5.8 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.

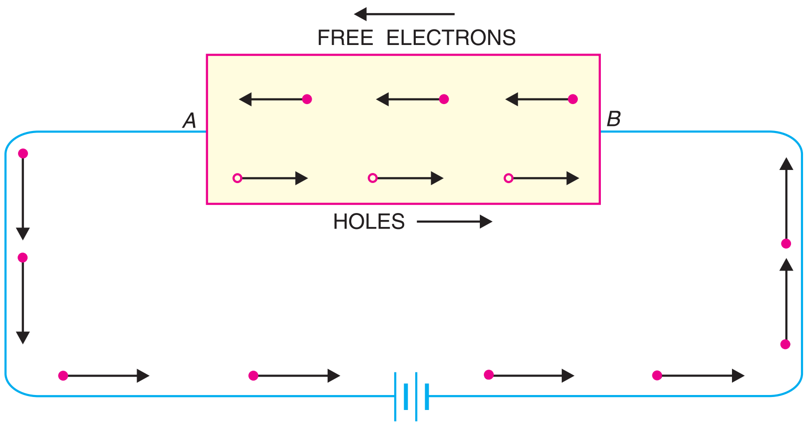


Fig. 5.10

It may be noted that current in the external wires is fully electronic *i.e.* by electrons. What about the holes ? Referring to Fig. 5.10, holes being positively charged move towards the negative terminal of supply. As the holes reach the negative terminal *B*, electrons enter the semiconductor crystal near the terminal and combine with holes, thus cancelling them. At the same time, the loosely held electrons near the positive terminal *A* are attracted away from their atoms into the positive terminal. This creates new holes near the positive terminal which again drift towards the negative terminal.

5.9 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 10^8 atoms of semiconductor, one impurity atom is added.

The purpose of adding impurity is to increase either the number of free electrons or holes in the semiconductor crystal. 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

5.10 *n*-type Semiconductor

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

The addition of pentavalent impurity provides a large number of free electrons in the semiconductor crystal. Typical examples of pentavalent impurities are *arsenic* (At. No. 33) and *antimony* (At. No. 51). Such impurities which produce *n*-type semiconductor are known as *donor impurities* because they donate or provide free electrons to the semiconductor crystal.

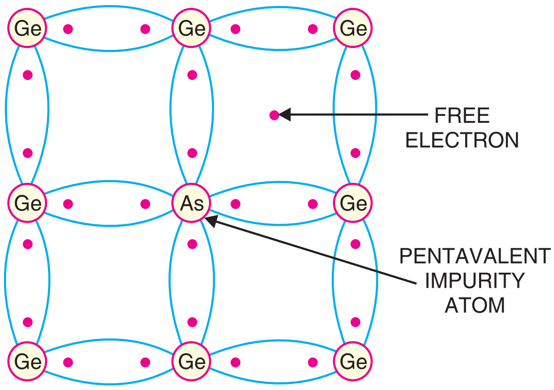


Fig. 5.11

To explain the formation of *n*-type semiconductor, consider a pure germanium crystal. We know that germanium atom has four valence electrons. 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. The *fifth* valence electron of arsenic atom finds no place in co-valent bonds and is thus free as shown in Fig. 5.11. 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.

Fig. 5.12 shows the energy band description of *n*-type semi-conductor. The addition of pentavalent impurity has produced a number of conduction band electrons *i.e.*, free electrons. The four valence electrons of pentavalent atom form covalent bonds with four neighbouring germanium atoms. The fifth left over valence electron of the pentavalent atom cannot be accommodated in the valence band and travels to the conduction band. The following points may be noted carefully :

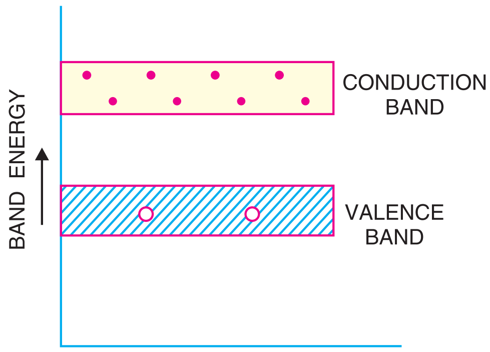


Fig. 5.12

(*i*) Many new free electrons are produced by the addition of pentavalent impurity.

(*ii*) Thermal energy of room temperature still generates a few hole-electron pairs. However, the number of free electrons provided by the pentavalent impurity far exceeds the number of holes. It is due to this predominance of electrons over holes that it is called *n*-type semiconductor (*n* stands for negative).

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*. To understand *n*-type conductivity, refer to Fig. 5.13. 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.

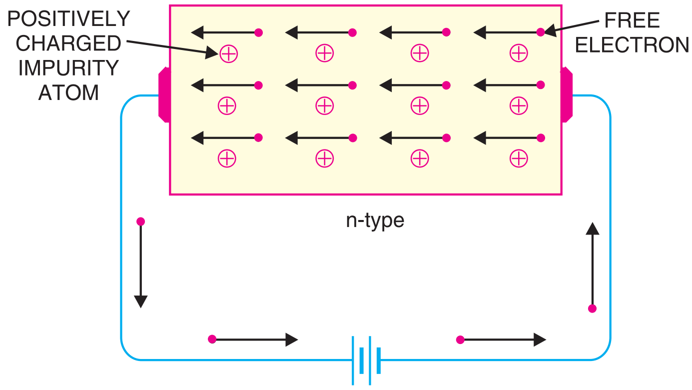


Fig. 5.13

5.11 *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.

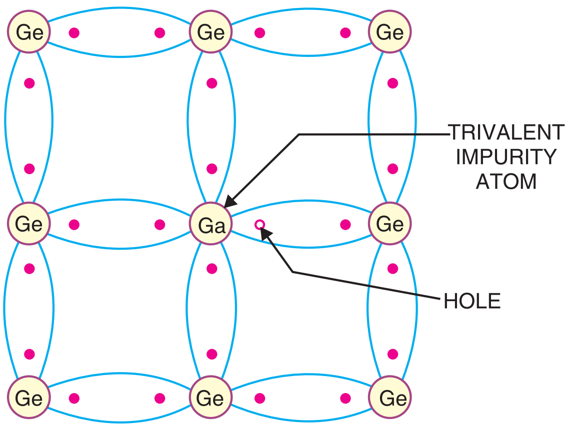


Fig. 5.14

To explain the formation of *p*-type semiconductor, consider a pure germanium crystal. When a small amount of trivalent impurity like gallium is added to germanium crystal, there exists a large number of holes in the crystal. The reason is simple. Gallium is trivalent *i.e.* its atom has three valence electrons. Each atom of gallium fits into the germanium crystal but now only three co-valent bonds can be formed. It is because three valence electrons of gallium atom can form only three single co-valent bonds with three germanium atoms as shown in Fig. 5.14. In the fourth co-valent bond, only germanium atom contributes one valence electron while gallium has no valence electron to contribute as all its three valence electrons are already engaged in the co-valent bonds with neighbouring germanium atoms. In other words, fourth bond is incomplete; being short of one electron. This missing electron is called a *hole*. Therefore, for each gallium atom added, one hole is created. A small amount of gallium provides millions of holes.

Fig. 5.15 shows the energy band description of the *p*-type semiconductor. The addition of trivalent impurity has produced a large number of holes. However, there are a few conduction band electrons due to thermal energy associated with room temperature. But the holes far outnumber the conduction band electrons. It is due to the predominance of holes over free electrons that it is called *p*-type semiconductor (*p* stands for positive).

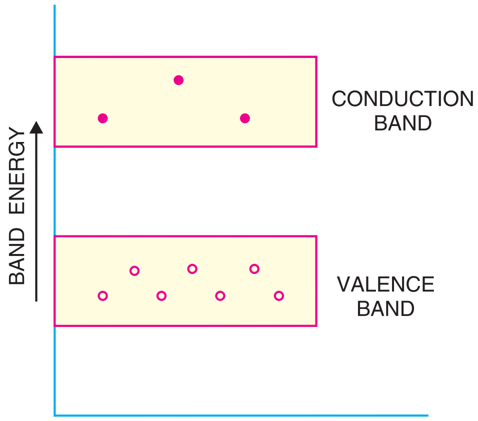


Fig. 5.15

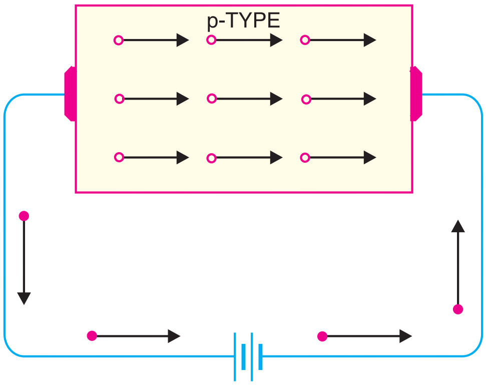


Fig. 5.16

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*. To understand *p*-type conductivity, refer to Fig. 5.16. 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.

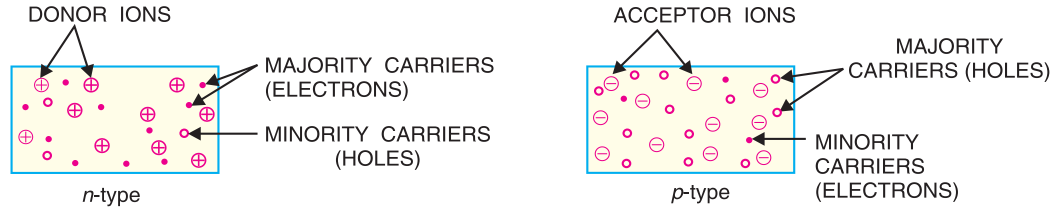
5.12 Charge on *n*-type and *p*-type Semiconductors

As discussed before, in *n*-type semiconductor, current conduction is due to excess of electrons whereas in a *p*-type semiconductor, conduction is by holes. The reader may think that *n*-type material has a net negative charge and *p*-type a net positive charge. But this conclusion is wrong. 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.*

5.13 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. 5.17 (*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*.

