Introduction to Semiconductor

Introduction

Certain substances like germanium, silicon, carbon etc. are neither good conductors like copper nor insulators like glass. The resistivity of these materials lies in between conductors and insulators. Such substances are classified as semiconductors. Semiconductors have some useful properties and are being extensively used in electronic circuits.

Semiconductor

A semiconductor is a substance which has resistivity 10^{-4} to 0.5 Ω-m in between conductors and insulators e.g. germanium, silicon, selenium, carbon etc.

The following table shows the resistivities of different types of materials.

Sl No	Substance	Nature	Resistivity
1	Copper	Good conductor	1.7×10^{-8} Ω-m
2	Germanium	Semiconductor	0.6 Ω-m
3	Glass	insulator	9×10^{11} Ω-m
4	Nichrome	resistance material	10^{-4} Ω-m

Properties of Semiconductors

i) The resistivity of a semiconductor is less than an insulator but more than a conductor.
ii) Semiconductors have negative temperature coefficient of resistance i.e. the resistance of a semiconductor decreases with the increase in temperature and vice versa.
iii) When a suitable metallic impurity e.g. arsenic, gallium etc is added to a semiconductor, its current conducting properties change appreciably.

Bonds in Semiconductors

The atoms of every element are held together by the bonding action of valence electrons. When the bonding takes place, the atom may lose, gain or share valence electrons with other atoms. In semiconductors, bonds are formed by sharing of valence electrons. Such bonds are called *co-valent* bonds.

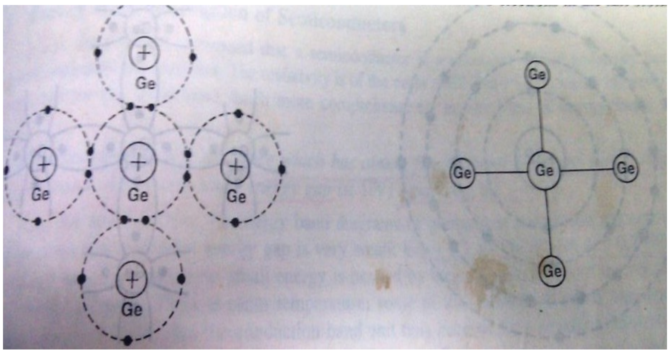

Figure 1.1.1

Figure 1.1.1 shows the co-valent bonds among germanium atoms. A Ge atom has 4 valence electrons. Ge atom has a tendency to have 8 electrons in the outer orbit. Each atom shares one valence electron with the neighboring atom and central atom sets up co-valent bond. Valence electrons in a semiconductor are not free.

Crystals

A substance in which the atoms or molecules are arranged in an orderly pattern is known as a crystal. All semiconductors have crystalline structure.

Commonly used Semiconductors

There are many semiconductors are available. But the two most frequently used materials are germanium (Ge) and silicon (Si), because the energy required to break their co-valent bonds is very small; being 0.7 eV for Ge and 1.1 eV for Si.

(i) **Germanium:** Germanium has become the model substance among the semiconductors. It can be purified relatively well and crystallized easily. Ge is an earth element and was discovered in 1886. It is recovered from ash of certain coals or from the flue dust of zinc smelters. It is generally recovered in the form of germanium dioxide powder which is then reduced to pure Ge. The atomic number of Ge is 32. So, it is a tetravalent element and has 4 electrons in its outer or valence orbit. Ge has crystalline structure.

(ii) **Silicon**: Silicon is an element in most of the common rocks. Sand is silicon dioxide. The silicon compounds are chemically reduced to silicon which is 100% pure for use as a semiconductor. Atomic number of Si is 14. It is a tetravalent element and has 4 valence electrons. Si atoms form co-valent bond and has crystalline structure.

Energy Band Description of Semiconductors

A semiconductor can be defined much more comprehensively on the basis of energy bands as:

A semiconductor is a substance which has almost filled valence band and nearly empty conduction band with a very small energy gap ≈ 1 eV separating the two.

