14. Semiconductors

Can you recall?

1. Your mobile handset is very efficient gadget.
2. International Space Station works using solar energy.
3. A LED TV screen produces brighter and vivid colours.
4. Good and bad conductor of electricity.

14.1 Introduction:

Modern life is heavily dependent on many electronic gadgets. It could be a cell phone, a smart watch, a computer or even an LED lamp, they all have one common factor, semiconductor devices that make them work. Semiconductors have made our life very comfortable and easy.

Semiconductors are materials whose electrical properties can be tailored to suit our requirements. Before the discovery of semiconductors, electrical properties of materials could be of two types, conductors or insulators. Conductors such as metals have a very high electrical conductivity, for example, conductivity of silver is 6.25×10^{7} Sm^{-1} whereas an insulator or a bad conductor like glass has a very low electrical conductivity of the order of 10^{-10} Sm^{-1}. Electrical conductivity of silicon, a semiconductor, for example is 1.56×10^{-3} Sm^{-1}. It lies between that of a good conductor and a bad conductor. A semiconductor can be customised to have its electrical conductivity as per our requirement. Temperature dependence of electrical conductivity of a semiconductor can also be controlled. Table 14.1 gives electrical conductivity of some materials which are commonly used.

14.2 Electrical conduction in solids:

Electrical conduction in a solid takes place by transport of charge carriers. It depends on its temperature, the number of charge carriers, how easily these carries can move inside a solid (mobility), its crystal structure, types and the nature of defects present in a solid etc. There can be three types of electrical conductors. It could be a good conductor, a semiconductor or a bad conductor.

1. Conductors (Metals): The best example of a conductor is any metal. They have a large number of free electrons available for electrical conduction. (A typical metal will have 10^{28} electrons per m^{3}). Metals are good conductors of electricity due to the large number of free electrons present in them.

2. Insulators: Glass, wood or rubber are some common examples of insulators. Insulators have very small number (10^{23} per m^{3}) of free electrons.

3. Semiconductors: Silicon, germanium, gallium arsenide, gallium nitride, cadmium sulphide are some of the commonly used semiconductors. The electrical conductivity of a semiconductor is between the conductivity of a metal and that of an insulator. The number of charge carriers in a semiconductor can be controlled as per our requirement. Their structure can also be designed to suit our requirement. Such materials are very useful in electronic industry and find applications in almost every gadget of daily use such as a cell phone, a solar cell or a complex system such as a satellite or the International Space Station.

Table 14.1: Electrical conductivities of some commonly used materials

Material	Electrical conductivity ($S\ m^{-1}$)
Silver	6.30×10^{7}
Copper	5.96×10^{7}
Aluminium	3.5×10^{7}
Gold	4.10×10^{7}
Nichrome	9.09×10^{5}
Platinum	9.43×10^{6}
Germanium	2.17
Silicon	1.56×10^{-3}
Air	3×10^{-15} to 8×10^{-15}
Glass	10^{-11} to 10^{-15}
Teflon	10^{-25} to 10^{-23}
Wood	10^{-16} to 10^{-24}

Do you know ?

Electrical conductivity σ of a solid is given by $\sigma = nq\mu$, where,

n = charge carrier density (number of carriers per unit volume)

q = charge on the carriers

μ = mobility of carriers

Mobility of a charge carrier is the measure of the ease with which a carrier can move in a material under the action of an external electric field. It depends upon many factors such as mass of the carrier, whether the material is crystalline or amorphous, the presence of structural defects in a material, the nature of impurities in a material and so on.

Figure 14.1 shows the temperature dependence of the electrical conductivity of a typical metal and a semiconductor. When the temperature of a semiconductor is increased, its electrical conductivity also increases. The electrical conductivity of a metal decreases with increase in its temperature.

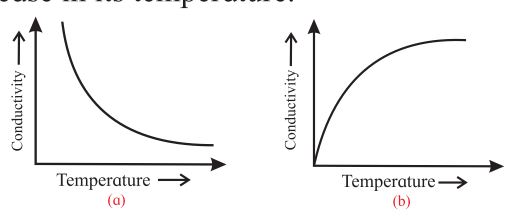


Fig. 14.1: Temperature dependence of electrical conductivity of (a) metals and (b)semiconductors.

Variation of electrical conductivity of semiconductors with change in its temperature is a very useful property and finds applications in a large number of electronic devices. A broad classification of semiconductors can be:

a. Elemental semiconductors: Silicon, germanium

b. Compound Semiconductors: Cadmium sulphide, zinc sulphide, etc.

c. Organic Semiconductors: Anthracene, doped pthalocyanines, polyaniline etc.

Elemental semiconductors and compound semiconductors are widely used in electronic industry. Discovery of organic semiconductors is relatively new and they find lesser applications.

Electrical properties of semiconductors are different from metals and insulators due to their unique conduction mechanism. The electronic configuration of the elemental semiconductors silicon and germanium plays a very important role in their electrical properties. They are from the fourth group of elements in the periodic table. They have a valence of four. Their atoms are bonded by covalent bonds. At absolute zero temperature, all the covalent bonds are completely satisfied in a single crystal of pure silicon or germanium.

The conduction mechanism in a semiconductor can be better understood with the help of the band theory of solids.

14.3 Band theory of solids, a brief introduction:

We begin with the way electron energies in an isolated atom are distributed. An isolated atom has its nucleus at the center which is surrounded by a number of revolving electrons. These electrons are arranged in different and discrete energy levels.

When a solid is formed, a large number of atoms are packed in it. The outermost electronic energy levels in a solid are occupied by electrons from all atoms in a solid. Sharing of the outermost energy levels and resulting formation of energy bands can be easily understood by considering formation of solid sodium.

The electronic configuration of sodium (atomic number 11) is $1s^2$, $2s^2$, $2p^6$, $3s^1$. The outermost level 3s can take one more electron but it is half filled in sodium.

When solid sodium is formed, atoms interact with each other through the electrons in each atom. The energy levels are filled according to the Pauli's exclusion principle. According to this principle, no two electrons can have the same set of quantum numbers, or in simple words, no two electrons with similar spin can occupy the same energy level.

Any energy level can accommodate only two electrons (one with spin up state and the other with spin down state). According to this principle, there can be two states per energy level. Figure 14.2 (a) shows the allowed energy levels of an isolated sodium atom by horizontal lines. The curved lines represent the potential energy of an electron near the nucleus due to Coulomb interaction.

