**PHY 102.2 (INTRODUCTION TO BASIC ELECTRONICS)**

# 1.0 ELECTRONICS

**1.1 Electronics**: is the branch of engineering which deals with current conduction through a vacuum or gas or semiconductor. An *electronic device* is that in which current flows through a vacuum or gas or semiconductor.

**1.2 Important of Electronics**

Electronics has gained much importance due to its numerous applications in industry. The electronic devices are capable of performing the following functions :

**(*i*) Rectification.** The conversion of a.c. into d.c. is called *rectification*. Electronic devices can convert a.c. power into d.c. power with very high efficiency. This d.c. supply can be used for charging storage batteries, field supply of d.c. generators, electroplating etc.

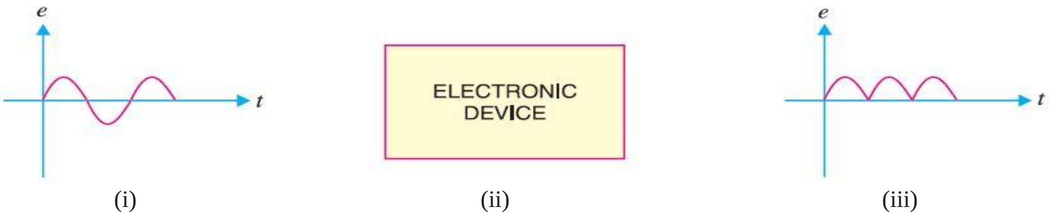



**Fig. 1.1**

**(*ii*) Amplification.** The process of raising the strength of a weak signal is known as *amplification*.
Electronic devices can accomplish the job of amplification and thus act as amplifiers. The amplifiers are used in a wide variety of ways. For example, an amplifier is used in a radioset where the weak signal is amplified so that it can be heard loudly. Similarly, amplifiers are used in public address system, television etc.

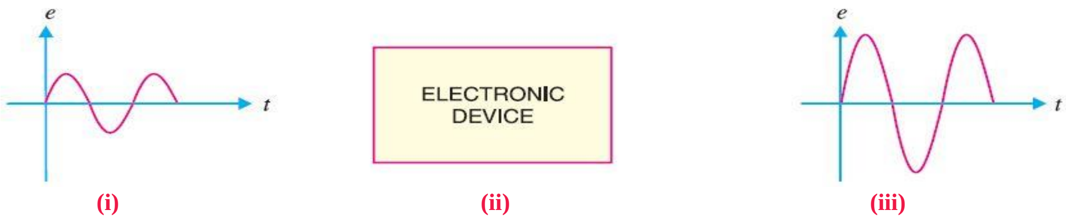



**Fig. 1.2**

**(*iii*) Control.** Electronic devices find wide applications in automatic control. For example, speed of a motor, voltage across a refrigerator etc. can be automatically controlled with the help of such devices.

**(*iv*) Generation.** Electronic devices can convert d.c. power into a.c. power of any frequency. When performing this function, they are known as *oscillators*. The oscillators are used in a wide variety of ways. For example, electronic high frequency heating is used for annealing and hardening.

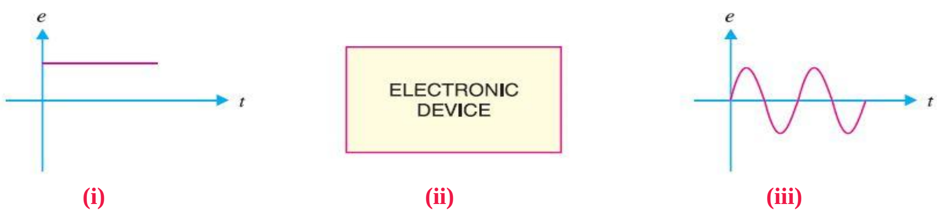



**Fig. 1.3**

**(*v*) Conversion of light into electricity.** Electronic devices can convert light into electricity. This conversion of light into electricity is known as *photo-electricity*. Photo-electric devices are used in Burglar alarms, sound recording on motion pictures *etc*.

**(*vi*) Conversion of electricity into light.** Electronic devices can convert electricity into light. .This valuable property is utilized in television and radar.

## 1.3 Valence Electrons

*The electrons in the outermost orbit of an atom are known as* ***valence electrons.*** The outermost orbit can have a maximum of 8 electrons *i.e.* the maximum number of valence electrons can be 8. The valence electrons determine the physical and chemical properties of a material. These electrons determine whether or not the material is chemically active; metal or non-metal or, a gas or solid. These electrons also determine the electrical properties of a material.

## 1.4 Energy Levels

The electrons moving in a particular orbit possess the energy of that orbit. The larger the orbit, the greater is its energy. It becomes clear that outer orbit electrons possess more energy than the inner orbit electrons. A convenient way of representing the energy of different orbits is shown in Fig. below. This is known as energy level diagram. The first orbit represents the *first energy level*, the second orbit indicates the *second energy level* and so on. The larger the orbit of an electron, the greater is its energy and higher is the energy level.

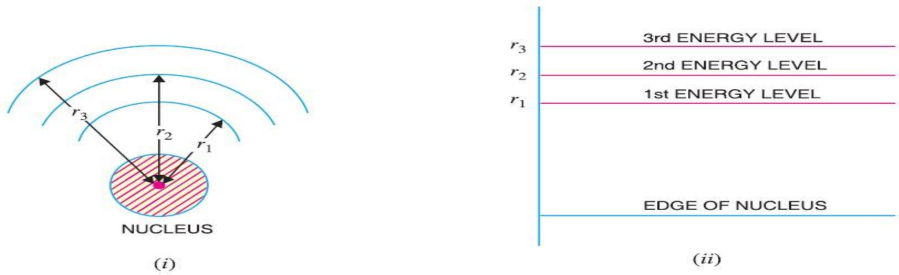



**Fig. 1.4**

## 1.5 Energy Bands

In case of a single isolated atom, the electrons in any orbit possess definite energy. However, an atom in a solid is greatly influenced by the closely-packed neighboring atoms. The result is that the electron in any orbit of such an atom can have a range of energies rather than a single energy. This is known as *energy band*. *The range of energies possessed by an electron in a solid is known as* ***energy band***.

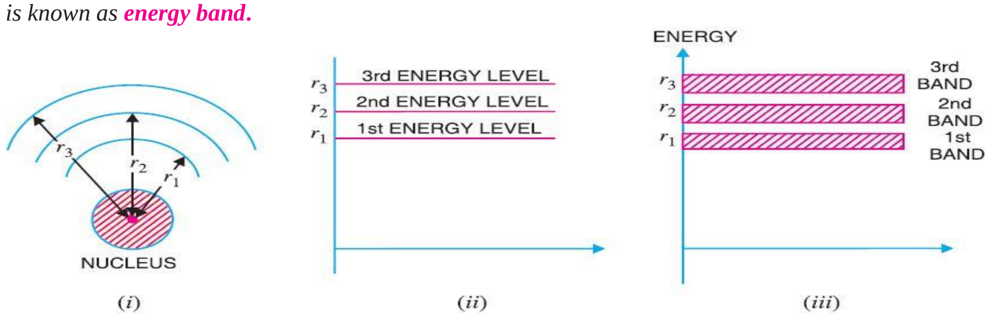



**Fig. 1.5**

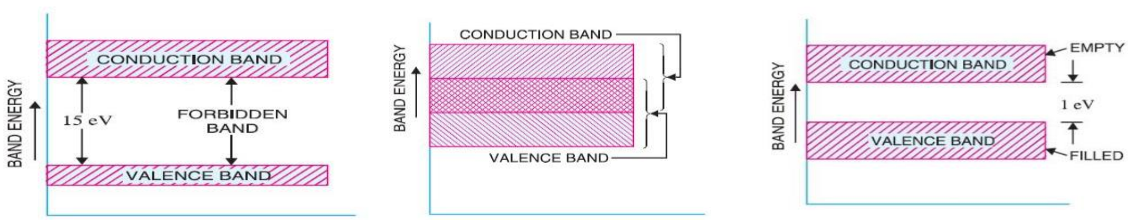
**(*i*) Valence band.** *The range of energies* (*i.e. band*) *possessed by valence electrons is known as* **valence band.** The electrons in the outermost orbit of an atom are known as valence electrons. In a normal atom, valence .band has the electrons of highest energy. This band may be completely or partially filled.

**(*ii*) Conduction band.** *The range of energies* (*i.e. band*) *possessed by conduction band electrons is known as* **conduction band.**

**(*iii*) Forbidden energy gap.** *The separation between conduction band and valence band on the energy level diagram is known as* **forbidden energy gap.**

## 1.6 Classification of Solids and Energy Bands

The difference in the behavior of solids as regards their electrical conductivity can be beautifully explained in terms of energy bands. The electrons in the lower energy band are tightly bound to the nucleus and play no part in the conduction process.




**(i)** **(ii)** **(iii)**

**Fig. 1.6**

**(*i*) Insulators.** Insulators (*e.g.* wood, glass etc.) are those substances which do not allow the passage of electric current through them. In terms of energy band, the valence band is full while the conduction band is empty. Further, the energy gap between valence and conduction bands is very large (15 eV) as shown in Fig. 1.6 (i). Therefore, a very high electric field is required to push the valence electrons to the conduction band.

**(*ii*) Conductors.** Conductors (*e.g.* copper, aluminium) are those substances which easily allow the passage of electric current through them. It is because there are a large number of free electrons available in a conductor. In terms of energy band, the valence and conduction bands overlap each other as shown in Fig. 1.6 (ii). Due to this overlapping, a slight potential difference across a conductor causes the free electrons to constitute electric current. Thus, the electrical behaviour of conductors can be satisfactorily explained by the band energy theory of materials.

**(*iii*) Semicondutors.** Semiconductors (*e.g.* germanium, silicon etc.) are those substances whose electrical conductivity lies in between conductors and insulators. In terms of energy band, the valence band is almost filled and conduction band is almost empty. Further, the energy gap between valence and conduction bands is very small as shown in Fig. 1.6 (iii). Therefore, comparatively smaller electric field (smaller than insulators but much greater than conductors) is required to push the electrons from the valence band to the conduction band. At low temperature, the valence band is completely full and conduction band is completely empty. Therefore, a semiconductor virtually behaves as an insulator at low temperatures. However, even at room temperature, some electrons (about one electron for $10^{10}$ atoms) cross over to the conduction band, imparting little conductivity to the semiconductor. As the temperature is increased, more valence electrons cross over to the conduction band and the conductivity increases.

## 2.0 SEMICONDUCTOR

*A* ***semiconductor*** *is a substance which has resistivity ($10^{-4}$ to 0.5 Ωm) inbetween conductors and insulators e.g. germanium, silicon, selenium, carbon etc.*

### 2.1 Properties of Semiconductors

**(*i*)** The resistivity of a semiconductor is less than an insulator but more than a conductor.
**(*ii*)** Semiconductors have *negative temperature co-efficient of resistance* *i.e.* the resistance of a semiconductor decreases with the increase in temperature and *vice-versa*. For example, germanium is actually an insulator at low temperatures but it becomes a good conductor at high temperatures.
**(*iii*)** When a suitable metallic impurity (*e.g.* arsenic, gallium etc.) is added to a semiconductor, its current conducting properties change appreciably.

### 2.2 Bonds in Semiconductors

In semiconductors, bonds are formed by sharing of valence electrons. Such bonds are called *co-valent bonds.* In the formation of a co-valent bond, each atom contributes equal number of valence electrons and the contributed electrons are shared by the atoms engaged in the formation of the bond.