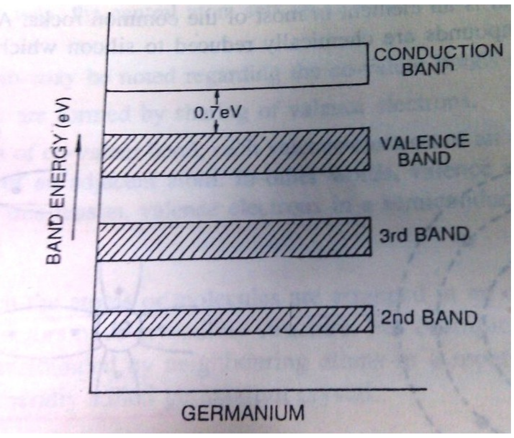

Figure 1.1.2

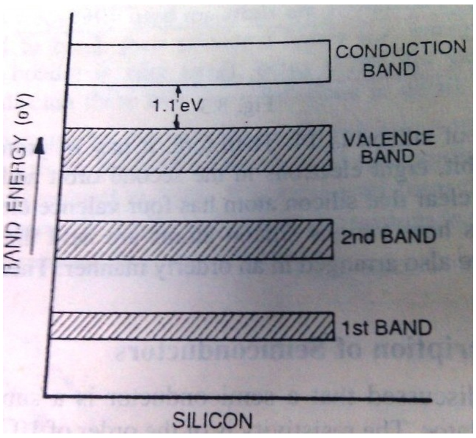

Figure 1.1.3

Figure 1.1.2 and 1.1.3 show the energy band diagrams of Ge and Si respectively. It is seen that forbidden energy gap is very small; being 1.1 eV for Si and 0.7 eV for Ge. Therefore, relatively small energy is needed by their valence electrons to cross over to the conduction band. Even at room temperature, some of the valence electrons may acquire sufficient energy to enter into the conduction band and thus become free electrons. However at room temperature, the number of free electrons available is very small. Therefore, at room temperature, a piece of Ge or Si is neither a good conductor nor an insulator. For this reason, such substances are called semiconductors.

Effect of Temperature on Semiconductors

The electrical conductivity of a semiconductor changes appreciably with temperature variations.

(i) **At absolute zero**: At absolute zero temperature, all the electrons are tightly bound by the semiconductor atoms. The inner orbit electrons are bound whereas the valence electrons are engaged in covalent bonding. At this temperature, the co-valent bonds are very strong and there are no free electrons. In other words, at absolute zero temperature, the valence band is filled and there is a large energy gap between valence band and conduction band. Therefore, no valence electron can reach the conduction band to become free electron. So, the semiconductor crystal behaves as a perfect insulator (Figure 1.1.4).

(ii) **Above absolute zero**: When the temperature is raised, some of the co-valent bonds in the semiconductors break due to the thermal energy supplied. The breaking of bonds sets those electrons free and as a result a few free electrons exist in the semiconductor. These free electrons can constitutes a tiny electric current if potential difference is applied across the semiconductor crystal (Figure 1.1.5 a). This shows that the resistance of a semiconductor decreases with the rise in temperature i.e. it has negative temperature coefficient of resistance. The current through a semiconductor at room temperature is too small.