Similarly, in a *p*-type material, holes outnumber the free electrons as shown in Fig. 5.17 (*ii*). Therefore, holes are the majority carriers and free electrons are the minority carriers.



(*i*) (*ii*)

Fig. 5.17

5.14 *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. A thorough knowledge of the formation and properties of *pn* junction can enable the reader to understand the semiconductor devices.

Formation of *pn* junction. In actual practice, the characteristic properties of *pn* junction will not be apparent if a *p*-type block is just brought in contact with *n*-type block. In fact, *pn* junction is fabricated by special techniques. One common method of making *pn* junction is called *alloying*. In this method, a small block of indium (trivalent impurity) is placed on an *n*-type germanium slab as shown in Fig. 5.18 (*i*). The system is then heated to a temperature of about 500ºC. The indium and some of the germanium melt to form a small puddle of molten germanium-indium mixture as shown in Fig. 5.18 (*ii*). The temperature is then lowered and puddle begins to solidify. Under proper conditions, the atoms of indium impurity will be suitably adjusted in the germanium slab to form a single crystal. The addition of indium overcomes the excess of electrons in the *n*-type germanium to such an extent that it creates a *p*-type region.

As the process goes on, the remaining molten mixture becomes increasingly rich in indium. When all germanium has been redeposited, the remaining material appears as indium button which is frozen on to the outer surface of the crystallised portion as shown in Fig. 5.18 (*iii*). This button serves as a suitable base for soldering on leads.

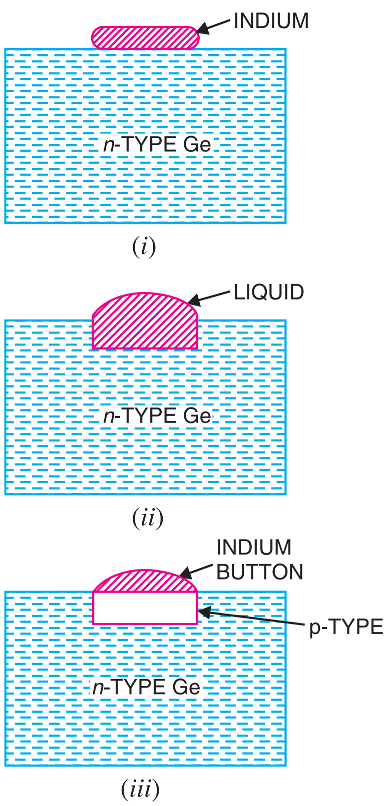
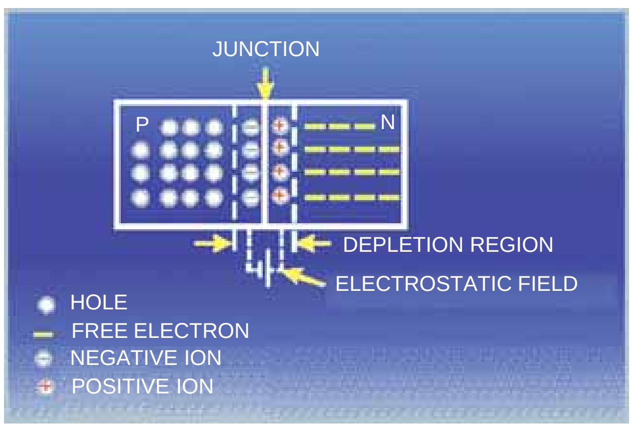


Fig. 5.18



5.15 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. For clarity, the width of the depletion layer is shown exaggerated.

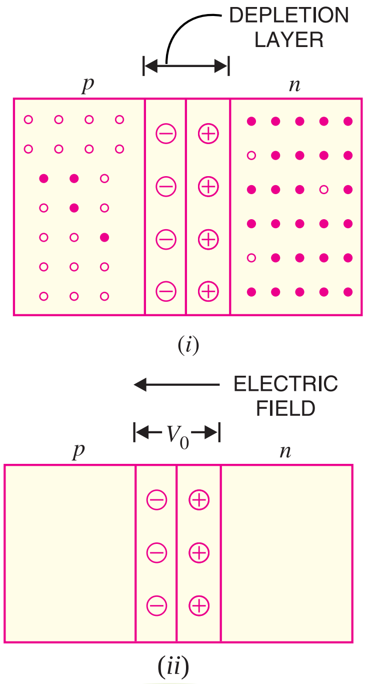


Fig. 5.19

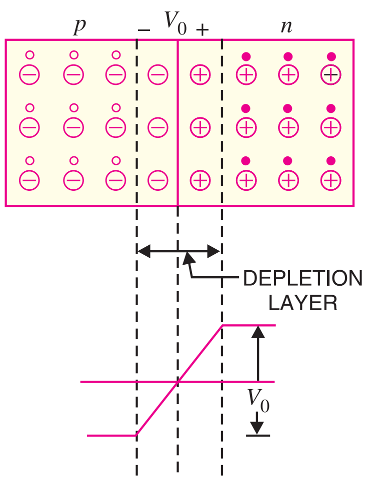


Fig. 5.20

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. 5.19 (*i*). 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. 5.20 shows the potential (V_0) distribution curve.

5.16 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.**

To apply forward bias, connect positive terminal of the battery to *p*-type and negative terminal to *n*-type as shown in Fig. 5.21. The applied forward potential establishes an electric field which acts against the field due to potential barrier. Therefore, the resultant field is weakened and the barrier height is reduced at the junction as shown in Fig. 5.21. As potential barrier voltage is very small (0.1 to 0.3 V), therefore, a small forward voltage is sufficient to completely eliminate the barrier. Once the potential barrier is eliminated by the forward voltage, junction resistance becomes almost zero and a low resistance path is established for the entire circuit. Therefore, current flows in the circuit. This is called *forward current.* 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.

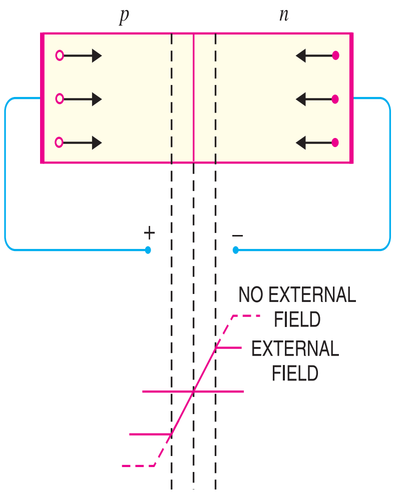


Fig. 5.21

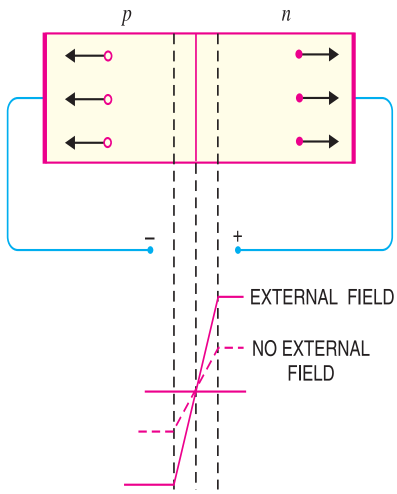
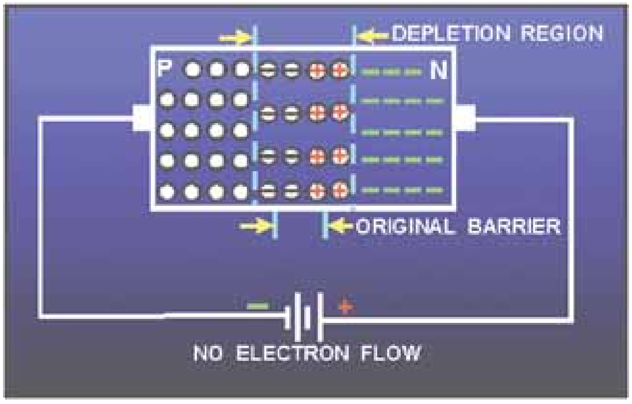


Fig. 5.22

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.**

To apply reverse bias, connect negative terminal of the battery to *p*-type and positive terminal to *n*-type as shown in Fig. 5.22. It is clear that applied reverse voltage establishes an electric field which acts in the same direction as the field due to potential barrier. Therefore, the resultant field at the junction is strengthened and the barrier height is increased as shown in Fig. 5.22. The increased potential barrier prevents the flow of charge carriers across the junction. Thus, a high resistance path is established for the entire circuit and hence the current does not flow. 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*, R_r) 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.

5.17 Current Flow in a Forward Biased pn Junction

We shall now see how current flows across *pn* junction when it is forward biased. Fig. 5.23 shows a forward biased *pn* junction. Under the influence of forward voltage, the free electrons in *n*-type move *towards the junction, leaving behind positively charged atoms. However, more electrons arrive from the negative battery terminal and enter the *n*-region to take up their places. 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.