(i) Each neighbouring atom shares one valence electron with the central atom. In this business of sharing, the central atom completes its last orbit by having 8 electrons revolving around the nucleus. In this way, the central atom sets up co-valent bonds.
(ii) Co-valent bonds are formed by sharing of valence electrons.
(iii) In the formation of co-valent bond, each valence electron of an atom forms direct bond with the valence electron of an adjacent atom. In other words, valence electrons are associated with particular atoms. For this reason, valence electrons in a semiconductor are not free.

### 2.3 Crystals

A substance in which the atoms or molecules are arranged in an orderly pattern is known as a *crystal*. All semi-conductors have crystalline structure. It is clear that each atom is surrounded by neighbouring atoms in a repetitive manner. Therefore, a piece of germanium is generally called germanium crystal.

### 2.4 Commonly Used Semiconductors

There are many semiconductors available, but very few of them have a practical application in electronics. The two most frequently used materials are *germanium* (Ge) and *silicon* (Si). It is because the energy required to break their co-valent bonds (*i.e.* energy required to release an electron from their valence bands) is very small; being about 0.7 eV for germanium and about 1.1 eV for silicon.

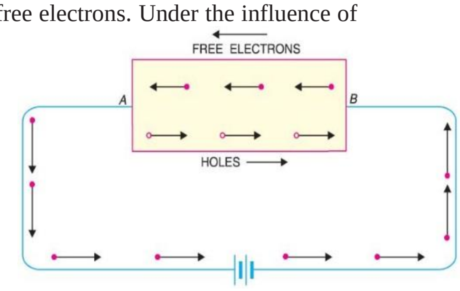
### 2.5 Effect of Temperature on Semiconductors

The electrical conductivity of a semiconductor changes appreciably with temperature variations. This is a very important point to keep in mind.
**(*i*) At absolute zero.** At absolute zero temperature, all the electrons are tightly held by the semiconductor atoms. The inner orbit electrons are bound whereas the valence electrons are engaged in co-valent bonding. At this temperature, the co-valent bonds are very strong and there are no free electrons. Therefore, the semiconductor crystal behaves as a perfect insulator.

**(*ii*) Above absolute zero.** When the temperature is raised, some of the covalent bonds in the semiconductor break due to the thermal energy supplied. The breaking of bonds sets those electrons *free* which are engaged in the formation of these bonds. The result is that a few free electrons exist in the semiconductor. These free electrons can constitute a tiny electric current if potential difference is applied across the semiconductor crystal. *This shows that the resistance of a semiconductor decreases with the rise in temperature i.e.* it has negative temperature coefficient of resistance.

### 2.6 Hole Current

At room temperature, some of the co-valent bonds in pure semiconductor break, setting up free electrons. Under the influence of electric field, these free electrons constitute electric current. At the same time, another current – the hole current – also flows in the semiconductor. When a covalent bond is broken due to thermal energy, the removal of one electron leaves a vacancy *i.e.* a missing electron in the covalent bond. This missing electron is called a *hole which acts as a positive charge. For one electron set free, one hole is created. Therefore, thermal energy creates *hole-electron pairs*;




### 2.7 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 Fig. 5.10. 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. Under the influence of electric field, conduction through the semiconductor is by both free electrons and holes. Therefore, the total current inside the semiconductor is the sum of currents due to free electrons and holes.

## 2.8 Extrinsic Semiconductor

The intrinsic semiconductor has little current conduction capability at room temperature. To be useful in electronic devices, the pure semiconductor must be altered so as to significantly increase its conducting properties. This is achieved by adding a small amount of suitable impurity to a semiconductor. 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 108 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. As we shall see, if a pentavalent impurity (having 5 valence electrons) is added to the semiconductor, a large number of free electrons are produced in the semiconductor. On the other hand, addition of trivalent impurity (having 3 valence electrons) creates a large number of holes in the semiconductor crystal. Depending upon the type of impurity added, extrinsic semiconductors are classified into:

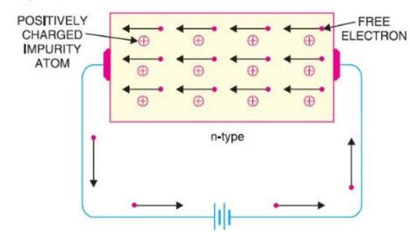
***(i) n*-type semiconductor** ***(ii) p*-type semiconductor**

### *(i) n*-type Semiconductor

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

When a small amount of pentavalent impurity like arsenic is added to germanium crystal, a large number of free electrons become available in the crystal. The reason is simple. Arsenic is pentavalent *i.e.* its atom has five valence electrons. An arsenic atom fits in the germanium crystal in such a way that its four valence electrons form covalent bonds with four germanium atoms. Therefore, for each arsenic atom added, one free electron will be available in the germanium crystal. Though each arsenic atom provides one free electron, yet an extremely small amount of arsenic impurity provides enough atoms to supply millions of free electrons.

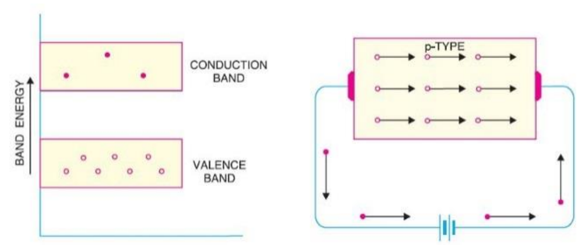
**n-type conductivity.** The current conduction in an *n*-type semiconductor is *predominantly* by free electrons *i.e.* negative charges and is called *n-type* or *electron type conductivity*. When p.d. is applied across the *n*-type semiconductor, the free electrons (donated by impurity) in the crystal will be directed towards the positive terminal, constituting electric current. As the current flow through the crystal is by free electrons which are carriers of negative charge, therefore, this type of conductivity is called negative or *n*-type conductivity. It may be noted that conduction is just as in ordinary metals like copper.




### (ii) *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. Typical examples of trivalent impurities are *gallium* (At. No. 31) and *indium* (At. No. 49). Such impurities which produce *p*-type semiconductor are known as *acceptor impurities* because the holes created can accept the electrons.

**p-type conductivity.** The current conduction in *p*-type semiconductor is predominantly by holes *i.e.* positive charges and is called *p-type* or *hole-type conductivity*. When *p.d.* is applied to the *p*-type semiconductor, the holes (donated by the impurity) are shifted from one co-valent bond to another. As the holes are positively charged, therefore, they are directed towards the negative terminal, constituting what is known as hole current. It may be noted that in *p*-type conductivity, the valence electrons move from one co-valent bond to another unlike the *n*-type where current conduction is by free electrons.




## 2.9 Charge on *n*-type and *p*-type Semiconductors

In *n*-type semiconductor, current conduction is due to excess of electrons whereas in a *p*-type semiconductor, conduction is by holes. It is true that *n*-type semiconductor has excess of electrons but these extra electrons were supplied by the atoms of donor impurity and each atom of donor impurity is electrically neutral. When the impurity atom is added, the term "excess electrons" refers to an excess with regard to the number of electrons needed to fill the co-valent bonds in the semiconductor crystal. The extra electrons are free electrons and increase the conductivity of the semiconductor. The situation with regard to *p*-type semiconductor is also similar. *It follows, therefore, that n-type as well as p-type semiconductor is electrically neutral.*

## 2.10 Majority and Minority Carriers

It has already been discussed that due to the effect of impurity, *n*-type material has a large number of free electrons whereas *p*- type material has a large number of holes. However, it may be recalled that even at room temperature, some of the co-valent bonds break, thus releasing an equal number of free electrons and holes. An *n*-type material has its share of electron-hole pairs (released due to breaking of bonds at room temperature) but in addition has a much larger quantity of free electrons due to the effect of impurity. These impurity-caused free electrons are not associated with holes. Consequently, an *n*-type material has a large number of free electrons and a small number of holes as shown in Fig. 2.3 (*i*). 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 the *minority carriers.*

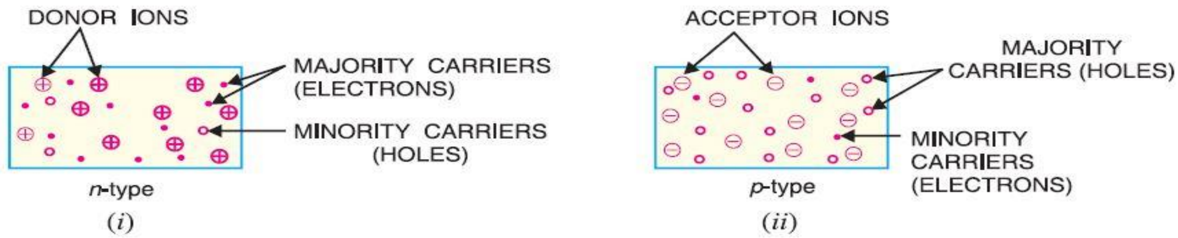



Fig. 2.3

## 2.11 *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.

## 2.12 Properties of *pn* Junction

At the instant of *pn*-junction formation, the free electrons near the junction in the *n* region begin to diffuse across the junction into the *p* region where they combine with holes near the junction. The result is that *n* region loses free electrons as they diffuse into the junction. This creates a layer of positive charges (pentavalent ions) near the junction. As the electrons move across the junction, the *p* region loses holes as the electrons and holes combine. The result is that there is a layer of negative charges (trivalent ions) near the junction. These two layers of positive and negative charges form the *depletion region* (or *depletion layer*). The term depletion is due to the fact that near the junction, the region is depleted (*i.e.* emptied) of *charge carries* (free electrons and holes) due to diffusion across the junction. It may be noted that depletion layer is formed very quickly and is very thin compared to the *n* region and the *p* region.

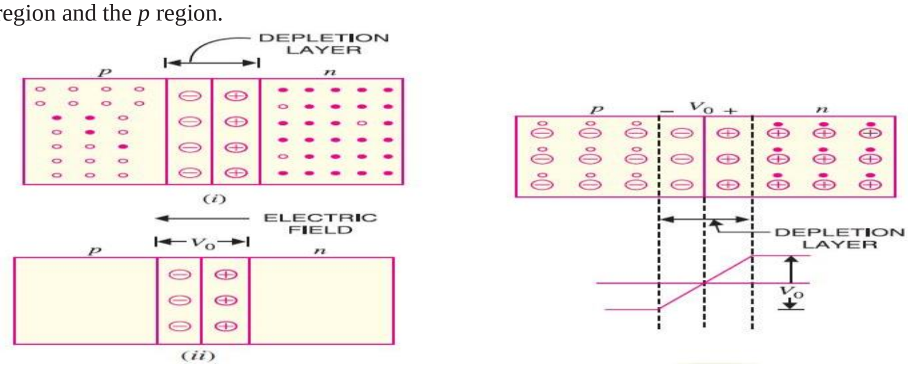



Fig. 2.4

Once *pn*-junction is formed and depletion layer created, the diffusion of free electrons stops. In other words, the depletion region acts as a barrier to the further movement of free electrons across the junction. The positive and negative charges set up an electric field. This is shown by a black arrow in Fig. 2.4 (ii). The electric field is a barrier to the free electrons in the *n*-region. There exists a potential difference across the depletion layer and is called **barrier potential** ($V_0$). The barrier potential of a *pn*-junction depends upon several factors including the type of semiconductor material, the amount of doping and temperature. The typical barrier potential is approximately: For silicon, $V_0$= 0.7 V ; For germanium, $V_0$ = 0.3 V. Fig. 2.4 (iii) shows the potential $V_0$ distribution curve.