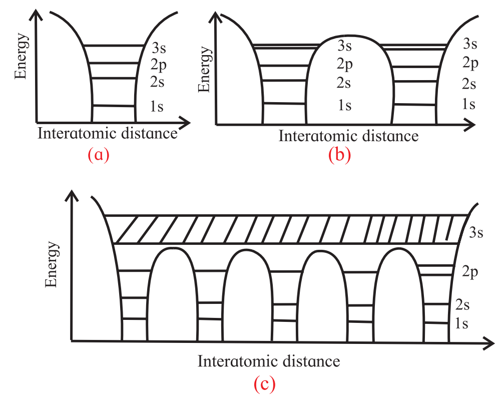


Fig. 14.2: Potential energy diagram, energy levels and bands (a) isolated atom, (b) two atoms, (c) sodium metal.

Consider two sodium atoms close enough so that outer 3s electrons are equally likely to be on any atom. The 3s electrons from both the sodium atoms need to be accommodated in the same level. This is made possible by splitting the 3s level into two sub-levels so that the Pauli's exclusion principle is not violated. Figure 14.2 (b) shows the splitting of the 3s level into two sub levels. When solid sodium is formed, the atoms come close to each other (distance between them ~ 2 - 3Å). Therefore, the electrons from different atoms interact with each other and also with the neighbouring atomic cores. The interaction between the outer most electrons is more due to overlap while the inner core electrons remain mostly unaffected. Each of these energy levels is split into a large number of sub levels, of the order of Avogadro's number. This is because the number of atoms in solid sodium is of the order of this number. The separation between the sublevels is so small that the energy levels appear almost continuous. This continuum of energy levels is called an energy band. The bands are called 1s band, 2s band, 2p band and so on. Figure 14.2 c shows these bands in sodium metal. Broadening of valence and higher bands is more because of stronger interaction of these electrons.

For sodium atom, the topmost occupied energy level is the 3s level. This level is called the valence level. Corresponding energy band is called the **valence band**. Thus, the valence band in solid sodium is the topmost occupied energy band. The valence band is half filled in sodium. Figure 14.3 shows the energy bands in sodium.

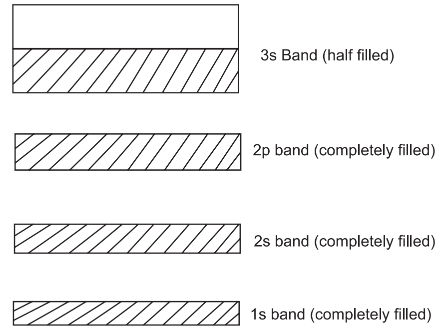


Fig. 14.3: Energy bands in sodium.

When sufficient energy is provided to electrons from the valence band they are raised to higher levels. The immediately next energy level that electrons from valence band can occupy is called conduction level. The band formed by conduction levels is called **conduction band**. In sodium valence and conduction bands overlap.

In a semiconductor or an insulator, there is a gap between the bottom of the conduction band and the top of the valence band. This is called the energy gap or the band gap.

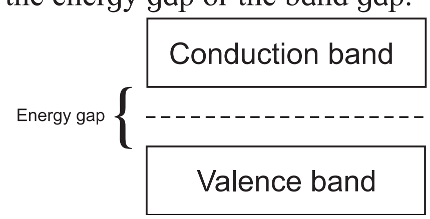


Fig. 14.4: Energy bands for a typical solid.

Figure 14.4 shows the conduction band, the energy gap and the valence band for a typical solid which is not a good conductor. **It is important to remember that this structure is related to the energy of electrons in a solid and it does not represent the physical structure of a solid in any way.**

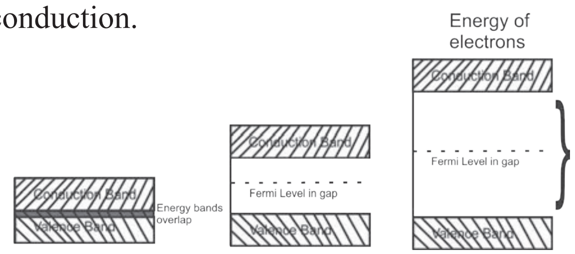
All the energy levels in a band, including the topmost band, in a semiconductor are completely occupied at absolute zero. At some finite temperature T, few electrons gain thermal energy of the order of kT, where k is the Boltzmann constant.

Electrons in the bands below the valence band cannot move to higher band since these are already occupied. Only electrons from the valence band can be excited to the empty

> Formation of energy bands in a solid is a result of the small distances between atoms, the resulting interaction amongst electrons and the Pauli's exclusion principle.

conduction band, if the thermal energy gained by these electrons is greater than the band gap. In case of sodium, electrons from the 3s band can gain thermal energy and occupy a slightly higher energy level because the 3s band is only half filled.

Electrons can also gain energy when an external electric field is applied to a solid. Energy gained due to electric field is smaller, hence only electrons at the topmost energy level gain such energy and participate in electrical conduction.



(a) (b) (c)

Fig. 14.5: Band structure of a (a) metal, (b) semiconductor, and an insulator (c).

The difference in electrical conductivities of various solids can be explained on the basis of the band structure of solids. Band structure in a metal, semiconductor and an insulator is different. Figure 14.5 shows a schematic representation of band structure of a metal, a semiconductor and an insulator.

For metals, the valence band and the conduction band overlap and there is no band gap as shown in Fig.14.5 (a). Electrons, therefore, find it easy to gain electrical energy when some external electric field is applied. They are, therefore, easily available for conduction.

In case of semiconductors, the band gap is fairly small, of the order of one electron volt or less as shown in Fig.14.5 (b). When excited, electrons gain energy and occupy energy levels in conduction band easily and can take part in electric conduction.

Insulators, on the contrary, have a wide gap between valence band and conduction band as shown in Fig.14.5 (c). Diamond, for example, has a band gap of about 5.0 eV. In an insulator, therefore, electrons find it very difficult to gain sufficient energy and occupy energy levels in the conduction band.

The magnitude of the band gap plays a very important role in electronic properties of a solid.

Table 14.2: Magnitude of energy gap in silicon, germanium and diamond.

Material	Energy gap (eV) At 300 K
Silicon	1.12
Germanium	0.66
Diamond	5.47

1 eV is the energy gained by an electron while it overcomes a potential difference of one volt. 1 ev = 1.6 × 10^{-19} J.

14.4 Intrinsic Semiconductor:

A pure semiconductor such as pure silicon or pure germanium is called an intrinsic semiconductor. Silicon (Si) has atomic number 14 and its electronic configuration is $1s^2\ 2s^2\ 2p^6\ 3s^2\ 3p^2$. Its valence is 4. Each atom of Si forms four covalent bonds with its neighbouring atoms. One Si atom is surrounded by four Si atoms at the corners of a regular tetrahedron Fig. 14.6.

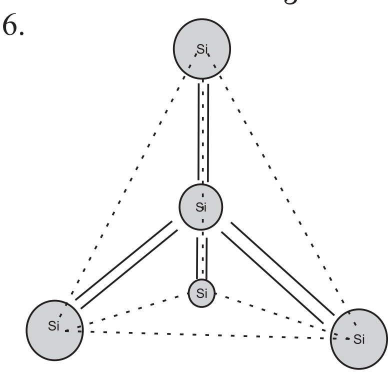


Fig. 14.6: Structure of silicon.

