just donates the extra electron in the crystal; therefore, these are called donor impurity levels.

Figure(12):  $N$  – type semiconductors crystalFigure(13): Donor level in  $n$  – type intrinsic semiconductor

### **P – type intrinsic semiconductors:**

When a trivalent ( $B$ ,  $Al$ ,  $Ga$ ,  $In$ ) replaces an  $Ge/Si$  atom in a crystal (1 PPM), only three valance electrons are available to form covalent bonds with neighboring  $Ge/Si$  atoms. This results in an empty space or a vacant position called a hole. When a voltage is applied to the crystal, then an electron bound to a neighbouring  $Ge/Si$  atom occupies the hole position, thereby creating a new hole. This process continues, and the hole moves in a crystal lattice. This type of semiconductor is called the  $P$  – type semiconductor.

These are called acceptor impurity levels, which are only  $0.01\text{ eV}$  above the valance band in the case of  $Ge$  and  $0.05\text{ eV}$  in the case of  $Si$ .



Figure(14): p – type semiconductor

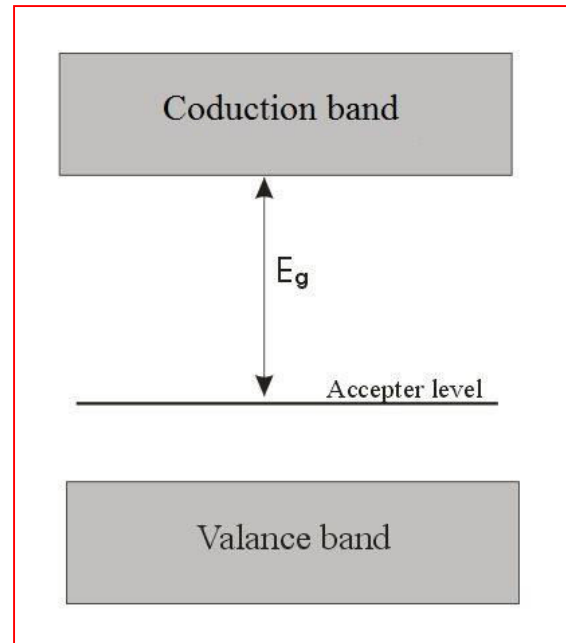


Figure (15): Acceptor level in extrinsic semiconductors.

## Charge mobility:

When an electric field,  $\vec{E}$  is applied to a conductor or semiconductor then the electrons (in opposite to  $\vec{E}$ ) and holes (in the same direction to  $\vec{E}$ ) starts flowing with drift velocity,  $v_d$ . This drift velocity is proportional to the applied field  $\vec{E}$ , i.e.

$$\begin{aligned} v_d &\propto \vec{E} \\ v_d &= \mu \vec{E} \end{aligned}$$

Here  $\mu$  is proportionality constant which is known as mobility of charge carriers.

So

$$\mu = \frac{|v_d|}{|\vec{E}|}$$

So mobility relates the drift velocity to electric field.

Mobility gauges how easily current carrier can move through a piece of conductor or semiconductor.

## Charge concentration:

### Intrinsic semiconductors:

- 1) Electrons in conduction band behave as free particle with effective mass  $m$
- 2) Number of conduction electrons per cubic meter whose energies lies between  $\vec{E}$  and  $\vec{E} + \vec{dE}$  given as -

$$dn_e = N(E)f(E)dE \quad \dots (1)$$

Where  $N(E)$  is the density of states at bottom of the conduction band and it is given as per quantum mechanics as

$$N(E) = \frac{4\pi}{h^3} (2m)^{\frac{3}{2}} (E - E_c)^{\frac{1}{2}} \quad \dots (2)$$

Here  $E_c$  is the energy at the bottom of the conduction band.

And  $f(E)$  is the Fermi-Dirac probability function, which is given as-

$$f(E) = \frac{1}{1 + \left( \frac{E - E_f}{kT} \right)} \quad \dots (3)$$

Where  $E_f$  is the Fermi level,  $T$  is the absolute temperature and  $k$  is Boltzmann constant.

Now since electron may have energies between  $E_c$  to  $\infty$  in conduction band so total number of electron will be given by integrating (1)

$$n_e = \int_{E_c}^{\infty} N(E)f(E)dE$$

$$n_e = \int_{E_c}^{\infty} \frac{4\pi}{h^3} (2m)^{\frac{3}{2}} (E - E_c)^{\frac{1}{2}} \frac{1}{1 + e^{\frac{E - E_f}{kT}}} dE$$

$$n_e = \frac{4\pi}{h^3} (2m)^{\frac{3}{2}} \int_{E_c}^{\infty} \frac{(E - E_c)^{\frac{1}{2}}}{1 + e^{\frac{E - E_f}{kT}}} dE$$

As  $E \gg E_f$  and  $(E - E_f)E \gg kT$   $1 + e^{\frac{E - E_f}{kT}} \approx e^{\frac{E - E_f}{kT}}$

So

$$n_e = \frac{4\pi}{h^3} (2m)^{\frac{3}{2}} \int_{E_c}^{\infty} \frac{(E - E_c)^{\frac{1}{2}}}{e^{\frac{E - E_f}{kT}}} dE$$

$$n_e = \frac{4\pi}{h^3} (2m)^{\frac{3}{2}} \int_{E_c}^{\infty} (E - E_c)^{\frac{1}{2}} e^{\left(\frac{E_f - E}{kT}\right)} dE$$

$$n_e = \frac{4\pi}{h^3} (2m)^{\frac{3}{2}} \int_{E_c}^{\infty} (E - E_c)^{\frac{1}{2}} e^{\left(\frac{E_f - E_c + E_c - E}{kT}\right)} dE$$

$$n_e = \frac{4\pi}{h^3} (2m)^{\frac{3}{2}} \int_{E_c}^{\infty} (E - E_c)^{\frac{1}{2}} e^{-\frac{E - E_c}{kT}} e^{\left(\frac{E_f - E_c}{kT}\right)} dE$$

$$n_e = \frac{4\pi}{h^3} (2m)^{\frac{3}{2}} e^{\frac{E_f - E_c}{kT}} \int_{E_c}^{\infty} (E - E_c)^{\frac{1}{2}} e^{-\left(\frac{E - E_c}{kT}\right)} dE$$

