Module 6

Semiconductor Devices 10

Syllabus :

PN junction diode, Zener diode, their construction, Working and characteristics, BJT, its construction, Characteristics and applications (only CE configuration).

10.1 Introduction :

- The electronic devices such as diodes, bipolar junction transistor (BJT), zener diodes, field effect transistors (FET) etc. are made from the special class of materials called **semiconductors**.
- In this chapter, we will discuss in brief the types of semiconductors and their properties and then proceed to explain the construction, operation, characteristics and applications of various semiconductor devices.

10.2 Classification of Materials :

- The materials can be broadly divided into three categories as conductors, insulators and semiconductors depending on their ability to conduct the electric current.

Conductors	:	They allow the current to flow easily.
Insulators	:	They do not allow the current to flow.
Semiconductors	:	They are in between conductors and insulators.

Let us understand them one by one based on their energy band diagrams.

- Fig. 10.2.1 shows the classification of materials.

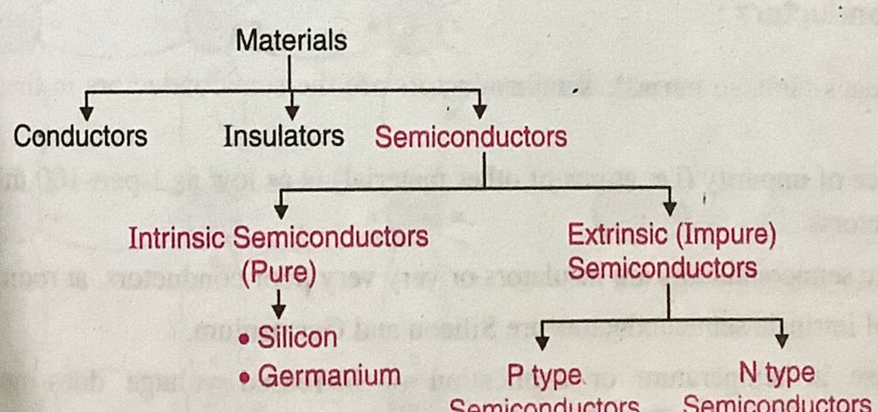


Fig. 10.2.1 : Classification of materials

10.2.1 Semiconductors :

- As far as the electronic components are concerned, semiconductors are the most important type of materials.
- They have conduction properties which are in between those of conductors and insulators.
- We can say that semiconductors are neither conductors nor insulators.
- At very low temperatures of the order of 0°K (– 273°C), semiconductors act like insulators.
- However with increase in temperature the valence electrons start acquiring additional energy and they can cross the narrow forbidden gap to enter into the conduction band. (See Fig. 10.2.2).
- Thus at temperatures close to 20°C the conduction begins in semiconductors. The conduction increases with increase in temperature.
- Fig. 10.2.2 shows the energy band diagram of a semiconductor.
- It shows that the forbidden gap between the valence band and the conduction band is very narrow.

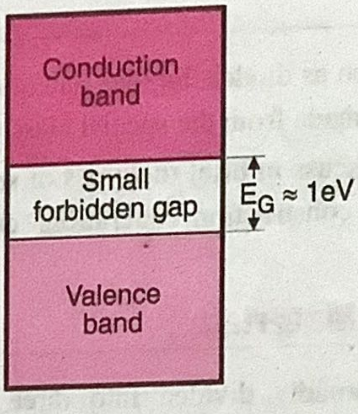


Fig. 10.2.2 : Energy band diagram of a semiconductor

Types of semiconductors :

The semiconductors are classified into two categories as :

- Intrinsic semiconductors and
- Extrinsic semiconductors.

Intrinsic semiconductors :

- Intrinsic means pure, so intrinsic semiconductors are the semiconductors in their purest possible form.
- The presence of impurity (i.e. atoms of other material) is as low as 1 part 100 million parts of the semiconductors.
- The intrinsic semiconductors are insulators or very very poor conductors, at room temperature.
- Examples of intrinsic semiconductors are Silicon and Germanium.
- The increase in temperature or application of increased voltage does not increase their conductivity significantly. Therefore, the intrinsic semiconductors are not practically used for manufacturing of devices.

- Examples of intrinsic semiconductors are Silicon and Germanium.

Extrinsic semiconductors and doping :

- Extrinsic means impure, so we can obtain the extrinsic semiconductors from intrinsic ones by adding impurities to them.
- Impurity is nothing but some other material. The process of adding impurities is called as **"Doping"**.
- Due to doping, the conductivity of the semiconductors increase. Thus extrinsic semiconductors have a better conductivity than the intrinsic semiconductors.
- Therefore they are used in manufacturing of all the electronic components such as diodes, transistors etc.
- Extrinsic semiconductors are further classified into two categories :
  1. N-type semiconductors
  2. P-type semiconductors

10.2.2 Intrinsic Semiconductors :

- Fig. 10.2.3 shows the crystalline structure of silicon which an intrinsic semiconductor.
- We know that in a Silicon or Germanium atom there are four valence electrons.
- In an intrinsic Silicon or Germanium crystal these four valence electrons are bounded to four adjoining atoms as shown in the two dimensional representation of Silicon or Germanium crystal of Fig. 10.2.3.
- Each one of the four valence electrons in each atoms forms a bond with a valence electron from the adjoining atom as shown in Fig. 10.2.3.
- This bond is nothing but sharing of electrons. These bonds are known as the **covalent bonds**. The covalent bonds result in a stronger bond between the valence electrons and their parent atoms.
- In each covalent bond, both the electrons involved are shared by both the parent atoms. Thus with four covalent bonds associated with each atom, all the silicon atoms will effectively have eight electrons in their valence shells.
- Four of these electrons are their own and remaining four are due to the four covalent bonds. Due to this, the outermost shells of all the atoms are completely filled.

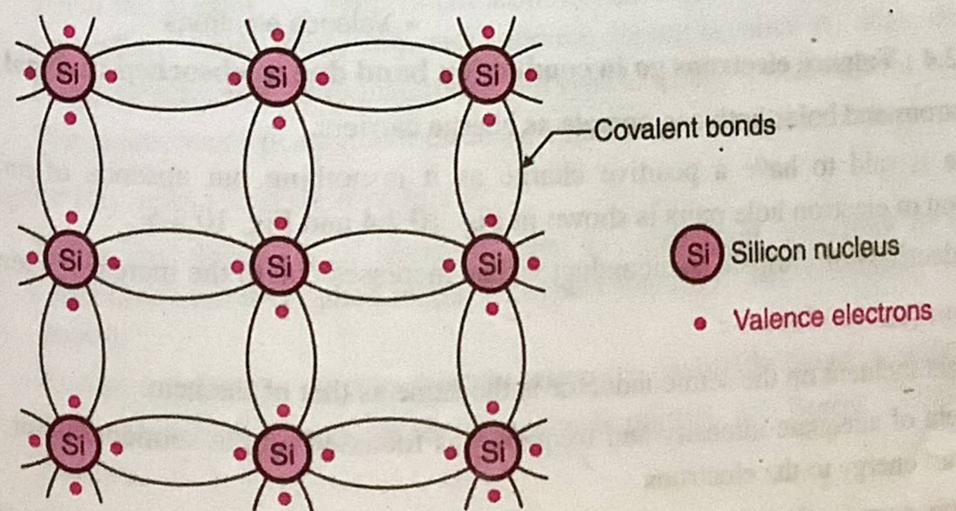


Fig. 10.2.3 : Two dimensional representation of a silicon crystal

- This makes the outermost shells of all atoms stable. Therefore not a single free electron is available at the absolute zero temperature i.e. at 0°K or – 273°C.
- Hence the intrinsic semiconductor acts like an insulator at the absolute zero temperature.

10.2.3 Conduction in Intrinsic Semiconductors :

- The intrinsic semiconductors behave like perfect insulators at the absolute zero temperature.
- But the behaviour changes with increase in temperature. At around the room temperature, electrons become available for conduction and current can flow.
- The generation of free electrons takes place as explained below.

Effect of increased temperature (Thermal generation of carriers) :

- With increase in temperature, many valence electrons will absorb the thermal energy, break the covalent bonds and go into the conduction band.
- Thus they become free for conduction. These electrons are called **conduction electrons**.

Generation of a hole :

- When an electron breaks a covalent bond and becomes free, a vacancy is created in the broken covalent bond.
- This vacancy is called as **"hole"**. Thus corresponding to every free electron, a hole is created.
- Therefore the number of free electrons generated due to increased temperature is exactly equal to the number of holes.
- As the free electrons and holes get generated in pairs they are called as thermally generated electron hole pairs.

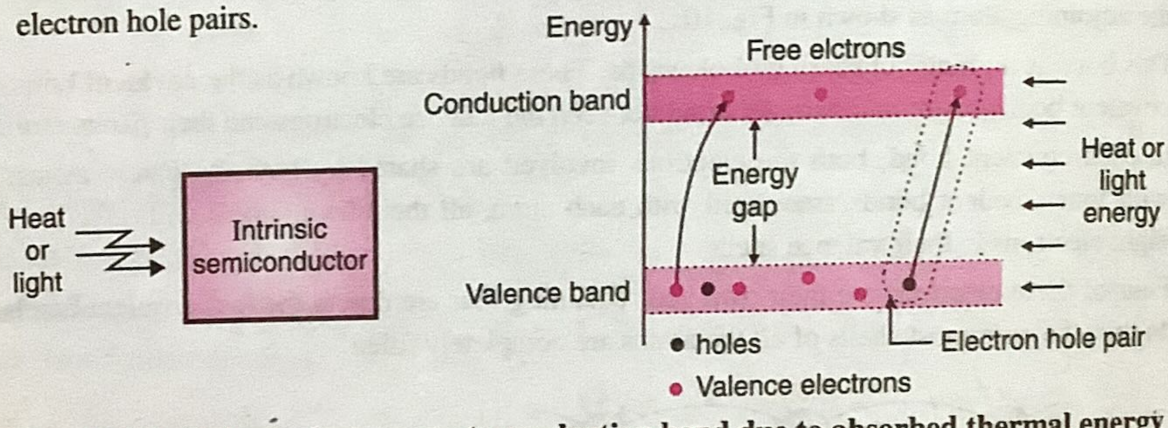


Fig. 10.2.4 : Valence electrons go to conduction band due to absorbed thermal energy

- The electrons and holes both can operate as charge carriers.
- The hole is said to have a positive charge as it is nothing but absence of an electron. The generation of electron hole pairs is shown in Fig. 10.2.4 and Fig. 10.2.5.
- The conductivity of intrinsic semiconductor thus increases due to the increase in temperature.