At absolute zero temperature, all valence electrons are tightly bound to respective atoms and the covalent bonds are complete. Electrons are not available to conduct electricity through the crystal because they cannot gain enough energy to get into higher energy levels. At room temperature, however, a few covalent bonds are broken due to thermal agitation and some valence electrons can gain energy. Thus we can say that a valence electron is moved to the conduction band. It creates a vacancy in the valence band as shown in Fig. 14.7.

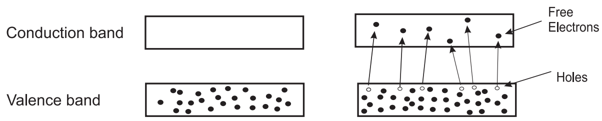


Fig. 14.7: Creation of vacancy in the valence band.

These vacancies of electrons in the valence band are called holes. The holes are thus absence of electrons in the valence band and they carry an *effective* positive charge.

For an intrinsic semiconductor, the number of holes per unit volume, (the number density, n_h) and the number of free electrons per unit volume, (the number density, n_e) is the same.

$$n_h = n_e$$

Electric conduction through an intrinsic semiconductor is quite interesting. There are two different types of charge carriers in a semiconductor. One is the electron and the other is the hole or absence of electron. Electrical conduction takes place by transportation of both carriers or any one of the two carriers in a semiconductor. When a semiconductor is connected in a circuit, electrons, being negatively charged, move towards positive terminal of the battery. Holes have an *effective positive charge*, and move towards negative terminal of the battery. Thus, the current through a semiconductor is carried by two types of charge carriers which move in opposite directions. This conduction mechanism makes semiconductors very useful in designing a large number of electronic devices. Figure 14.8 represents the current through a semiconductor.

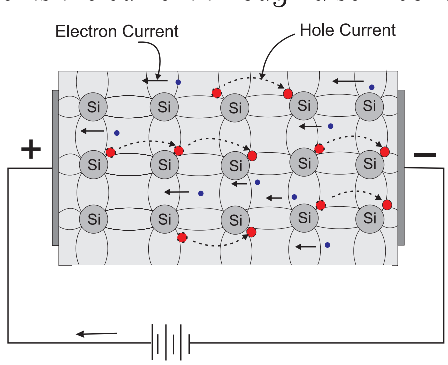


Fig. 14.8: Current through a semiconductor, transport of electrons and holes.

14.5 Extrinsic semiconductors:

The electric conductivity of an intrinsic semiconductor is very low at room temperature; hence no electronic devices can be fabricated using them. Addition of a small amount of a suitable impurity to an intrinsic semiconductor increases its conductivity appreciably. **The process of adding impurities to an intrinsic semiconductor is called doping.** The semiconductor with impurity is called a doped semiconductor or an extrinsic semiconductor. The impurity is called the dopant. The parent atoms are called hosts. The dopant material is so selected that it does not disturb the crystal structure of the host. The size and the electronic configuration of the dopant should be compatible with that of the host. Silicon or germanium can be doped with a pentavalent impurity such as phosphorus (P) arsenic (As) or antimony (Sb) . They can also be doped with a trivalent impurity such as boron (B) aluminium (Al) or indium (In).

Addition of pentavalent or trivalent impurities in intrinsic semiconductors gives rise to different conduction mechanisms. This is very useful in designing many electronic devices. Extrinsic semiconductors can be of two types a) n-type semiconductor or b) p-type semiconductor.

a) n-type semiconductor: When silicon or germanium crystal is doped with a pentavalent impurity such as phosphorus, arsenic, or antimony we get n-type semiconductor. Figure 14.9 shows the schematic electronic structure of antimony.

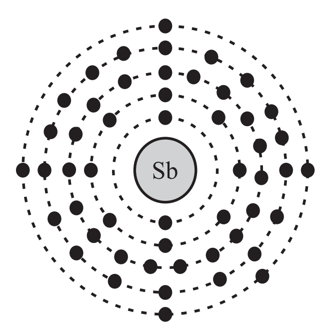


Fig. 14.9: Schematic electronic structure of antimony.

When a dopant atom of 5 valence electrons occupies the position of a Si atom in the crystal lattice, 4 electrons from the dopant form bonds with 4 neighbouring Si atoms and the fifth electron from the dopant remains very weakly bound to its parent atom. Figure 14.10 shows a pentavalent impurity in silicon lattice.

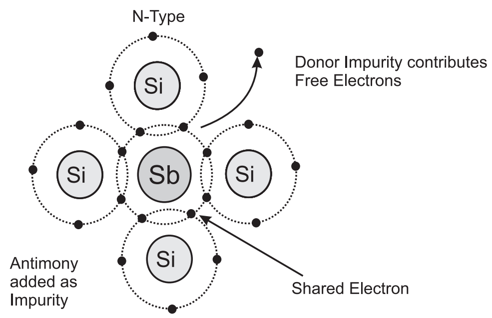


Fig. 14.10: Pentavalent impurity in silicon crystal.

To make this electron free even at room temperature, very small energy is required. It is 0.01 eV for Ge and 0.05 eV for Si.

Do you know ?

One cm^3 specimen of a metal or semiconductor has of the order of 10^{22} atoms. In a metal, every atom donates at least one free electron for conduction, thus 1 cm^3 of metal contains of the order of 10^{22} free electrons, whereas 1 cm^3 of pure germanium at 20 °C contains about 4.2×10^{22} atoms, but only 2.5×10^{13} free electrons and 2.5×10^{13} holes. Addition of 0.001% of arsenic (an impurity) donates 10^{17} extra free electrons in the same volume and the electrical conductivity is increased by a factor of 10,000.

Since every pentavalent dopant atom donates one electron for conduction, it is called a donor impurity. As this semiconductor has large number of electrons in conduction band and its conductivity is due to negatively charged carriers, it is called n-type semiconductor. The n-type semiconductor also has a few electrons and holes produced due to the thermally broken bonds. The density of conduction electrons (n_e) in a doped semiconductor is the sum total of the electrons contributed by donors and the thermally generated electrons from the host. The density of holes (n_h) is only due to the thermal breakdown of some covalent bonds of the host Si atoms. Some electrons and holes recombine continuously because they carry opposite charges. The number of free electrons exceeds the number of holes. Thus, in a semiconductor doped with pentavalent impurity, electrons (negative charge) are the majority carriers and holes are the minority carriers. Therefore, it is called n-type semiconductor. **For n-type semiconductor, $n_e >> n_h$.**

The free electrons donated by the impurity atoms occupy energy levels which are in the band gap and are close to the conduction band. They can be easily available for conduction. Figure 14.11 shows the schematic band structure of an n-type semiconductor.