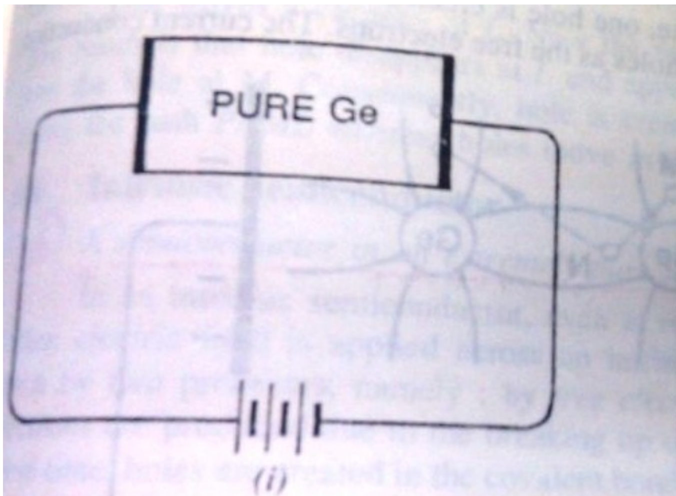

Figure 1.1.4

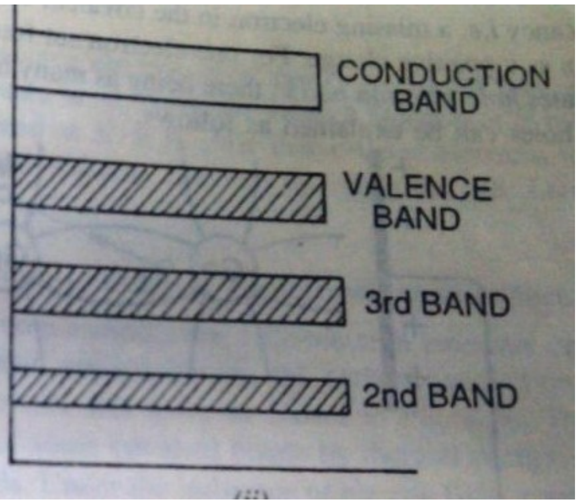

Figure1.1.5

Figure1.1.5 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. If a voltage is applied across the crystal, these free electrons will constitute electric current. Each time a valence electron enters into the conduction band, a hole is created in the valence band and the holes also contribute to current.

Hole current

At room temperature, some of the co-valent bonds in pure semiconductor break, setting up free electrons. The removal of one electron leaves a vacancy i.e. a missing electron in the covalent bond. This missing electron is called a “hole”. The hole acts as virtual positive charge. For one electron set free, one hole is created. Therefore, thermal energy creates hole-electron pairs.

When potential difference is applied across the semiconductor, the free electrons constitute electric current. At the same time the hole current also flows in the semiconductor. The hole current is due to movement of valence electrons from one co-valent bond to another bond. The holes move towards the negative terminal of supply.

Intrinsic Semiconductor

A semiconductor in an extremely pure form is known as an *intrinsic semiconductor*. In an intrinsic semiconductor, even at room temperature, hole-electron pairs are created. When electric field is applied across an intrinsic semiconductor, the current conduction takes place by two processes, namely; by free electrons and holes as shown in Figure 1.1.6. The free electrons are produced due to the breaking up of some covalent bonds by thermal energy. At the same time, holes are created in the covalent bonds. So, conduction through it is by both free electrons and holes. Therefore, the total current is the sum of currents due to free electrons and holes.

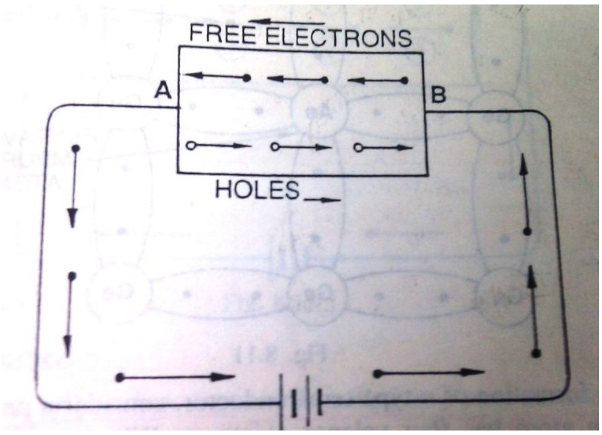

Figure 1.1.6.

Extrinsic Semiconductor

The intrinsic semiconductor has little current conduction capability at room temperature. To increase its conducting properties, a small amount of suitable impurity is added to it. It is then called impurity or *extrinsic* semiconductor. The process of adding impurities to a semiconductor is known as doping. The amount and type of such impurities have to be closely controlled during the preparation of extrinsic semiconductor. Generally, for 10^8 atoms of semiconductor, one impurity atom is added.

The purpose of adding impurity is to increase either the number of free electrons or holes in the semiconductor crystal. If a pentavalent impurity, having 5 valence electrons, is added, a large number of free electrons are produced. On the other hand, addition of trivalent impurity, having 3 electrons, creates a large number of holes. Depending upon the type of impurity added, extrinsic semiconductors are classified in to

1) n-type semiconductor and
2) p-type semiconductor.

N-type semiconductor

When a small amount of pentavalent impurity is added to a pure semiconductor, it is known as n-type semiconductor.