## 2.13 Applying D.C. Voltage Across *pn*-Junction or Biasing a pn Junction

In electronics, the term bias refers to the use of d.c. voltage to establish certain operating conditions for an electronic device. In relation to a *pn* junction, there are following two bias conditions :

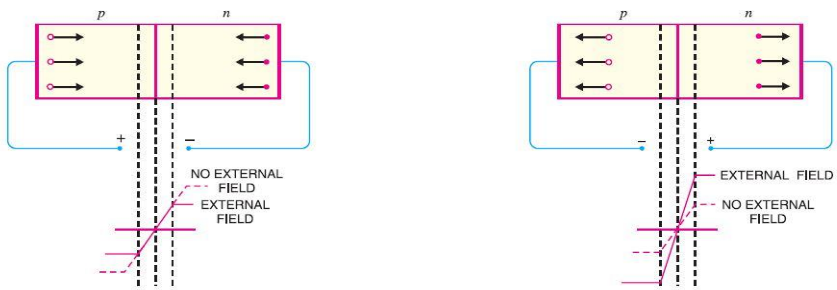
**(1) Forward biasing** **(2) Reverse biasing**

**(1) Forward biasing.** *When external d.c. 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.** With forward bias to *pn* junction, the following points are worth noting;

***(i)*** The potential barrier is reduced and at some forward voltage (0.1 to 0.3 V), it is eliminated altogether.

***(ii)*** The junction offers low resistance (called *forward resistance*, $R_f$) to current flow.

***(iii)*** Current flows in the circuit due to the establishment of low resistance path. The magnitude of current depends upon the applied forward voltage.




**(i)** **(ii)**

**Fig. 2.5**

**2. Reverse biasing.** *When the external d.c. voltage applied to the junction is in such a direction that potential barrier is increased, it is called* **reverse biasing.** With reverse bias to *pn*-junction, the following points are worth noting :

(i) The potential barrier is increased.

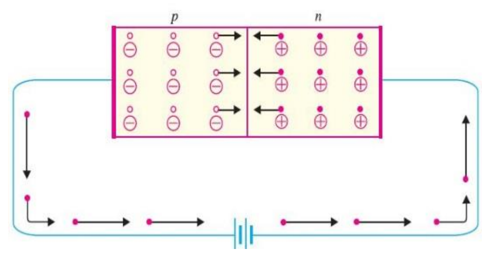
***ii*)** The junction offers very high resistance (called *reverse resistance, Rr*) to current flow.

**(*iii*)** No current flows in the circuit due to the establishment of high resistance path.

**Conclusion.** From the above discussion, it follows that with reverse bias to the junction, a high resistance path is established and hence no current flow occurs. On the other hand, with forward bias to the junction, a low resistance path is set up and hence current flows in the circuit.

### 2.14 Current Flow in a Forward Biased pn Junction

We shall now see how current flows across *pn* junction when it is forward biased. 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. As the free electrons reach the junction, they become **valence electrons. 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 electrons reach the left end of the crystal, they flow into the positive terminal of the battery. The mechanism of current flow in a forward biased *pn* junction can be summed up as under :




**(*i*)** 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.

**(*ii*)** The electrons travel through the *n*-region as free-electrons *i.e.* current in *n*-region is by free electrons.

**(*iii*)** When these electrons reach the junction, they combine with holes and become valence electrons.

**(*iv*)** The electrons travel through *p*-region as valence electrons *i.e.* current in the *p*-region is by holes.

**(*v*)** When these valence electrons reach the left end of crystal, they flow into the positive terminal of the battery. From the above discussion, it is concluded that in *n*-type region, current is carried by free electrons whereas in *p*-type region, it is carried by holes. However, in the external connecting wires, the current is carried by free electrons.

### 5.19 Important Terms

Two important terms often used with *pn* junction (*i.e.* crystal diode) are *breakdown voltage* and *knee voltage*. We shall now explain these two terms in detail.

**(*i*) Breakdown voltage.** *It is the minimum reverse voltage at which pn junction breaks down with sudden rise in reverse current*.

**(*ii*) Knee voltage.** *It is the forward voltage at which the current through the junction starts to increase rapidly*.

### 5.20 Limitations in the Operating Conditions of *pn* Junction

Every *pn* junction has limiting values of *maximum forward current, peak inverse voltage* and *maximum power rating*. The *pn* junction will give satisfactory performance if it is operated within these limiting values. However, if these values are exceeded, the *pn* junction may be destroyed due to excessive heat.

**(*i*)** *Maximum forward current*. It is the highest instantaneous forward current that a *pn* junction can conduct without damage to the junction. Manufacturer's data sheet usually specifies this rating. If the forward current in a *pn* junction is more than this rating, the junction will be destroyed due to overheating.

**(*ii*)** *Peak inverse voltage (PIV)*. It is the maximum reverse voltage that can be applied to the *pn* junction without damage to the junction. If the reverse voltage across the junction exceeds its PIV, the junction may be destroyed due to excessive heat.

**(*iii*)** *Maximum power rating.* It is the maximum power that can be dissipated at the junction without damaging it. The power dissipated at the junction is equal to the product of junction current and the voltage across the junction. This is a very important consideration and is invariably specified by the manufacturer in the data sheet.

## 3.0 SEMICONDUCTOR DIODE

*A pn junction is known as a* **semi-conductor** *or* *** crystal diode**.


Fig. 3.1

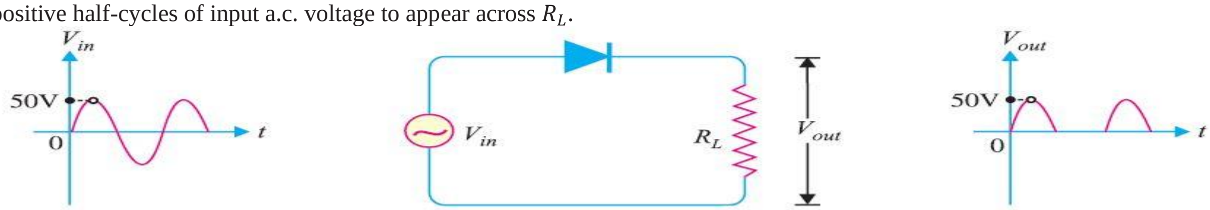
The outstanding property of a crystal diode to conduct current in one direction only permits it to be used as a rectifier. A crystal diode is usually represented by the schematic symbol shown in Fig. 3.1. The arrow in the symbol indicates the direction of easier conventional current flow. A crystal diode has two terminals. When it is connected in a circuit, one thing to decide is whether the diode is forward or reverse biased. If the external circuit is trying to push the conventional current in the direction of arrow, the diode is forward biased. On the other and, if the conventional current is trying to flow opposite to arrowhead, the diode is reverse biased. Putting in simple words :

**(*i*)** If *arrowhead* of diode symbol is *positive w.r.t. bar* of the symbol, the diode is forward biased.

**(*ii*)** If the *arrowhead* of diode symbol is *negative w.r.t. bar*, the diode is reverse biased.

### 3.1 Crystal Diode as a Rectifier

Fig. 3.2 illustrates the rectifying action of a crystal diode. The a.c. input voltage to be rectified, the diode and load $R_L$ are connected in series. The d.c. output is obtained across the load as explained in the following discussion. During the positive half-cycle of a.c. input voltage, the arrowhead becomes positive *w.r.t.* bar. Therefore, diode is forward biased and conducts current in the circuit. The result is that positive half-cycle of input voltage appears across $R_L$ as shown. However, during the negative half-cycle of input a.c. voltage, the diode becomes reverse biased because now the arrowhead is negative *w.r.t.* bar. Therefore, diode does not conduct and no voltage appears across load $R_L$. The result is that output consists of positive half-cycles of input a.c. voltage while the negative half-cycles are suppressed. In this way, crystal diode has been able to do rectification i.e. change a.c. into d.c. It may be seen that output across $R_L$ is pulsating d.c. It is interesting to see that behaviour of diode is like a *switch.* When the diode is forward biased, it behaves like a closed switch and connects the a.c. supply to the load $R_L$. However, when the diode is reverse biased, it behaves like an open switch and disconnects the a.c. supply from the load *RL*. This switching action of diode permits only the positive half-cycles of input a.c. voltage to appear across $R_L$.




**(i)** **(ii)** **(iii)**

**Fig. 3.2**

### 3.2 Equivalent Circuit of Crystal Diode

It is generally profitable to replace a device or system by its equivalent circuit. An equivalent circuit of a device (*e.g.* crystal diode, transistor etc.) is a combination of electric elements, which when connected in a circuit, acts exactly as does the device when connected in the same circuit. Once the device is replaced by its equivalent circuit, the resulting network can be solved by traditional circuit analysis techniques. We shall now find the equivalent circuit of a crystal diode.

**(*i*) Approximate Equivalent circuit.** When the forward voltage $V_F$ is applied across a diode, it will not conduct till the potential barrier $V_0$ at the junction is overcome. When the forward voltage exceeds the potential barrier voltage, the diode starts conducting as shown in Fig. 3.3 (*i*). The forward current $I_f$ flowing through the diode causes a voltage drop in its internal resistance $r_f$ . Therefore, the forward voltage $V_F$ applied across the *actual* diode has to overcome :

**(*a*)** potential barrier $V_0$

**(*b*)** internal drop $I_f r_f$

$\because \qquad V_F = V_0 + I_f r_f$

For a silicon diode, $V_0$ = 0.7 V whereas for a germanium diode, $V_0$ = 0.3 V.

Therefore, approximate equivalent circuit for a crystal diode is a switch in series with a battery $V_0$ and internal resistance $r_f$ as shown in Fig. 3.3 (*ii*). This approximate equivalent circuit of a diode is very helpful in studying the performance of the diode in a circuit.

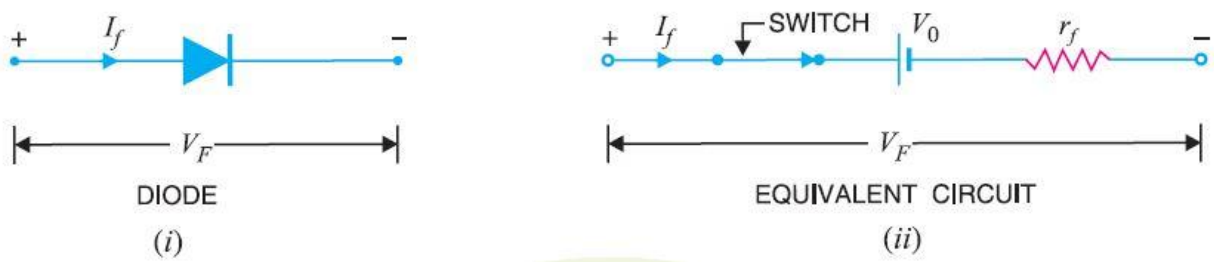



**Fig. 3.3**

**(*ii*) Simplified Equivalent circuit.** For most applications, the internal resistance $r_f$ of the crystal diode can be ignored in comparison to other elements in the equivalent circuit. The equivalent circuit then reduces to the one shown in Fig. 3.4 (*ii*). This simplified equivalent circuit of the crystal diode is frequently used in diode-circuit analysis.


**Fig. 3.4**

**(*iii*) Ideal diode model.** An ideal diode is one which behaves as a perfect conductor when forward biased and as a perfect insulator when reverse biased. Obviously, in such a hypothetical situation, forward resistance $r_f$ = 0 and potential barrier $V_0$ is considered negligible. It may be mentioned here that although ideal diode is never found in practice, yet diode circuit analysis is made on this basis.