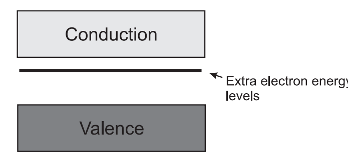


Fig.14.11: Schematic band structure of an n-type semiconductor.

Extrinsic semiconductors are thus far better conductors than intrinsic semiconductors. The conductivity of an extrinsic semiconductor can be controlled by controlling the amount of impurities added. The amount of impurities is expressed as part per million or ppm, that is, one impurity atom per one million atoms of the host.

Features of n-type semiconductors: These are materials doped with pentavalent impurity (donors) atoms . Electrical conduction in these materials is due to electrons as majority charge carriers.

1. The donor atom lose electrons and become positively charged ions.
2. Number of free electrons is very large compared to the number of holes, $n_e >> n_h$. Electrons are majority charge carriers.
3. When energy is supplied externally, negatively charged free electrons (majority charges carries) and positively charged holes (minority charge carriers) are available for conduction.

b) p-type semiconductor: When silicon or germanium crystal is doped with a trivalent impurity such as boron, aluminium or indium, we get a p-type semiconductor. Figure 14.12 shows the schematic electronic structure of boron.

The dopant trivalent atom has one valence electron less than that of a silicon atom. Every trivalent dopant atom shares its three electrons with three neighbouring Si atoms to form covalent bonds. But the fourth bond between silicon atom and its neighbour is not complete.

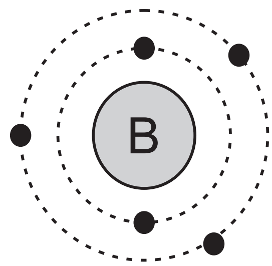


Fig. 14.12: Schematic electronic structure of boron.

Figure 14.13 shows a trivalent impurity in a silicon crystal. The incomplete bond can be completed by another electron in the neighbourhood from Si atom. Since each donar trivalent atom can accept an electron, it is called an acceptor impurity. The shared electron creates a vacancy in its place. This vacancy or the absence of electron is a hole.

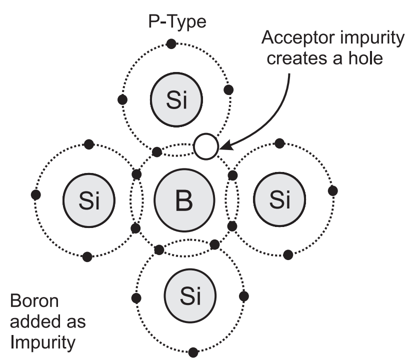


Fig. 14.13: A trivalent impurity in a silicon crystal.

Thus, a hole is available for conduction from each acceptor impurity atom. Holes are majority carriers and electrons are minority carriers in such materials. Acceptor atoms are negatively charged and majority carriers are holes (positively charged). Therefore, extrinsic semiconductor doped with trivalent impurity is called a p-type semiconductor. For a p-type semiconductor, $n_h >> n_e$.

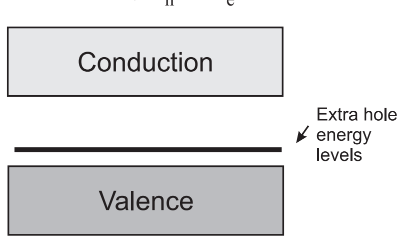


Fig. 14.14: Schematic band structure of a p-type semiconductor.

These vacancies of electrons are created in the valence band; therefore we can say that the holes are created in the valence band. The impurity levels are created just above the valence band in the band gap. Electrons from valence band can easily occupy these levels and conduct electricity. Figure 14.14 shows the schematic band structure of a p-type semiconductor.

Features of p-type semiconductor: These are materials doped with trivalent impurity atoms (acceptors). Electrical conduction in these materials is due to holes as majority charge carriers.

1. The acceptor atoms acquire electron and become negatively charged-ions.
2. Number of holes is very large compared to the number of free electrons. ($n_h \gg n_e$). Holes are majority charge carriers.
3. When energy is supplied externally, positively charged holes (majority charge carriers) and negatively charged free electrons (minority charge carriers) are available for conduction.

c) Charge neutrality of extrinsic semiconductors: The n-type semiconductor has excess of electrons but these extra electrons are supplied by the donor atoms which become positively charged. Since each atom of donor impurity is electrically neutral, the semiconductor as a whole is electrically neutral. Here, excess electron refers to an excess with reference to the number of electrons needed to complete the covalent bonds in a semiconductor crystal. These extra free electrons increase the conductivity of the semiconductor.

Similarly, a p-type semiconductor has holes or absence of electrons in some energy levels. When an electron from a host atom fills this level, the host atom is positively charged and the dopant atom is negatively charged but the semiconductor as a whole is electrically neutral. *Thus, n-type as well as p-type semiconductors are electrically neutral.*

Always remember, for a semiconductor,

$$\mathbf{n_e \cdot n_h = n_i^2}$$

Example 14.1: A pure Si crystal has 4×10^{28} atoms m^{-3}. It is doped by 1ppm concentration of antimony. Calculate the number of electrons and holes. Given $n_i = 1.2 \times 10^{16}/m^3$.

Solution: 1 ppm = 1 part per million = $1/10^6$

$\therefore$ no. of Sb atoms $= \dfrac{4\times10^{28}}{10^6} = 4\times10^{22}$

As one pentavalent impurity atom donates one free electron to the crystal,

Number of free electrons in the crystal $n_e = 4 \times 10^{22}\ m^{-3}$

Number of holes,

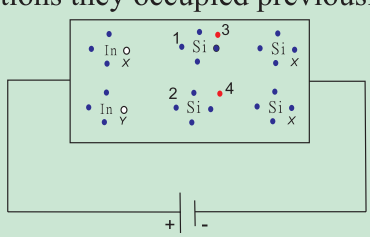
$$n_h = \frac{(n_i)^2}{n_e} = \frac{(1.2\times10^{16})^2}{4\times10^{22}}$$

$n_h = 3.6 \times 10^9\ m^{-3}$

Do you know ?

Transportation of holes

Consider a p-type semiconductor connected to terminals of a battery as shown. When the circuit is switched on, electrons at 1 and 2 are attracted to the positive terminal of the battery and occupy nearby holes at x and y. This generates holes at the positions 1 and 2 previously occupied by electrons. Next, electrons at 3 and 4 move towards the positive terminal and create holes in the positions they occupied previously.



Finally, the hole is captured at the negative terminal by the electron supplied by the battery at that end. This keeps the density of holes constant and maintains the current so long as the battery is working.