Effect of light on semiconductor :

The effect of light incident on the semiconductor is the same as that of the heat.

- When light of adequate intensity and frequency is focussed on the semiconductor, the "photons" will impart energy to the electrons.
- Due to this energy, electrons will break their covalent bonds and enter into the conduction band and become free for conduction.

The conductivity of a semiconductor thus increases due to incident light. In other words the resistivity of the material decreases due to the light incident on it.

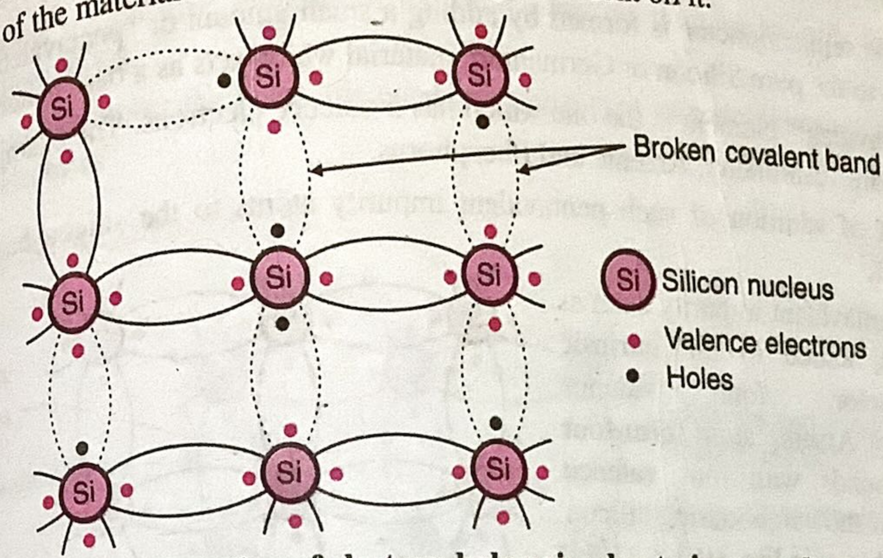


Fig. 10.2.5 : Generation of electron-hole pairs due to increased temperature

- The amount of charge on a hole is exactly same as that on an electron.
- The current in a semiconductor flows due to holes as well as electrons.

10.3 Extrinsic Semiconductors :

Doping process :

- In the previous section we have learnt that to increase the conductivity of intrinsic semiconductors we have to supply the heat energy or light energy externally.
- These methods of increasing the conduction are not practically usable. Hence the conductivity is increased by means of the doping process.
- In the process of doping, impurities are added to the pure Silicon or Germanium.
- The impurities are the materials used to **dope** the intrinsic semiconductor materials. These materials can be of two types :
  1. Donor impurity
  2. Acceptor impurity

1. Donor impurity (Pentavalent impurity) :

- The material which is being used as impurity in the process of doping is called as "dopant".
- When the dopant is a pentavalent atom i.e. the atom containing five valence electrons then it is called as the "donor impurity" and the doping is called as "donor doping".
- Donor doping is used to manufacture n-type extrinsic semiconductor.
- The examples of pentavalent or donor impurities are Arsenic, Phosphorous and Antimony.

2. Acceptor impurity (Trivalent impurity) :

- When the dopant is a trivalent atom i.e. the atom consisting of only three valence electrons, then it is called as the "acceptor impurity" and the doping is called as "acceptor doping".
- Acceptor doping is used to manufacture p-type extrinsic semiconductors.
- The examples of trivalent or acceptor impurities are Boron, Gallium, Aluminium and Indium.

10.3.1 n-type Semiconductors :

- The n-type semiconductor is formed by adding a small amount of "pentavalent" impurity (donar impurity) to the pure Silicon or Germanium material which acts as a base material.
- The "pentavalent" element is the one which has 5 valence electrons. The examples of pentavalent materials are : Antimony, Arsenic and Phosphorus.
- The effect of addition of such pentavalent impurity atoms to the silicon base is as shown in Fig. 10.3.1.
- When a pentavalent impurity such as Arsenic is added to the intrinsic semiconductor, four valence electrons of Arsenic atom form four covalent bonds with four valence electrons of the neighbouring silicon atoms, as shown in Fig. 10.3.1.
- The fifth electron of the Arsenic atom does not have a chance to form a covalent bond.

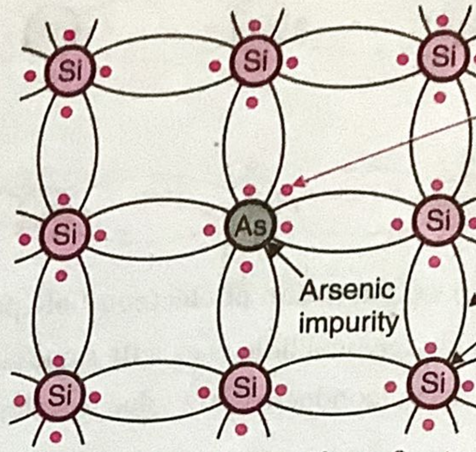


Fig. 10.3.1 : Formation of n-type semiconductor

- This is an additional valence electron which can enter the conduction band very easily to be a free electron.
- **Thus corresponding to each impurity atom an extra electron becomes available for conduction.**
- This increased number of electrons will make the semiconductor an "n-type semiconductor".
- It is possible to control the number of free electrons available for conduction by changing the number of pentavalent atoms added to silicon material.
- Thus conductivity is increased in a controlled manner with the help of the doping process.

Majority and minority carriers in the n-type material :

- A large number of free electrons are present alongwith a small number of thermally generated holes in an n-type semiconductor.
- So the conduction largely takes place due to the free electrons. Therefore the free electrons are called as "majority carriers" and holes are known as "minority carriers".

Conduction in n-type material :

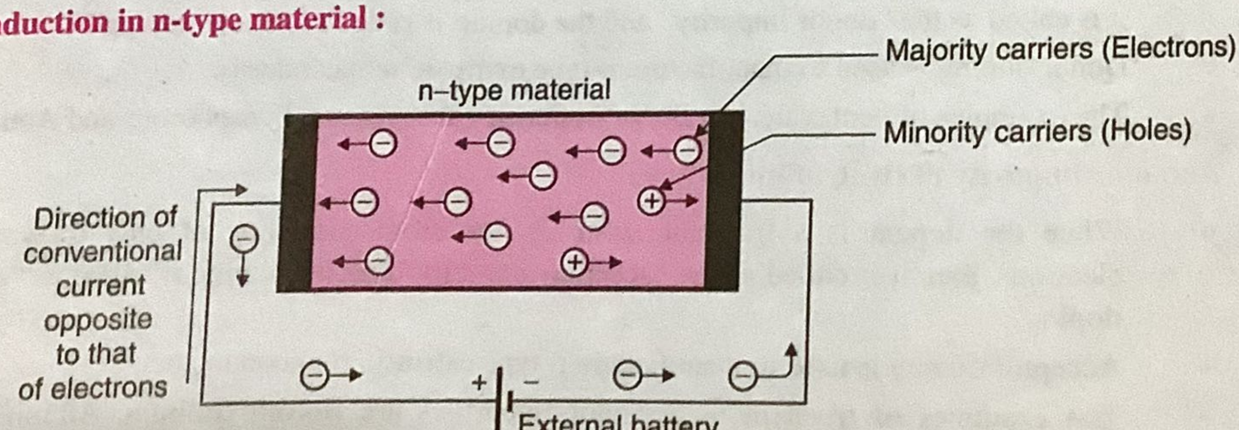


Fig. 10.3.2 : Conduction in n-type material

When an external DC voltage is applied to the n-type semiconductor material, the free electrons move towards the positive terminal of the source and holes move towards the negative end as shown in Fig. 10.3.2.

As electrons outnumber the holes, the conduction in n-type material is mainly due to the majority carriers "electrons".