### 3.3 Crystal Diode Rectifiers

For reasons associated with economics of generation and transmission, the electric power available is usually an a.c. supply. The supply voltage varies sinusoidally and has a frequency of 50 Hz. It is used for lighting, heating and electric motors. But there are many applications (*e.g*. electronic circuits) where d.c. supply is needed. When such a d.c. supply is required, the mains a.c. supply is rectified by using crystal diodes. The following two rectifier circuits can be used :

(1) Half-wave rectifier (*2*) Full-wave rectifier

### (1) Half-Wave Rectifier

In half-wave rectification, the rectifier conducts current only during the positive half-cycles of input a.c. supply. The negative half-cycles of a.c. supply are suppressed *i.e.* during negative half-cycles, no current is conducted and hence no voltage appears across the load. Therefore, current always flows in one direction (*i.e*. d.c.) through the load though after every half-cycle.

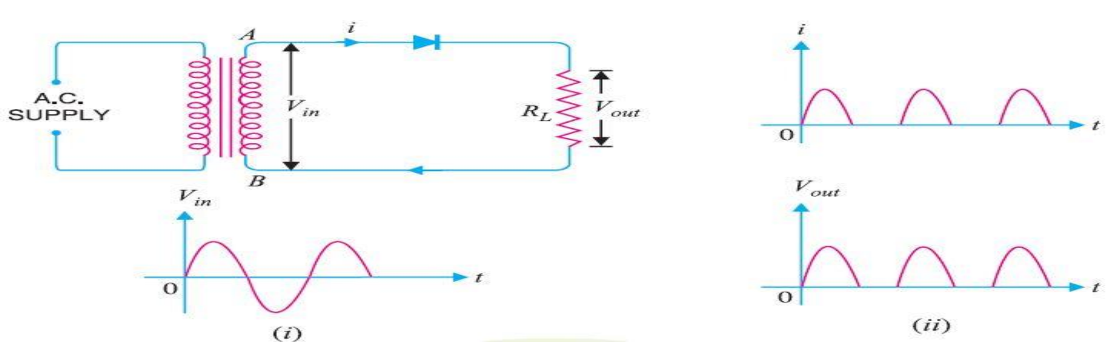



Fig. 3.5

**Circuit details.** Fig. 3.5 shows the circuit where a single crystal diode acts as a half-wave rectifier. The a.c. supply to be rectified is applied in series with the diode and load resistance $R_L$. Generally, a.c. supply is given through a transformer. The use of transformer permits two advantages. Firstly, it allows us to step up or step down the a.c. input voltage as the situation demands. Secondly, the transformer isolates the rectifier circuit from power line and thus reduces the risk of electric shock.

**Operation.** The a.c. voltage across the secondary winding *AB* changes polarities after every half-cycle. During the positive half-cycle of input a.c. voltage, end *A* becomes positive *w.r.t.* end *B*. This makes the diode forward biased and hence it conducts current. During the negative half-cycle, end *A* is negative *w.r.t.* end *B*. Under this condition, the diode is reverse biased and it conducts no current. Therefore, current flows through the diode during positive half-cycles of input a.c. voltage only ; it is blocked during the negative half-cycles [See Fig. 3.5 (*ii*)]. In this way, current flows through load $R_L$ always in the same direction. Hence d.c. output is obtained across $R_L$. It may be noted that output across the load is pulsating d.c. These pulsations in the output are further smoothened with the help of *filter circuits*.

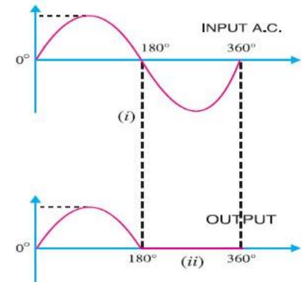
**Disadvantages :** The main disadvantages of a half-wave rectifier are :

I. The pulsating current in the load contains alternating component whose basic frequency is equal to the supply frequency. Therefore, an elaborate filtering is required to produce steady direct current.

II. The a.c. supply delivers power only half the time. Therefore, the output is low.

**Output Frequency of Half-Wave Rectifier**

The output frequency of a half-wave rectifier is equal to the input frequency (50 Hz). A waveform has a complete cycle when it repeats the same wave pattern over a given time. Thus in Fig. 3.5 (*i*), the a.c. input voltage repeats the same wave pattern over 0° – 360°, 360° – 720° and so on. In Fig. 3.5 (*ii*), the output waveform also repeats the same wave pattern over 0° – 360°, 360° – 720° and so on. This means that when input a.c. completes one cycle, the output half-wave rectified wave also completes one cycle. In other words, the output frequency is equal to the input frequency *i.e. fout = fin*




For example, if the input frequency of sine wave applied to a half-wave rectifier is 100 Hz, then frequency of the output wave will also be 100 Hz.

**Efficiency of Half-Wave Rectifier**

*The ratio of d.c. power output to the applied input a.c. power is known as* **rectifier efficiency**

*i.e.* Rectifier efficiency, $\eta = \frac{\text{d.c power output}}{\text{Input a.c. power}}$

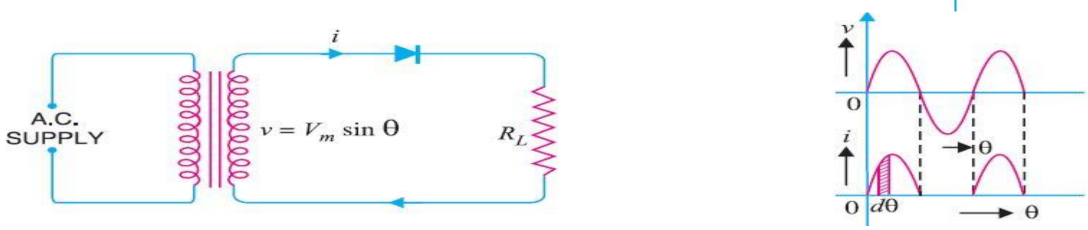



Fig. 3.7

Consider a half-wave rectifier shown in Fig. 3.7. Let $v = V_m \sin\theta$ be the alternating voltage that appears across the secondary winding. Let $r_f$ and $R_L$ be the diode resistance and load resistance respectively. The diode conducts during positive half-cycles of a.c. supply while no current conduction takes place during negative half-cycles.

**d.c. power.** The output current is pulsating direct current. Therefore, in order to find d.c. power, average current has to be found out.

$$\text{d.c. power, } P_{dc} = I_{dc}^2 \times R_L = \left(\frac{I_m}{\pi}\right)^2 \times R_L$$

**a.c. power input :** The a.c. power input is given by : $P_{ac} = I_{rms}^2 (r_f + R_L)$

For a half-wave rectified wave, $I_{rms} = I_m/2$ , $\Longrightarrow P_{ac} = \left(\frac{I_m}{2}\right)^2 \times (r_f + R_L)$

Rectifier efficiency $= \frac{d.c.\ output\ power}{a.c.\ input\ power} = \frac{(I_m/\pi)^2 \times R_L}{(I_m/2)^2 (r_f + R_L)} = \frac{0.406\, R_L}{r_f + R_L} = \frac{0.406}{1 + \frac{r_f}{R_L}}$

The efficiency will be maximum if $r_f$ is negligible as compared to $R_L$ .

∴ Max. rectifier efficiency = 40.6%

This shows that in half-wave rectification, a maximum of 40.6% of a.c. power is converted into d.c. power.

**Example 1:** *A half-wave rectifier is used to supply 50V d.c. to a resistive load of 800 Ω. The diode has a resistance of 25 Ω. Calculate a.c. voltage required.*

Solution:

Output d.c. voltage, $V_{dc} = 50\,V$.  Diode resistance, $r_f = 25\ \Omega$.  Load resistance, $R_L = 800\ \Omega$

Let $V_m$ be the maximum value of a.c. voltage required.

∵ $V_{dc} = I_{dc} \times R_L = \frac{I_m}{\pi} \times R_L = \frac{V_m}{\pi(r_f + R_L)} \times R_L$  $\left[\because I_m = \frac{V_m}{r_f + R_L}\right]$

Or $50 = \frac{V_m}{\pi(25+800)} \times 800$  ∴ $V_m = \frac{\pi \times 825 \times 50}{800} = 162\,V$

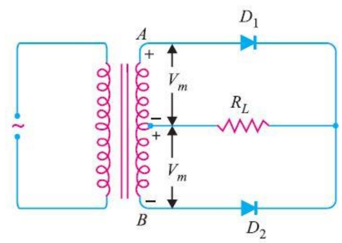
Hence a.c. voltage of maximum value 162 V is required.

(2) Full-Wave Rectifier

In full-wave rectification, current flows through the load in the same direction for both half-cycles of input a.c. voltage. This can be achieved with two diodes working alternately. For the positive half-cycle of input voltage, one diode supplies current to the load and for the negative half-cycle, the other diode does so ; current being always in the same direction through the load. Therefore, a full-wave rectifier utilises both half-cycles of input a.c. voltage to produce the d.c. output. The following two circuits are commonly used for full-wave rectification :

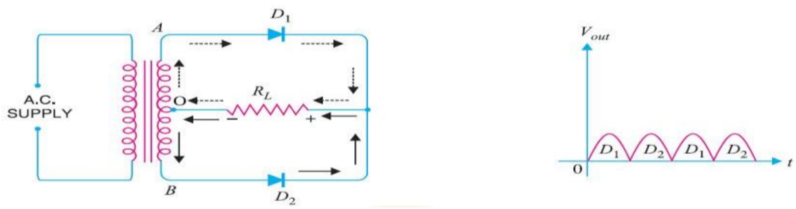
(i) Centre-tap full-wave rectifier (*ii*) Full-wave bridge rectifier

(i) Centre-Tap Full-Wave Rectifier




The circuit employs two diodes $D_1$ and $D_2$ as shown in Fig. 3.8. A centre tapped secondary winding *AB* is used with two diodes connected so that each uses one half-cycle of input a.c. voltage. In other words, diode $D_1$ utilises the a.c. voltage appearing across the upper half (*OA*) of secondary winding for rectification while diode $D_2$ uses the lower half winding *OB*.

**Operation.** During the positive half-cycle of secondary voltage, the end *A* of the secondary winding becomes positive and end *B* negative. This makes the diode $D_1$ forward biased and diode $D_2$ reverse biased. Therefore, diode $D_1$ conducts while diode $D_2$ does not. The conventional current flow is through diode $D_1$, load resistor *RL* and the upper half of secondary winding as shown by the dotted arrows. During the negative half-cycle, end *A* of the secondary winding becomes negative and end *B* positive. Therefore, diode $D_2$ conducts while diode $D_1$ does not. The conventional current flow is through diode $D_2$, load $R_L$ and lower half winding as shown by solid arrows. Referring to Fig. 3.9, it may be seen that current in the load $R_L$ is *in the same direction* for both half-cycles of input a.c. voltage. Therefore, d.c. is obtained across the load $R_L$. Also, the polarities of the d.c. output across the load should be noted.




(i) (ii)

**Fig. 3.9**

**Peak inverse voltage.** Suppose $V_m$ is the maximum voltage across the half secondary winding. Fig. 6.25 shows the circuit at the instant secondary voltage reaches its maximum value in the positive direction. At this instant, diode $D_1$ is conducting while diode $D_2$ is non-conducting. Therefore, whole of the secondary voltage appears across the non-conducting diode. Consequently, the peak inverse voltage is twice the maximum voltage across the half-secondary winding *i.e.* PIV = 2 $V_m$

**Disadvantages**

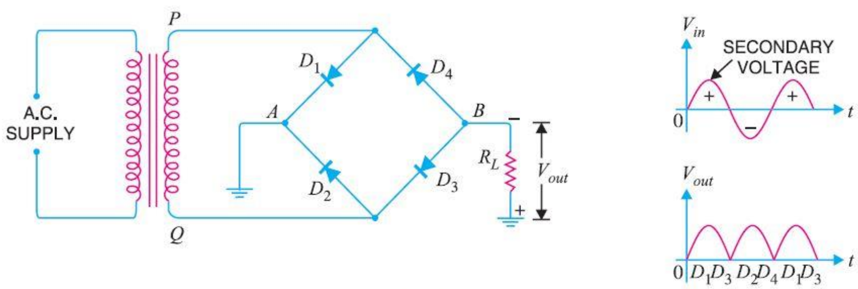
**(a)** It is difficult to locate the centre tap on the secondary winding.