Thus, physical transportation is of the electrons only. However, we feel that the holes are moving towards the negative terminal of the battery. Positive charge is attracted towards negative terminal. Thus holes, which are not actual charges, behave like a positive charge. In this case, there is an indirect movement of electrons and their drift speed is less than that in the n-type semiconductors. The mobility of holes is, therefore, less than that of the electrons.

Example 14.2: A pure silicon crystal at temperature of 300 K has electron and hole concentration 1.5×10^{16} m^{-3} each. ($n_e = n_h$). Doping by indium increases n_h to 4.5×10^{22} m^{-3}. Calculate n_e for the doped silicon crystal.

Solution: We know,

$n_e n_h = n_i^2$ and $n_e = \dfrac{(n_i)^2}{n_h}$

Given

$n_i = 1.5 \times 10^{16} m^{-3}$ and $n_h = 4.5 \times 10^{22}\ m^{-3}$

$$n_e = \frac{(1.5 \times 10^{16})^2}{4.5 \times 10^{22}} = 5 \times 10^9\ m^{-3}$$

14.6 p-n junction:

When n-type and p-type semiconductor materials are fused together, a p-n junction is formed. A p-n junction shows many interesting properties and it is the basis of almost all modern electronic devices. Figure 14.15 shows a schematic structure of a p-n junction.

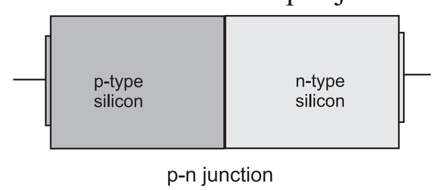


Fig. 14.15: Schematic structure of a p-n junction.

Diffision: When n-type and p-type semiconductor materials are fused together, initially, the number of electrons in the n-side of the junction is very large compared to the number of electrons on the p-side. The same is true for the number of holes on the p-side and on the n-side. Thus, the density of carriers on both sides is different and a large density gradient exists on both sides of the p-n junction. This density gradient causes migration of electrons from the n-side to the p-side of the junction. They fill up the holes in the p-type material and produce negative ions.

When the electrons from the n-side of a junction migrate to the p-side, they leave behind positively charged donor ions on the n-side. Effectively, holes from the p-side migrate into the n-region.

As a result, in the p-type region near the junction there are negatively charged acceptor ions, and in the n-type region near the junction there are positively charged donor ions. The transfer of electrons and holes across the p-n junction is called diffusion. The extent up to which the electrons and the holes can diffuse across the junction depends on the density of the donor and the acceptor ions on the n-side and the p-side respectively, of the junction. Figure 14.16 shows the diffusion of charge carriers across the junction.

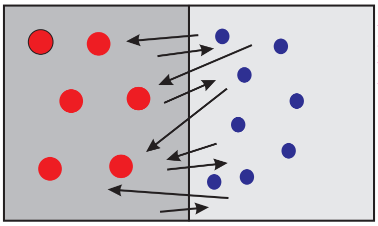


Fig. 14.16: Diffusion of charge carriers across a junction.

Depletion region: The diffusion of carriers across the junction and resultant accumulation of positive and negative charges across the junction builds a potential difference across the junction. This potential difference is called the potential barrier. The magnitude of the potential barrier for silicon is about 0.6 – 0.7 volt and for germanium, it is about 0.3 – 0.35 volt. This potential barrier always exists even if the device is not connected to any external power source. It prevents continuous diffusion of carriers across the junction. A state of electrostatic equilibrium is thus reached across the junction.

Free charge carriers cannot be present in a region where there is a potential barrier. The regions on either side of a junction, therefore, becomes completely devoid of any charge carriers. This region across the p-n junction where there are no charges is called the depletion layer or the depletion region. Figure 14.17 shows the potential barrier and the depletion layer.

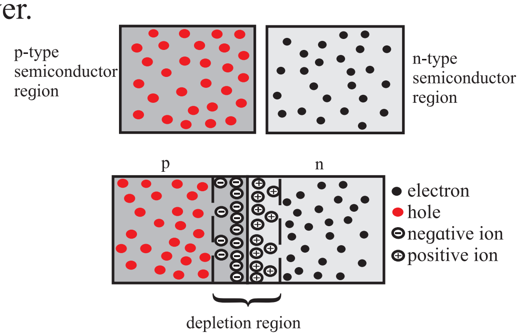


Fig. 14.17: Potential barrier and the depletion layer.

The potential across a junction and width of the potential barrier can be controlled. This is very interesting and useful property of a p-n junction.

The n-side near the boundary of a p-n junction becomes positive with respect to the p-side because it has lost electrons and the p-side has lost holes. Thus the presence of impurity ions on both sides of the junction establishes an electric field across this region such that the n-side is at a positive voltage relative to the p-side. Figure 14.18 shows the electric field thus produced.

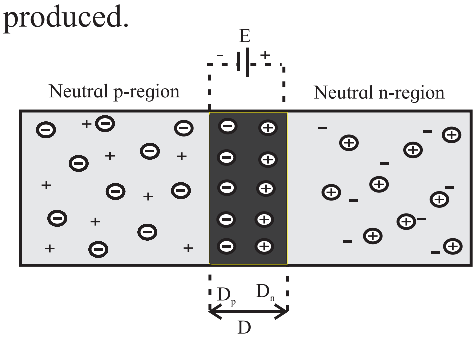


Fig. 14.18: Electric field across a junction.

Biasing a p-n junction: As a result of potential barrier across depletion region, charge carriers require some extra energy to overcome the barrier. A suitable voltage needs to be applied to the junction externally, so that these charge carriers can overcome the potential barrier and move across the junction. Figure 14.19 shows two possibilities of applying this external voltage across the junction.

Figure 14.19 (a) shows a p-n junction connected in an electric circuit where the p-region is connected to the positive terminal and the n-region is connected to the negative terminal of an external voltage source. This external voltage effectively opposes the built-in potential of the junction. The width of potential barrier is thus reduced. Also, negative charge carriers (electrons) from the n-region are pushed towards the junction. A similar effect is experienced by positive charge carriers (holes) in the p-region and they are pushed towards the junction. Both the charge carriers thus find it easy to cross over the barrier and contribute towards the electric current. Such arrangement of a p-n junction in an electric circuit is called **forward bias**.

Figure 14.19 (b) shows the other possibility, where, the p-region is connected to the negative terminal and the n-region is connected to the positive terminal of the external voltage source. This external voltage effectively adds to the built-in potential of the junction. The width of potential barrier is thus increased. Also, the negative charge carriers (electrons) from the n-region are pulled away from the junction. Similar effect is experienced by the positive charge carriers (holes) in the p-region and they are pulled away from the junction. Both the charge carriers thus find it very difficult to cross over the barrier and thus do not contribute towards the electric current. Such arrangement of a p-n junction in an electric circuit is called **reverse bias**.