3.2 p-type Semiconductors :

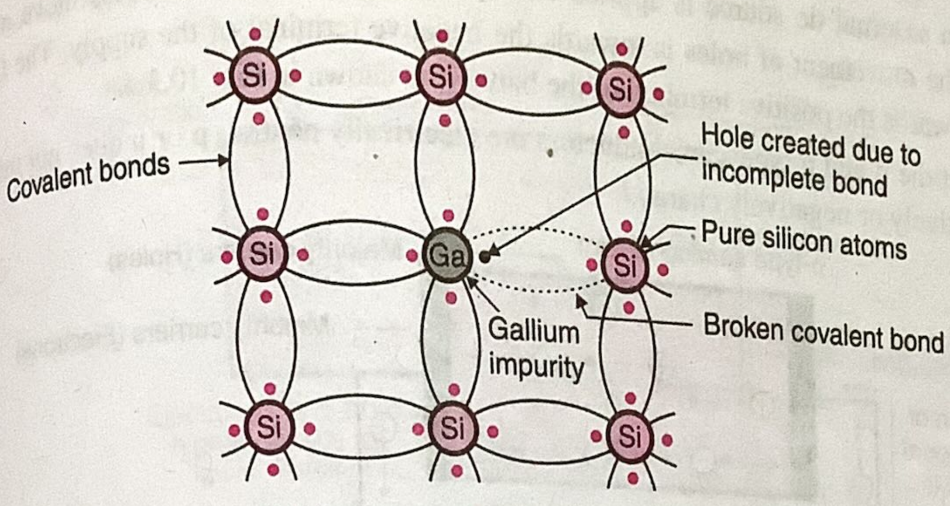


Fig. 10.3.3 : Formation of p-type semiconductor

- The p-type semiconductors are formed by doping a pure germanium or silicon crystal with the "trivalent" impurity atoms.
- The materials having three valence electrons per atom are known as the trivalent materials.
- **Examples of "trivalent" materials are : Boron, Gallium and Indium.** The effect of adding one of these elements "Gallium" on the base of silicon is as shown in Fig. 10.3.3.

Covalent bonds and creation of a hole :

- As shown in Fig. 10.3.3, when a Gallium atom is added to the silicon base, its three valence electrons will form covalent bonds with the valence electrons of three neighbouring silicon atoms.
- The fourth covalent bond however, remains incomplete as the Gallium atom has only three valence electrons. The resulting vacancy is called as a "hole" and it is represented by a small circle in Fig. 10.3.3.
- A hole is positively charged as it represents the absence of a negative charge. Thus corresponding to each trivalent impurity atom added, a hole is created.
- This increased number of holes will make the semiconductor a p-type semiconductor. It is possible to control the number of holes by controlling the "doping concentration" of trivalent impurity atoms.

Majority and minority carriers in p-type material :

- A large number of holes are present in a p-type semiconductor along with a small number of thermally generated electrons.

- Hence the conduction largely takes place due to the holes. Therefore holes are called as the "majority carriers" and electrons are "minority carriers" for a p-type semiconductor.
- This is exactly opposite to what we learnt for the n-type semiconductor.

Conduction in p-type semiconductors :

The conduction inside a p-type semiconductor is as shown in Fig. 10.3.4.

- When an external dc source is applied across a p-type material, the holes move in the valence band. The movement of holes is towards the negative terminal of the supply. The free electrons move towards the positive terminal of the battery, as shown in Fig. 10.3.4.
- Note that the p and n type semiconductors are electrically neutral. p or n does not mean that they are positively or negatively charged.

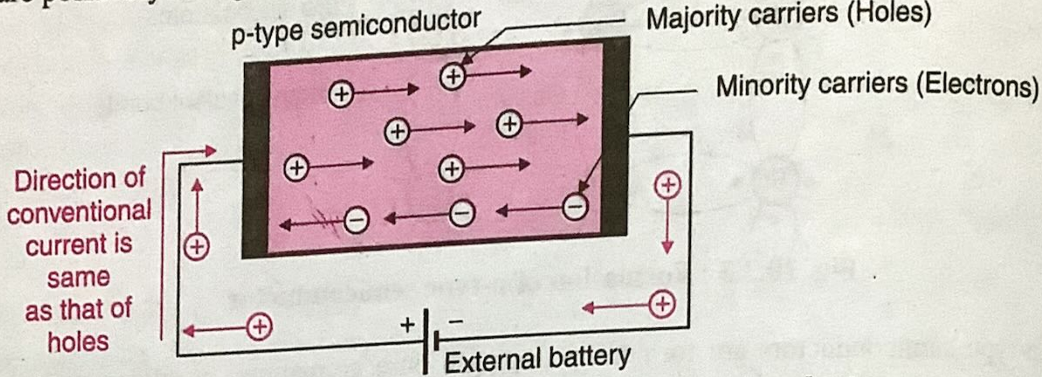


Fig. 10.3.4 : Conduction in a p-type semiconductor

10.3.3 Diffusion and Diffusion Current :

- The two basic processes which are responsible for the movement of electrons and holes in a semiconductor are :

  1. Drift and 2. Diffusion.
- The drift current flows inside a semiconductor under the influence of externally applied electric field.
- In addition to this, the transport of charges takes place in a semiconductor which can be explained by a mechanism called "Diffusion".
- The concentration of electrons in an n-type semiconductor or concentration of holes in the P type semiconductor is always non-uniform.
- The electrons or holes tend to travel from higher concentration area to lower concentration area.
- This movement gives rise to a current called diffusion current.

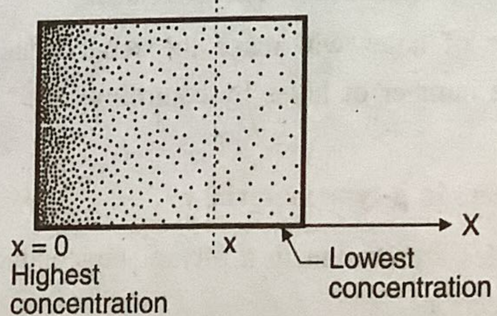


Fig. 10.3.5 : Nonuniform concentration of particles in a semiconductor

Diffusion current :

- Note that the diffusion current does not flow due to the repulsive force that exists between the holes.
- It exists due to the nonuniform concentration i.e. due to the existence of concentration gradient.
- Such a diffusion current will be present in p-type as well as in the n-type semiconductor, as shown in Fig. 10.3.6.

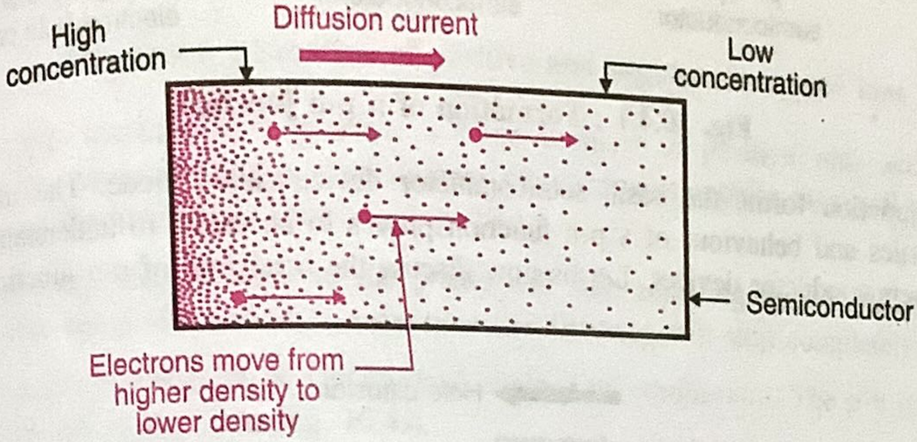


Fig. 10.3.6 : Diffusion current

10.4 Introduction to p-n Junction :

- Earlier in this chapter, we have learnt about the two types of extrinsic semiconductor materials i.e. p and n-type materials, their characteristics and behaviour.
- But it is not possible to manufacture any device using only a p-type or n-type semiconductor.
- Instead we have to use them together. Let us see the effect of operating them together.
- The p-n junction is the basic building block on which the operation of all the semiconductor devices is dependent.
- The behaviour of the p-n junction is developed based on the semiconductor properties described earlier in this chapter.
- **Diode** means a device with two elements namely anode and cathode. **Since a p-n junction itself is a two element devices it becomes the most basic electronic device i.e. the diode.**

10.4.1 Formation of a p-n Junction (p-n Junction with no External Bias) :

- As shown in Fig. 10.4.1, a p-type semiconductor and an n-type semiconductor are joined together with the help of a special fabrication technique to form a p-n junction.
- Terminals are brought out for the external connection with p and n-type semiconductors. The p-side is called as anode and the n-side is called as cathode.
- The "n" side consists of a large number of electrons and few thermally generated holes whereas the "p" side consists of a large number of holes and a few thermally generated electrons.
- Thus the electrons are majority carriers and holes are minority carriers in the n-region whereas their roles are exactly opposite in the p-region.

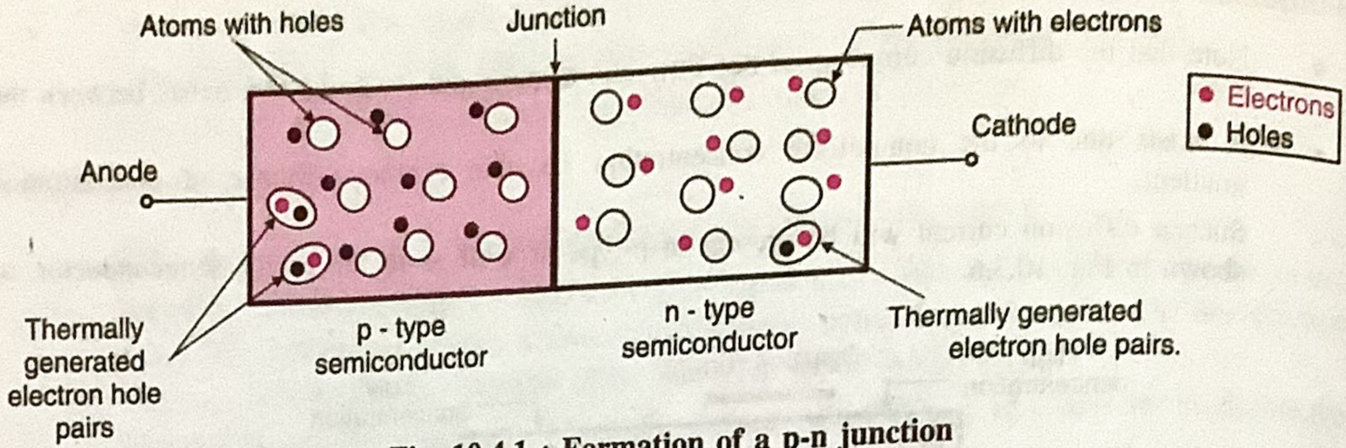


Fig. 10.4.1 : Formation of a p-n junction

- The p-n junction forms the basic semiconductor device called diode. The understanding of characteristics and behaviour of a p-n junction proves to be useful to understand the operation of many semiconductor devices. Let us now discuss the behaviour of p-n junction.