The addition of pentavalent impurity provides a large number of free electrons in the semiconductor crystal. Examples of pentavalent impurities are As (Z=33) and Sb (Z=51). Such impurities which produce n-type semiconductor are known as *donor* impurities because they donate or provide free electrons to the semiconductor crystal.

For example, when a Sb atom is added, the 4 valence electrons form covalent bond with 4 Ge atoms. The fifth valence electron of Sb finds no place in covalent bond and is thus free as shown in Figure 1.1.7. So the left over fifth electron travels to the conduction band.

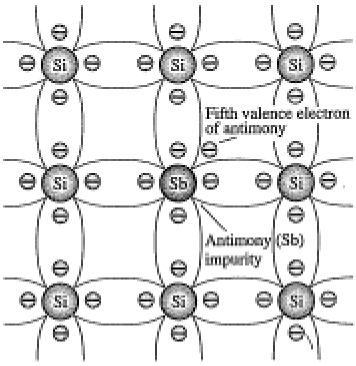

Figure 1.1.7

It is important to note that

i) Many new free electrons are produced by the addition of pentavalent impurity.
ii) Thermal energy of room temperature still generates hole-electron pairs. But the number of free electrons provided by pentavalent impurity is much more than the number of holes. So it is called n-type semiconductor.

The current conduction in an n-type semiconductor is predominantly by free electrons. When p.d is applied across the n-type semiconductor, the free electrons in the crystal will be directed towards the positive terminal, and thus constitute electric current as shown in Figure 1.1.7.

P-type semiconductor

When a small amount of trivalent impurity is added to a pure semiconductor, it is called p-type semiconductor.

The addition of trivalent impurity provides a large number of holes in the semiconductor crystal. Examples of trivalent impurities are Ga (Z=31) and In (Z=49). Such impurities which produce p-type semiconductor are known as *acceptor* impurities because the holes created can accept electrons.

For example, when an Ga atom is added, only 3 valence electrons form covalent bond with 3 Ge atoms. In the fourth covalent bond only Ge contributes one valence electron while Ga has no valence electron to contribute. That means the fourth bond is incomplete, being short of one electron. This missing electron is called a hole. Therefore, for each Ga atom added, one hole is created. A small amount of Ga provides millions of holes.

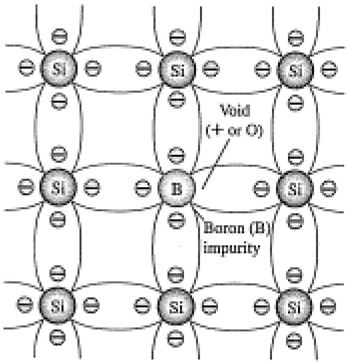

Figure 1.1.8.

The current conduction in a p-type semiconductor is predominantly by holes or positive charges. When p.d is applied across the p-type semiconductor, the holes are shifted from one covalent bond to another. As the holes are positively charged, they are directed towards the negative terminal, and thus constitute hole current as shown in Figure 1.1.8.

Majority and Minority Carriers

N-type material has a large number of free electrons and a small number of holes as shown in Figure 1.1.9. The free electrons in this case are considered majority carriers, since the majority portion of current in n-type material is by the flow of free electrons and the holes are minority carriers.

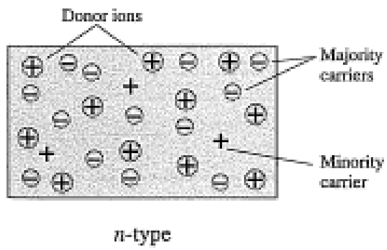

Figure 1.1.9.

In a p-type material, holes outnumber the free electrons as shown in Figure 1.1.10. Therefore, holes are majority carriers and free electrons are minority carriers.

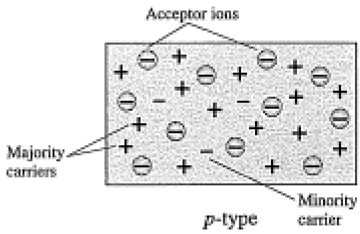

Figure 1.1.10.

pn Junction

When a p-type semiconductor is suitably joined to n-type semiconductor, the contact surface is called ***pn junction***. Most semiconductor devices contain one or more pn junctions. The pn junction is of great importance because it is in effect, the control element for semiconductor devices. To understand the behavior of semiconductor devices a thorough knowledge of the formation and properties of pn junction is required.