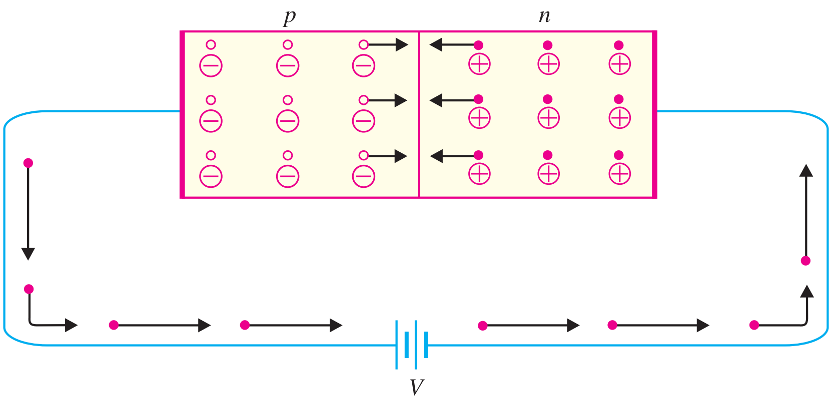


Fig. 5.23

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.

* Note that negative terminal of battery is connected to *n*-type. It repels the free electrons in *n*-type towards the junction.

** A hole is in the co-valent bond. When a free electron combines with a hole, it becomes a valence electron.

(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.

5.18 Volt-Ampere Characteristics of *pn* Junction

Volt-ampere or *V-I* characteristic of a *pn* junction (also called a *crystal or semiconductor diode*) is the curve between voltage across the junction and the circuit current. Usually, voltage is taken along *x*-axis and current along *y*-axis. Fig. 5.24 shows the *circuit arrangement for determining the *V-I* characteristics of a *pn* junction. The characteristics can be studied under three heads, namely; *zero external voltage, forward bias* and *reverse bias.*

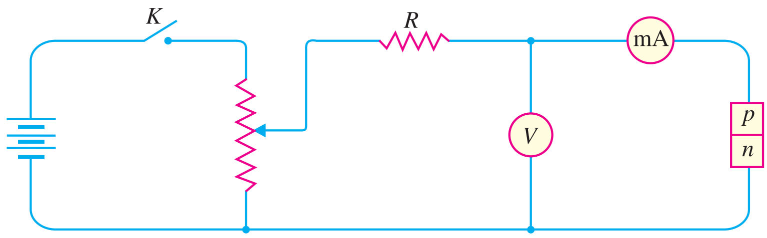


Fig. 5.24

(i) Zero external voltage. When the external voltage is zero, *i.e.* circuit is open at *K*, the potential barrier at the junction does not permit current flow. Therefore, the circuit current is zero as indicated by point *O* in Fig. 5.25.

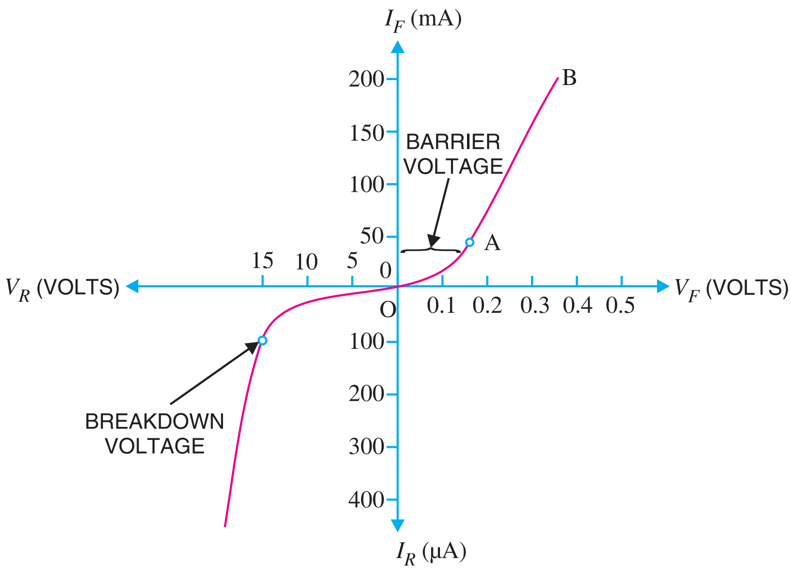


Fig. 5.25

* *R* is the current limiting resistance. It prevents the forward current from exceeding the permitted value.

***(ii)* Forward bias.** With forward bias to the *pn* junction *i.e.* *p*-type connected to positive terminal and *n*-type connected to negative terminal, the potential barrier is reduced. At some forward voltage (0.7 V for Si and 0.3 V for Ge), the potential barrier is altogether eliminated and current starts flowing in the circuit. From now onwards, the current increases with the increase in forward voltage. Thus, a rising curve *OB* is obtained with forward bias as shown in Fig. 5.25. From the forward characteristic, it is seen that at first (*region OA*),the current increases very slowly and the curve is non-linear. It is because the external applied voltage is used up in overcoming the potential barrier. However, once the external voltage exceeds the potential barrier voltage, the *pn* junction behaves like an ordinary conductor. Therefore, the current rises very sharply with increase in external voltage (*region AB on the curve*). The curve is almost linear.

***(iii)* Reverse bias.** With reverse bias to the *pn* junction *i.e.* *p*-type connected to negative terminal and *n*-type connected to positive terminal, potential barrier at the junction is increased. Therefore, the junction resistance becomes very high and practically no current flows through the circuit. However, in practice, a very small current (of the order of μ*A*) flows in the circuit with reverse bias as shown in the reverse characteristic. This is called *reverse *saturation current* (I_s) and is due to the minority carriers. It may be recalled that there are a few free electrons in *p*-type material and a few holes in *n*-type material. These undesirable free electrons in *p*-type and holes in *n*-type are called *minority carriers*. As shown in Fig. 5.26, to these minority carriers, the applied reverse bias appears as forward bias. Therefore, a **small current flows in the reverse direction.

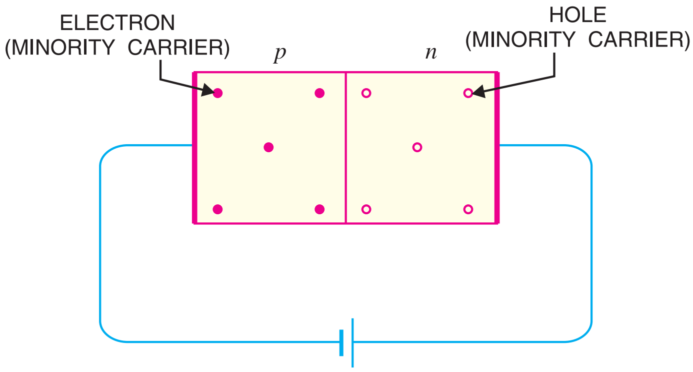


Fig. 5.26

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

Note. The forward current through a *pn* junction is due to the *majority carriers* produced by the impurity. However, reverse current is due to the *minority carriers* produced due to breaking of some co-valent bonds at room temperature.

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.*

Under normal reverse voltage, a very little reverse current flows through a *pn* junction. However, if the reverse voltage attains a high value, the junction may break down with sudden rise in

* The term saturation comes from the fact that it reaches its maximum level quickly and does not significantly change with the increase in reverse voltage.

** Reverse current increases with reverse voltage but can generally be regarded as negligible over the working range of voltages.

reverse current. For understanding this point, refer to Fig. 5.27. Even at room temperature, some hole-electron pairs (minority carriers) are produced in the depletion layer as shown in Fig. 5.27 (*i*). With reverse bias, the electrons move towards the positive terminal of supply. At large reverse voltage, these electrons acquire high enough velocities to dislodge valence electrons from semiconductor atoms as shown in Fig. 5.27 (*ii*). The newly liberated electrons in turn free other valence electrons. In this way, we get an *avalanche* of free electrons. Therefore, the *pn* junction conducts a very large reverse current.

Once the breakdown voltage is reached, the high reverse current may damage the junction. Therefore, care should be taken that reverse voltage across a *pn* junction is always less than the breakdown voltage.

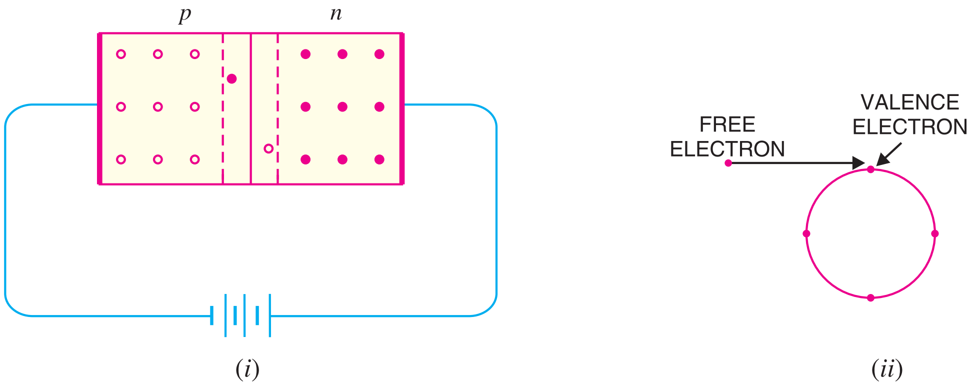


Fig. 5.27

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

When a diode is forward biased, it conducts current very slowly until we overcome the potential barrier. For silicon *pn* junction, potential barrier is 0.7 V whereas it is 0.3 V for germanium junction. It is clear from Fig. 5.28 that knee voltage for silicon diode is 0.7 V and 0.3 V for germanium diode.

Once the applied forward voltage exceeds the knee voltage, the current starts increasing rapidly. It may be added here that in order to get useful current through a *pn* junction, the applied voltage must be more than the knee voltage.

Note. The potential barrier voltage is also known as *turn-on voltage.* This is obtained by taking the straight line portion of the forward characteristic and extending it back to the horizontal axis.