Let  $\frac{E - E_c}{kT} = x$  so that  $dE = kT \cdot dx$

Limits:-

As  $E \rightarrow E_c \Rightarrow x = 0$

And  $E \rightarrow \infty \Rightarrow x = \infty$

so

$$n_e = \frac{4\pi}{h^3} (2m)^{\frac{3}{2}} e^{\left(\frac{E_f - E_c}{kT}\right)} \int_0^{\infty} (x kT)^{\frac{1}{2}} e^{-x} kT \cdot dx$$

$$n_e = \frac{4\pi}{h^3} (2mkT)^{\frac{3}{2}} e^{\left(\frac{E_f - E_c}{kT}\right)} \int_0^{\infty} (x)^{\frac{1}{2}} e^{-x} dx$$

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

$$n_e = \frac{4\pi}{h^3} (2\pi mkT)^{\frac{3}{2}} e^{\left(\frac{E_f - E_c}{kT}\right)} \left[ \frac{\sqrt{\pi}}{2} \right]$$

$$n_e = 2 \left( \frac{2\pi mkT}{h^2} \right)^{\frac{3}{2}} e^{\left(\frac{E_f - E_c}{kT}\right)} \quad \dots (4)$$

This is the density or concentration of electron in conduction band in intrinsic semiconductor.

### Hole concentration in valance band:

Since holes are created by removal of an electron so Fermi function will be  $1 - f(E)$

So let us calculate the Fermi-Dirac distribution for holes as

$$\begin{aligned}
 1 - f(E) &= \frac{1}{1 + e^{\left(\frac{E-E_f}{kT}\right)}} \\
 1 - f(E) &= \frac{1}{1 + \left[1 + \left(\frac{E-E_f}{kT}\right)\right]^{-1}} \\
 1 - f(E) &= \frac{1}{1 + \left[1 + \left(\frac{E-E_f}{kT}\right)\right]^{-1}} \\
 1 - f(E) &= \frac{1}{1 + e^{\left(\frac{E-E_f}{kT}\right)}} \\
 1 - f(E) &= e^{\left(\frac{E-E_f}{kT}\right)} \quad \dots \quad (5)
 \end{aligned}$$

And for the top of the valance band the density of the states will be given as

$$N(E) = \frac{4\pi}{h^3} (2m_h)^{\frac{3}{2}} (E_v - E)^{\frac{1}{2}}$$

Here  $m_h$  is the effective mass of the hole near the top of the valance band.

So the hole concentration will be given as

$$dn_h = \frac{4\pi}{h^3} (2m_h)^{\frac{3}{2}} (E_v - E)^{\frac{1}{2}} e^{\left(\frac{E-E_f}{kT}\right)} dE$$

On integrating we get

$$\begin{aligned}
 n_h &= \int_{-\infty}^{E_v} \frac{4\pi}{h^3} (2m_h)^{\frac{3}{2}} (E_v - E)^{\frac{1}{2}} e^{\left(\frac{E-E_f}{kT}\right)} dE \\
 n_h &= \frac{4\pi}{h^3} (2m_h)^{\frac{3}{2}} \int_{-\infty}^{E_v} (E_v - E)^{\frac{1}{2}} e^{\left(\frac{E-E_f}{kT}\right)} dE \\
 n_h &= \frac{4\pi}{h^3} (2m_h)^{\frac{3}{2}} \int_{-\infty}^{E_v} (E_v - E)^{\frac{1}{2}} e^{\left(\frac{E-E_v+E_v-E_f}{kT}\right)} dE \\
 n_h &= \frac{4\pi}{h^3} (2m_h)^{\frac{3}{2}} \int_{-\infty}^{E_v} (E_v - E)^{\frac{1}{2}} e^{\left(\frac{E-E_v}{kT}\right)} e^{\left(\frac{E_v-E_f}{kT}\right)} dE \\
 n_h &= \frac{4\pi}{h^3} (2m_h)^{\frac{3}{2}} e^{\left(\frac{E_v-E_f}{kT}\right)} \int_{-\infty}^{E_v} (E_v - E)^{\frac{1}{2}} e^{-\left(\frac{E_v-E}{kT}\right)} dE
 \end{aligned}$$

$$\text{Let } \frac{E_v-E}{kT} = x \Rightarrow -dE = kT dx$$

And limits

$$\text{As } E \rightarrow -\infty \Rightarrow x \rightarrow \infty$$

$$\text{And } E \rightarrow E_v \Rightarrow x \rightarrow 0$$

$$\begin{aligned}
 n_h &= \frac{4\pi}{h^3} (2m_h)^{\frac{3}{2}} e^{\left(\frac{E_v-E_f}{kT}\right)} \int_{\infty}^0 (x kT)^{\frac{1}{2}} e^{-x} (-kT dx) \\
 n_h &= -\frac{4\pi}{h^3} (2m_h)^{\frac{3}{2}} e^{\left(\frac{E_v-E_f}{kT}\right)} \int_{\infty}^0 (x kT)^{\frac{1}{2}} e^{-x} kT dx
 \end{aligned}$$

$$\begin{aligned}
 n_h &= -\frac{4\pi}{h^3} (2m_h)^{\frac{3}{2}} e^{\frac{E_v-E_f}{kT}} (kT)^{\frac{3}{2}} \int_{\infty}^0 (x)^{1/2} e^{-x} dx \\
 n_h &= \frac{4\pi}{h^3} (2m_h kT)^{\frac{3}{2}} e^{\frac{E_v-E_f}{kT}} \int_0^{\infty} (x)^{1/2} e^{-x} dx \\
 n_h &= \frac{4\pi}{h^3} (2m_h kT)^{\frac{3}{2}} e^{\frac{E_v-E_f}{kT}} \left( \frac{\sqrt{\pi}}{2} \right) \\
 n_h &= 2 \left( \frac{2\pi m_h kT}{h^2} \right)^{\frac{3}{2}} e^{(E_v-E_f)/kT} \quad \dots \dots (6)
 \end{aligned}$$

This relation gives the density or concentration of holes in the valence band of an intrinsic semiconductor.