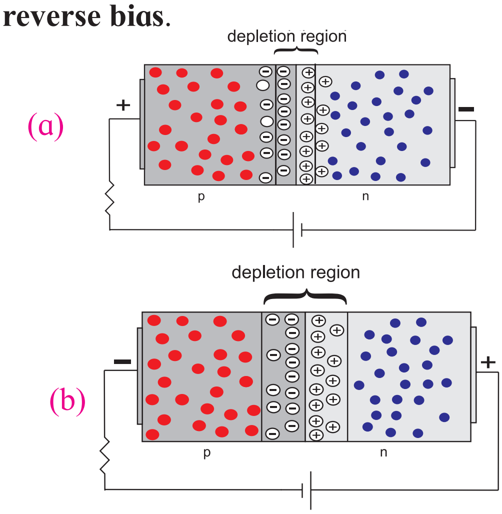


Fig. 14.19: Forward biased (a) and reverse biased (b) junction.

Therefore, when used in forward bias mode, a p-n junction allows a large current to flow across. This current is normally of the order of a few milliamperes, (10^{-3} A). A reverse biased p-n junction on the other hand, carries a very small current that is normally a few microamperes (10^{-6} A).

A p-n junction can be thus used as a one way switch or a gate in an electric circuit. It conducts easily in forward bias and acts as an open switch in reverse bias.

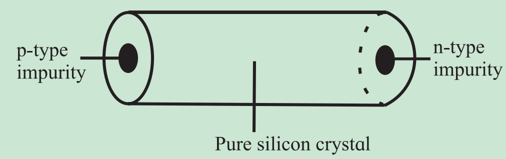
Features of the depletion region:

1. It is formed by diffusion of electrons from n-region to the p-region. This leaves positively charged ions in the n-region.
2. The p-region accumulates electrons (negative charges) and the n-region accumulates the holes (positive charges).
3. The accumulation of charges on either sides of the junction results in forming a potential barrier and prevents flow of charges across it.
4. There are no charges in this region.
5. The depletion region has higher potential on the n-side and lower potential on the p-side of the junction.

Do you know ?

Fabrication of p-n junction diode:

It was mentioned previously, for easy understanding, that a p-n junction is formed by fusing a p-type and a n-type material together. However, in practice, a p-n junction is formed from a crystalline structure of silicon or germanium by adding carefully controlled amounts of donor and acceptor impurities.



The impurities grow on either side of the crystal after heating in a furnace. Electrons and holes combine at the center and the depletion region develops. A junction is thus formed. Electrodes are inserted after cutting transverse sections and hundreds of diodes are prepared. All semiconductor devices, including ICs, are fabricated by 'growing' junctions at the required locations.

Mobility of a hole is less than that of an electron and the hole current is lesser. This imbalance between the two currents is removed by increasing the doping percentage in the p-region. This ensures that the same current flows through the p-region and the n-region of the junction.

14.7 A p-n junction diode:

A p-n junction, when provided with metallic connectors on each side is called a junction diode or simply, a diode. (Diode is a device with two electrodes or di-electrodes). Figure 14.20 shows the circuit symbol for a junction diode.

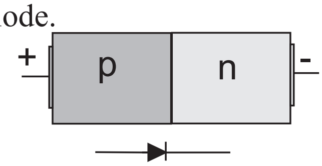


Fig. 14.20: Circuit symbol for a p-n junction diode.

The 'arrow' indicates the direction of the conventional current. The p-side is called the anode and the n-side is called the cathode of the diode. When a diode is connected across a battery, the carriers can gain additional energy to cross the barrier as per biasing.

A diode can be connected across a battery in two different ways, forward bias and reverse bias as shown in the (Fig. 14.21).

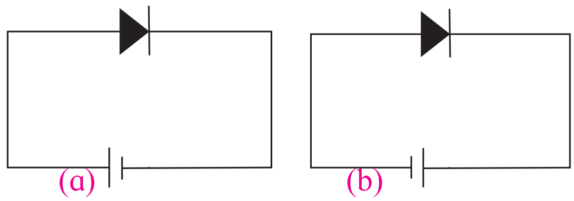


Fig. 14.21: (a) Forward bias, (b) Reverse bias.

The behavior of a diode in both cases is different. This is because the barrier potential is affected differently in the two cases. The barrier potential is reduced in forward biased mode and it is increased in reverse biased mode.

Carriers find it easy to cross the junction in forward bias and contribute towards current for two reasons; first the barrier width is reduced and second, they are pushed towards the junction and gain extra energy to cross the junction. The current through the diode in forward bias is, therefore, large. It is of the order of a few milliamperes (10^{-3} A) for a typical diode.

When connected in reverse bias, width of the potential barrier is increased and the carriers are pushed away from the junction so that very few thermally generated carriers can cross the junction and contribute towards current. This results in a very small current through a reverse biased diode. The current in reverse biased diode is of the order of a few microamperes (10^{-6} A).

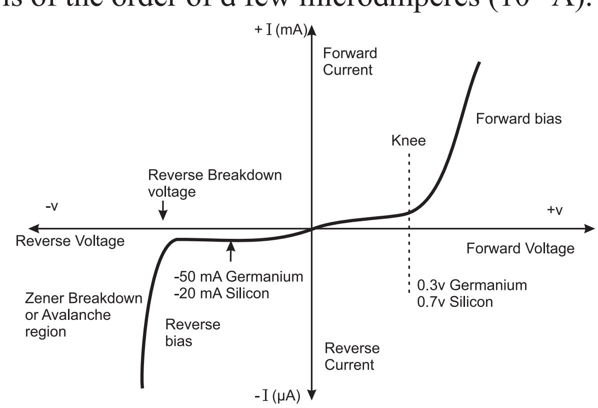


Fig. 14.22: Asymmetrical current flow through a diode.

The width of the depletion layer decreases with an increase in the application of a forward voltage. It increases when a reverse voltage is applied. We have discussed the reasons for this difference earlier. When the polarity of bias voltage is reversed, the width of the depletion layer changes. This results in asymmetrical current flow through a diode as shown in (Fig. 14.22).

A diode can be thus used as a one way switch in a circuit. It is forward biased when its anode is connected to be at a higher potential than that of the cathode. When the anode is at lower potential than that of the cathode, it is reverse biased. A diode can be zero biased if no external voltage is applied across it.

a) **Forward biased:** The positive terminal of the external voltage is connected to the anode (p-side) and negative terminal to the cathode (n-side) across the diode.

In case of forward bias, the width of the depletion region decreases and the p-n junction offers a low resistance path allowing a high current to flow across the junction (Fig. 14.23).