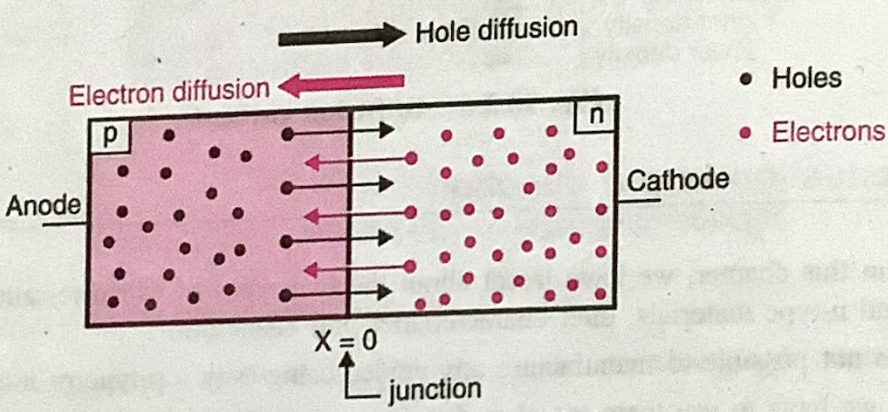


Fig. 10.4.2 : Process of diffusion

- At the junction, one side has a high concentration of holes whereas the other side has high concentration of electrons.
- Due to this a concentration gradient is created across the junction, and the process of diffusion of the charge carrier, as shown in Fig. 10.4.2.

10.4.2 Formation of the Depletion Region :

The behaviour of a p-n junction immediately after its formation is as follows :

- Note that no external voltage is applied between the terminals of the p-n junction, hence the p-n junction is said to be unbiased.
- The free electrons from "n" side will diffuse into the p-side and recombine with the holes present there.
- Each electron diffusing into the "p" side will leave behind a positive immobile ion on the n-side as shown in Fig. 10.4.3.
- When an electron combines with a hole on the "p" side, an atom which accepts this electron, loses its electrically neutral status and becomes a negative immobile ion as shown in Fig. 10.4.3.

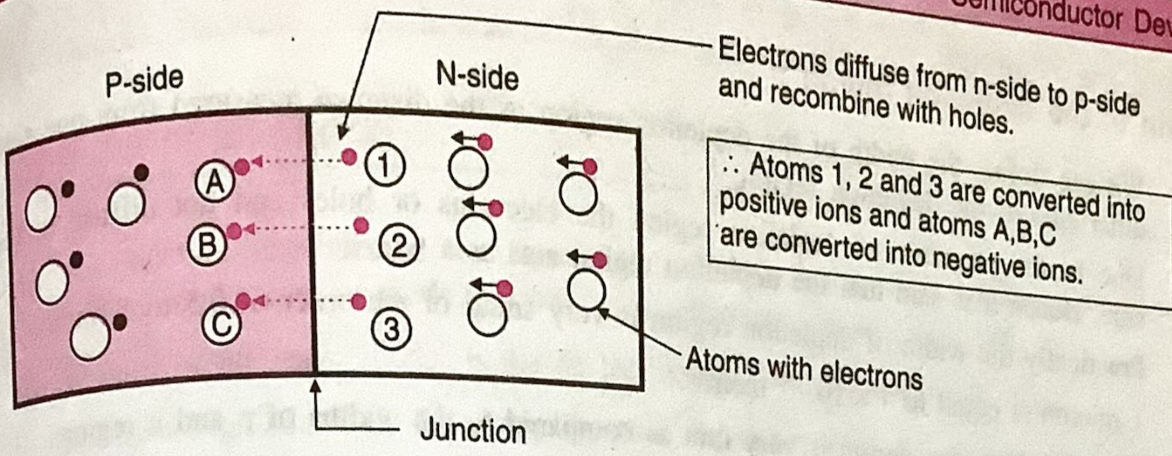


Fig. 10.4.3 : Creation of positive and negative immobile ions

- Due to this recombination process, a large number of positive ions accumulate near the junction on the n-side and a large number of negative immobile ions will accumulate on the p-side near the junction as shown in Fig. 10.4.4.
- The negatively charged ions on the p-side will start repelling the electrons which attempt to diffuse into the p-side and after some time the diffusion will stop completely.
- At this point, the junction is said to have attained an equilibrium. The p-n junction in the state of equilibrium is shown in Fig. 10.4.4.

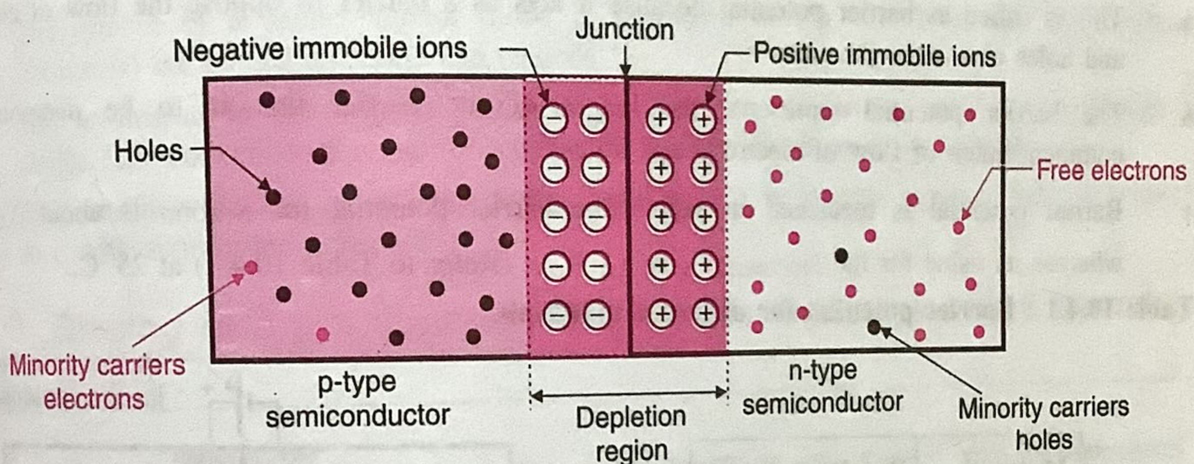


Fig. 10.4.4 : p-n junction with the depletion region

Depletion region :

- The shaded region on both sides of junction in Fig. 10.4.4 contains only immobile ions and no free charge carriers such as electrons or holes. In other words this region is "depleted" of the free charge carriers.
- Therefore this region is called as the "depletion region".
- This region is also known as the "space charge region". In the state of equilibrium, the depletion region gets widened to such an extent that electrons cannot cross the junction any more.
- In the state of equilibrium, the depletion region gets widened to such an extent that electrons can not cross the junction any more.

Note : In the unbiased p-n junction, the depletion region gets formed very quickly after the formation of the junction.

Width of the depletion region :

- We can define the width of the depletion region as the distance measured from one side to the other side of the depletion region.
- Due to the presence of depletion region the electrons or holes can not diffuse to the other side. Hence it is said that the depletion region acts as a **barrier**.
- Practically the width of depletion region is very small of the order of 0.5 to 1 micron where 1 micron is equal to 1×10^{-6} metres.
- Thus the depletion region is very thin as compared to the widths of p and n regions.

10.4.3 Barrier Potential or Junction Potential (V_j) :

- Due to the presence of immobile positive and negative ions on opposite sides of the junction, an electric field is created across the junction. This electric field is known as the "barrier potential" or "junction potential" or cut in voltage. It has fixed polarities as shown in Fig. 10.4.5.
- The polarities of barrier potential are decided by the type of immobile ions present on the two sides of the junction. Thus the negative terminal of the barrier potential is on the p side and positive side is on the n-side as shown n Fig. 10.4.5.
- This is called as barrier potential because it acts as a barrier to oppose the flow of electrons and holes across the junction.
- The barrier potential represents the height of the barrier that is to be overcome for commencement of flow of electrons and holes.
- Barrier potential is measured in volts. The barrier potential for Silicon is about 0.6 Volt whereas its value for the Germanium is 0.2 Volt. (Refer to Table 10.4.1) at 25 °C.

Table 10.4.1 : Barrier potential for different materials

Material	Barrier Potential
Silicon	0.6 volt
Germanium	0.2 volt

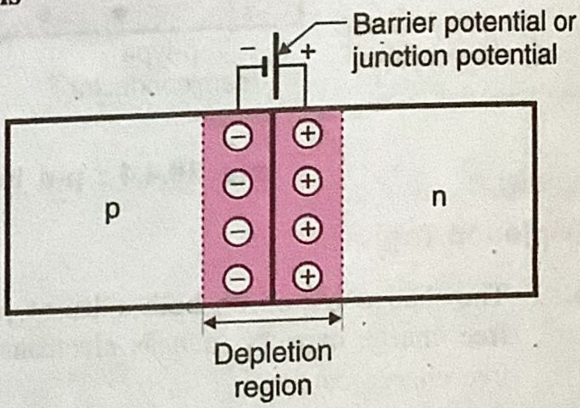


Fig. 10.4.5 : Barrier potential

The factors deciding the barrier potential are : type of semiconductor material used, level of doping and temperature.