### Intrinsic concentration of charge

On combining the equation number (4) and (6) we get the following expression for the product of electron-hole concentration

$$\begin{aligned}
 n_e n_h &= 2 \left( \frac{2\pi m_e kT}{h^2} \right)^{\frac{3}{2}} e^{\left(\frac{E_f-E_c}{kT}\right)} 2 \left( \frac{2\pi m_h kT}{h^2} \right)^{\frac{3}{2}} e^{\left(\frac{E_v-E_f}{kT}\right)} \\
 n_e n_h &= 4 \left( \frac{2\pi kT}{h^2} \right)^3 (m_e m_h)^{\frac{3}{2}} e^{\left(\frac{E_f-E_c+E_v-E_f}{kT}\right)} \\
 n_e n_h &= 4 \left( \frac{2\pi kT}{h^2} \right)^3 (m_e m_h)^{\frac{3}{2}} e^{\left(\frac{E_v-E_c}{kT}\right)} \\
 n_e n_h &= A T^3 e^{-\left(\frac{E_g}{kT}\right)}
 \end{aligned}$$

Where  $A = \frac{2\pi kT}{h^2} \left( \frac{2\pi kT}{h^2} \right)^3 (m_e m_h)^{\frac{3}{2}}$  and  $E_v - E_c = -E_g$

### (A) Fermi levels in intrinsic semiconductors:

In an intrinsic semiconductor electron and holes are always generated in pair so  $n_c = p$  i.e.

$$\begin{aligned}
 2 \left( \frac{2\pi m_e kT}{h^2} \right)^{\frac{3}{2}} e^{\left(\frac{E_f-E_c}{kT}\right)} &= 2 \left( \frac{2\pi m_h kT}{h^2} \right)^{\frac{3}{2}} e^{\left(\frac{E_v-E_f}{kT}\right)} \\
 e^{-\left(\frac{E_v-E_f}{kT}\right)} \cdot e^{\left(\frac{E_f-E_c}{kT}\right)} &= \left( \frac{m_h}{m_e} \right)^{\frac{3}{2}} \\
 e^{\left(\frac{E_f-E_c-E_v+E_f}{kT}\right)} &= \left( \frac{m_h}{m_e} \right)^{\frac{3}{2}}
 \end{aligned}$$

Taking log of both sides

$$\begin{aligned}
 \left( \frac{E_f - E_c - E_v + E_f}{kT} \right) &= \ln \left( \frac{m_h}{m_e} \right)^{\frac{3}{2}} \\
 2E_f - E_c - E_v &= kT \ln \left( \frac{m_h}{m_e} \right)^{\frac{3}{2}}
 \end{aligned}$$

$$E_f = \frac{E_c + E_v}{2} + \frac{kT}{2} \ln \left( \frac{m_h}{m_e} \right)^{\frac{3}{2}}$$

Now if the effective mass of the electrons and holes are same then

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

This shows that the Fermi level  $E_f$  lies exactly in the middle of the forbidden energy gap  $E_g$  as depicted in figure. The Fermi level can also be defined as the energy level at which there is a 0.5 probability of finding an electron. It depends on the distribution of energy level and number of electron available.

## (B) Fermi level in extrinsic semiconductor:

### (i) n-type extrinsic semiconductor:

At usual temperature all the donor level will be fully activated and the donor atoms will be ionised. It means the density of electrons will be increase. It means the density of electrons in the conduction band will be approximately equal to the density of donor atoms, i.e.  $n_e = N_d$  (density of donor atoms)

$$\text{Then } n = N_d \cdot 2 \left[ \frac{2\pi m_e kT}{h^2} \right]^{\frac{3}{2}} \cdot e^{\left( \frac{E_f - E_c}{kT} \right)}$$

$$\text{Let } 2 \left[ \frac{2\pi m_e kT}{h^2} \right]^{\frac{3}{2}} = N_c = \text{constant}$$

$$\begin{aligned} \text{Then } N_d &= N_c \cdot e^{\left( \frac{E_f - E_c}{kT} \right)} \\ \frac{N_d}{N_c} &= e^{\left( \frac{E_f - E_c}{kT} \right)} \\ \frac{N_c}{N_d} &= e^{-\left( \frac{E_f - E_c}{kT} \right)} \end{aligned}$$

Taking log on both sides

$$\begin{aligned} \ln \left[ \frac{N_c}{N_d} \right] &= - \left( \frac{E_f - E_c}{kT} \right) \\ E_f - E_c &= -kT \ln \left[ \frac{N_c}{N_d} \right] \\ E_f &= E_c - kT \ln \left[ \frac{N_c}{N_d} \right] \end{aligned}$$

It shows that the Fermi level lies below the bottom of the conduction band, as shown in the figure.

In intrinsic semiconductor, Fermi level lies in the middle of the forbidden energy  $E_g$  indicating equal concentrations of free electrons and holes. When a donor type impurity is added to the crystal, then if we assume that all the donor atoms are ionised, the donor electrons will occupy the states near the bottom of the conduction band. Hence it will be more difficult for the electrons from the valance band to cross the energy gap by thermal agitation. Consequently, the number of holes of the valance band is decreased. Since Fermi level is a measure of the probability of occupancy of the allowed energy states,  $E_f$  for n-type

semiconductors must move closer to the conduction band, as shown in the figure.