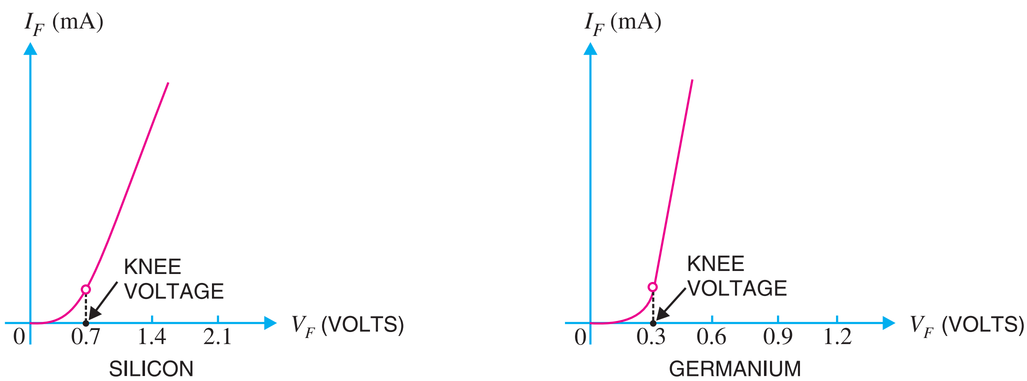


Fig. 5.28

***(ii)* Peak inverse voltage.** *It is the maximum reverse voltage that a diode can withstand without destroying the junction.*

If the reverse voltage across a diode exceeds this value, the reverse current increases sharply and breaks down the junction due to excessive heat. Peak inverse voltage is extremely important when diode is used as a rectifier. In rectifier service, it has to be ensured that reverse voltage across the diode does not exceed its PIV during the negative half-cycle of input a.c. voltage. As a matter of fact, PIV consideration is generally the deciding factor in diode rectifier circuits. The peak inverse voltage may be between 10V and 10 kV depending upon the type of diode.

***(iii)* Reverse current or leakage current.** It is the current that flows through a reverse biased diode. This current is due to the minority carriers. Under normal operating voltages, the reverse current is quite small. Its value is extremely small (< 1μ A) for silicon diodes but it is appreciable (≃ 100 μA) for germanium diodes.

It may be noted that the reverse current is usually very small as compared with forward current. For example, the forward current for a typical diode might range upto 100 mA while the reverse current might be only a few μA—a ratio of many thousands between forward and reverse currents.

6.7 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 :

(*i*) Half-wave rectifier (*ii*) Full-wave rectifier

6.8 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.

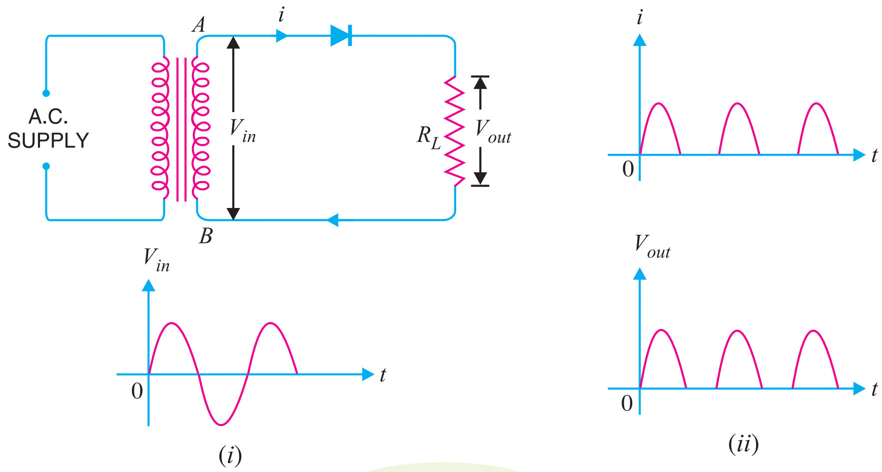


Fig. 6.20

Circuit details. Fig. 6.20 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. 6.20 (*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* discussed later.

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.

6.9 Output Frequency of Half-Wave Rectifier

The output frequency of a half-wave rectifier is equal to the input frequency (50 Hz). Recall how a complete cycle is defined. A waveform has a complete cycle when it repeats the same wave pattern over a given time. Thus in Fig. 6.21 (*i*), the a.c. input voltage repeats the same wave pattern over 0° – 360°, 360° – 720° and so on. In Fig. 6.21 (*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.*

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

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.

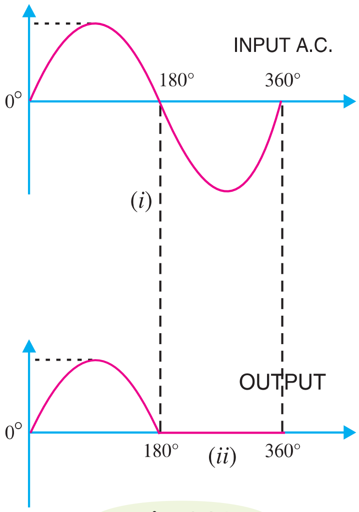


Fig. 6.21

6.10 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.*

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

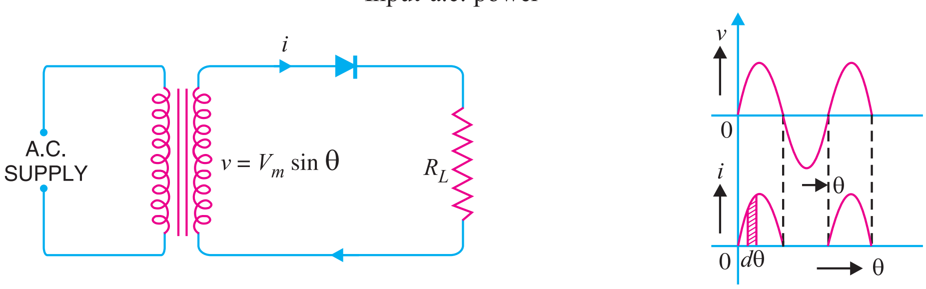


Fig. 6.22

Consider a half-wave rectifier shown in Fig. 6.22. 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.

$$*I_{av} = I_{dc} = \frac{1}{2\pi}\int_0^{\pi} i\, d\theta = \frac{1}{2\pi}\int_0^{\pi} \frac{V_m \sin\theta}{r_f + R_L}\, d\theta$$

$$= \frac{V_m}{2\pi(r_f + R_L)}\int_0^{\pi} \sin\theta\, d\theta = \frac{V_m}{2\pi(r_f + R_L)}[-\cos\theta]_0^{\pi}$$

$$= \frac{V_m}{2\pi(r_f + R_L)} \times 2 = \frac{V_m}{(r_f + R_L)} \times \frac{1}{\pi}$$

$$= \frac{**I_m}{\pi} \qquad \left[\because I_m = \frac{V_m}{(r_f + R_L)}\right]$$

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

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, $I_{rms} = I_m/2$

$$\therefore \quad P_{ac} = \left(\frac{I_m}{2}\right)^2 \times (r_f + R_L) \qquad ...(ii)$$

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

$$= \frac{0.406\, R_L}{r_f + R_L} = \frac{0.406}{1 + \dfrac{r_f}{R_L}}$$

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 6.12. *The applied input a.c. power to a half-wave rectifier is 100 watts. The d.c. output power obtained is 40 watts.*

(*i*) *What is the rectification efficiency ?*

(*ii*) *What happens to remaining 60 watts ?*

Solution.

$$(i) \quad \text{Rectification efficiency} = \frac{\text{d.c. output power}}{\text{a.c. input power}} = \frac{40}{100} = 0.4 = \mathbf{40\%}$$

(*ii*) 40% efficiency of rectification does not mean that 60% of power is lost in the rectifier circuit. In fact, a crystal diode consumes little power due to its small internal resistance. The 100 W

. . . .

* Average value = $\dfrac{\text{Area under the curve over a cycle}}{\text{Base}} = \dfrac{\int_0^{\pi} i\, d\theta}{2\pi}$

** It may be remembered that the *area of one-half cycle of a sinusoidal wave* is twice the peak value. Thus in this case, peak value is I_m and, therefore, area of one-half cycle is $2\, I_m$.

$$\therefore \quad I_{av} = I_{dc} = \frac{2\, I_m}{2\,\pi} = \frac{I_m}{\pi}$$

a.c. power is contained as 50 watts in positive half-cycles and 50 watts in negative half-cycles. The 50 watts in the negative half-cycles are not supplied at all. Only 50 watts in the positive half-cycles are converted into 40 watts.

$$\therefore \quad \text{Power efficiency} = \frac{40}{50} \times 100 = 80\%$$

Although 100 watts of a.c. power was supplied, the half-wave rectifier accepted only 50 watts and converted it into 40 watts d.c. power. Therefore, it is appropriate to say that efficiency of rectification is 40% and *not* 80% which is power efficiency.

Example 6.13. *An a.c. supply of 230 V is applied to a half-wave rectifier circuit through a transformer of turn ratio 10 : 1. Find (i) the output d.c. voltage and (ii) the peak inverse voltage. Assume the diode to be ideal.*

Solution.

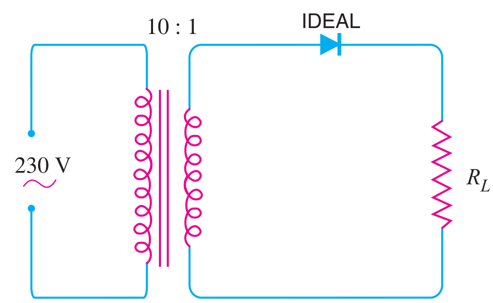


Fig. 6.23

Primary to secondary turns is

$$\frac{N_1}{N_2} = 10$$

R.M.S. primary voltage

$$= 230 \text{ V}$$

$\therefore$ Max. primary voltage is

$$V_{pm} = (\sqrt{2}) \times \text{r.m.s. primary voltage}$$
$$= (\sqrt{2}) \times 230 = 325.3 \text{ V}$$

Max. secondary voltage is

$$V_{sm} = V_{pm} \times \frac{N_2}{N_1} = 325.3 \times \frac{1}{10} = 32.53 \text{ V}$$

(i) $$I_{d.c.} = \frac{I_m}{\pi}$$

$$\therefore \quad V_{dc} = \frac{I_m}{\pi} \times R_L = \frac{V_{sm}}{\pi} = \frac{32.53}{\pi} = \mathbf{10.36 \text{ V}}$$

(ii) During the negative half-cycle of a.c. supply, the diode is reverse biased and hence conducts no current. Therefore, the maximum secondary voltage appears across the diode.