Formation of pn junction

pn junction is fabricated by special techniques. One common method of making pn junction is called alloying. A small block of indium trivalent impurity is placed on an n-type Ge slab. The system is then heated to a temperature of about 500ºC. The indium and some of the Ge melt to form a small puddle of molten Ge-In mixture. The temperature is then lowered and puddle is then begins to solidify. Under proper conditions, the atoms of In impurity will be suitably adjusted in the Ge slab to form a single crystal shown in Figure 1.1.11. The addition of In overcomes the excess of electrons in the n-type Ge to such an extent that it creates a p-type region.

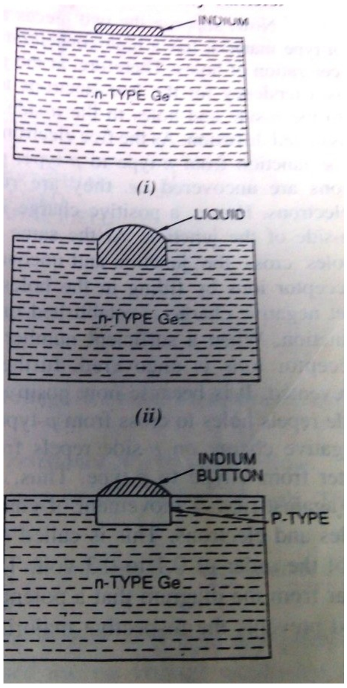

Figure 1.1.11.

Properties of pn junction

Let us suppose that two pieces one of n-type and the other is p-type, are suitably treated to form pn junction. Note that n-type material has a high concentration of free electrons while p-type material has a high concentration of holes. Therefore, at the junction, there is a tendency for the free electrons to diffuse over to the p-side and holes to n-side. This process is called ***diffusion***. As the free electrons move across the junction from n-type to p-type, positive donor ions are uncovered i.e. they are robbed of free electrons. Hence, a positive charge is built on the n-side of the junction. At the same time, the free holes cross the junction and uncover the negative acceptor ions by filling in the holes. Therefore, a net negative charge is established on p-side of the junction.

When a sufficient number of donor and acceptor ions are uncovered, further diffusion is prevented. It is because now positive charges on n-side repels holes to cross from p-type to n-type and negative charges on p-side repels free electrons to enter from n-type to p-type. Thus, a barrier is set up against further movement of charge carriers i.e. holes and electrons. This is called *potential barrier* or *junction barrier* V_o. The potential barrier is of the order of 0.1 to 0.3V.

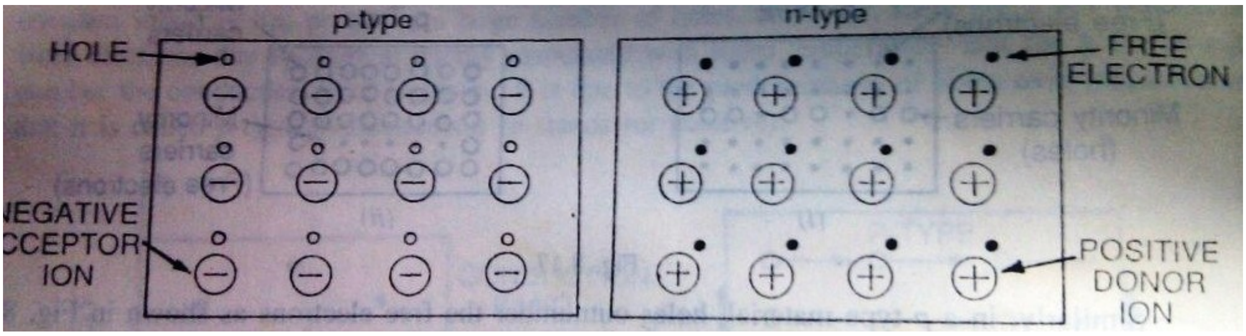

Figure 1.1.12.