**(ii) P-Type extrinsic semiconductor:**

When an acceptor type impurity is added it also modifies the energy level diagram of semiconductor and makes the conduction easier. The presence of impurity creates new energy levels which are in the gap in the neighbourhood of the top of valence band of energies as shown in figure. Ambient temperature results in ionisation of most acceptor atoms and thus an apparent movement of holes takes place from the acceptor level to the valence band. The energies for holes are highest near the valence band decreases vertically upward in the energy level diagram. Alternatively, one may say that electrons are accepted by the acceptors and these electrons are supplied from the valence band, thus leaving a preponderance of holes in the valence band.

If we assume that there are only acceptor atoms present and that these are all ionised, we have

$$n_h = N_a = 2 \left[ \frac{2\pi m_h kT}{h^2} \right]^{3/2} \cdot e^{\left( \frac{E_v - E_f}{kT} \right)}$$

$$N_a = N_v e^{\left( \frac{E_v - E_f}{kT} \right)}$$

Where  $N_v = \left[ \frac{2\pi m_h kT}{h^2} \right]^{3/2} = \text{constant}$

$$\frac{N_a}{N_v} = e^{\left( \frac{E_v - E_f}{kT} \right)}$$

$$\frac{N_v}{N_a} = e^{-\left( \frac{E_v - E_f}{kT} \right)}$$

Taking log on both side,

$$\ln \left[ \frac{N_v}{N_a} \right] = -(E_v - E_f)/kT$$

$$E_f = E_v + kT \ln \left[ \frac{N_v}{N_a} \right]$$

It shows that the Fermi level lies above the top of the valence band.

## Hall Effect:

According to Hall when a current carrying metal or semiconductor is placed in a transverse magnetic field, a potential difference is developed across it; the direction of the developed potential difference is perpendicular to the direction of both applied magnetic field and applied current.

In a P type semiconductor slab the current is given by

$$i = peAv_d \quad \dots (1)$$

Where

$p$  = Concentration of holes

$e$  = The charge on the hole

$A$  = Area of cross-section

$v_d$  = Drift velocity of the charge carrier

Therefore the current density along the external applied electric field will be given by

$$\begin{aligned} \vec{J} &= \frac{i}{A} \\ \vec{J} &= pev_d \quad \dots (2) \end{aligned}$$

When a transverse magnetic field is applied, the hole experience a Lorentz force ( $F_L$ ) which deflect them towards face  $F_1$  (in our case). Because of this at face  $F_1$  the holes starts gathering at surface  $F_1$  and it acquires a positive polarity. An equivalent negative charge is developed at surface  $F_2$ . Due to this potential difference developed between the faces and an electric field ( $E_H$ ) is produced. This field is called Hall field. This electric field produces a force ( $F_H$ ) on the hole in opposite to Lorentz force ( $F_L$ ).

### 1. Hall Voltage ( $V_H$ ):

When a sufficient number of holes accumulates at the surface  $F_1$ , the force  $F_H$  balance the Lorentz force i.e.

$$F_L = F_H \quad \dots (3)$$

This equilibrium condition usually reached in  $10^{-14}$  s

Now the Lorentz force on holes due to magnetic field is given by

$$\begin{aligned} F_L &= ev_d B \sin 90 \\ F_L &= ev_d B \quad \dots (4) \end{aligned}$$

Substituting the value of  $v_d$  from equation (2) we have

$$\begin{aligned} F_L &= e \frac{\vec{J}}{pe} B \\ F_L &= \frac{\vec{J}B}{p} \quad \dots (5) \end{aligned}$$

And the electric force on the hole due to Hall voltage

$$F_H = e E_H$$

But

$$E_H = V_H/b$$

$$F_H = e \left( \frac{V_H}{b} \right) \quad \dots (6)$$

Where  $b$  is the width of the semiconductor slab.

Putting the value of  $F_L$  and  $F_H$  in equation (3) we have

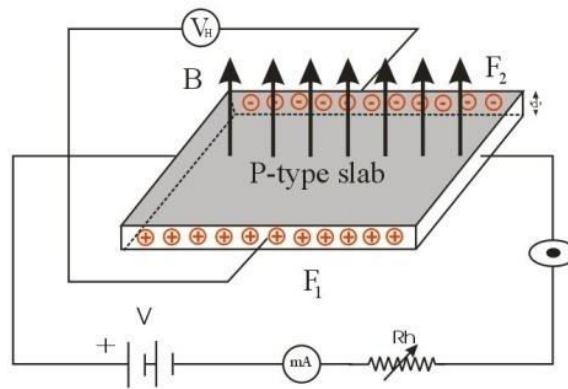
$$e \frac{V_H}{b} = \left( \frac{JB}{p} \right)$$

But  $J = i/A$

$$\begin{aligned} \text{So } e \frac{V_H}{b} &= \left( \frac{i}{A} \right) \frac{B}{p} \\ V_H &= \frac{B i b}{p e A} \end{aligned} \quad \dots(7)$$

If  $d$  is the thickness of the semiconductor slab then  $A = bd$

$$\begin{aligned} \therefore V_H &= \frac{B i b}{p e d \cdot b} \\ V_H &= \frac{B i}{p e d} \end{aligned} \quad \dots(8)$$



Figure(17): Hall Effect

## 2. Hall coefficient( $R_H$ ):

Hall coefficient  $R_H$  is defined as the Hall field per unit magnetic induction per unit current density.

$$R_H = \frac{E_H}{JB} = \frac{(V_H/b)}{JB}$$

Putting the value of  $V_H$  from equation (7)

$$\begin{aligned} R_H &= \frac{Bib}{peA} \times \frac{1}{b} \times \frac{1}{JB} \\ R_H &= \frac{i}{peA} \times \frac{1}{\frac{i}{A}} = \frac{1}{pe} \end{aligned} \quad \dots(9)$$