$\therefore$ Peak inverse voltage = **32.53 V**

Example 6.14. *A crystal diode having internal resistance $r_f = 20\Omega$ is used for half-wave rectification. If the applied voltage $v = 50 \sin \omega t$ and load resistance $R_L = 800\ \Omega$, find :*

(i) I_m, I_{dc}, I_{rms} *(ii) a.c. power input and d.c. power output*

(iii) d.c. output voltage *(iv) efficiency of rectification.*

Solution.

$$v = 50 \sin \omega\, t$$

$$\therefore \quad \text{Maximum voltage, } V_m = 50 \text{ V}$$

(i) $$I_m = \frac{V_m}{r_f + R_L} = \frac{50}{20 + 800} = 0.061 \text{ A} = \mathbf{61 \text{ mA}}$$

$$I_{dc} = I_m/\pi = 61/\pi = \mathbf{19.4 \text{ mA}}$$

$$I_{rms} = I_m/2 = 61/2 = \mathbf{30.5 \text{ mA}}$$

(ii) $$\text{a.c. power input} = (I_{rms})^2 \times (r_f + R_L) = \left(\frac{30.5}{1000}\right)^2 \times (20 + 800) = \mathbf{0.763 \text{ watt}}$$

$$\text{d.c. power output} = I_{dc}^2 \times R_L = \left(\frac{19.4}{1000}\right)^2 \times 800 = \mathbf{0.301\ watt}$$

(*iii*) $$\text{d.c. output voltage} = I_{dc} R_L = 19.4\ \text{mA} \times 800\ \Omega = \mathbf{15.52\ volts}$$

(*iv*) $$\text{Efficiency of rectification} = \frac{0.301}{0.763} \times 100 = \mathbf{39.5\%}$$

Example 6.15. *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.

$$\therefore \quad V_{dc} = I_{dc} \times R_L$$

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

or $$50 = \frac{V_m}{\pi (25 + 800)} \times 800$$

$$\therefore \quad V_m = \frac{\pi \times 825 \times 50}{800} = \mathbf{162\ V}$$

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

6.11 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

6.12 Centre-Tap Full-Wave Rectifier

The circuit employs two diodes D_1 and D_2 as shown in Fig. 6.24. 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 R_L 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. 6.24, 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.

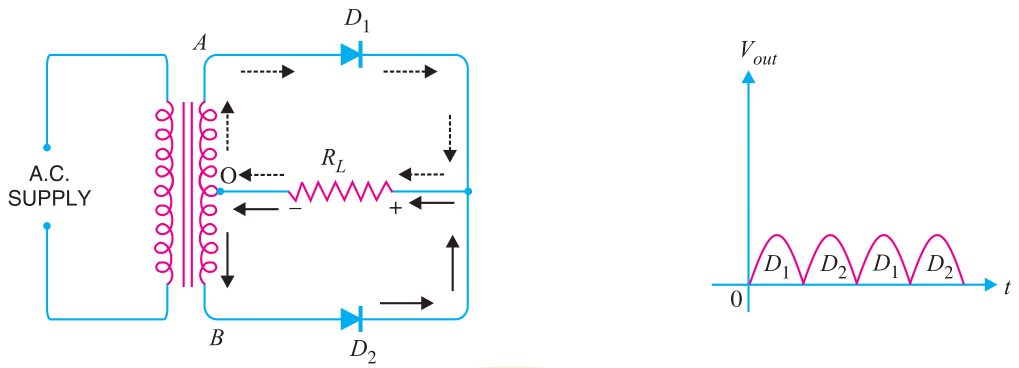


Fig. 6.24

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.*

$$\text{PIV} = 2\,V_m$$

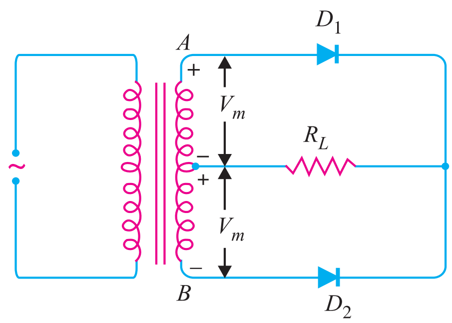


Fig. 6.25

Disadvantages

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

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

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

6.13 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. 6.26. 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.

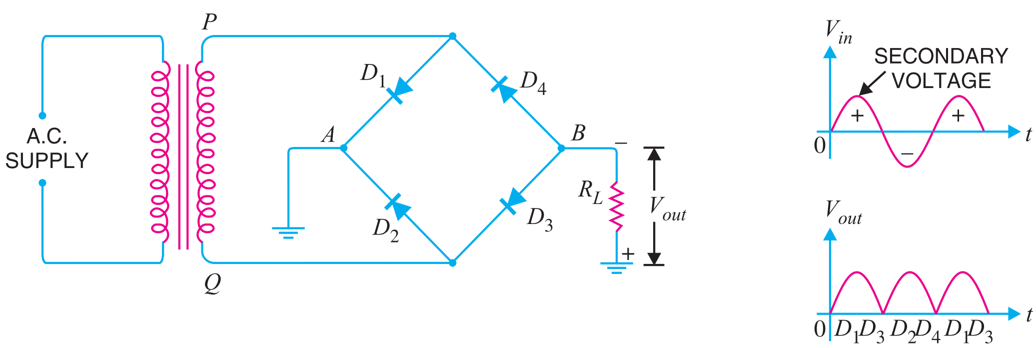


Fig. 6.26

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 R_L as shown in Fig. 6.27 (*i*). The conventional current flow is shown by dotted arrows. It may be seen that current flows from *A* to *B* through the load R_L .

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. 6.27 (*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.

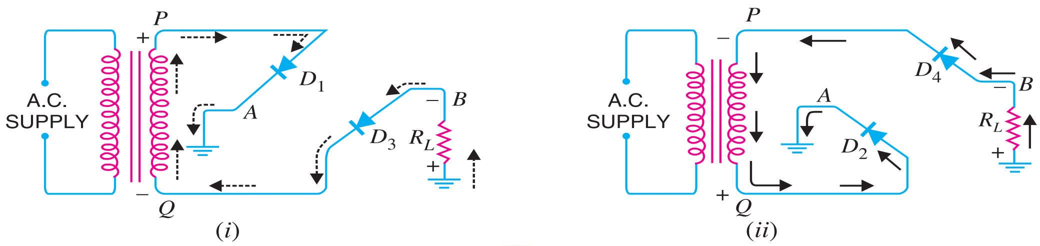


Fig. 6.27

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. 6.28 (*i*). This circuit is the same as shown in Fig. 6.28 (*ii*).

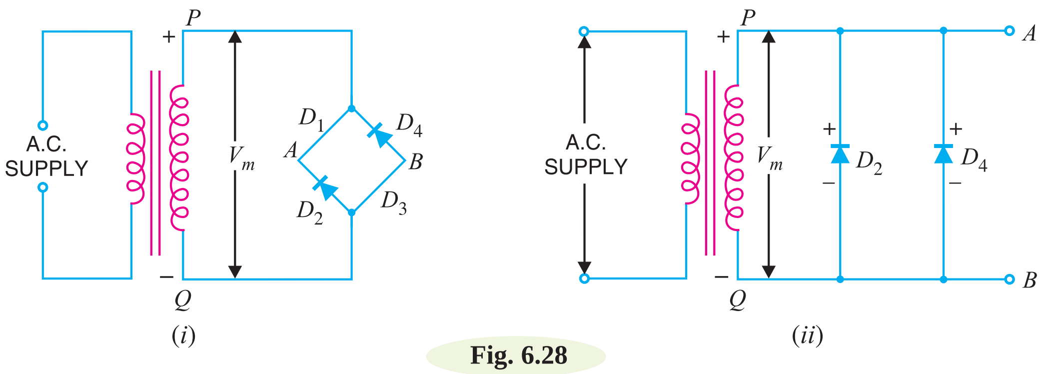


Fig. 6.28

Referring to Fig. 6.28 (*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

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

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

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

Disadvantages

(*i*) It requires four diodes.

(*ii*) 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.

6.14 Output Frequency of Full-Wave Rectifier

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. 6.29 (*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. 6.29 (*ii*)]. Therefore, output frequency is twice the input frequency *i.e.*

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

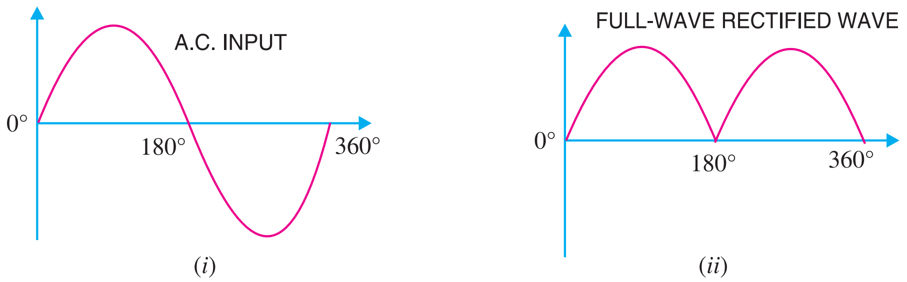


Fig. 6.29

For example, if the input frequency to a full-wave rectifier is 100 Hz, then the output frequency will be 200 Hz.