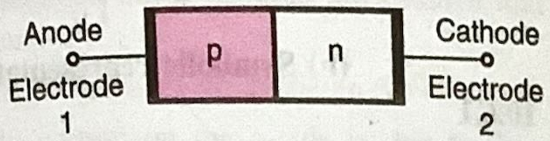
Penetration of depletion region :

- The penetration of the depletion region into p or n-side depends on the doping levels of those sides.

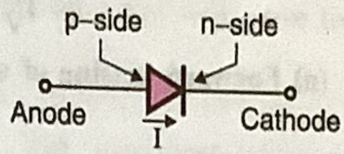
The depletion region always penetrates more on the side which is lightly doped as compared to the other.

10.5 p-n Junction Diode :

- The p-n junction itself forms the most basic semiconductor device called Semiconductor Diode. Thus semiconductor diode and the p-n junction are one and the same.
- The meaning of the term "diode" is the device having "two electrodes" (di-ode).
- As shown in Fig. 10.5.1(a), the diode has two electrodes one each for the two regions on either sides of the junction.



(a) A p-n junction forms a semiconductor diode



(b) Circuit symbol of a diode

Fig. 10.5.1

Symbol of the p-n junction diode :

- The symbol of a semiconductor diode is as shown in Fig. 10.5.1(b). The two electrodes (terminals) are named as anode and cathode.
- The arrowhead in the symbol points in the direction of conventional current through the device. The conventional current through a diode flows from anode to cathode.
- This current will flow through the diode, if and only if an external voltage source is connected to it with appropriate polarities.

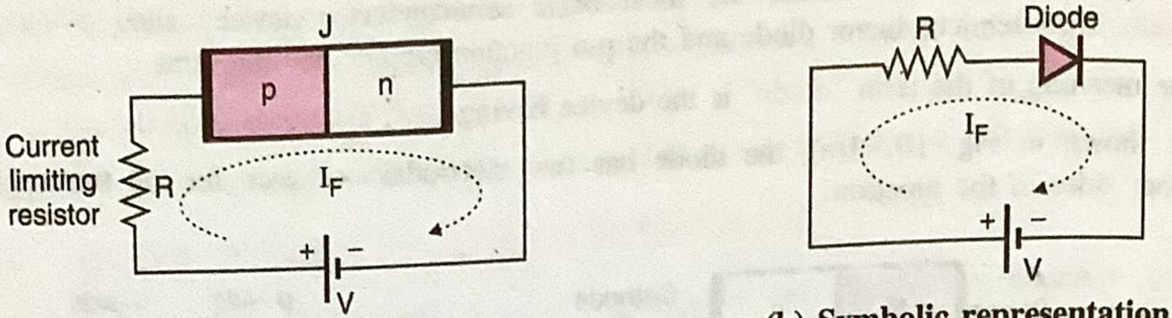
10.6 Biasing of a p-n Junction Diode : (p-n Junction with External Bias) :

- When the p-n junction is formed, the depletion region gets created and the movement of electrons and holes stops. Thus the current flowing through an unbiased p-n junction is zero. To make the current to flow we have to bias the p-n junction diode.
- **Biasing is the process of applying external DC voltage to the semiconductor diode.**
- When the external voltage is not applied to the diode, the p-n junction will remain in the state of equilibrium. Therefore there is no current flowing through it.
- To make the current to flow, it is necessary to "bias" the diode. The biasing can be of two types :
  1. Forward bias.
  2. Reverse bias.

10.6.1 Forward Biasing of a p-n Junction Diode :

- If the p-region (anode) is connected to the positive terminal of the external DC source and n-side (cathode) is connected to the negative terminal of the DC source then the biasing is said to be "forward biasing".
- In other words the diode is then said to be forward biased. Generally a resistance is connected in series with the diode to limit the current flowing through it.

- Forward biasing of a diode is as shown in Fig. 10.6.1(a) and the symbolic representation is as shown in Fig. 10.6.1(b). The current " I_F" is a conventional current that flows in the circuit due to the forward biasing.



(a) Forward biasing of a diode

(b) Symbolic representation

Fig. 10.6.1

Operation of a forward biased diode :

- Due to the negative terminal of external source connected to the n-region, free electrons from n-side are pushed towards the p-side. Similarly the positive end of the supply will push holes from p-side towards the n-side.
- With increase in the external supply voltage V, more and more number of holes (p-side) and electrons (n-side) start travelling towards the junction as shown in Fig. 10.6.2.

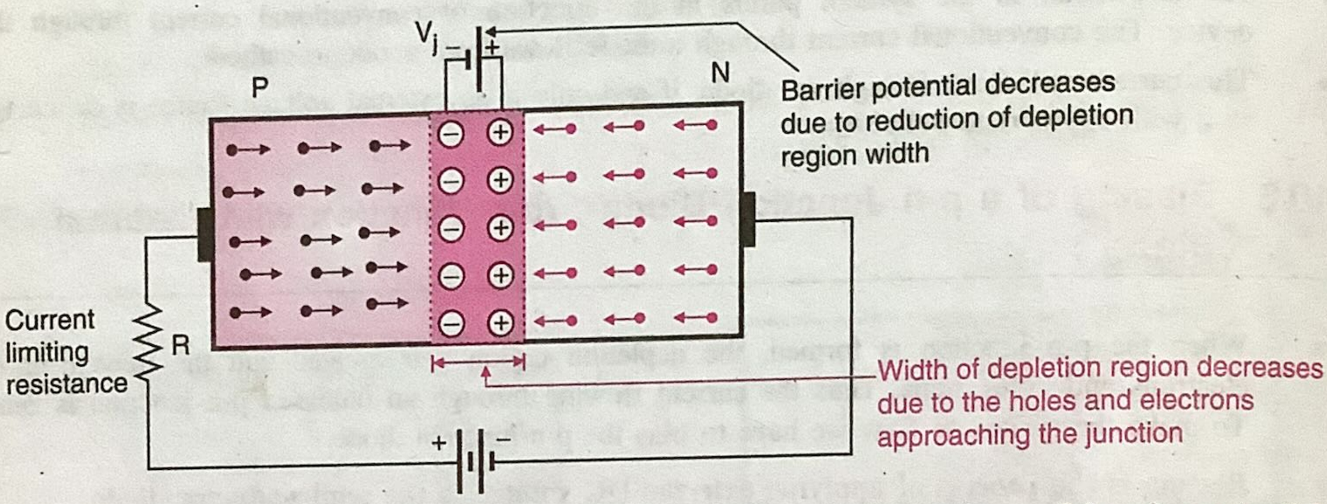


Fig. 10.6.2 : The effect of increased forward bias on the depletion region and barrier potential

- The holes will start converting the negative ions into neutral atoms and the electrons will convert the positive ions into neutral atoms. **As a result of this, the width of depletion region will reduce.**
- Due to reduction in the depletion region width, the barrier potential will also reduce. Eventually at a particular value of V the depletion region will collapse. Now there is absolutely no opposition to the flow of electrons and holes.
- Hence a large number of electrons and holes (majority carriers) can cross the junction under the influence of externally connected DC voltage.
- The large number of majority carriers crossing the junction constitute a current called as the forward current. The current flow shown in Fig. 10.6.3 is the electron current which is in the opposite direction to that of a conventional current.

Effect of forward bias on the width of depletion region :

With increase in the forward bias, the width of the depletion region decreases and so does the barrier potential.

Current flow in forward biased diode :

- As soon as the free electrons enter into the p-region from the n-side, they become valence electrons. So these electrons will jump from one atom to the other to fill up the holes present there.
- Thus movement of electrons on p-side will be due to the movement of holes.
- These electrons move towards the positive end of the source and the holes will move towards the junction.
- Thus current through the p-region flows due to the movement of majority carriers.
- Similarly current on the n-side is due to the movement of free electrons which are the majority carriers.

Hence we can conclude that ;

The forward current through a p-n junction diode flows due to the majority carriers and its direction of flow (conventional) is always from anode to cathode.

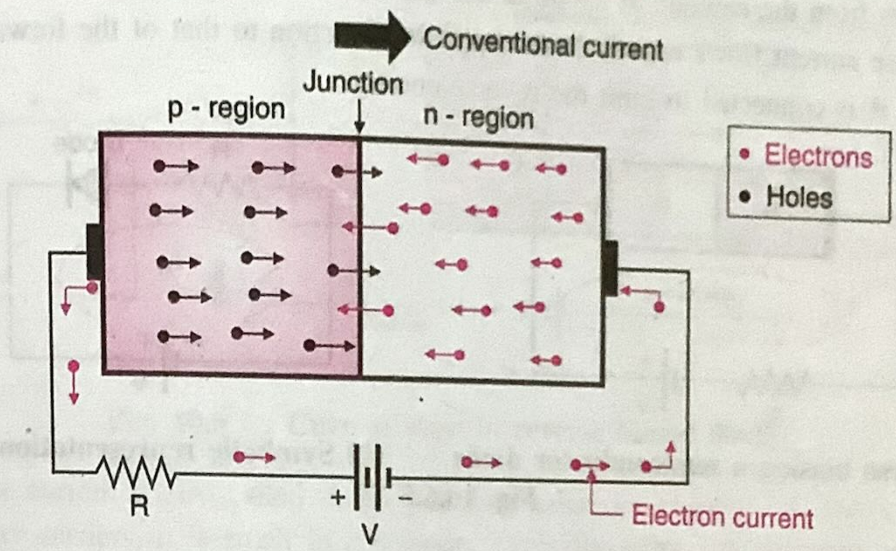


Fig. 10.6.3 : Current flow in the forward biased diode

Forward resistance of diode :

- The forward current of a diode (I_F) is the current flowing through the forward biased diode. Which flows due to the majority carriers. Hence I_F is of the order of few mA.
- Due to large current, the forward resistance of the diode is very small. Typically it is of the order of few ohms (10 to 100 Ω).