Again putting the value of  $\frac{1}{pe}$  from equation (9) into (8) we get-

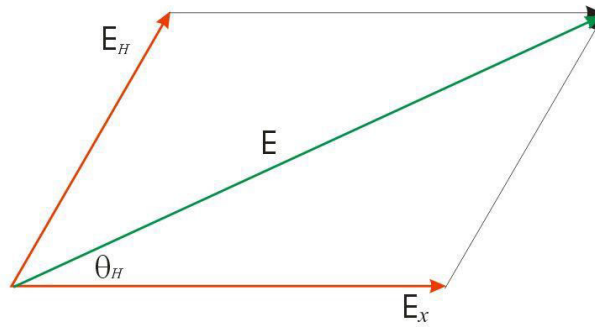
$$V_H = \frac{iB}{d} \times R_H$$

$$R_H = \frac{V_H d}{iB} \quad \dots(10)$$

$$\mu = \sigma R_H \quad \dots (11)$$

### 3. Hall Angle( $\theta_H$ )

In the semiconductor the resultant electric field  $E$  is the vector sum of the applied field ( $E_x$ ) and the developed Hall field ( $E_H$ ) as shown in figure. If  $\theta_H$  is the angle between the resultant electric  $E$  field and the direction along which the current is flowing as shown in the figure then-



Figure(18)

$$\tan \theta = \frac{E_H}{E_x} \quad \dots (12)$$

But we know that

$$E_H = \frac{V_H}{b} = \frac{JB}{pe} \quad \dots (13)$$

$$\text{And } E_x = \frac{J}{\sigma} \text{ where } \sigma \text{ is conductivity} \quad \dots (14)$$

So by (12), (13) and (14)

$$\tan \theta = \frac{JB}{pe} \times \frac{1}{\left(\frac{J}{\sigma}\right)}$$

$$\tan \theta = \frac{B\sigma}{pe}$$

But  $\frac{1}{pe} = \frac{R_H}{\mu}$  by equation (9) then

$$\tan \theta = B\sigma R_H$$

Now  $\sigma R_H = \mu$

$$\tan \theta = \mu B$$

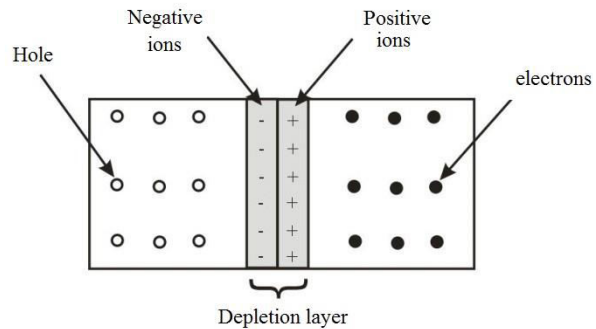
$$\theta_H = \tan^{-1} \mu B \quad \dots (15)$$

## P-N junction Diode:

When P-type and N-type semiconductors are joined together by some special techniques, a p-n junction is formed. A P-N junction allows the flow of current in one direction only, and this property is called rectifying action.



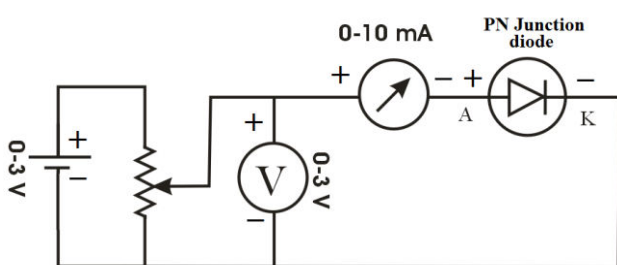
Figure (19): Symbol of P-N junction diode.



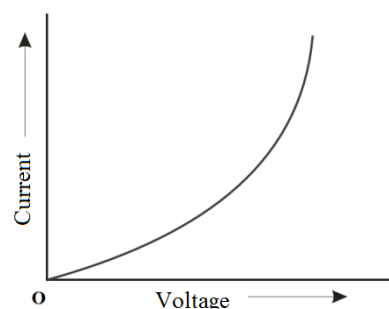
Figure(20): Diode

There are two operating regions and three possible biasing conditions of a P-N junction.

- i) **Zero biasing:** When no external potential is applied to the p-n junction, the diode is said to be unbiased. The potential barrier discourages the diffusion of any majority carrier across the junction. However, the potential barrier helps minority carriers to drift across the junction. Then an equilibrium will be established.
- ii) **Forward bias:** The P-N junction is said to be forward biased when its p-side is connected to the positive terminal and the n-side to the negative terminal of the battery. If the applied voltage becomes greater than the value of the potential barrier, the potential barrier will be overcome and current starts flowing. When the applied voltage is increased gradually more and more charge carriers of lower energy gain sufficient energy and current starts increasing.

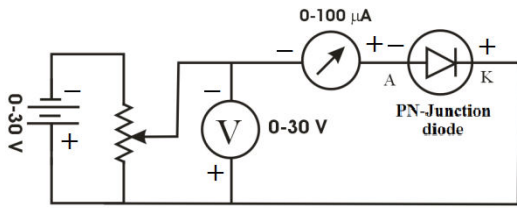


Figure(21): Forward bias circuit



Figure(22): Forward bias characteristic

- iii) **Reverse bias:** When positive voltage is applied to the n-type and negative voltage is applied to the p-type semiconductor, the diode is said to be reverse biased. The depletion layer grows wide in this case; only a small amount of current flows due to the minority charge carriers. The circuit of reverse bias P-N junction diode and reverse bias characteristics are shown in the figure.



Figure(23): Reverse bias PN junction circuit diagram

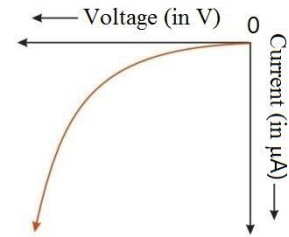


Figure (24): Reverse bias characteristics curve.