**(b)** The d.c. output is small as each diode utilises only one-half of the transformer secondary voltage.

(c) The diodes used must have high peak inverse voltage.

**(i). Full-Wave Bridge Rectifier**

The need for a centre tapped power transformer is eliminated in the bridge rectifier. It contains four diodes $D_1, D_2, D_3$ and $D_4$ connected to form bridge as shown in Fig. 3.10. The a.c. supply to be rectified is applied to the diagonally opposite ends of the bridge through the transformer. Between other two ends of the bridge, the load resistance $R_l$ is connected.




(i) (ii)

**Fig. 3.10**

**Operation.** During the positive half-cycle of secondary voltage, the end *P* of the secondary winding becomes positive and end *Q* negative. This makes diodes $D_1$ and $D_3$ forward biased while diodes $D_2$ and $D_4$ are reverse biased. Therefore, only diodes $D_1$ and

$D_3$ conduct. These two diodes will be in series through the load $RL$ as shown in Fig. 3.11 (*i*). The conventional current flow is shown by dotted arrows. It may be seen that current flows from $A$ to $B$ through the load $RL$ . During the negative half-cycle of secondary voltage, end $P$ becomes negative and end $Q$ positive. This makes diodes $D_2$ and $D_4$ forward biased whereas diodes $D_1$ and $D_3$ are reverse biased. Therefore, only diodes $D_2$ and $D_4$ conduct. These two diodes will be in series through the load $R_L$ as shown in Fig. 3.11 (*ii*). The current flow is shown by the solid arrows. It may be seen that again current flows from $A$ to $B$ through the load *i.e.* in the same direction as for the positive half-cycle. Therefore, d.c. output is obtained across load $R_L$.

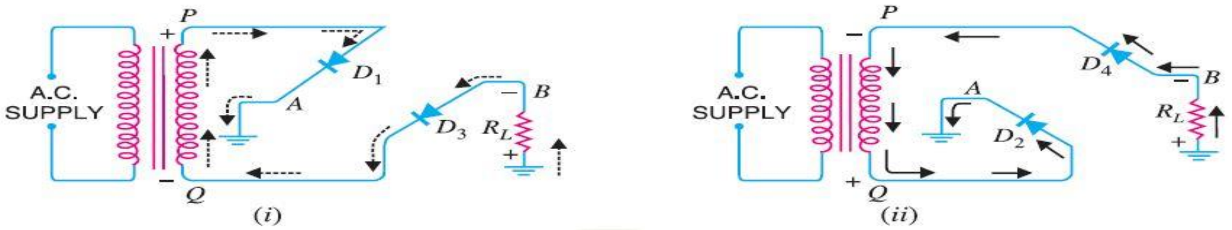



**Fig. 3.11**

**Peak inverse voltage.** The peak inverse voltage (PIV) of each diode is equal to the maximum secondary voltage of transformer. Suppose during positive half cycle of input a.c., end $P$ of secondary is positive and end $Q$ negative. Under such conditions, diodes $D_1$ and $D_3$ are forward biased while diodes $D_2$ and $D_4$ are reverse biased. Since the diodes are considered ideal, diodes $D_1$ and $D_3$ can be replaced by wires as shown in Fig. 3.12 (*i*). This circuit is the same as shown in Fig. 3.12 (*ii*).

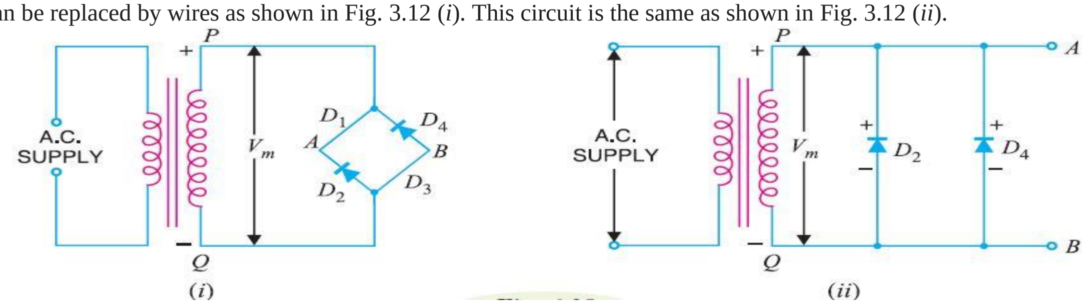



Fig. 3.12

Referring to Fig. 3.12 (*ii*), it is clear that two reverse biased diodes (*i.e.*, $D_2$ and $D_4$) and the secondary of transformer are in parallel. Hence PIV of each diode ($D_2$ and $D_4$) is equal to the maximum voltage ($V_m$) across the secondary. Similarly, during the next half cycle, $D_2$ and $D_4$ are forward biased while $D_1$ and $D_3$ will be reverse biased. It is easy to see that reverse voltage across $D_1$ and $D_3$ is equal to $V_m$.

**Advantages**

**(a)** The need for centre-tapped transformer is eliminated.

**(b)** The output is twice that of the centre-tap circuit for the same secondary voltage.

**(c)** The PIV is one-half that of the centre-tap circuit (for same d.c. output).

**Disadvantages**

(a). It requires four diodes.

***(b)*** As during each half-cycle of a.c. input two diodes that conduct are in series, therefore, voltage drop in the internal resistance of the rectifying unit will be twice as great as in the centre tap circuit. This is objectionable when secondary voltage is small.

**Output Frequency of Full-Wave Rect ifier**

The output frequency of a full-wave rectifier is double the input frequency. Remember that a wave has a complete cycle when it repeats the same pattern. In Fig. 3.12 (*i*), the input a.c. completes one cycle from 0° – 360°. However, the full-wave rectified wave completes 2 cycles in this period [See Fig. 3.12 (*ii*)]. Therefore, output frequency is twice the input frequency *i.e.*

$f_{out} = 2f_{in}$

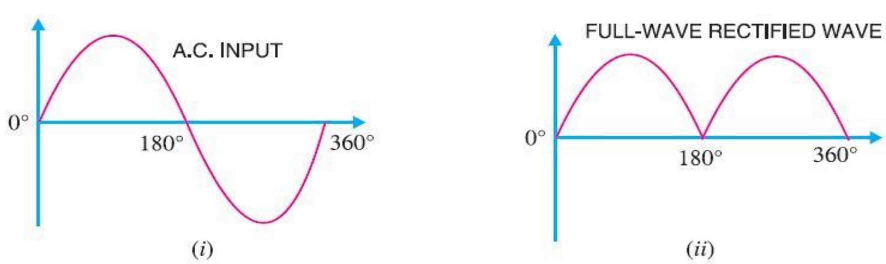



**Fig. 3.13**

### Efficiency of Full-Wave Rectifier

Let $v = V_m \sin\theta$ be the a.c. voltage to be rectified. Let $r_f$ and $R_L$ be the diode resistance and load resistance respectively. Obviously, the rectifier will conduct current through the load in the same direction for both half-cycles of input a.c. voltage. The instantaneous current $i$ is given by

$$i = \frac{v}{r_f + R_L} = \frac{V_m \sin\theta}{r_f + R_L}$$

**d.c. output power.** The output current is pulsating direct current. Therefore, in order to find the d.c. power, average current has to be found out.

$$I_{dc} = \frac{2I_m}{\pi}$$

∴ d.c. power output, $P_{dc} = I_{dc}^2 \times R_L = \left(\frac{2I_m}{\pi}\right)^2 \times R_L$

**a.c. input power.** The a.c. input power is given by :

$$P_{ac} = I_{rms}^2(r_f + R_L)$$

For a full-wave rectified wave, we have,

$I_{rms} = I_m/\sqrt{2}$

∴ $\qquad P_{ac} = \left(\frac{I_m}{\sqrt{2}}\right)^2 (r_f + R_L)$

Full-wave rectification efficiency is

$\eta = \frac{P_{dc}}{P_{ac}} = \frac{(2I_m/\pi)^2 R_L}{\left(\frac{I_m}{\sqrt{2}}\right)^2 (r_f+R_L)} = \frac{8}{\pi^2} \times \frac{R_L}{(r_f+R_L)} = \frac{0.812R_L}{r_f+R_L} = \frac{0.812}{1+\frac{r_f}{R_L}}$

The efficiency will be maximum if $r_f$ is negligible as compared to $R_L$.

∴ Maximum efficiency = 81.2%

This is double the efficiency due to half-wave rectifier. Therefore, a full-wave rectifier is twice as effective as a half-wave rectifier.

**Example 2**. *A full-wave rectifier uses two diodes, the internal resistance of each diode may be assumed constant at 20 Ω. The transformer r.m.s. secondary voltage from centre tap to each end of secondary is 50 V and load resistance is 980 Ω. Find:*

*(i). the mean load current (ii) the r.m.s. value of load current*

**Solution: Given** $r_f = 20\,\Omega$, $\quad R_L = 980\,\Omega$

*Max. a.c. voltage,* $V_m = 50 \times \sqrt{2} = 70.7\ V$

*Max. load current,* $I_m = \frac{V_m}{r_f+R_L} = \frac{70.7\ V}{(20+980)\Omega} = 70.7\ mA$

*(i)* *Mean load current,* $I_{dc} = \frac{2I_m}{\pi} = \frac{2\times 70.7}{\pi} = 45\ mA$

*(ii)* *R.M.S. value of load current is* $I_{rms} = \frac{I_m}{\sqrt{2}} = \frac{70.7}{\sqrt{2}} = 50\ mA$

**Example 3**: *The four diodes used in a bridge rectifier circuit have forward resistances which may be considered constant at 1Ω and infinite reverse resistance. The alternating supply voltage is 240 V r.m.s. and load resistance is 480 Ω. Calculate (i) mean load current and (ii) power dissipated in each diode.*

**Solution**:

Max. a.c. voltage, $V_m = 240 \times \sqrt{2}$ V

(i) At any instant in the bridge rectifier, two diodes in series are conducting. Therefore, total circuit resistance $= 2r_f + R_L$.

Max. load current, $I_m = \frac{V_m}{2r_f+R_L} = \frac{240\times\sqrt{2}}{2\times 1+480} = 0.7\ A$

∴ $\quad Mean\ load\ current, I_{dc} = \frac{2I_m}{\pi} = \frac{2\times 0.7}{\pi} = 0.45\ A$

(ii) Since each diode conducts only half a cycle, diode r.m.s current is:

(iii) $I_{r.m.s} = I_m/2 = 0.7/2 = 0.35\ A$

Thus, Power dissipated in each diode $= I_{r.m.s}^2 \times r_f = (0.35)^2 \times 1 = 0.123\ W$

### 3.4 Special-Purpose Diodes

A number of specific types of diodes are manufactured for specific applications in this fast developing world. Some of the more common special-purpose diodes are:

(*i*) Zener diode (*ii*) Light-emitting diode (LED) (*iii*) Photo-diode (*iv*) Tunnel diode (*v*) Varactor diode and (*vi*) Shockley diode.