6.15 Efficiency of Full-Wave Rectifier

Fig. 6.30 shows the process of full-wave rectification. 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 :

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

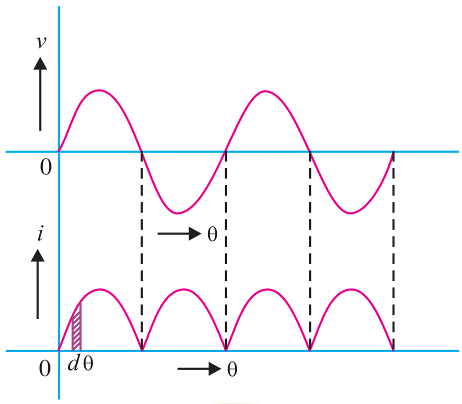


Fig. 6.30

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. From the elementary knowledge of electrical engineering,

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

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

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,

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

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

$\therefore$ Full-wave rectification efficiency is

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

$$= \frac{8}{\pi^2} \times \frac{R_L}{(r_f + R_L)} = \frac{0.812\ R_L}{r_f + R_L} = \frac{0.812}{1 + \frac{r_f}{R_L}}$$

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

$\therefore$ 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 6.16. *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.

$$r_f = 20\ \Omega, \quad R_L = 980\ \Omega$$

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

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

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

(*ii*) R.M.S. value of load current is

$$I_{rms} = \frac{I_m}{\sqrt{2}} = \frac{70.7}{\sqrt{2}}\overrightarrow{AB} = \textbf{50 mA}$$

Example 6.17. *In the centre-tap circuit shown in Fig. 6.31, the diodes are assumed to be ideal i.e. having zero internal resistance. Find :*

(*i*) *d.c. output voltage* (*ii*) *peak inverse voltage* (*iii*) *rectification efficiency.*

Solution.

Primary to secondary turns, $N_1/N_2 = 5$

The fact that a pulsating d.c. contains both d.c. and a.c. components can be beautifully illustrated by referring to Fig. 6.38. Fig. 6.38 (*i*) shows a pure d.c. component, whereas Fig. 6.38 (*ii*) shows the *a.c. component. If these two waves are added together, the resulting wave will be as shown in Fig. 6.38 (*iii*). It is clear that the wave shown in Fig. 6.38 (*iii*) never becomes negative, although it contains both a.c. and d.c. components. The striking resemblance between the rectifier output wave shown in Fig. 6.37 and the wave shown in Fig. 6.38 (*iii*) may be noted.

Rectifier

It follows, therefore, that a pulsating output of a rectifier contains a d.c. component and an a.c. component.

6.18 Ripple Factor

The output of a rectifier consists of a d.c. component and an a.c. component (also known as *ripple*). The a.c. component is undesirable and accounts for the pulsations in the rectifier output. The effectiveness of a rectifier depends upon the magnitude of a.c. component in the output ; the smaller this component, the more effective is the rectifier.

The ratio of r.m.s. value of a.c. component to the d.c. component in the rectifier output is known as **ripple factor** *i.e.*

$$\text{Ripple factor} = \frac{\text{r.m.s. value of a.c component}}{\text{value of d.c. component}} = \frac{I_{ac}}{I_{dc}}$$

Therefore, ripple factor is very important in deciding the effectiveness of a rectifier. The smaller the ripple factor, the lesser the effective a.c. component and hence more effective is the rectifier.

Mathematical analysis. The output current of a rectifier contains d.c. as well as a.c. component. The undesired a.c. component has a frequency of 100 Hz (*i.e.* double the supply frequency 50 Hz) and is called the *ripple* (See Fig. 6.39). It is a fluctuation superimposed on the d.c. component.

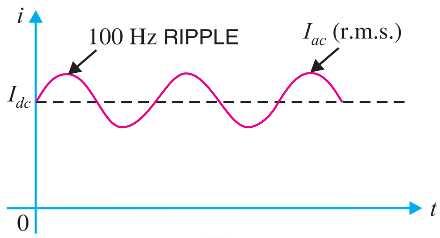


Fig. 6.39

By definition, the effective (*i.e.* r.m.s.) value of total load current is given by :

$$I_{rms} = \sqrt{I_{dc}^2 + I_{ac}^2}$$

or
$$I_{ac} = \sqrt{I_{rms}^2 - I_{dc}^2}$$

Dividing throughout by I_{dc}, we get,

$$\frac{I_{ac}}{I_{dc}} = \frac{1}{I_{dc}}\sqrt{I_{rms}^2 - I_{dc}^2}$$

But I_{ac}/I_{dc} is the ripple factor.

$$\therefore \quad \text{Ripple factor} = \frac{1}{I_{dc}}\sqrt{I_{rms}^2 - I_{dc}^2} = \sqrt{\left(\frac{I_{rms}}{I_{dc}}\right)^2 - 1}$$

(*i*) For half-wave rectification. In half-wave rectification,

$$I_{rms} = I_m/2 \quad ; \quad I_{dc} = I_m/\pi$$

* Although the a.c. component is not a sine-wave, yet it is alternating one.

$\therefore$ Ripple factor $= \sqrt{\left(\dfrac{I_m/2}{I_m/\pi}\right)^2 - 1} = 1.21$

It is clear that a.c. component exceeds the d.c. component in the output of a half-wave rectifier. This results in greater pulsations in the output. Therefore, half-wave rectifier is ineffective for conversion of a.c. into d.c.

(*ii*) For full-wave rectification. In full-wave rectification,

$$I_{rms} = \frac{I_m}{\sqrt{2}} \quad ; \quad I_{dc} = \frac{2\,I_m}{\pi}$$

$\therefore$ Ripple factor $= \sqrt{\left(\dfrac{I_m/\sqrt{2}}{2\,I_m/\pi}\right)^2 - 1} = 0.48$

i.e. $\dfrac{\text{effective a.c. component}}{\text{d.c. component}} = 0.48$

This shows that in the output of a full-wave rectifier, the d.c. component is more than the a.c. component. Consequently, the pulsations in the output will be less than in half-wave rectifier. For this reason, full-wave rectification is invariably used for conversion of a.c. into d.c.

Example 6.22. *A power supply A delivers 10 V dc with a ripple of 0.5 V r.m.s. while the power supply B delivers 25 V dc with a ripple of 1 mV r.m.s. Which is better power supply ?*

Solution. The lower the ripple factor of a power supply, the better it is.

For power supply A

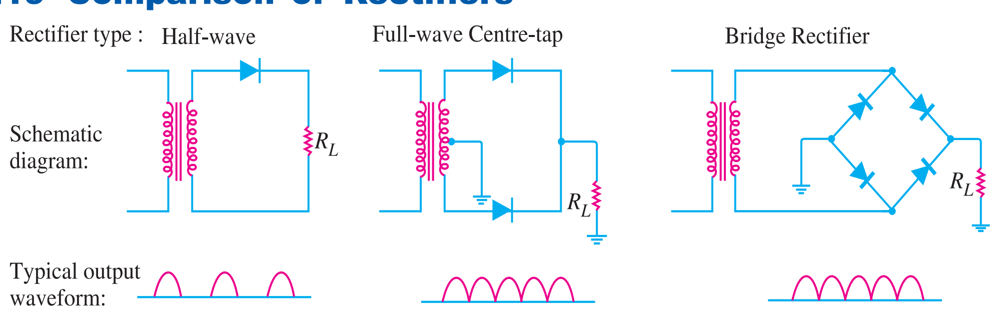
Ripple factor $= \dfrac{V_{ac(r.m.s.)}}{V_{dc}} = \dfrac{0.5}{10} \times 100 = 5\%$

For power supply B

Ripple factor $= \dfrac{V_{ac(r.m.s.)}}{V_{dc}} = \dfrac{0.001}{25} \times 100 = 0.004\%$

Clearly, power supply B is better.

6.19 Comparison of Rectifiers



S. No.	Particulars	Half-wave	Centre-tap	Bridge type
1	No. of diodes	1	2	4
2	Transformer necessary	no	yes	no
3	Max. efficiency	40.6%	81.2%	81.2%
4	Ripple factor	1.21	0.48	0.48
5	Output frequency	f_{in}	$2\,f_{in}$	$2\,f_{in}$
6	Peak inverse voltage	V_m	$2\,V_m$	V_m

A comparison among the three rectifier circuits must be made very judiciously. Although bridge circuit has some disadvantages, it is the best circuit from the viewpoint of overall performance. When cost of the transformer is the main consideration in a rectifier assembly, we invariably use the bridge circuit. This is particularly true for large rectifiers which have a low-voltage and a high-current rating.

6.20 Filter Circuits

Generally, a rectifier is required to produce pure d.c. supply for using at various places in the electronic circuits. However, the output of a rectifier has pulsating *character *i.e.* it contains a.c. and d.c. components. The a.c. component is undesirable and must be kept away from the load. To do so, a *filter circuit* is used which removes (or *filters out*) the a.c. component and allows only the d.c. component to reach the load.

A **filter circuit** *is a device which removes the a.c. component of rectifier output but allows the d.c. component to reach the load.*

Obviously, a filter circuit should be installed between the rectifier and the load as shown in Fig. 6.40. A filter circuit is generally a combination of inductors (L) and capacitors (C). The filtering action of L and C depends upon the basic electrical principles. A capacitor passes a.c. readily but does not **pass d.c. at all. On the other hand, an inductor †opposes a.c. but allows d.c. to pass through it. It then becomes clear that suitable network of L and C can effectively remove the a.c. component, allowing the d.c. component to reach the load.