## Zener Diode:

Zener diode is a special purpose heavily doped PN-junction diode, designed to operate in the breakdown region. The symbol of Zener diode is shown below



Figure(25): Symbol Zener Diode

### Construction:

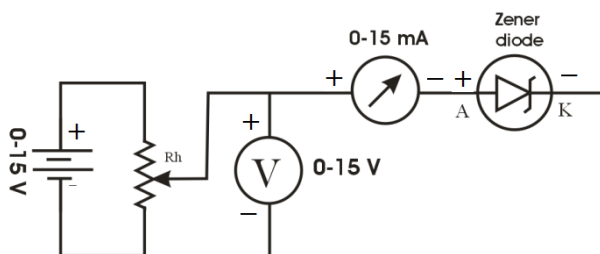
Zener diodes are like ordinary PN junction diode except that they are fabricated by varying the doping so that sharp and specific breakdown is obtained. Zener diode consists of two *N* and *P* substrates diffused together and has metallic layer deposited on both sides to connect anode and cathode terminals.

### V-I Characteristics:

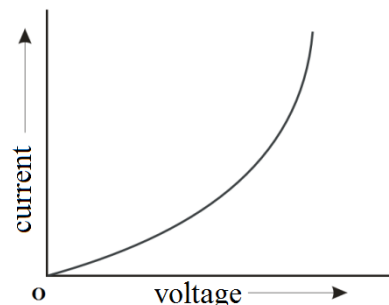
The graph plotted between voltage taking on x-axis and current on the Y-axis is called the  $V - I$  characteristics.

#### Forward bias characteristics:

The forward bias V-I Characteristics of Zener diode is shown below. It is almost identical to forward bias characteristics of PN junction diode.



Figure(26): Forward bias Zener Diode

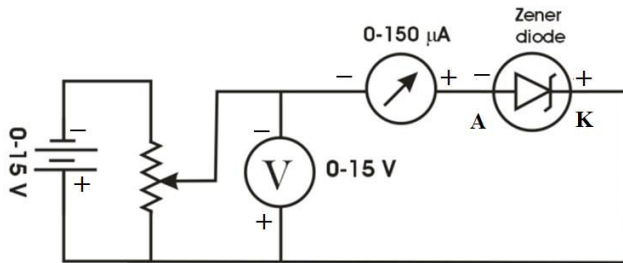


Figure(27): Forward bias characteristics of Zener diode

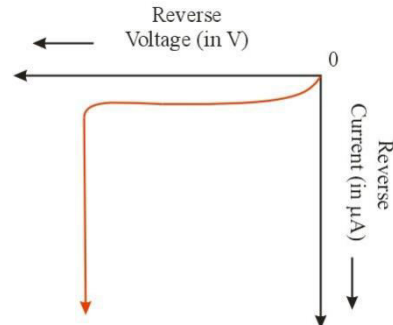
#### Reverse Bias Characteristics:

The reverse bias characteristic of Zener diode is generally different from that of the PN-junction diode. As we

increase the reverse voltage, initially small current starts flowing due to thermally generated minority charge carriers. At a certain value of reverse voltage the reverse current will increase suddenly. This voltage is called Zener break down voltage. Once the break down occurs the voltage across Zener diode remains constant.



Figure(28): Zener diode Reverse bias



Figure(29): Zener diode reverse bias characteristics

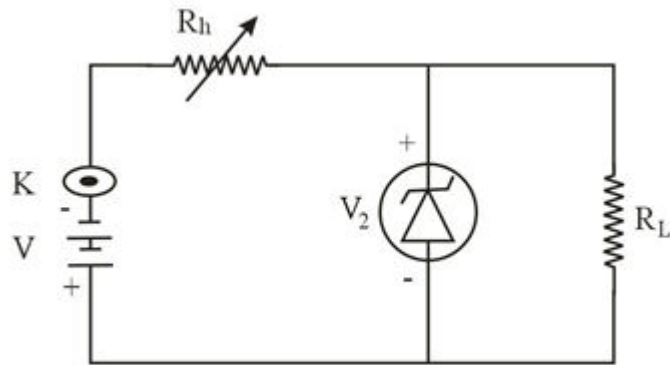
The sudden increase in the current may occurs due to the following reasons-

- i) **Avalanche effect:** This type of breakdown takes place when both side of junction are lightly doped in this case the electric field is not so strong to produce Zener break down. Here the minority carrier accelerates by the field, collides with the atoms of semiconductors due to the collision with valance electrons, covalent bonds are broken and electron hole pair are produced. This is called avalanche break down. At this point the device damages permanently and cannot be used again by removing the reverse voltage.
- ii) **Zener effect:** When both side of junction are very heavily doped and small reverse bias voltage is applied, a very strong electric field is set. This field is enough to break the covalent bonds. This is called the Zener effect or Zener break down. Due to which an abrupt increase in the reverse current occurs, and the device stats acting as a conductor. After the removal of reverse voltage the device will be available to use and at Zener voltage the device do not damages.

#### Applications of Zener diode:

- i) As a voltage regulator
- ii) Switching operations
- iii) Clipping and clamping circuits.

Zener diode as a voltage regulator: A simple voltage regulator use a Zener diode in reverse bias in parallel with the load  $R_L$  as shown in the figure-



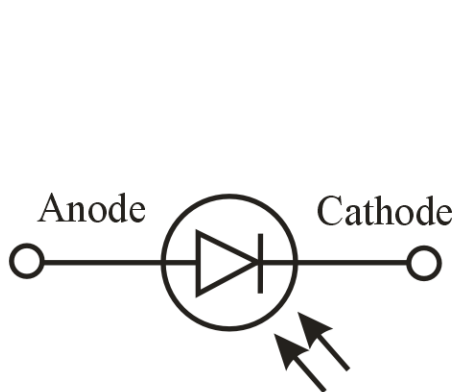
Figure(30): Zener Diode as a voltage Regulator

When the voltage in the circuit increases the voltage across Zener diode remains constant which appears across the load. The Zener diode draws more current and voltage across the diode remains constant.