10.6.2 Voltage Drop Across the Forward Biased Diode (V_F) :

- As soon as the applied external voltage overcomes the barrier potential, the currents starts flowing.
- There is a potential drop across the conducting forward biased diode, which has opposite polarities to the barrier potential but has a magnitude which is approximately equal to the

barrier potential.

- The forward voltage drop is denoted by V_F as shown in Fig. 10.6.4 and equal to 0.7 V for silicon diode and 0.3 V for Germanium diode.
- The forward voltage drop V_F is due to two factors namely the drop due to barrier potential and drop due to internal resistance R_F.

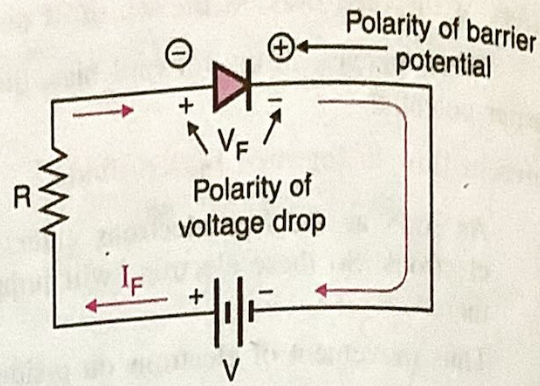
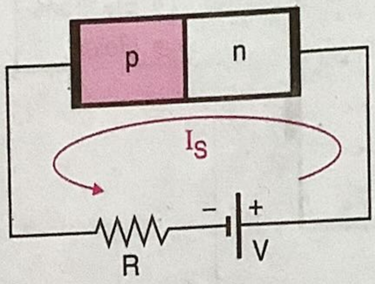


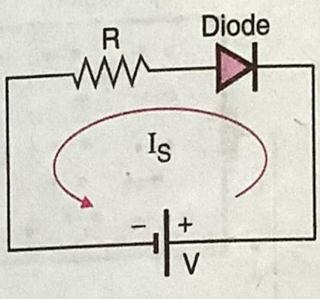
Fig. 10.6.4 : Forward voltage drop

10.6.3 Reverse Biasing a Diode :

- If the p-region of a diode is connected to the negative terminal of the external DC supply and n-region is connected to the positive terminal of the DC supply as shown in Fig. 10.6.5(a) then a diode is said to be "reverse biased".
- Fig. 10.6.5(b) shows the reverse biasing schematically. The reverse current is denoted by I_s and it flows from the cathode to anode of the diode.
- Thus reverse current flows exactly in the opposite direction to that of the forward current.
- Resistance R is connected to limit the reverse current.



(a) Reverse biasing a semiconductor diode



(b) Symbolic representation

Fig. 10.6.5

Operation of a reverse biased diode :

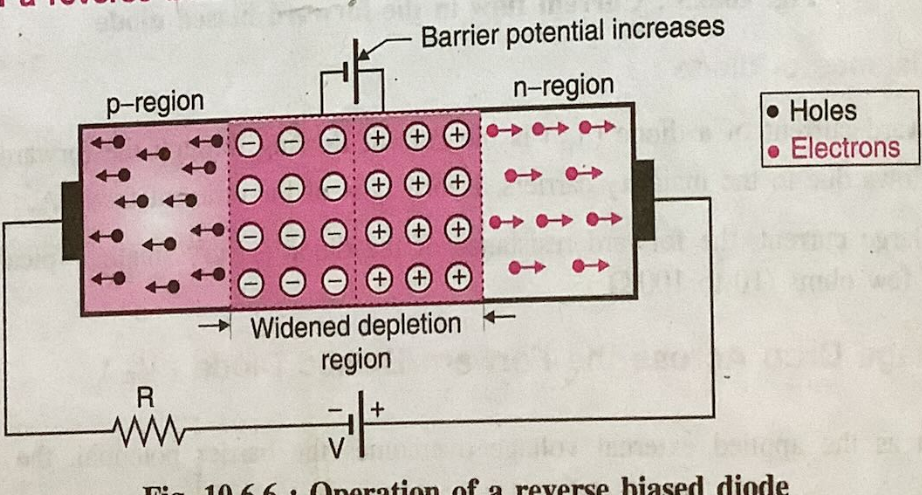


Fig. 10.6.6 : Operation of a reverse biased diode

- When a diode is reverse biased, holes in the p-region are attracted towards the negative terminal of the supply and electrons on the n-side are attracted towards the positive terminal of the supply as shown in Fig. 10.6.6.

- Due to the movement of electrons and holes away from the junction, width of the depletion region increases as shown in Fig. 10.6.6. This happens due to the creation of more number of positive and negative immobile ions.
- Due to more number of ions present on opposite sides of the junction, the barrier potential or junction potential will increase.
- The process of widening of depletion region does not continue for a long time, because there is no steady flow of holes from right to left i.e. from the n-side to p-side.

Current flow in the reverse biased diode (Reverse Saturation Current) :

- We know that the p-region consists of a small number of electrons and the n-region contains a small number of holes. These are the minority carriers which are generated thermally.
- The minority electrons in the p-region are attracted by the positive end of the dc supply. Hence these electrons will cross the junction and constitute the reverse current I_S of the diode. This is shown in Fig. 10.6.7.

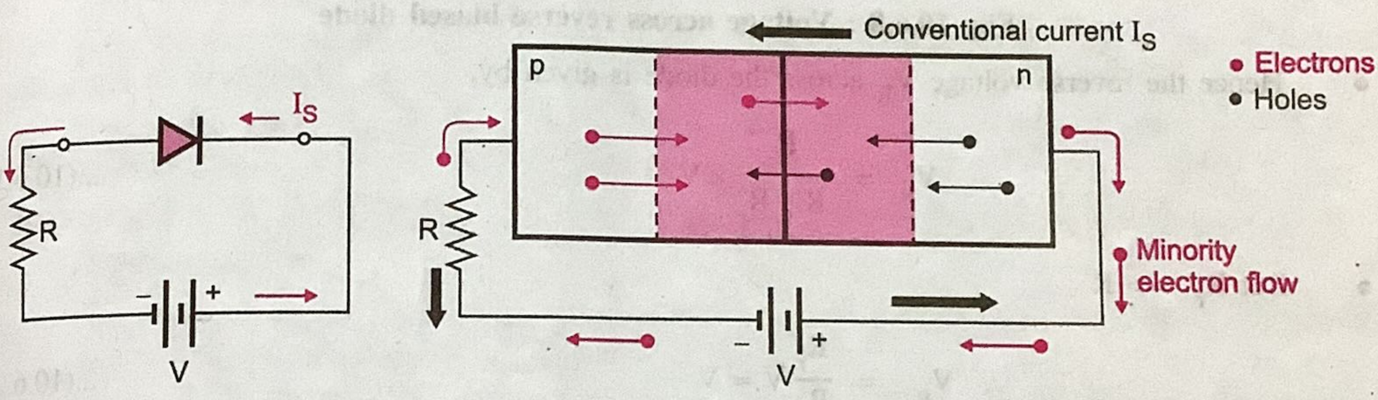


Fig. 10.6.7 : Current flow in reverse biased diode

- The reverse current is also called as the "Reverse saturation current". As this current is due to the minority carriers, it is small in amplitude. Typically a few μA for germanium diodes and few nanoamperes for the silicon diode.
- The reverse saturation current depends on the temperature. It doubles its value for every 10° C rise in temperature. Hence at a constant temperature the reverse saturation current remains constant independent of the reverse voltage.
- Reverse current flows due to minority carriers which exist due to elevated temperatures. Hence reverse current is dependent on temperature.

Important points about the reverse current :

1. It flows from cathode to anode.
2. It flows due to minority carriers.
3. Its value is much smaller than that of the forward current.
4. It is independent of reverse voltage but dependent on the temperature.

Resistance of reverse biased diode :

The reverse current is small which indicates that the resistance offered by a reverse biased diode is very large. It is denoted by R_r and its value is a few hundred k Ω.

Voltage across reverse biased diode :

- The reverse biased diode is equivalent to a large value resistor. It forms a potential divider with the current limiting resistance R, across the external voltage V, as shown in Fig. 10.6.8(a).

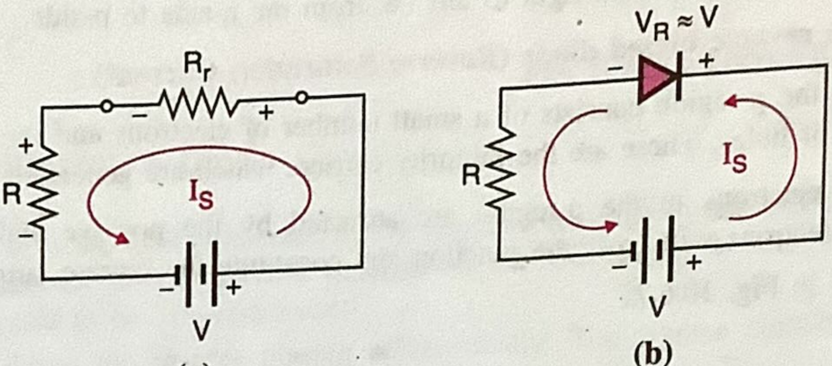


Fig. 10.6.8 : Voltage across reverse biased diode

- Hence the reverse voltage V_R across the diode is given by,

$$V_R = \frac{R_r}{R+R_r} \times V \qquad ...(10.6.1)$$

- But $R_r >> R$

$$\therefore \; V_R \approx \frac{R_r}{R_r} V \approx V \qquad ...(10.6.2)$$

- Thus the reverse voltage is approximately equal to the applied voltage and its polarity is as shown in Fig. 10.6.8(b).
- Since the polarity of V_R is opposite to the polarity of V_F, the reverse voltage is treated as a negative voltage.