**(i) Zener Diode** is a special type of diode that is designed to operate in the reverse breakdown region. An ordinary diode operated in this region will usually be destroyed due to excessive current. This is not the case for the zener diode. A zener diode is heavily doped to reduce the reverse breakdown voltage. This causes a very thin depletion layer. As a result, a zener diode has a sharp reverse breakdown voltage *VZ*. Note that the reverse characteristic drops in an almost vertical manner at reverse voltage *VZ*. As the curve reveals, two things happen when *VZ* is reached :

**(*a*)** The diode current increases rapidly.

**(b)** The reverse voltage *VZ* across the diode remains almost constant.

In other words, *the zener diode operated in this region will have a relatively constant voltage across it, regardless of the value of current through the device.* This permits the zener diode to be used as a *voltage regulator.*

**(ii) light-emitting diode (LED)** *is a diode that gives off visible light when forward biased.* Light-emitting diodes are not made from silicon or germanium but are made by using elements like gallium, phosphorus and arsenic. By varying the quantities of these elements, it is possible to produce light of different wavelengths with colours that include red, green, yellow and blue.

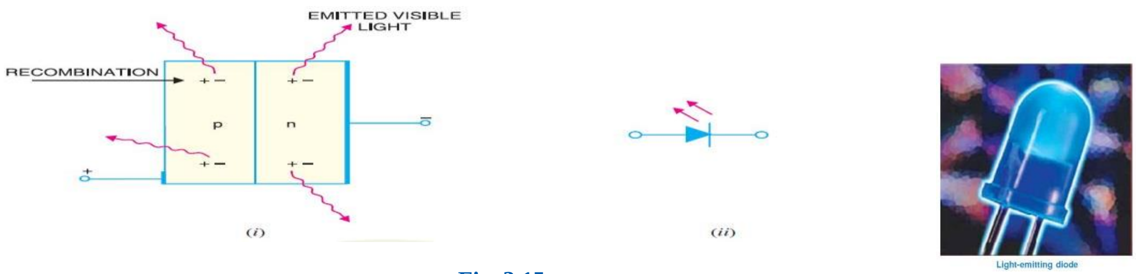



**Fig. 3.15**

Advantages of LED

The light-emitting diode (LED) is a solid-state light source. LEDs have replaced incandescent lamps in many applications because they have the following advantages :

(a) Low voltage

(b) Longer life (more than 20 years)

(c) Fast on-off switching

**(iii). Photo-diode** *is a reverse-biased silicon or germanium pn junction in which reverse current increases when the junction is exposed to light*.


Fig. 3.6

The reverse current in a photo-diode is directly proportional to the intensity of light falling on its *pn* junction. This means that greater the intensity of light falling on the *pn* junction of photo-diode, the greater will be the reverse current. **Principle.** When a rectifier diode is reverse biased, it has a very small reverse leakage current. The same is true for a photo-diode. The reverse current is produced by thermally generated electron-hole pairs which are swept across the junction by the electric field created by the reverse voltage. In a rectifier diode, the reverse current increases with temperature due to an increase in the number of electron-hole pairs. *A photo-diode differs from a rectifier diode in that when its pn junction is exposed to light, the reverse current increases with the increase in light intensity and vice-versa*.

This is explained as follows. When light (photons) falls on the *pn* junction, the energy is imparted by the photons to the atoms in the junction. This will create more free electrons (and more holes). These additional free electrons will increase the reverse current. As the intensity of light incident on the *pn* junction increases, the reverse current also increases. In other words, as the incident light intensity increases, the resistance of the device (photo-diode) decreases.

<u>Applications of Photo-diodes</u>

There are a large number of applications of photodiodes. However, we shall give two applications of photodiodes by way of illustration.

**(*i*) Alarm circuit using photo-diode.** Light from a light source is allowed to fall on a photo-diode fitted in the doorway. The reverse current *IR* will continue to flow so long as the light beam is not broken. If a person passes through the door, light beam is broken and the reverse current drops to the dark current level. As a result, an alarm is sounded.
**(*ii*) Counter circuit using photo-diode.** A photodiode may be used to count items on a conveyor belt. In this circuit, a source of light sends a concentrated beam of light across a conveyor to a photo-diode. As the object passes, the light beam is broken, *IR* drops to the dark current level and the count is increased by one.

**Optoisolator** *(also called optocoupler) is a device that uses light to couple a signal from its input (a photoemitter e.g., a LED) to its output (a photodetector e.g., a photo-diode).*

**(iv) Tunnel Diode** *is a pn junction that exhibits negative resistance between two values of forward voltage* (*i.e., between peak-point voltage and valley-point voltage*). A conventional diode exhibits *positive resistance when it is forward biased or reverse biased. However, if a semiconductor junction diode is heavily doped with impurities, it exhibits negative resistance (*i.e.* current decreases as the voltage is increased) in certain regions in the forward direction, Such a diode is called *tunnel diode*.
*The movement of valence electrons from the valence energy band to the conduction band with little or no applied forward voltage is called* **tunneling.** *Valence electrons seem to tunnel through the forbidden energy band.*

**(v) Varactor Diode is** *junction diode which acts as a variable capacitor under changing reverse bias is known as a* ***varactor diode.*** When a *pn* junction is formed, depletion layer is created in the junction area. Since there are no charge carriers within the depletion zone, the zone acts as an insulator. The *p*-type material with holes (considered positive) as majority carriers and *n*-type material with electrons (−ve charge) as majority carriers act as charged plates. Thus the diode may be considered as a capacitor with *n*-region and *p*-region forming oppositely charged plates and with depletion zone between them acting as a dielectric.

**(vi) Shockley Diode** is a *PNPN* device having two terminals. This *device acts as a switch and consists of four alternate *P*-type and *N*-type layers in a single crystal. the Shockley diode is equivalent to three junction diodes connected in series.

## 4.0 TRANSISTOR

*A* **transistor** *consists of two pn junctions formed by *sandwiching either p-type or n-type semiconductor between a pair of opposite types.* Accordingly ; there are two types of transistors, namely;
(*i*) *n-p-n* transistor (*ii*) *p-n-p* transistor
An *n-p-n* transistor is composed of two *n*-type semiconductors separated by a thin section of *p*-type as shown in Fig. 4.1 (*i*). However, a *p-n-p* transistor is formed by two *p*-sections separated by a thin section of *n*-type as shown in Fig. 4.1 (*ii*).


Fig. 4.1

In each type of transistor, the following points may be noted :
**(a)** These are two *pn* junctions. Therefore, a transistor may be regarded as a combination of two diodes connected back to back.
**(b)** There are three terminals, one taken from each type of semiconductor.
**(c)** The middle section is a very thin layer. This is the most important factor in the function of a transistor.

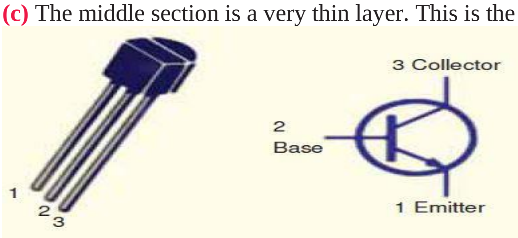



Fig. 4.2

### 4.1 Naming the Transistor Terminals

A transistor (*pnp* or *npn*) has three sections of doped semiconductors. The section on one side is the *emitter* and the section on the opposite side is the *collector*. The middle section is called the *base* and forms two junctions between the emitter and collector.
**(1) Emitter.** The section on one side that supplies charge carriers (electrons or holes) is called the *emitter*. *The emitter is always forward biased w.r.t. base* so that it can supply a large number of *majority carriers. In Fig. 4.3 (*i*), the emitter (*p*-type) of *pnp* transistor is forward biased and supplies hole charges to its junction with the base. Similarly, in Fig. (*ii*), the emitter (*n*-type) of *npn* transistor has a forward bias and supplies free electrons to its junction with the base.

**(*2*) Collector.** The section on the other side that collects the charges is called the *collector*. *The collector is always reverse biased*. Its function is to remove charges from its junction with the base. In Fig. 4.3 (*i*), the collector (*p*-type) of *pnp* transistor has a reverse bias and receives hole charges that flow in the output circuit. Similarly, in Fig. 4.3 (*ii*), the collector (*n*-type) of *npn* transistor has reverse bias and receives electrons.

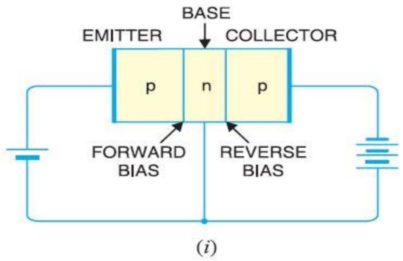



Fig. 4.3

**(*3*) Base.** The middle section which forms two *pn*-junctions between the emitter and collector is called the *base*. The base-emitter junction is forward biased, allowing low resistance for the emitter circuit. The base-collector junction is reverse biased and provides high resistance in the collector circuit.

### 4.2 Some Facts about the Transistor

Before discussing transistor action, it is important that the reader may keep in mind the following facts about the transistor:

***(i)*** The transistor has three regions, namely; *emitter, base* and *collector*. The base is much thinner than the emitter while collector is wider than both as shown in Fig. 8.3. However, for the sake of convenience, it is customary to show emitter and collector to be of equal size.

***(ii)*** The emitter is heavily doped so that it can inject a large number of charge carriers (electrons or holes) into the base. The base is lightly doped and very thin; it passes most of the emitter injected charge carriers to the collector. The collector is moderately doped.

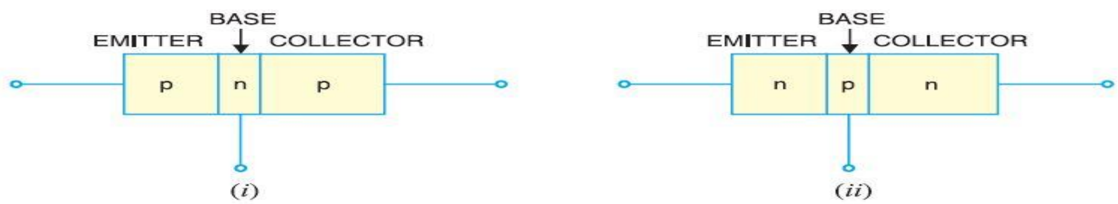



Fig. 4.4

***(iii)*** The transistor has two *pn* junctions *i.e.* it is like two diodes. The junction between emitter and base may be called *emitter-base diode* or simply the *emitter diode*. The junction between the base and collector may be called *collector-base diode* or simply *collector diode*.

***(iv)*** The emitter diode is always forward biased whereas collector diode is always reverse biased.

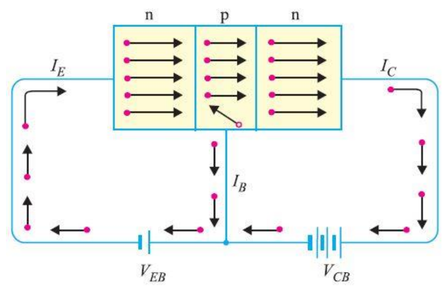
***(v)*** The resistance of emitter diode (forward biased) is very small as compared to collector diode (reverse biased). Therefore, forward bias applied to the emitter diode is generally very small whereas reverse bias on the collector diode is much higher.

### 4.3 Transistor Action

The emitter-base junction of a transistor is forward biased whereas collector-base junction is reverse biased. If for a moment, we ignore the presence of emitter-base junction, then *practically* no current would flow in the collector circuit because of the reverse bias. However, if the emitter-base junction is also present, then forward bias on it causes the emitter current to flow. It is seen that this emitter current almost entirely flows in the collector circuit. Therefore, the current in the collector circuit depends upon the emitter current. If the emitter current is zero, then collector current is nearly zero. However, if the emitter current is 1 mA, then collector current is also about 1 mA.