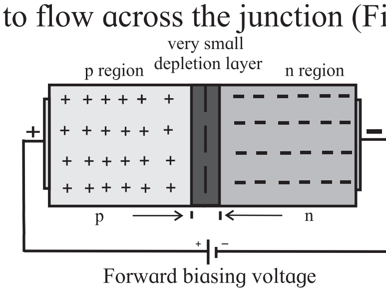


Fig. 14.23: Decrease in width of depletion region.

Figure 14.24 shows the I-V characteristic of a forward biased diode. Initially, the current is very low and then there is a sudden rise in the current. The point at which current rises sharply is shown as the 'knee' point on the I-V characteristic curve. The corresponding voltage is called the 'knee voltage'. It is about 0.7 V for silicon and 0.3 V for germanium.

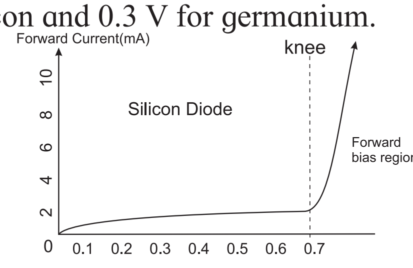


Fig. 14.24: I-V characteristic of a forward biased diode.

A diode effectively becomes a short circuit above this knee point and can conduct a very large current. Resistors are, therefore, used in series with diode to limit its current flow. If the current through a diode exceeds the specified value, it can heat up the diode due to the Joule heating and can result in its physical damage.

b) Reverse biased: The positive terminal of the external voltage is connected to the cathode (n-side) and negative terminal to the anode (p-side) across the diode. In case of reverse bias, the width of the depletion region increases and the p-n junction behaves like a high resistance (Fig. 14.25). Practically, no current flows through it with an increase in the reverse bias voltage. However, a very small **leakage current** does flow through the junction which is of the order of a few micro-amperes, (μA).

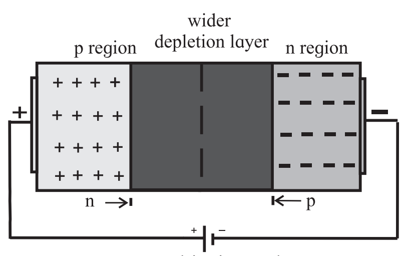


Fig. 14.25: Increase in width of depletion region.

When the reverse bias voltage applied to a diode is increased to sufficiently large value, it causes the p-n junction to overheat. The overheating of the junction results in a sudden rise in the current through the junction. This is because the covalent bonds break and a large number of carriers are available for conduction. The diode, thus, no longer behaves like a diode. This effect is called the avalanche breakdown. The reverse biased characteristic of a diode is shown in Fig 14.26.

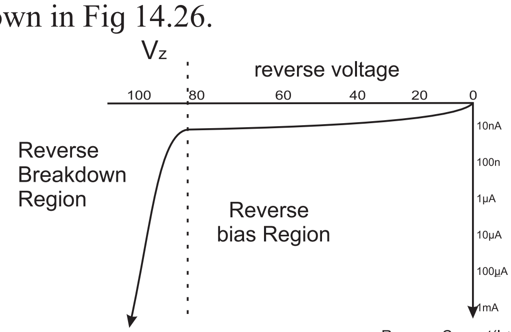
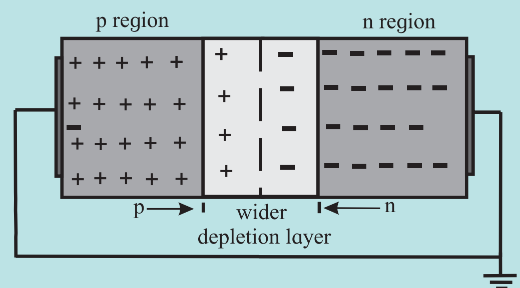


Fig. 14.26: Reverse biased characteristic of a diode.

Zero Biased Junction Diode.

When a diode is connected in a **zero bias** condition, no external potential energy is applied to the p-n junction. When the diode terminals are shorted together, some holes (majority carriers) in the p-side have enough thermal energy to overcome the potential barrier. Such carriers cross the barrier potential and contribute to current. This current is known as the **forward current.** .

Similarly, some holes generated in the n-side (minority carriers), also move across the junction in the opposite direction and contribute to current. This current is known as the **reverse current.** This transfer of electrons and holes back and forth across the p-n junction is known as diffusion, as discussed previously.



Zero biased p-n junction diode

The potential barrier that exists in a junction prevents the diffusion of any more majority carriers across it. However, some minority carriers (few free electrons in the p-region and few holes in the n-region) do drift across the junction.

An equilibrium is established when the majority carriers are equal in number (n_e=n_h) and are moving in opposite directions. The net current flowing across the junction is zero. This is a state of '**dynamic equilibrium**'.

Minority carriers are continuously generated due to thermal energy. When the temperature of the p-n junction is raised, this state of equilibrium is changed. This results in generating more minority carriers and an increase in the leakage current. An electric current, however, cannot flow through the diode because it is not connected in any electric circuit.

c) Static and dynamic resistance of a diode:

One of the most important properties of a diode is its resistance in the forward biased mode and in the reverse biased mode. Figure 14.27 shows the I-V characteristics of an ideal diode.

An ideal diode offers zero resistance in forward biased mode and infinite resistance in reverse biased mode.

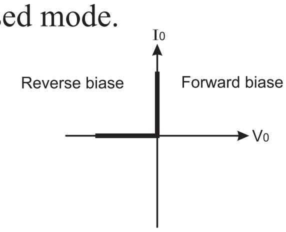


Fig. 14.27: I-V characteristics of an ideal diode.

The I-V characteristics of a forward biased diode (Fig. 14.24) is used to define two of its resistances i) the static (DC) resistance and ii) the dynamic (AC) resistance.

i) Static (DC) resistance: When a p-n junction diode is forward biased, it offers a definite resistance in the circuit. This resistance is called the static or DC resistance (R_g) of a diode. The DC resistance of a diode is the ratio of the DC voltage across the diode to the DC current flowing through it at a particular voltage.

$$R_g = \frac{V}{I}$$

ii) Dynamic (AC) resistance: The dynamic (AC) resistance of a diode, r_g, at a particular applied voltage, is defined as

$$r_g = \frac{\Delta V}{\Delta I}$$

The dynamic resistance of a diode depends on the operating voltage. It is the reciprocal of the slope of the characteristics at that point. Figure 14.28 shows how the DC and the AC resistance of a diode are found out.

