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Department of Physics

ANALOG ELECTRONICS

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Unit-I: Semi conductor & Rectifiers

5. Semiconductor Physics

INTRODUCTION

Certain substances like germanium, silicon, carbon etc. are neither good conductors like copper nor insulators like glass. In other words, the resistivity of these materials lies inbetween conductors and insulators. Such substances are classified as *semiconductors*. Semiconductors have some useful properties and are being extensively used in electronic circuits. For instance, *transistor*—a semiconductor device is fast replacing bulky vacuum tubes in almost all applications. Transistors are only one of the family of semiconductor devices ; many other semiconductor devices are becoming increasingly popular. In this chapter, we shall focus our attention on the different aspects of semiconductors.

5.1 Semiconductor

It is not easy to define a semiconductor if we want to take into account all its physical characteristics. However, generally, a semiconductor is defined on the basis of electrical conductivity as under :

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.*

The reader may wonder, when a semiconductor is neither a good conductor nor an insulator, then why not to classify it as a *resistance material* ? The answer shall be readily available if we study the following table :

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

Comparing the resistivities of above materials, it is apparent that the resistivity of germanium (semiconductor) is quite high as compared to copper (conductor) but it is quite low when compared with glass (insulator). This shows that resistivity of a semiconductor lies inbetween conductors and insulators. However, it will be wrong to consider the semiconductor as a resistance material. For example, nichrome, which is one of the highest resistance material, has resistivity much lower than germanium. This shows that electrically germanium cannot be regarded as a conductor or insulator or a resistance material. This gave such substances like germanium the name of semiconductors.

It is interesting to note that it is not the resistivity alone that decides whether a substance is semiconductor or not. For example, it is just possible to prepare an alloy whose resistivity falls within the range of semiconductors but the alloy cannot be regarded as a semiconductor. In fact, semiconductors have a number of peculiar properties which distinguish them from conductors, insulators and resistance materials.

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. This property is most important and is discussed later in detail.

5.2 Bonds in Semiconductors

The atoms of every element are held together by the bonding action of valence electrons. This bonding is due to the fact that it is the tendency of each atom to complete its last orbit by acquiring 8 electrons in it. However, in most of the substances, the last orbit is incomplete *i.e.* the last orbit does not have 8 electrons. This makes the atom active to enter into bargain with other atoms to acquire 8 electrons in the last orbit. To do so, the atom may lose, gain or share valence electrons with other atoms. In semiconductors, bonds are formed by sharing of valence electrons. Such bonds are called *co-valent bonds*. 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.

5.5 Energy Band Description of Semiconductors

It has already been discussed that a semiconductor is a substance whose resistivity lies between conductors and insulators. The resistivity is of the order of 10^{-4} to 0.5 ohm metre. However, a semiconductor can be defined much more comprehensively on the basis of energy bands as under :