The potential distribution diagram is shown in Figure 1.1.12. It is clear from the diagram that a potential barrier V_0 is set up which gives rise to electric field. This field prevents the respective majority carriers from crossing the barrier region. Out side of this barrier on each side of the junction, the material is still neutral. Only inside of the barrier, there is a positive charge on n-side and negative charge on p-side. This region is called ***depletion layer***. It is so called because the mobile charge carriers have been depleted i.e. emptied in this region.

Applying Voltage across pn junction

The potential difference across a pn junction can be applied in two ways, namely, ***forward biasing*** and ***reverse biasing***.

Forward biasing

When external voltage applied to the junction is in such a direction that it cancels the potential barrier, thus permitting current flow, it is called ***forward biasing***.

To apply forward bias, connect positive terminal of the battery to p-type and negative terminal to n-type as shown in Figure 1.1.13. The applied forward potential establishes an electric field which acts against the field due to potential barrier. Therefore, the resultant field is weakened and the barrier height is reduced at the junction as shown in Figure 1.1.13. As potential barrier voltage is very small 0.1 to 0.3 V, **a small forward voltage is sufficient to completely eliminate the barrier**. Once the barrier is eliminated, junction resistance becomes almost zero and **a low resistance called** forward resistance R_f **path** is established. Therefore current flows in the circuit. This is called *forward current*.

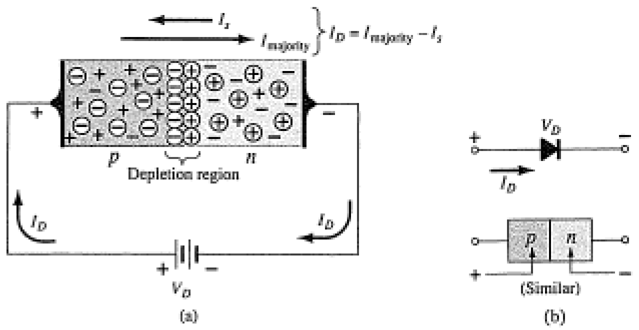

Figure 1.1.13

Reverse biasing

When external voltage applied to the junction is in such a direction that the potential barrier is increased, thus prevents the current flow, it is called ***reverse biasing***.

To apply reverse bias, connect negative terminal of the battery to p-type and positive terminal to n-type as shown in Figure 1.1.14. The applied reverse potential establishes an electric field which acts in the same direction as the field due to potential barrier. Therefore, the resultant field is strengthened and the barrier height is increased at the junction as shown in Figure 1.1.14. The increased potential barrier prevents the flow of charge carriers across the junction. Thus, a very high resistance called reverse resistance R_r **path** is established. Hence, current does not flow in the circuit.

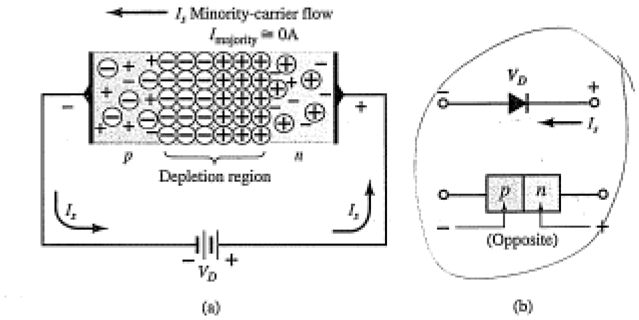

Figure 1.1.14

Conclusion: Reverse bias to the junction establishes a high resistance path and hence no current flows. And the forward bias to the junction establishes a low resistance path and hence current flows in the circuit.

Current flow in a forward biased pn junction

Figure 1.1.15 shows a forward biased pn junction. Under the influence of forward voltage, the free electrons in n-type move towards the junction leaving behind positively charged atoms. However, more electrons arrive from the negative battery terminal and enter the n-region to take up their places.