10.6.4 Breakdown in the Reverse Biased Diode :

The reverse saturation current flowing in the reverse biased diode is dependent only on the temperature and independent of the reverse voltage applied externally. However now we are going to learn the phenomenon called reverse breakdown which takes place at a large reverse voltage. The breakdown in a reverse biased diode can take place due to the following effects :

- Avalanche effect and
- Zener effect.

Breakdown due to the avalanche effect :

When a very large reverse voltage is applied to a diode the events take place in the following sequence :

- Due to large reverse voltage the velocity of the minority carriers will increase to a great extent. Therefore the kinetic energy associated with them will also increase.

- While travelling, these minority carriers will collide with the stationary atoms and impart some of the kinetic energy to the valence electrons present in the covalent bonds.
- Due to this additionally acquired energy, these valence electrons will break the covalent bonds and jump into the conduction band to become free for conduction.
- Now these free electrons will be accelerated and they knock out some more valence electrons by means of collisions. This "chain reaction" is called as "Avalanche effect".
- In a very short time, a large number of free minority electrons will be available for conduction and a large reverse current will flow through the reverse biased diode. The avalanche breakdown has thus taken place.

Why should we avoid breakdown ?

- At the time of the avalanche breakdown, a large reverse voltage appears across the diode and a large reverse current flows through it.
- Therefore a large power gets dissipated in the diode. The junction temperature of the diode may exceed its safe limits and the diode will be damaged permanently.
- Therefore, the reverse breakdown should always be avoided.

Breakdown due to the zener effect :

The reverse breakdown can take place due to another effect called zener effect. The events take place in the following sequence in the process of breakdown due to zener effect :

- Due to the heavy doping of p and n-sides of the diode, the depletion region is narrow in the reverse biased condition. All the reverse voltage V appears across the depletion region.
- Therefore the electric field which is the voltage per unit distance is very intense across the depletion region.
- This intense electric field can pull some of the valence electrons by breaking the covalent bonds. These electrons then become free electrons.
- A large number of such electrons can constitute a large reverse current through the diode. This is called as the breakdown due to zener effect.

Does the breakdown always damage the diode ?

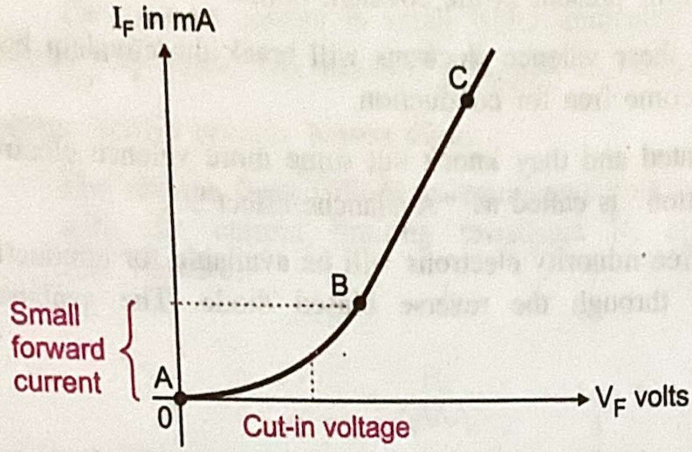
The answer is no. If we use the external current limiting resistance such that the reverse current at the time of breakdown is kept at a low value, then the power dissipation taking place in the diode will be well below the dangerous level and the diode does not get damaged.

But otherwise the diode cannot sustain the breakdown and it will be damaged permanently.

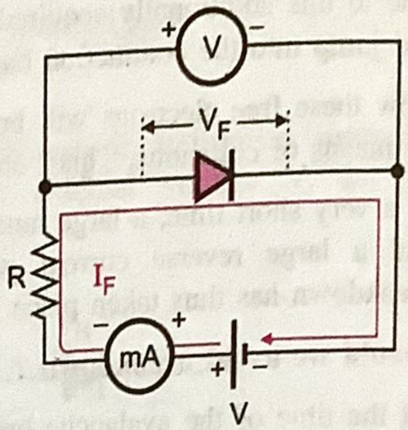
10.7 The Volt-ampere (V-I) Characteristics of a Diode :

- The behaviour of a p-n junction diode is indicated by its volt-ampere characteristics (V-I characteristics).
- The V-I characteristics of a p-n junction diode is a graph of voltage across the diode versus the current flowing through it.
- The V-I characteristics can be divided into two parts :
  1. Forward characteristics
  2. Reverse characteristics

10.7.1 Forward Characteristics of p-n Junction Diode :



(a)



(b) Set up to draw the forward characteristics

Fig. 10.7.1 : Forward characteristics of a diode

- The forward characteristics is the graph of the anode to cathode forward voltage V_F versus the forward current through the diode (I_F).
- The forward characteristics is divided into two portions, AB and BC as shown in Fig. 10.7.1(a) and the corresponding circuit is shown in Fig. 10.7.1(b).

Region A to B :

- In the region A to B of the forward characteristics shown in Fig. 10.7.1(a), the forward voltage is small and less than the cut in voltage.
- Therefore the forward current flowing through the diode is small. With further increase in the forward voltage, it reaches the level of the cut in voltage and the width of depletion region goes on decreasing.

Region B to C :

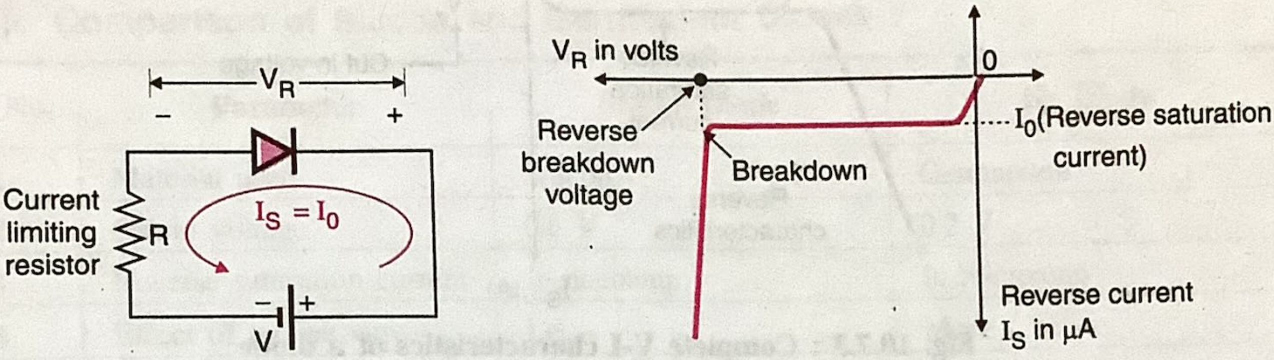
- As soon as the forward voltage equals the cut in voltage, current through the diode increases suddenly. The nature of this current is exponential. The large forward current in the region B-C of the forward characteristics is limited by connecting a resistor "R" in series with the diode. Forward current is of the order of a few mA.
- The forward current is a conventional current that flows from anode to cathode. Therefore it is considered to be a positive current, and the forward characteristics appears in the first quadrant as shown in Fig. 10.7.1(a).

Cut-in voltage (V_γ) :

- The voltage at which the forward diode current starts increasing rapidly is known as the "cut-in" voltage of a diode. As shown in Fig. 10.7.1(a), the cut-in voltage is very close to the barrier potential. Cut-in voltage is denoted by V_γ
- Generally a diode is forward biased above the cut in voltage. The cut-in voltage for a silicon diode is 0.6 V and that for a germanium diode is 0.2 V.
- The forward voltage V_F is treated as a positive voltage, because the anode is more positive than cathode.
- As mentioned earlier, the forward resistance is very small of the order of few ohms.

10.7.2 Reverse Characteristics of a Diode :

- Reverse characteristics is a graph of reverse voltage (V_R) versus the reverse current (I_S) as shown in Fig. 10.7.2(b).
- Current flowing through a diode in the reverse biased state is the reverse saturation current which flows due to the minority carriers.



(a) Arrangement to reverse bias a diode **(b) Reverse characteristics of a diode**

Fig. 10.7.2

- Therefore it is treated as a negative current. Hence the reverse characteristics appears in the third quadrant as shown in Fig. 10.7.2(b).
- As the reverse voltage is increased, the reverse saturation current remains constant equal to I_o if the temperature is constant. This is because, reverse saturation current does not depend on reverse voltage but it depends only on temperature.
- But as the reverse voltage reaches the breakdown voltage value, a large current flows through the diode, due to the reasons discussed earlier.
- Operation in the breakdown region should be avoided because the diode may be damaged due to excessive power dissipation.
- Typically the reverse breakdown voltage for a p-n junction diode is in the range of 50 to 100 Volts.
- The resistance of the diode in the reverse biased condition is called as the reverse resistance and its value is very high (of the order of few hundred k Ω).

10.7.3 Complete V-I Characteristics of a Diode :

- The complete V-I characteristics is shown in Fig. 10.7.3. It is obtained by combining the forward and the reverse characteristics of the diode.