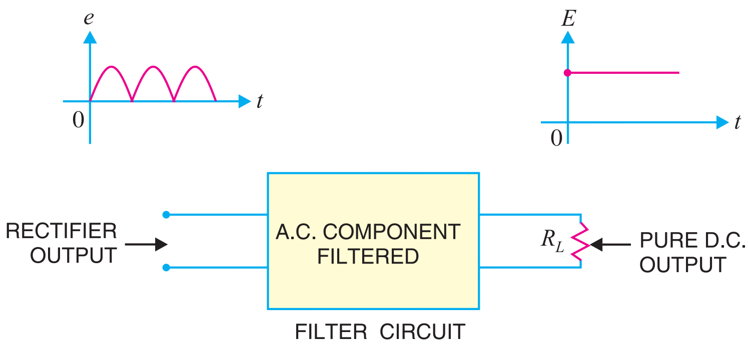


Fig. 6.40

6.21 Types of Filter Circuits

The most commonly used filter circuits are *capacitor filter*, *choke input filter* and *capacitor input filter or π-filter*. We shall discuss these filters in turn.

(*i*) Capacitor filter. Fig. 6.41 (*ii*) shows a typical capacitor filter circuit. It consists of a capacitor C placed across the rectifier output in parallel with load R_L. The pulsating direct voltage of the rectifier is applied across the capacitor. As the rectifier voltage increases, it charges the capacitor and also supplies current to the load. At the end of quarter cycle [Point A in Fig. 6.41 (*iii*)], the

* If such a d.c. is applied in an electronic circuit, it will produce a *hum.*

** A capacitor offers infinite reactance to d.c. For d.c., $f = 0$.

$$\therefore \qquad X_C = \frac{1}{2\pi fC} = \frac{1}{2\pi \times 0 \times C} = \infty$$

Hence, a capacitor does not allow d.c. to pass through it.

† We know $X_L = 2\pi fL$. For d.c., $f = 0$ and, therefore, $X_L = 0$. Hence inductor passes d.c. quite readily. For a.c., it offers opposition and drops a part of it.

capacitor is charged to the peak value V_m of the rectifier voltage. Now, the rectifier voltage starts to decrease. As this occurs, the capacitor discharges through the load and voltage across it (*i.e.* across parallel combination of *R-C*) decreases as shown by the line *AB* in Fig. 6.41 (*iii*). The voltage across load will decrease only slightly because immediately the next voltage peak comes and recharges the capacitor. This process is repeated again and again and the output voltage waveform becomes *ABCDEFG*. It may be seen that very little ripple is left in the output. Moreover, output voltage is higher as it remains substantially near the peak value of rectifier output voltage.

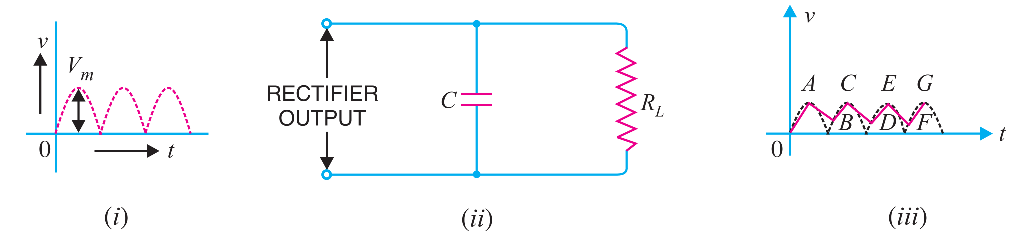


Fig. 6.41

The capacitor filter circuit is extremely popular because of its low cost, small size, little weight and good characteristics. For small load currents (say upto 50 mA), this type of filter is preferred. It is commonly used in transistor radio battery eliminators.

(*ii*) Choke input filter. Fig. 6.42 shows a typical choke input filter circuit. It consists of a *choke *L* connected in series with the rectifier output and a filter capacitor *C* across the load. Only a single filter section is shown, but several identical sections are often used to reduce the pulsations as effectively as possible.

The pulsating output of the rectifier is applied across terminals 1 and 2 of the filter circuit. As discussed before, the pulsating output of rectifier contains a.c. and d.c. components. The choke offers high opposition to the passage of a.c. component but negligible opposition to the d.c. component. The result is that most of the a.c. component appears across the choke while whole of d.c. component passes through the choke on its way to load. This results in the reduced pulsations at terminal 3.

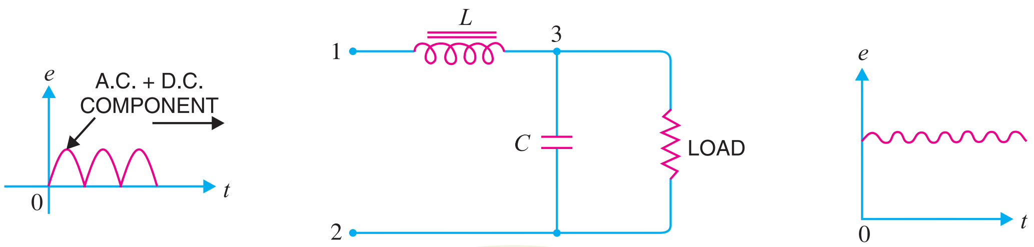


Fig. 6.42

At terminal 3, the rectifier output contains d.c. component and the remaining part of a.c. component which has managed to pass through the choke. Now, the low reactance of filter capacitor bypasses the a.c. component but prevents the d.c. component to flow through it. Therefore, only d.c. component reaches the load. In this way, the filter circuit has filtered out the a.c. component from the rectifier output, allowing d.c. component to reach the load.

(*iii*) Capacitor input filter *or* π-filter. Fig. 6.43 shows a typical capacitor input filter or **π-filter. It consists of a filter capacitor C_1 connected across the rectifier output, a choke *L* in series and

* The shorthand name of inductor coil is choke.

** The shape of the circuit diagram of this filter circuit appears like Greek letter π (pi) and hence the name π-filter.

another filter capacitor C_2 connected across the load. Only one filter section is shown but several identical sections are often used to improve the smoothing action.

The pulsating output from the rectifier is applied across the input terminals (*i.e.* terminals 1 and 2) of the filter. The filtering action of the three components *viz* C_1, L and C_2 of this filter is described below :

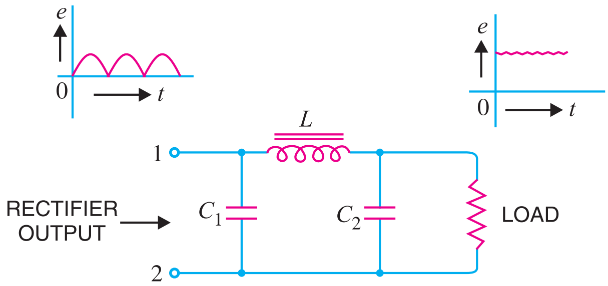


Fig. 6.43

(a) The *filter capacitor C_1* offers low reactance to a.c. component of rectifier output while it offers infinite reactance to the d.c. component. Therefore, capacitor C_1 bypasses an appreciable amount of a.c. component while the d.c. component continues its journey to the choke L.

(b) The *choke L* offers high reactance to the a.c. component but it offers almost zero reactance to the d.c. component. Therefore, it allows the d.c. component to flow through it, while the *unbypassed a.c. component is blocked.

(c) The *filter capacitor C_2* bypasses the a.c. component which the choke has failed to block. Therefore, only d.c. component appears across the load and that is what we desire.

Example 6.23. *For the circuit shown in Fig. 6.44, find the output d.c. voltage.*

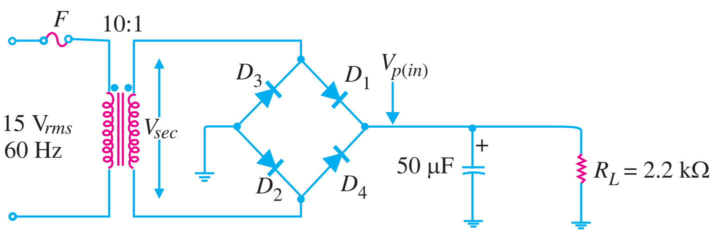


Fig. 6.44

Solution. It can be proved that output d.c. voltage is given by :

$$V_{dc} = V_{p(in)}\left(1 - \frac{1}{2f\ R_L C}\right)$$

Here $\quad V_{p(in)}$ = Peak rectified full-wave voltage applied to the filter

$\quad f$ = Output frequency

Peak primary voltage, $V_{p(prim)} = \sqrt{2} \times 115 = 163\text{V}$

Peak secondary voltage, $V_{p(sec)} = \left(\frac{1}{10}\right) \times 163 = 16.3\text{V}$

Peak full-wave rectified voltage at the filter input is

$$V_{p\ (in)} = V_{p\ (sec)} - 2\times0.7 = 16.3 - 1.4 = 14.9\text{V}$$

For full-wave rectification, $f = 2\ f_{in} = 2\times60 = 120$ Hz

Now $\quad \dfrac{1}{2f\ R_L C} = \dfrac{1}{2\times120\times(2.2\times10^3)\times(50\times10^{-6})} = 0.038$

* That part of a.c. component which could not be bypassed by capacitor C_1.

Referring to Fig. 6.50 (*ii*), it is easy to see that C_1 (charged to $V_{S\,(pk)}$)and the source voltage (V_S) now act as *series-aiding* voltage sources. Thus C_2 will be charged to the sum of the series peak voltages *i.e.* 2 $V_{S(pk)}$.

(*iii*) When V_S returns to its original polarity (*i.e.* negative half-cycle), D_2 is again turned off (*i.e.* reverse biased). With D_2 turned off, the only discharge path for C_2 is through the load resistance R_L. The time constant (= R_L C_2) of this circuit is so adjusted that C_2 has little time to lose any of its charge before the input polarity reverses again. During the positive half-cycle, D_2 is turned on and C_2 recharges until voltage across it is again equal to 2 $V_{S\,(pk)}$.