**(*i*) Working of npn transistor.** Fig. 4.5 shows the *npn* transistor with forward bias to emitter-base junction and reverse bias to collector-base junction. The forward bias causes the electrons in the *n*-type emitter to flow towards the base. This constitutes the emitter current *IE*. As these electrons flow through the *p*-type base, they tend to combine with holes. As the base is lightly doped and very thin, therefore, only a few electrons (less than 5%) combine with holes to constitute base current $I_B$. The remainder (more than 95%) cross over into the collector region to constitute collector current $I_C$. In this way, almost the entire emitter current flows in the collector circuit. It is clear that emitter current is the sum of collector and base currents *i.e.* $I_E = I_B + I_C$

**(*ii*) Working of pnp transistor.** Fig. 4.6 shows the basic connection of a *pnp* transistor. The forward bias causes the holes in the *p*-type emitter to flow towards the base. This constitutes the emitter current $I_E$. As these holes cross into *n*-type base, they tend to combine with the electrons. As the base is lightly doped and very thin, therefore, only a few holes (less than 5%) combine with the electrons. The remainder (more than 95%) cross into the collector region to constitute collector current $I_C$. In this way, almost the entire emitter current flows in the collector circuit. It may be noted that current conduction within *pnp* transistor is by holes. However, in the external connecting wires, the current is still by electrons.



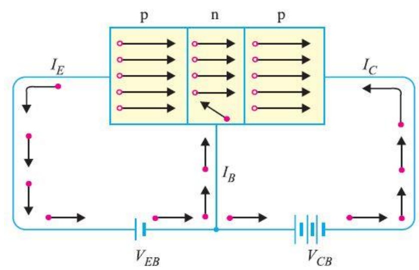
Basic connection of *npn* transistor

**Importance of transistor action.**

The input circuit (*i.e.* emitter-base junction) has low resistance because of forward bias whereas output circuit (*i.e.* collector-base junction) has high resistance due to reverse bias. As we have seen, the input emitter current almost entirely flows in the collector circuit. Therefore, a transistor transfers the input signal current from a low-resistance circuit to a high-resistance circuit. This is the key factor responsible for the amplifying capability of the transistor.

## 4.4 Transistor Symbols

In the earlier diagrams, the transistors have been shown in diagrammatic form. However, for the sake of convenience, the transistors are represented by schematic diagrams. The symbols used for *npn* and *pnp* transistors are shown in Fig. 4.7.



Basic connection of *pnp* transistor

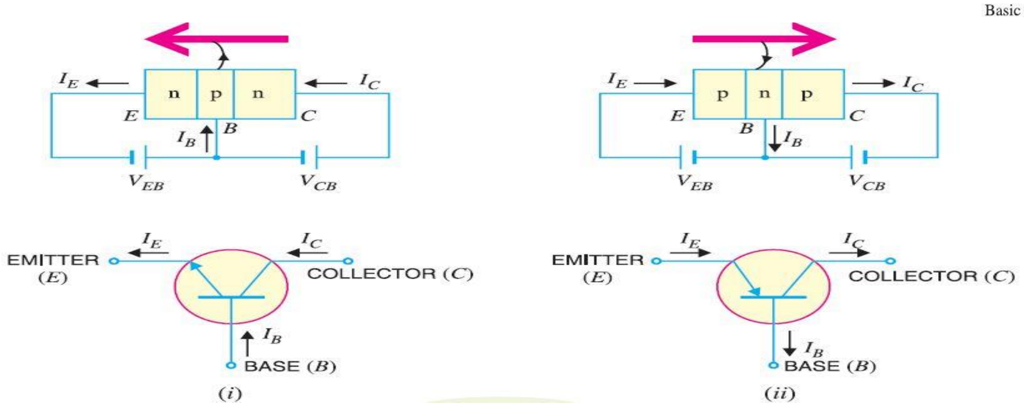


Fig. 4.7

## 4.5 Transistor Connections

There are three leads in a transistor *viz*., emitter, base and collector terminals. However, when a transistor is to be connected in a circuit, we require four terminals; two for the input and two for the output. This difficulty is overcome by making one terminal of the transistor common to both input and output terminals. The input is fed between this common terminal and one of the other two terminals. The output is obtained between the common terminal and the remaining terminal. Accordingly; a transistor can be connected in a circuit in the following three ways:

(***i***) common base connection (***ii***) common emitter connection (***iii***) common collector connection

Each circuit connection has specific advantages and disadvantages. It may be noted here that regardless of circuit connection, the emitter is always biased in the forward direction, while the collector always has a reverse bias.

**(i) Common Base Connection**

In this circuit arrangement, input is applied between emitter and base and output is taken from collector and base. Here, base of the transistor is common to both input and output circuits and hence the name common base connection. In Fig. 4.8 (*i*), a common base *npn* transistor circuit is shown whereas Fig. 4.8 (*ii*) shows the common base *pnp* transistor circuit.

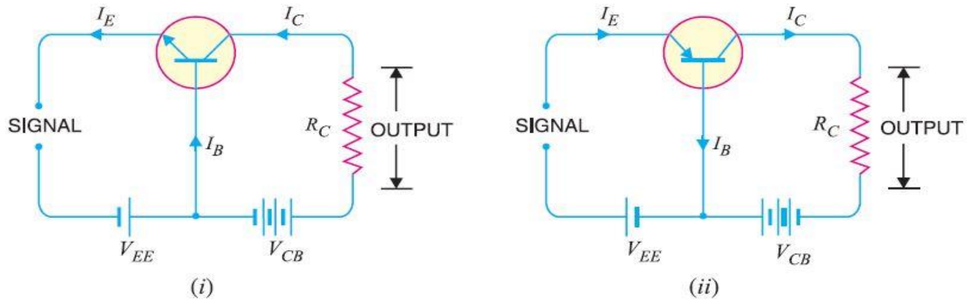
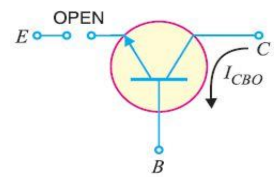



Fig. 4.8

**1. Current amplification factor ($\alpha$).** It is the ratio of output current to input current. In a common base connection, the input current is the emitter current $I_E$ and output current is the collector current $I_C$. *The ratio of change in collector current to the change in emitter current at constant collector base voltage $V_{CB}$ is known as* **current amplification factor** *i.e.*

$\alpha = \frac{\Delta I_C}{\Delta I_E}$ *at constant* $V_{CB}$

It is clear that current amplification factor is less than unity. This value can be increased (but not more than unity) by decreasing the base current. This is achieved by making the base thin and doping it lightly. Practical values of $\alpha$ in commercial transistors range from 0.9 to 0.99.




**2. Expression for collector current.** The whole of emitter current does not reach the collector. It is because a small percentage of it, as a result of electron-hole combinations occurring in base area, gives rise to base current. Moreover, as the collector-base junction is reverse biased, therefore, some leakage current flows due to minority carriers. It follows, therefore, that total collector current consists of :

**(*i*)** That part of emitter current which reaches the collector terminal *i.e.* $\alpha I_E$

**(*ii*)** The leakage current $I_{leakage}$. This current is due to the movement of minority carriers across base-collector junction on account of it being reverse biased. This is generally much smaller than $\alpha I_E$

∴Total collector current, $I_C = \alpha I_E + I_{leakage}$

It is clear that if $I_E = 0$ (*i.e.*, emitter circuit is open), a small leakage current still flows in the collector circuit. This $I_{leakage}$ is abbreviated as $I_{CBO}$, meaning collector-base current with emitter open. The $I_{CBO}$, is indicated in Fig. above

∴ $I_C = \alpha I_E + I_{CBO}$

*Now* $I_E = I_C + I_B$

∴ $I_C = \alpha(I_C + I_B) + I_{CBO}$

Or $I_C(1-\alpha) = \alpha I_B + I_{CBO}$

Or $I_C = \frac{\alpha}{1-\alpha} I_B + \frac{I_{CBO}}{1-\alpha}$

Relation (*i*) or (*ii*) can be used to find $I_C$. It is further clear from these relations that the collector current of a transistor can be controlled by either the emitter or base current.

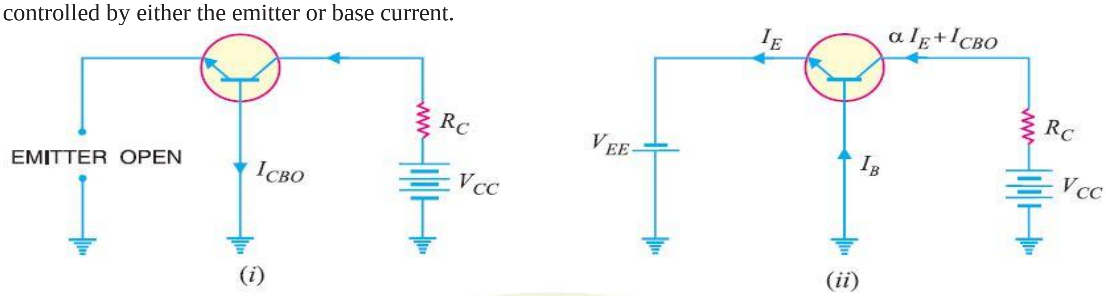



Fig. 4.9

**<u>Example 4</u>:** *In a common base connection, current amplification factor is 0.9. If the emitter current is 1mA, determine the value of base current.*

**Solution***:* $I_E = I_B + I_C \Longrightarrow 1 = I_B + 0.95 \Longrightarrow 1 - 0.95 = 0.05\ mA$

**<u>Example 5</u>:** *In a common base connection, IC = 0.95 mA and IB = 0.05 mA. Find the value of* $\alpha$

**Solution***: Here,* $\alpha = 0.9,\ \ I_E = 1\ mA \qquad \alpha = \frac{I_C}{I_E}$

*Thus,* $I_C = \alpha I_E = 0.9 \times 1 = 0.9\ mA$

∴ $I_E = I_B + I_C$

*Hence* $I_B = I_E - I_C = 1 - 0.9 = 0.1\ mA$

**Example 6**: *In a common base connection, the emitter current is 1mA. If the emitter circuit is open, the collector current is 50µA. Find the total collector current. Given that α= 0.92.*
**Solution**: *Here,* $I_E = 1\ mA, \alpha = 0.92,\ \ I_{CBO} = 50\mu A$
*Thus,* $I_C = \alpha I_E + I_{CBO} = 0.92 \times 1 + 50 \times 10^{-3} = 0.92 + 0.05 = 0.97\ mA$

**(ii) Common Emitter Connection**
In this circuit arrangement, input is applied between base and emitter and output is taken from the collector and emitter. Here, emitter of the transistor is common to both input and output circuits and hence the name common emitter connection. Fig. 4.10 (*i*) shows common emitter *npn* transistor circuit whereas Fig. 4.10 (*ii*) shows common emitter *pnp* transistor circuit.