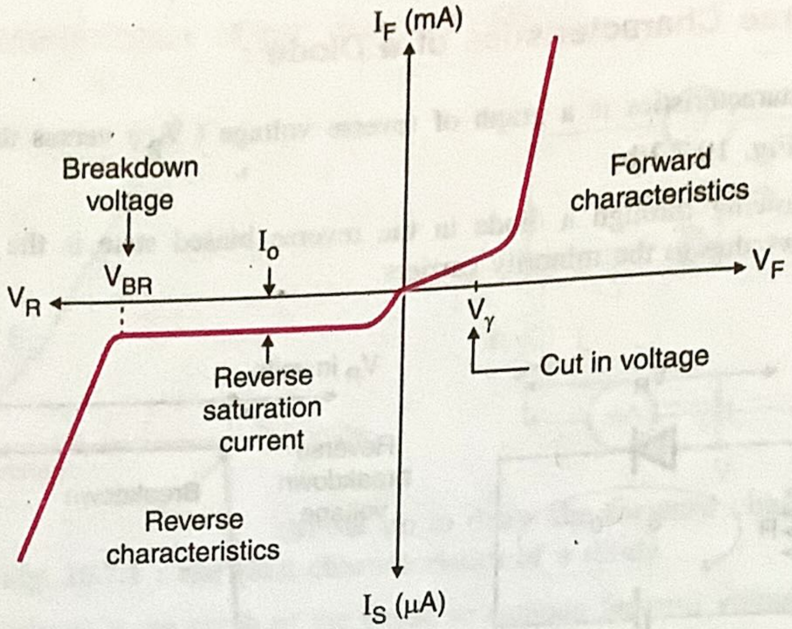


Fig. 10.7.3 : Complete V-I characteristics of a diode

- V_{BR} is the reverse breakdown voltage. It is the reverse voltage at which the breakdown occurs.
- The reverse current I_o upto V_{BR} is practically constant and negligibly small. So we can neglect it at low operating temperatures.

10.7.4 Complete V-I Characteristics of Silicon and Germanium Diodes :

The complete V-I characteristics is the combination of forward and reverse characteristics. The typical V-I characteristics of Silicon and Germanium diodes are as shown in Fig. 10.7.4.

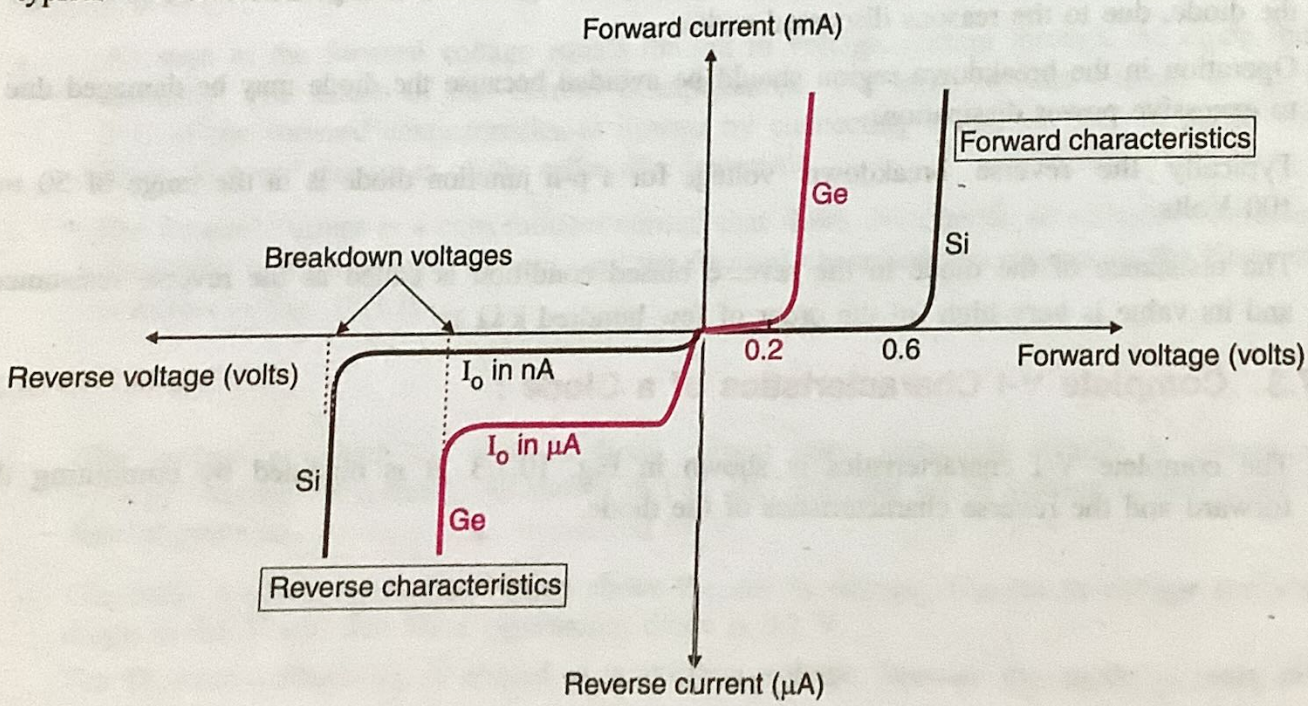


Fig. 10.7.4 : V-I characteristics of Silicon and Germanium diodes

Observations :

1. Cut-in voltages for Silicon and Germanium diodes are 0.6 and 0.2 V respectively.
2. Breakdown voltage of Silicon diode is higher than that of the Germanium diode. So Silicon diodes can withstand to a higher reverse voltage.
3. The reverse saturation current I_0 for a Germanium diode is few μA whereas that for a Silicon diode is in nA at room temperature.

10.7.5 Comparison of Silicon and Germanium Diodes :

Sr. No.	Parameter	Silicon Diode	Ge Diode
1.	Material used	Silicon	Germanium
2.	Cut-in voltage	0.6 V	0.2 V
3.	Reverse saturation current	In nanoamp	In microamp
4.	Effect of temperature	Less	More
5.	Breakdown voltage	Higher	Lower
6.	Applications	Rectifiers, clippers clampers, freewheeling	Low voltage Low temperature applications

10.8 Applications of p-n Junction Diode :

Some of the applications of a p-n junction diode are as follows :

1. Rectifier circuits
2. Clipping and clamping circuits
3. Voltage multipliers
4. A. M. detection
5. Feedback diodes
6. Freewheeling diodes
7. Log and antilog amplifiers using OP-AMP.
8. Precision rectifiers using OP-AMP.

10.9 Diode Specifications :

- The manufacturers of electronic components list the device specifications in the data sheet.
- Some of the important specifications of the p-n junction diode are as follows :
  1. Forward voltage drop (V_F) .
  2. Maximum forward current.
  3. Average forward current.
  4. Reverse saturation current.
  5. Power dissipation.
  6. Junction temperature.
  7. Peak inverse voltage (PIV).

10.10 Zener Diode :

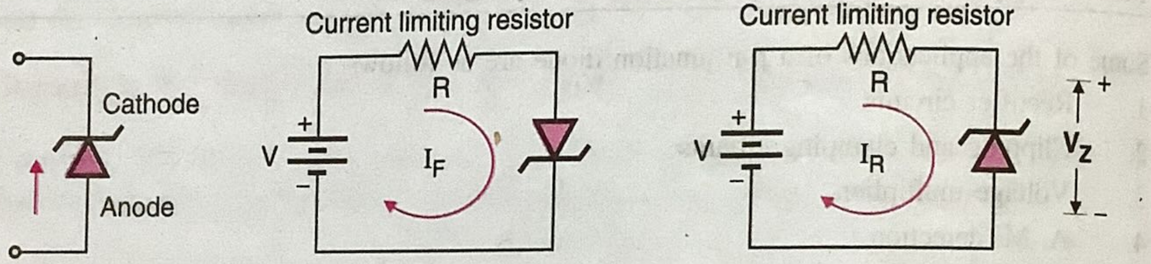
- "Zener diode" is a special type of p-n junction semiconductor diode. Its construction is similar to that of a conventional p-n junction diode.
- However in constructing the zener diodes, the reverse breakdown voltage is adjusted precisely between 3V to 200V.
- Its applications are based on this principle hence zener diode is called as a breakdown diode.
- The doping level of the impurity added to manufacture the zener diodes is controlled in order to adjust the precise value of reverse breakdown voltage.

10.10.1 Operating Principle :

The zener diode can be forward biased or reverse biased. Its operation in the forward biased mode is same as that of a p-n junction diode. **But the operation in the reverse biased mode is substantially different.**

10.10.2 Circuit Symbol and Biasing of a Zener Diode :

- The circuit symbol of a zener diode is as shown in Fig. 10.10.1(a). It is a two terminal device and the terminals are anode and cathode.
- The arrowhead in the symbol points towards the conventional direction of current through the zener diode, when it is forward biased.



(a) Circuit symbol of a zener diode (b) Forward biasing of a zener diode (c) Reverse biasing of a zener diode

Fig. 10.10.1 : Circuit symbol and biasing of a zener diode

Forward biasing of zener diode :

- When the anode of the zener diode is connected to the positive terminal of the dc source and the cathode is connected to the negative terminal, the zener diode is said to be forward biased.
- The forward biased zener diode behaves identical to a forward biased diode. The forward biasing of a zener diode is shown in Fig. 10.10.1(b).
- The zener diode is generally not used in the forward biased condition.

Reverse biasing of zener diode :

- When the cathode is connected to the positive terminal and anode is connected to the negative terminal of the dc source, the zener diode is said to be reverse biased.
- The operation of zener diode in the reverse biased condition is substantially different from that of a diode.
- The reverse biasing of a zener diode is shown in Fig. 10.10.1(c). **Zener diode in the reverse biased condition is used as a voltage regulator.**