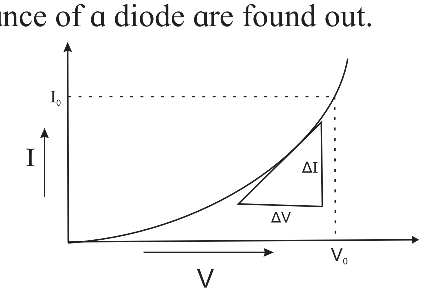
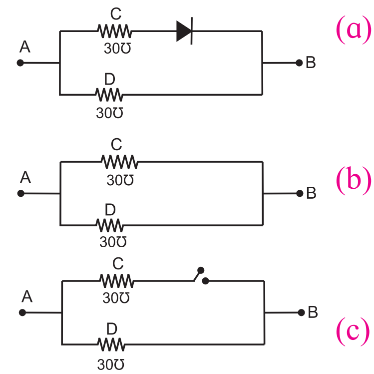


Fig. 14.28: DC and the AC resistance of a diode.

Example 14.3 Refer to the figure a shown below and find the resistance between point A and B when an ideal diode is (1) forward biased and (2) reverse biased.



Solution: We know that for an ideal diode, the resistance is zero when forward biased and infinite when reverse biased.

i) Figure b shows the circuit when the diode is forward biased. An ideal diode behaves as a conductor and the circuit is similar to two resistances in parallel.

R_{AB} = (30 x 30)/(30+30) = 900/60 = 15 Ω

ii) Figure c shows the circuit when the diode is reverse biased. It does not conduct and behaves as an open switch, path ACB. Therefore, R_{AB}= 30 Ω, the only resistance in the circuit along the path ADB.

14.8 Semiconductor devices:

Semiconductor devices find applications in variety of fields. They have many advantages. They also have some disadvantages. Here we discuses some advantages and disadvantages.

14.8.1 Advantages:

1. Electronic properties of semiconductors can be controlled to suit our requirement.
2. They are smaller in size and light weight.
3. They can operate at smaller voltages (of the order of few mV) and require less current (of the order of µA or mA), therefore, consume lesser power.
4. Almost no heating effects occur, therefore these devices are thermally stable.
5. Faster speed of operation due to smaller size.
6. Fabrication of ICs is possible.

14.8.2 Disadvantages:

1. They are sensitive to electrostatic charges.
2. Not vary useful for controlling high power.
3. They are sensitive to radiation.
4. They are sensitive to fluctuations in temperature.
5. They need controlled conditions for their manufacturing.
6. Very few matreials are semiconductors.

14.9 Applications of semiconductors and p-n junction diode:

A p-n junction diode is the basic block of a number of semiconductor devices. A semiconductor device can have more than one junction. Properties of a device can be controlled by controlling the concentration of dopants.

1. **Solar cell**: Converts light energy into electric energy. Useful to produce electricity in remote areas and also for providing electricity for satellites, space probes and space stations.
2. **Photo resistor**: Changes its resistance when light is incident on it.
3. **Bi-polar junction transistor**: These are devices with two junctions and three terminals. A transistor can be a p-n-p or n-p-n transistor. Conduction takes place with holes and electrons. Many other types of transistors are designed and fabricated to suit specific requirements. They are used in almost all semiconductor devices.
4. **Photodiode**: It conducts when illuminated with light.
5. **LED**: Light Emitting Diode: Emits light when current passes through it. House hold LED lamps use similar technology. They consume less power, are smaller in size and have a longer life and are cost effective.
6. **Solid State Laser**: It is a special type of LED. It emits light of specific frequency. It is smaller in size and consumes less power.
7. **Integrated Circuits (ICs):** A small device having hundreds of diodes and transistors performs the work of a large number of electronic circuits.

14.10 Thermistor:

Thermistor is a temperature sensitive resistor. Its resistance changes with change in its temperature. There are two types of thermistors, the Negative Temperature Coefficient (NTC) and the Positive Temperature Coefficient (PTC).

Resistance of a NTC thermistor decreases with increase in its temperature. Its temperature coefficient is negative. They are commonly used as temperature sensors and also in temperature control circuits.

Resistance of a PTC thermistor increases with increase in its temperature. They are commonly used in series with a circuit. They are generally used as a reusable fuse to limit current passing through a circuit to protect against *over current* conditions, as resettable fuses.

Thermistors are made from thermally sensitive metal oxide semiconductors. Thermistors are very sensitive to changes in temperature. A small change in surrounding temperature causes a large change in their resistance. They can measure temperature variations of a small area due to their small size. Both types of thermistors have many applications in industry.

Do you know ?

Electric and electronic devices

Electric devices: These devices convert electrical energy into some other form. Fan, refrigerator, geyser etc. are some examples. Fan converts electrical energy into mechanical energy. A geyser converts it into heat energy. They use good conductors (mostly metals) for conduction of electricity. Common working range of currents for electric circuits is milli ampers (mA) to amperes. Their energy consumption is also moderate to high. A typical geyser consumes about 2.0 to 2.50 kW of power. They are moderate to large in size and are costly.

Electronic devices: Electronic circuits work with control or sequential changes in current through a cell. A calculator, a cell phone a smart watch or the remote control of a TV set are some of the electronic devices. Semiconductors are used to fabricate such devices. Common working range of currents for electronic circuits it is nano-ampere to μA. They consume very low energy. They are very compact, and cost effective.

Internet my friend

1. https://www.electronics-tutorials.ws>diode
2. https://www.hitachi-hightech.com
3. https://ntpel.ac.in>courses
4. https://physics.info>semiconductors
5. https://www.hyperphysics.phy-astr.gsu.edu>semcn

Exercises

1. Choose the correct option.

i) Electric conduction through a semiconductor is due to:

(A) electrons

(B) holes

(C) none of these

(D) both electrons and holes

ii) The energy levels of holes are:

(A) in the valence band

(B) in the conduction band

(C) in the band gap but close to valence band

(D) in the band gap but close to conduction band

iii) Current through a reverse biased p-n junction, increases abruptly at:

(A) breakdown voltage (B) 0.0 V

(C) 0.3V (D) 0.7V

iv) A reverse biased diode, is equivalent to:

(A) an off switch

(B) an on switch

(C) a low resistance

(D) none of the above

v) The potential barrier in p-n diode is due to:

(A) depletion of positive charges near the junction

(B) accumulation of positive charges near the junction

(C) depletion of negative charges near the junction,

(D) accumulation of positive and negative charges near the junction

2. Answer the following questions.

i) What is the importance of energy gap in a semiconductor?

ii) Which element would you use as an impurity to make germanium an n-type semiconductor?

iii) What causes a larger current through a p-n junction diode when forward biased?

iv) On which factors does the electrical conductivity of a pure semiconductor depend at a given temperature?

v) Why is the conductivity of a n-type semiconductor greater than that of p-type semiconductor even when both of these have same level of doping?

3. Answer in detail.

i) Explain how solids are classified on the basis of band theory of solids.

ii) Distinguish between intrinsic semiconductors and extrinsic semiconductors.

iii) Explain the importance of the depletion region in a p-n junction diode.

iv) Explain the I-V characteristic of a forward biased junction diode.

v) Discuss the effect of external voltage on the width of depletion region of a p-n junction

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