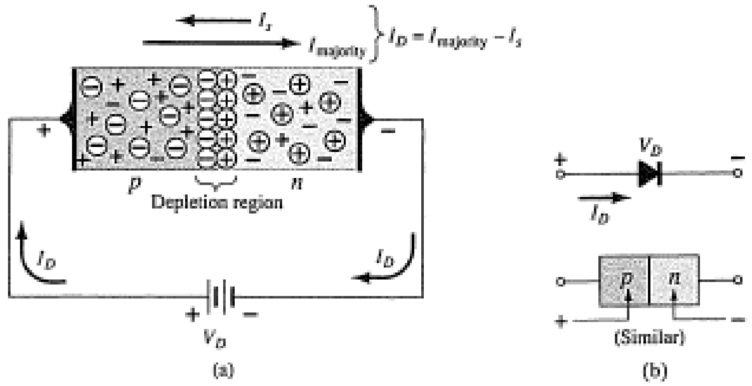

Figure 1.1.15

As the free electrons reach the junction, they become valence electron. When a free electron combines with a hole, it becomes a valence electron. As valence electrons, they move through the holes in the p-region. The valence electrons move towards left in the p-region which is equivalent to the holes moving to right. When the valence electron reaches the left end of the crystal, they flow into the positive terminal of the battery. This fact can be summed up as follows:

1. The free electrons from the negative terminal continue to pour into the n-region while the free electrons in the n-region move towards the junction.
2. The electrons travel through the n-region as free electrons i.e. current in n-region is by free electrons.
3. When these electrons reach the junction, they combine with holes and become valence electron.
4. The electrons travel through p-region as valence electrons i.e. current in the p-region is by holes.

5. When these valence electrons reach the left end of crystal, they flow into the positive terminal of the battery.

So, current in n-region is by free electrons and current in the p-region is by holes. In external connecting wires, the current is carried by electrons.

Volt-Ampere Characteristics of pn Junction

Volt-ampere or V-I characteristic of a pn junction i.e. semiconductor junction diode, is the curve between voltage across the junction and the circuit current. Figure 1.1.16 shows the circuit arrangement for determining the V-I characteristics of a junction diode.