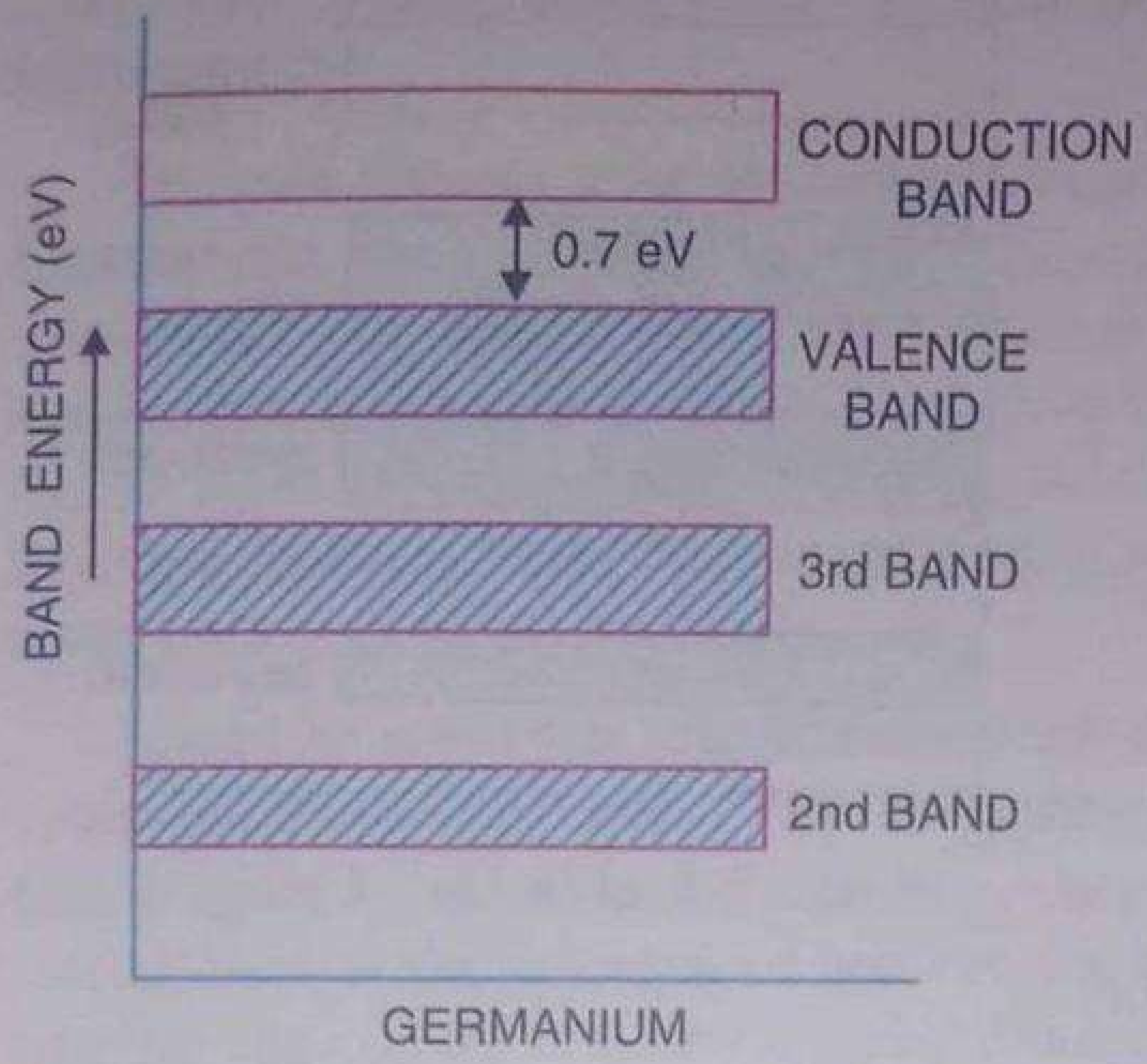


Fig. 5.4

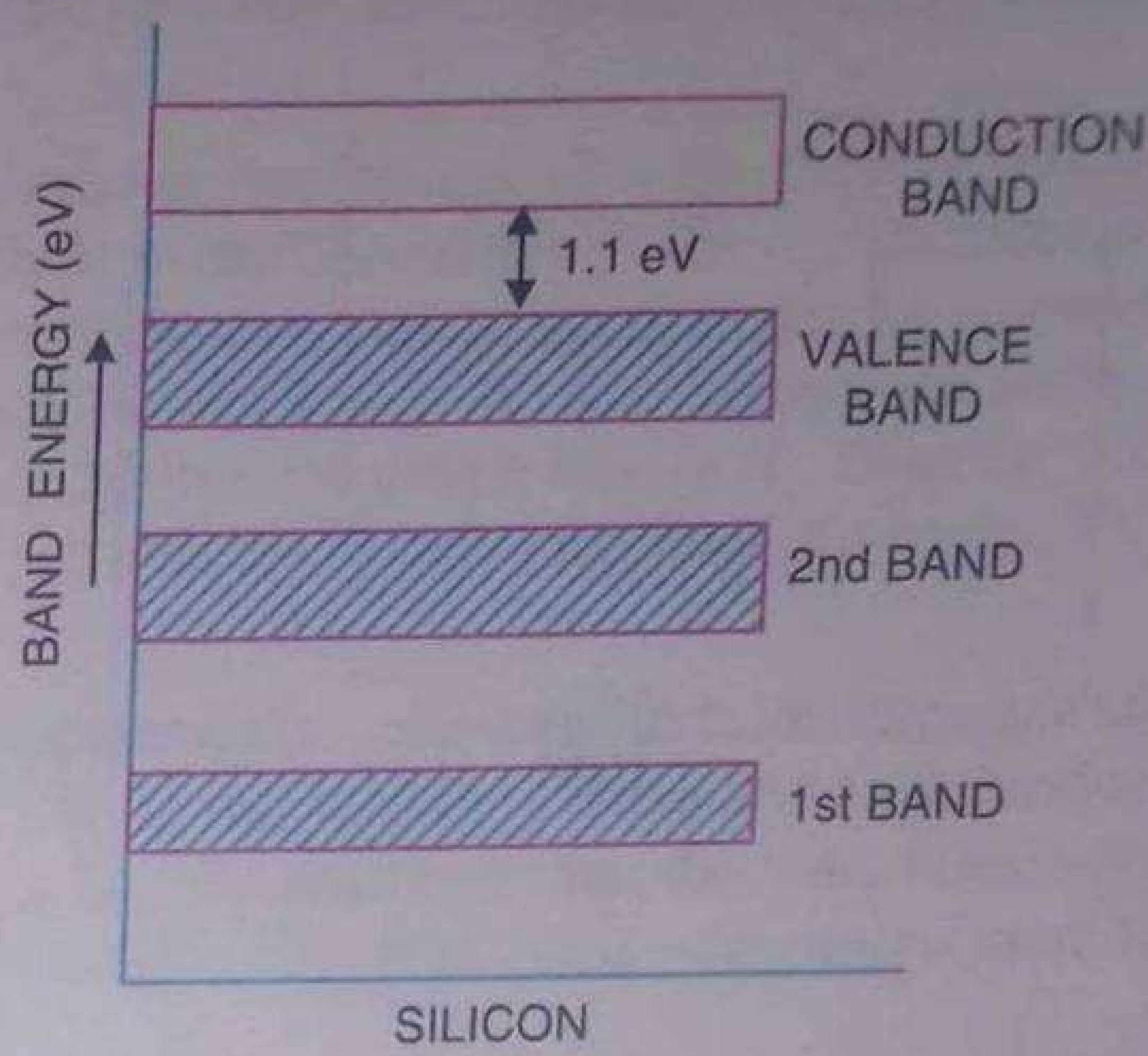


Fig. 5.5

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

Figs. 5.4 and 5.5 show the energy band diagrams of germanium and silicon respectively. It may be seen that forbidden energy gap is very small; being 1.1 eV for silicon and 0.7 eV for germanium. Therefore, relatively small energy is needed by their valence electrons to cross over to the conduction band. Even at room temperature, some of the valence electrons may acquire sufficient energy to enter into the conduction band and thus become free electrons. However, at this temperature, the number of free electrons available is very *small. Therefore, at room temperature, a piece of germanium or silicon is neither a good conductor nor an insulator. For this reason, such substances are called *semiconductors*.

The energy band description is extremely helpful in understanding the current flow through a semiconductor. Therefore, we shall frequently use this concept in our further discussion.