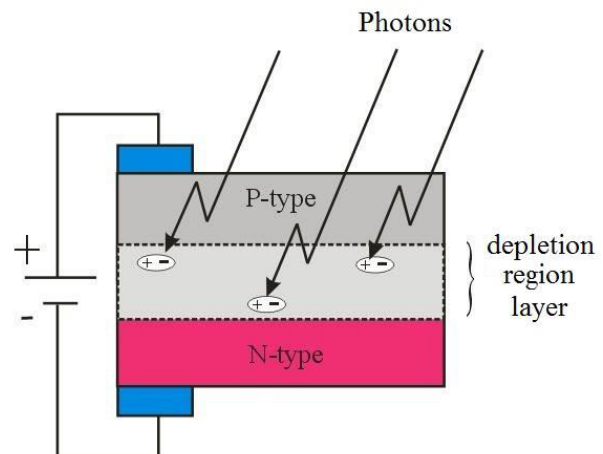
## Photo Diode:

The Photo diode is a PN junction semiconductor diode which is always operates in the reverse bias condition

**Construction:** the construction of a photodiode and its circuit and symbol are shown in the figure. The light is always focused through glass lens on the junction of photodiode. As the photodiode is reverse biased the depletion region is quite wide. The photons incident on the depletion region will impart their energy to the ions present there and generate electrons hole pair. The number of electrons-hole pair will be depend on the intensity of the light. With increase in the light intensity number of electrons –holes pairs are produced and the photo current increase.

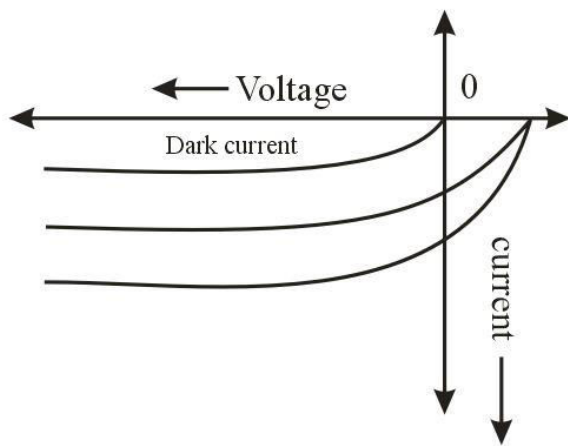


Figure(33): Symbol Photo diode

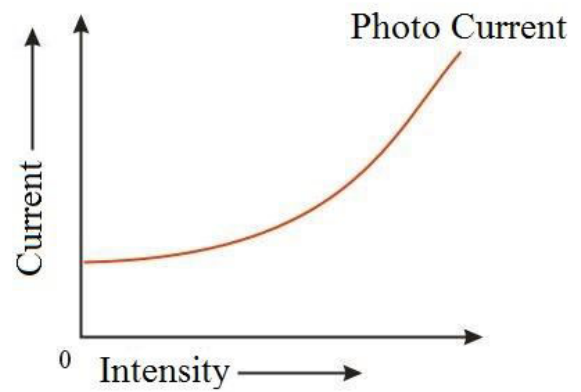


Figure(34):Construction of photo diode

**Photo diode Characteristics:** V-I characteristics are shown below and the variation of photocurrent with light intensity is shown below in the figure



Figure(35): Photo diode V-I Characteristics



Figure(36): Photo diode intensity/current characteristics

**Dark Current:** It is the current flowing through a photodiode in the absence of light. Dark current flows due to thermally generated minority charge carrier and hence increase with increase in temperature. The reverse current ( $I_r$ ) depends on the intensity of light incident on the junction. It is almost independent of the reverse voltage.

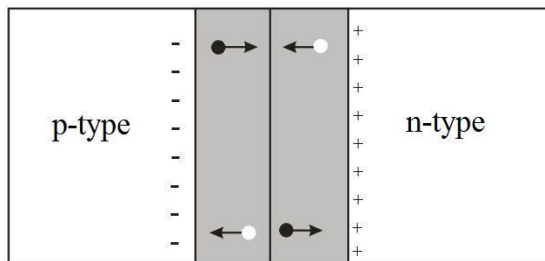
## Solar Cell:

A solar cell is a photovoltaic device designed to convert sunlight (solar energy) into the electrical energy.

### **Construction:**

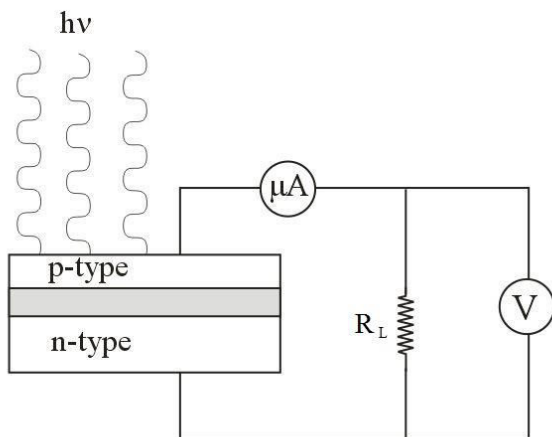
The solar cell is made from semiconductor materials like silicon. The p-type layer is made very thin so that the light radiation may penetrate to fall on junction. The doping level of p-type semiconductor is very high. As the photon reaches at the junction, here it is absorbed and an electron from valance band jump to conduction band this creates an electron hole pair.

The electron produced in the p-side and the hole produced at the n-side works as minority carriers. These minority carriers cross the junction due to the depletion region electric field across the junction, even in the absence of applied voltage. This phenomenon is clearly depicted in figure.