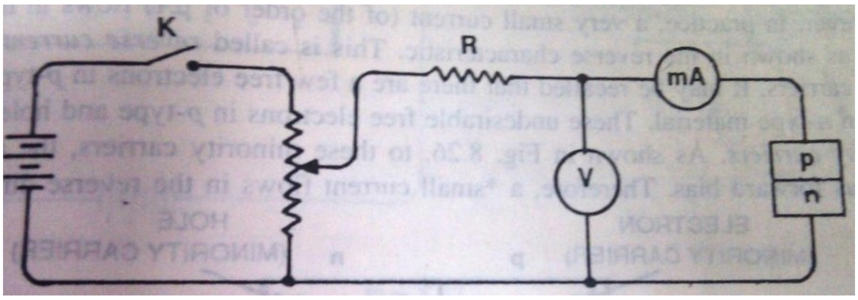

Figure 1.1.16

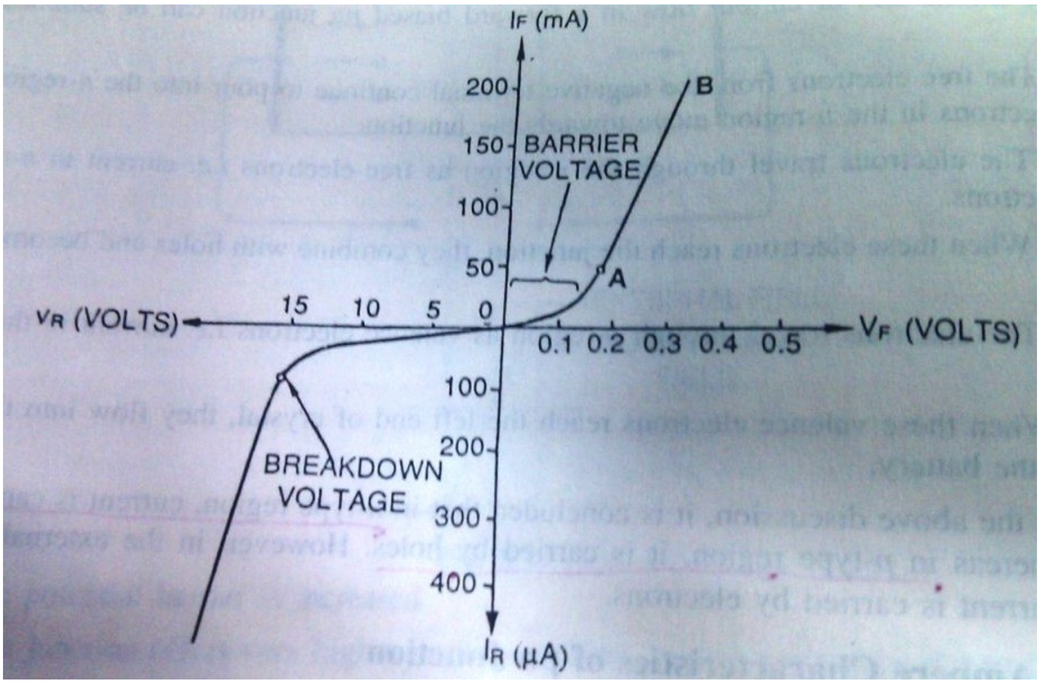

Figure 1.1.17

The characteristics can be studied under three cases, namely, zero external voltage, forward bias and reverse bias.

i) **Zero external voltage**: When the external voltage is zero, i.e. circuit is open at K, the potential barrier at the junction does not permit current flow. Therefore, the circuit current is zero as indicated by point O in Figure 1.1.17.

ii) **Forward bias**: With forward bias to the pn junction i.e. p-type end connected to positive terminal and n-type end connected to negative terminal, the potential barrier is reduced. At some forward voltage 0.7 V for Si and 0.3 V for Ge, the potential barrier is completely eliminated and current starts flowing in the circuit. From now onwards, the current increases with the increase in forward voltage. Thus a rising curve OB is obtained with forward bias as shown in Figure 1.1.17.

From the forward characteristic, it is seen that at first (region OA), the current increases very slowly and the curve is non-linear. In this region the external applied voltage is used up in overcoming the potential barrier. However, once the external voltage exceeds the potential barrier voltage, the pn junction behaves like an ordinary conductor. Therefore, the current rises very sharply with increase in external voltage (region AB). The curve is almost linear.

iii) **Reverse bias**: With reverse bias to the pn junction i.e. p-type end connected to negative terminal and n-type end connected to positive terminal, the potential barrier at the junction is increased. Therefore, the junction resistance becomes very high and practically no current flows through the circuit. However, a very small (of the order of μA) flows in the circuit with reverse bias as shown in the reverse characteristic. This is called reverse current and is due to minority carriers. It may be recalled that there are a few electrons in p-type material and holes in n-type material. These undesirable free electrons in p-type and holes in n-type are called minority carriers. The applied reverse voltage appears a forward bias for these minority carriers. Therefore, a small current flows in the reverse direction.

If reverse voltage is increased continuously, the KE of electrons minority carriers may become high enough to knock out electrons from the semiconductor atoms. At this stage breakdown of the junction occurs, characterized by a sudden rise of reverse current and a sudden fall of the resistance of barrier region. This may destroy the junction permanently.

Breakdown voltage

Under normal reverse voltage, a very little reverse current flows through a pn junction. Even at room temperature, some hole-electron pairs are produced in the depletion layer. With reverse bias, the electrons move towards the positive terminal of supply. At large reverse voltage, these electrons acquire high enough velocities to dislodge valence electrons from semiconductor atoms. The newly liberated electrons in turn free other valence electrons. In this way, an avalanche of free electrons is obtained. Therefore, the pn junction conducts a very large reverse current.

Knee voltage

It is the forward voltage at which the current through the junction starts to increase rapidly. For Si knee voltage is 0.7 V and for Ge 0.3 V.

Limitations of the operating conditions of pn junction diode

1) Maximum forward current: Highest instantaneous forward current that a pn junction can conduct without damaging it.

2) Peak inverse voltage: Maximum reverse voltage that can be applied to the pn junction diode without damaging it.
3) Maximum power rating: Maximum power that can be dissipated in the junction without damaging it.

Questions

1. What do you understand by a semiconductor? Discuss the properties of semiconductors.
2. Which are commonly used semiconductors and why?
3. Discuss the effect of temperature on semiconductors.
4. What do you understand by intrinsic and extrinsic semiconductors?
5. What is a pn junction? Explain the formation of potential barrier in pn junction.
6. Discuss the behavior of a pn junction under forward and reverse biasing.
7. Draw and explain the V-I characteristics of a pn junction.
8. Write notes on Breakdown voltage, Knee voltage and Limitations in the operating conditions of pn junction.