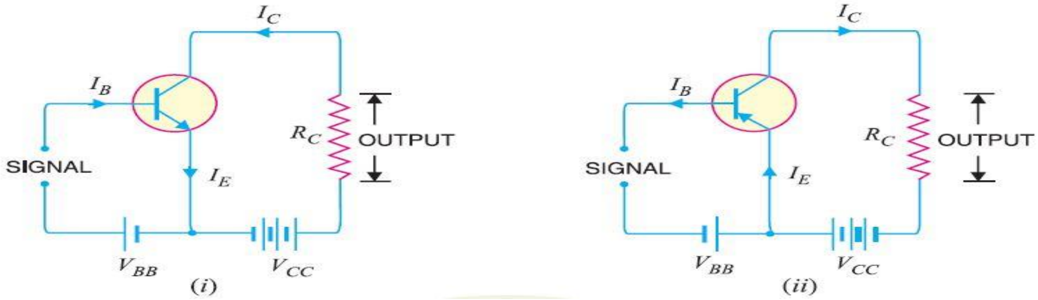


Fig. 4.10

**1. Base current amplification factor ( $\beta$).** In common emitter connection, input current is $I_B$ and output current is $I_C$.
*The ratio of change in collector current* ($\Delta I_C$) *to the change in base current* ($\Delta I_B$) *is known as* **base current amplification factor** *i.e.*

$$\beta = \frac{\Delta I_C}{\Delta I_B}$$

In almost any transistor, less than 5% of emitter current flows as the base current. Therefore, the value of $\beta$ is generally greater than 20. Usually, its value ranges from 20 to 500. This type of connection is frequently used as it gives appreciable current gain as well as voltage gain.
**Relation between $\beta$ and $\alpha$.** A simple relation exists between $\beta$ and $\alpha$. This can be derived as follows:
$\beta = \frac{\Delta I_C}{\Delta I_B}$ *and* $\alpha = \frac{\Delta I_C}{\Delta I_E}$
*Now* $I_E = I_B + I_C \implies \Delta I_E = \Delta I_B + \Delta I_C \implies$ *Or* $\Delta I_B = \Delta I_E - \Delta I_C$
*Substituting the value of* $\Delta I_B$ *in* $\beta = \frac{\Delta I_C}{\Delta I_B}, \implies \beta = \frac{\Delta I_C}{\Delta I_E - \Delta I_C}$
*Dividing the numerator and denominator of R. H. S. of* $\beta = \frac{\Delta I_C}{\Delta I_E - \Delta I_C}$ *by* $\Delta I_E, \implies \beta = \frac{\Delta I_C / \Delta I_E}{\frac{\Delta I_E}{\Delta I_E} - \frac{\Delta I_C}{\Delta I_E}} = \frac{\alpha}{1-\alpha}$ $\left[\because \alpha = \frac{\Delta I_C}{\Delta I_E}\right]$

$\therefore \quad \beta = \frac{\alpha}{1-\alpha}$

It is clear that as $\alpha$ approaches unity, $\beta$approaches infinity. In other words, the current gain in common emitter connection is very high. It is due to this reason that this circuit arrangement is used in about 90 to 95 percent of all transistor applications.

**2. Expression for collector current.** In common emitter circuit, $I_B$ is the input current and $I_C$ is the output current.

We know $I_E = I_B + I_C$ and $I_C = \alpha I_E + I_{CBO}$
Substitute for $I_E, \implies I_C = \alpha I_E + I_{CBO} = \alpha(I_B + I_C) + I_{CBO}$
*Or* $I_C(1-\alpha) = \alpha I_E + I_{CBO}$ *or* $I_C = \frac{\alpha}{1-\alpha} I_B + \frac{1}{1-\alpha} I_{CBO}$
it is apparent that if $I_B$ = 0 (*i.e.* base circuit is open), the collector current will be the current to the emitter. This is abbreviated as $I_{CEO}$, meaning collector-emitter current with base open.
$I_{CEO} = \frac{1}{1-\alpha} I_{CEO}$
Substituting the value of $\frac{1}{1-\alpha} I_{CBO} = I_{CEO}$ in exp. $I_C$, we get,

$$I_C = \frac{\alpha}{1-\alpha} I_B + I_{CEO}$$

$I_C = \beta I_B + I_{CEO}$ $\left(\because \beta = \frac{\alpha}{1-\alpha}\right)$

**Concept of $I_{CEO}$ .** In *CE* configuration, a small collector current flows even when the base current is zero [See Fig. 4.12(*i*)]. This is the collector cut off current (*i.e.* the collector current that flows when base is open) and is denoted by $I_{CEO}$. The value of $I_{CEO}$ is much larger than $I_{CBO}$.

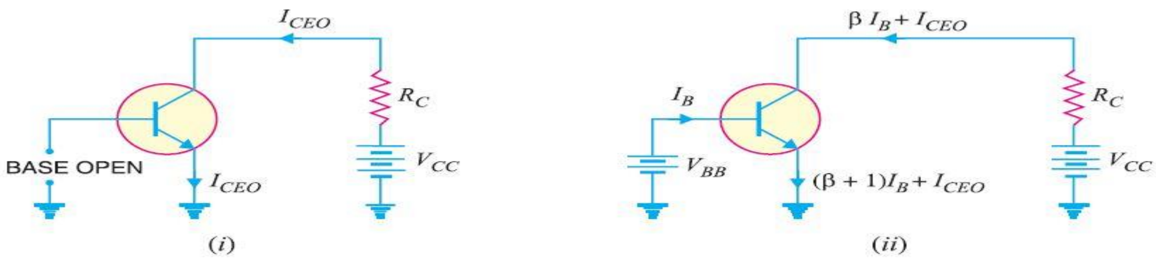



Fig. 4.11

When the base voltage is applied as shown in Fig. 4.11 (*ii*), then the various currents are :

Base current = $I_B$ and Collector current = $\beta I_B + I_{CEO}$

Emitter current = Collector current + Base current

= $(\beta I_B + I_{CEO}) + I_B = (\beta + 1)I_B + I_{CEO}$

It may be noted here that :

$I_{CEO} = \frac{1}{1-\alpha} I_{CBO} = (\beta + 1)I_{CBO}$ $\left[\because \frac{1}{1-\alpha} = \beta + 1\right]$

### 4.6 Measurement of Leakage Current

A very small leakage current flows in all transistor circuits. However, in most cases, it is quite small and can be neglected.

**(*i*) Circuit for $I_{CEO}$ test.** Fig.4.12 shows the circuit for measuring $I_{CEO}$. Since base is open ($I_B$ = 0), the transistor is in cut off. Ideally, $I_C$ = 0 but actually there is a small current from collector to emitter due to minority carriers. It is called $I_{CEO}$ (collector-to-emitter current with base open). This current is usually in the nA range for silicon. A faulty transistor will often have excessive leakage current.

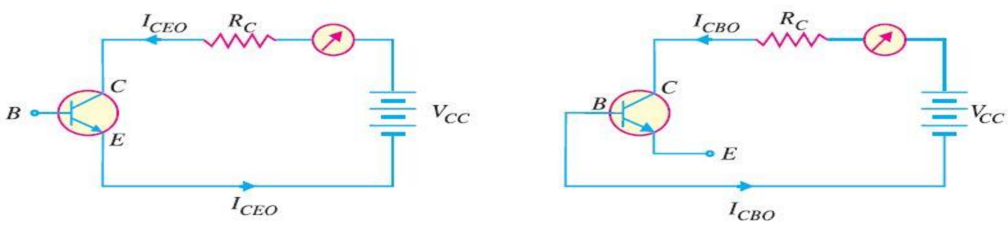



Fig. 4.12

**(*ii*) Circuit for $I_{CEO}$ test.** Fig. 4.12 shows the circuit for measuring $I_{CBO}$. Since the emitter is open ($I_E$ = 0), there is a small current from collector to base. This is called $I_{CBO}$ (collector-to-base current with emitter open). This current is due to the movement of minority carriers across base-collector junction. The value of $I_{CEO}$ is also small. If in measurement, $I_{CBO}$ is excessive, then there is a possibility that collector-base is shorted.

**Example 7:** *Find the value of $\beta$ if (i) $\alpha$= 0.9 (ii) $\alpha$= 0.98 (iii) $\alpha$= 0.99.*

**Solution**

(*i*) $\beta = \frac{\alpha}{1-\alpha} = \frac{0.9}{1-0.9}$

(*ii*) $\beta = \frac{\alpha}{1-\alpha} = \frac{0.99}{1-0.98}$

(*iii*) $\beta = \frac{\alpha}{1-\alpha} = \frac{0.99}{1-0.99}$

**Example 8:** *Calculate $I_E$ in a transistor for which $\beta$= 50 and $I_B$ = 20 $\mu A$.*

$\beta = 50, \quad I_B = 20\ \mu A = 0.02\ mA$

$\beta = \frac{I_C}{I_B}$ *while* $I_C = \beta I_B = 50 \times 0.02 = 1\ mA$

*Using the relation* $I_E = I_B + I_C = 0.02 + 1 = 1.02\ mA$

### (iii) Common Collector Connection

In this circuit arrangement, input is applied between base and collector while output is taken between the emitter and collector. Here, collector of the transistor is common to both input and output circuits and hence the name common collector connection. Fig. 4.13 (*i*) shows common collector *npn* transistor circuit whereas Fig. 4.13 (*ii*) shows common collector *pnp* circuit.

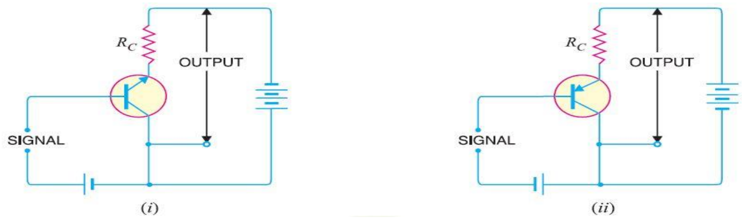



Fig. 13

**(1) Current amplification factor $\gamma$.** In common collector circuit, input current is the base current $I_B$ and output current is the emitter current $I_E$. Therefore, current amplification in this circuit arrangement can be defined as under :

*The ratio of change in emitter current ($\Delta I_E$) to the change in base current ($\Delta I_B$) is known as* ***current amplification factor*** *in common collector (CC) arrangement i.e.*

$$\gamma = \frac{\Delta I_E}{\Delta I_B}$$

This circuit provides about the same current gain as the common emitter circuit as $\Delta I_E \simeq \Delta I_C$.
However, its voltage gain is always less than 1.

**Relation between $\gamma$ and $\alpha$**

$\gamma = \frac{\Delta I_E}{\Delta I_B}$ and $\alpha = \frac{\Delta I_C}{\Delta I_E}$

Now $I_E = I_B + I_C$

or $\Delta I_E = \Delta I_B + \Delta I_C$

or $\Delta I_B = \Delta I_E - \Delta I_C$

Substituting the value of $\Delta I_B$ in exp. (*i*), we get,

$\gamma = \frac{\Delta I_E}{\Delta I_E - \Delta I_C}$

Dividing the numerator and denominator of R.H.S. by $\Delta I_E$, we get,

$\gamma = \frac{\frac{\Delta I_E}{\Delta I_E}}{\frac{\Delta I_E}{\Delta I_E} - \frac{\Delta I_C}{\Delta I_E}} = \frac{1}{1-\alpha}$ $\left(\because \alpha = \frac{\Delta I_C}{\Delta I_E}\right)$

$\gamma = \frac{1}{1-\alpha}$

**(2) Expression for collector current**

We know $I_C = \alpha I_E + I_{CBO}$

Also $I_E = I_B + I_C = I_B + (\alpha I_E + I_{CBO})$

$\therefore$ $I_E(1-\alpha) = I_B + I_{CBO}$

or $I_E = \frac{I_B}{1-\alpha} + \frac{I_{CBO}}{1-\alpha}$

or $I_C \simeq I_E = (\beta + 1)I_B + (\beta + 1)I_{CBO}$

**(3) Applications.** The common collector circuit has very high input resistance (about 750 kΩ) and very low output resistance (about 25 Ω). Due to this reason, the voltage gain provided by this circuit is always less than 1. Therefore, this circuit arrangement is seldom used for amplification. However, due to relatively high input resistance and low output resistance, this circuit is primarily used for impedance matching *i.e.* for driving a low impedance load from a high impedance source.