∴ D.C. output voltage, $V_{dc} = 2\ V_{S\,(pk)}$

Since C_2 barely discharges between input cycles, the output waveform of the half-wave voltage doubler closely resembles that of a filtered half-wave rectifier. Fig. 6.51 shows the input and output waveforms for a half-wave voltage doubler.

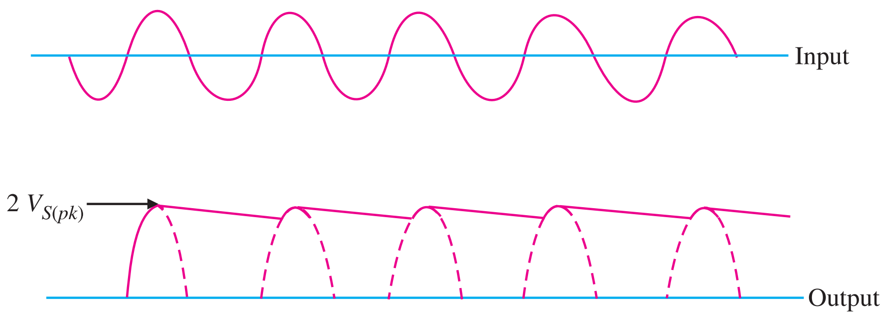


Fig. 6.51

The voltage multipliers have the disadvantage of poor voltage regulation. This means that d.c. output voltage drops considerably as the load current increases. Large filter capacitors are needed to help maintain the output voltage.

6.24 Voltage Stabilisation

A rectifier with an appropriate filter serves as a good source of d.c. output. However, the major disadvantage of such a power supply is that the output voltage changes with the variations in the input voltage or load. Thus, if the input voltage increases, the d.c. output voltage of the rectifier also increases. Similarly, if the load current increases, the output voltage falls due to the voltage drop in the rectifying element, filter chokes, transformer winding etc. In many electronic applications, it is desired that the output voltage should remain constant regardless of the variations in the input voltage or load. In order to ensure this, a voltage stabilising device, called voltage stabiliser is used. Several stabilising circuits have been designed but only *zener diode* as a voltage stabiliser will be discussed.

6.25 Zener Diode

It has already been discussed that when the reverse bias on a crystal diode is increased, a critical voltage, called *breakdown voltage* is reached where the reverse current increases sharply to a high value. The breakdown region is the knee of the reverse characteristic as shown in Fig. 6.52. The satisfactory explanation of this breakdown of the junction was first given by the American scientist *C.* Zener. Therefore, the breakdown voltage is sometimes called *zener voltage* and the sudden increase in current is known as zener current.

The breakdown or zener voltage depends upon the amount of doping. If the diode is heavily doped, depletion layer will be thin and consequently the breakdown of the junction will occur at a lower reverse voltage. On the other hand, a lightly doped diode has a higher breakdown voltage. When an ordinary crystal diode is properly doped so that it has a sharp breakdown voltage, it is called

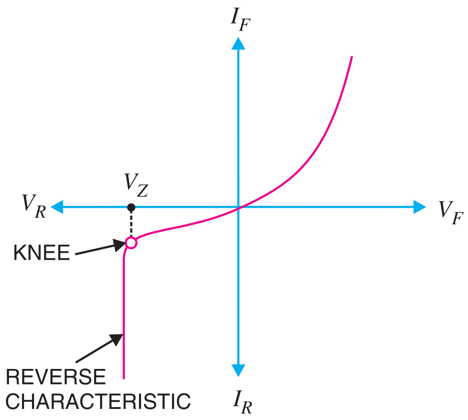


Fig. 6.52

a zener diode.

A properly doped crystal diode which has a sharp breakdown voltage is known as a **zener diode.**

Fig. 6.53 shows the symbol of a zener diode. It may be seen that it is just like an ordinary diode except that the bar is turned into z-shape. The following points may be noted about the zener diode:

(i) A zener diode is like an ordinary diode except that it is properly doped so as to have a sharp breakdown voltage.

(ii) A zener diode is always reverse connected *i.e.* it is always reverse biased.

(iii) A zener diode has sharp breakdown voltage, called zener voltage V_Z.

(iv) When forward biased, its characteristics are just those of ordinary diode.

(v) The zener diode is not immediately burnt just because it has entered the *breakdown region. As long as the external circuit connected to the diode limits the diode current to less than *burn out* value, the diode will not burn out.

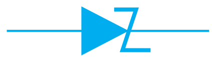
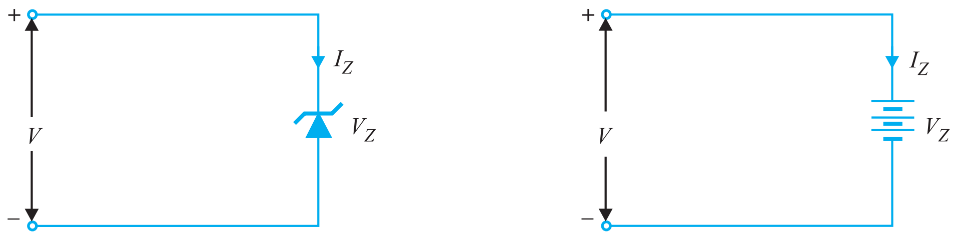


Fig. 6.53

6.26 Equivalent Circuit of Zener Diode

The analysis of circuits using zener diodes can be made quite easily by replacing the zener diode by its equivalent circuit.

(i) "On" state. When reverse voltage across a zener diode is equal to or more than break down voltage V_Z, the current increases very sharply. In this region, the curve is almost vertical. It means that voltage across zener diode is constant at V_Z even though the current through it changes. Therefore, in the breakdown region, an **ideal zener diode can be represented by a battery of voltage V_Z as shown in Fig. 6.54 (*ii*). Under such conditions, the zener diode is said to be in the "ON" state.



(*i*)
$V \geq V_Z$

(*ii*)
Equivalent circuit of zener for ''on'' state

Fig. 6.54

(ii) "OFF" state. When the reverse voltage across the zener diode is less than V_Z but greater than 0 V, the zener diode is in the "OFF" state. Under such conditions, the zener diode can be represented by an open-circuit as shown in Fig. 6.55 (*ii*).

* The current is limited only by both external resistance and the power dissipation of zener diode.

** This assumption is fairly reasonable as the impedance of zener diode is quite small in the breakdown region.

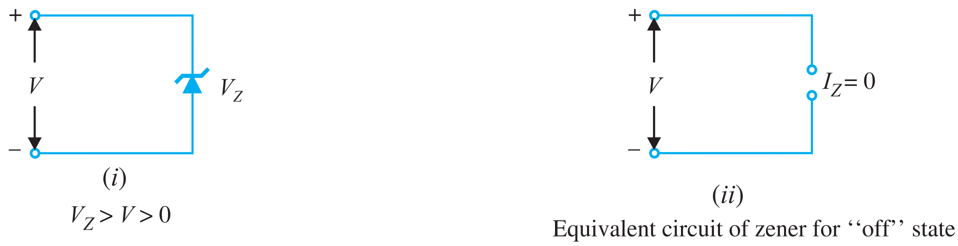


Fig. 6.55

6.27 Zener Diode as Voltage Stabiliser

A zener diode can be used as a voltage regulator to provide a constant voltage from a source whose voltage may vary over sufficient range. The circuit arrangement is shown in Fig. 6.56 (*i*). The zener diode of zener voltage V_Z is reverse connected across the load R_L across which constant output is desired. The series resistance R absorbs the output voltage fluctuations so as to maintain constant voltage across the load. It may be noted that the zener will maintain a constant voltage V_Z (= E_0) across the load so long as the input voltage does not fall below V_Z.

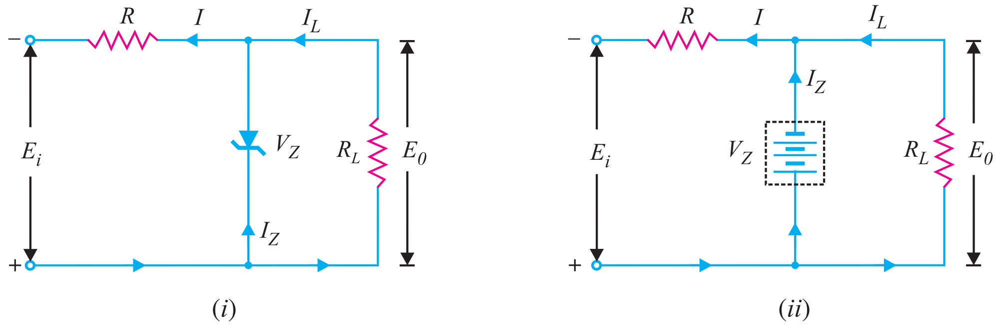


Fig. 6.56

When the circuit is properly designed, the load voltage E_0 remains essentially constant (equal to V_Z) even though the input voltage E_i and load resistance R_L may vary over a wide range.

(*i*) Suppose the input voltage increases. Since the zener is in the breakdown region, the zener diode is equivalent to a battery V_Z as shown in Fig. 6.56 (*ii*). It is clear that output voltage remains constant at V_Z (= E_0). The excess voltage is dropped across the series resistance R. This will cause an increase in the value of total current I. The zener will conduct the increase of current in I while the load current remains constant. Hence, output voltage E_0 remains constant irrespective of the changes in the input voltage E_i.

(*ii*) Now suppose that input voltage is constant but the load resistance R_L decreases. This will cause an increase in load current. The extra current cannot come from the source because drop in R (and hence source current I) will not change as the zener is within its regulating range. The additional load current will come from a decrease in zener current I_Z. Consequently, the output voltage stays at constant value.

$$\text{Voltage drop across } R = E_i - E_0$$

$$\text{Current through } R, I = I_Z + I_L$$