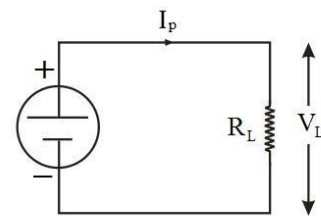


Figure(37): Generation of photo electrons

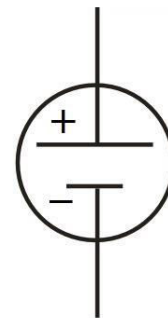
Thus a photo current flows in the circuit



Figure(39): Solar cell circuit



Figure(38): Circuit of solar cell



Figure(40): Symbol of solar cell

### **Advantages:**

- 1) It is a pollution free energy conversion system.
- 2) Cheap for solar power aircrafts.
- 3) Useful in remote areas where no other source of energy can be frequently transferred.
- 4) It is clean source of energy.

**Disadvantages:**

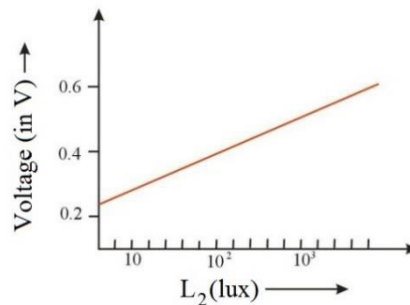
- 1) It does not convert all the solar energy in to the electrical energy.
- 2) Its efficiency depends on the temperature.
- 3) Requires large area for power applications.
- 4) The output is DC which cannot be transported through large distance without significant loss.

**Applications:**

- 1) In space satellite.
- 2) In low resistance relay for ON and OFF applications.

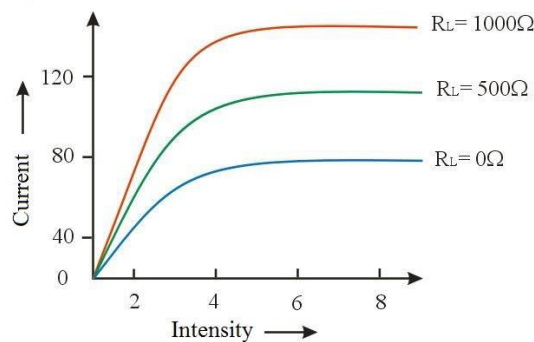
**Characteristics of solar cell:**

- 1) **Voltage v/s intensity of incident light:** - The voltage increases linearly with increase in the intensity of light.



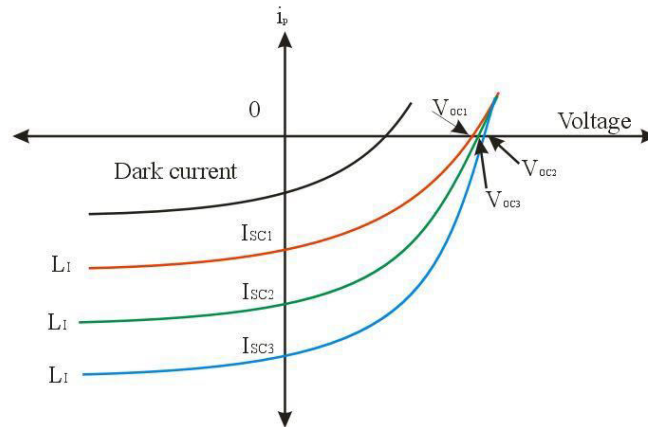
Figure(41):Voltage/current intensity

- 2) **Current v/s intensity of incident light:** The current v/s intensity at a given load resistance are shown in figure below. The current increases linearly first and after a certain point the current stops increasing



Figure(42): Current/intensity graph

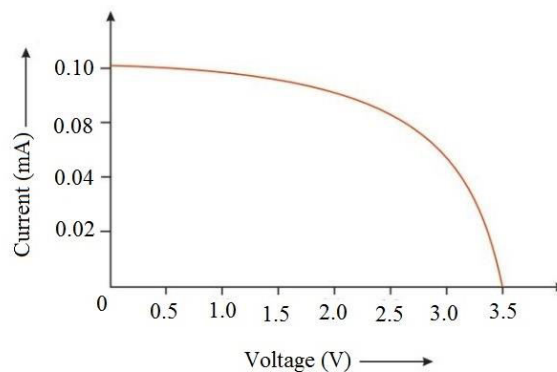
- 3) **Voltage v/s current or V-I characteristics:** Voltage current characteristics for fixed load resistance  $R_L$  is shown in the figure(43).



Figure(43): Voltage v/s current or V-I characteristics

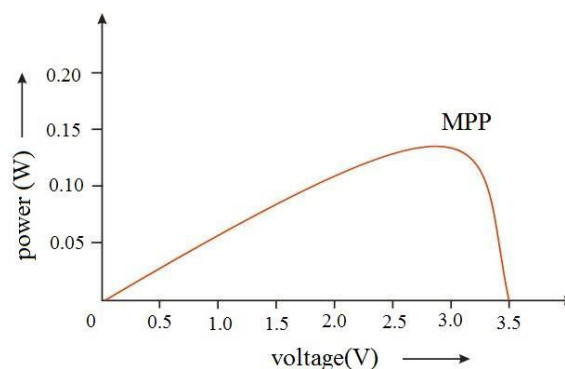
The nature of the V-I characteristic of a solar cell is similar to that of a photo diode. Typical V-I characteristics of a solar cell is shown in the figure. On the vertical axis  $i_p$  the applied voltage  $V$  is zero everywhere and therefore the point of intersection represents the short circuit condition. The point of intersection of the characteristic curve with  $i_p$  axis represents the short circuit current  $I_{sc1}$ ,  $I_{sc2}$ ,  $I_{sc3}$  ... and  $V_{oc1}$ ,  $V_{oc2}$  ... are open circuit current.

4) **V-I characteristic as a function of load resistance:**



Figure(44):VI graph

- 5) **Voltage v/s power i.e. V/W characteristics curve:** the voltage v/s power characteristic curve as a function of load resistance  $R_L$  at fix light intensity is shown in figure below-



Figure(45):Voltage/power graph