5.6 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 [See Fig. 5.6 (*i*)].

In terms of energy band description, the valence band is filled and there is a large energy gap between valence band and conduction band. Therefore, no valence electron can reach the conduction band to become free electron. It is due to the non-availability of free electrons that a semiconductor behaves as an insulator.

* Out of 10^{10} semiconductor atoms, one atom provides a free electron.

(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 [See Fig. 5.7 (*i*)]. *This shows that the resistance of a semiconductor decreases with the rise in temperature* *i.e.* it has negative temperature coefficient of resistance. It may be added that at room temperature, current through a semiconductor is too small to be of any practical value.

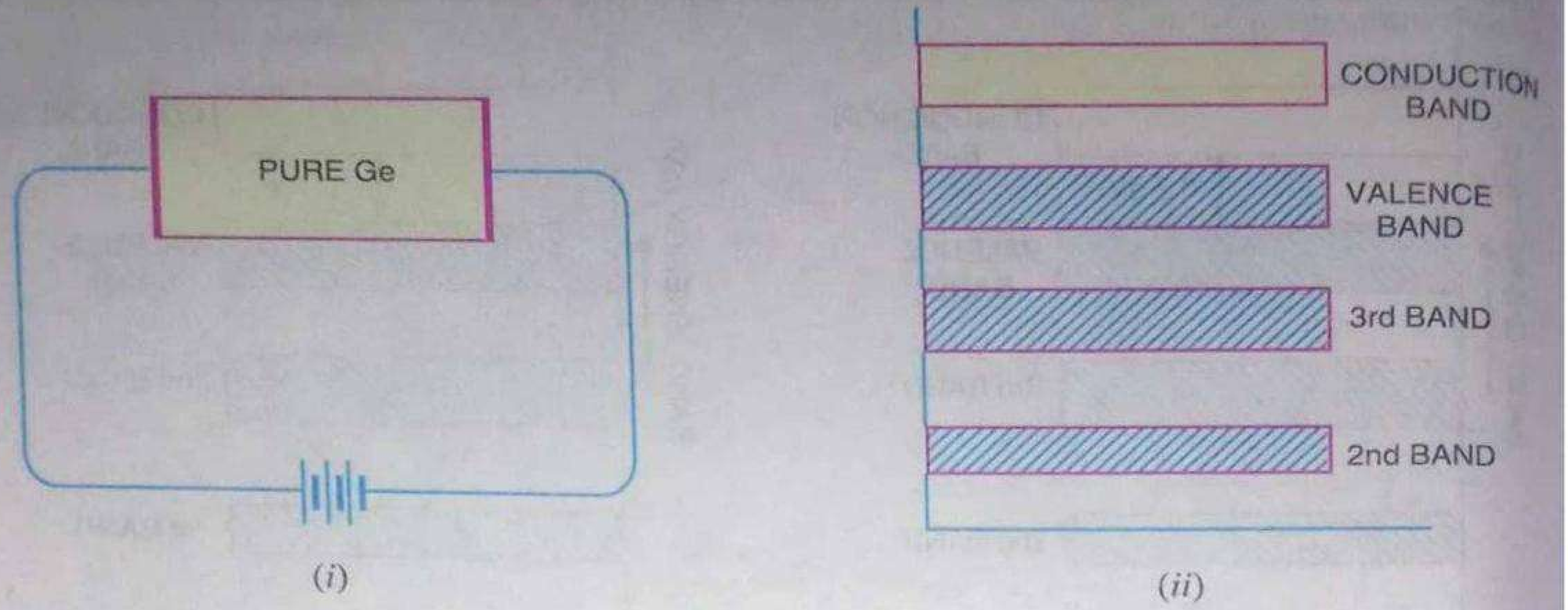


Fig. 5.6

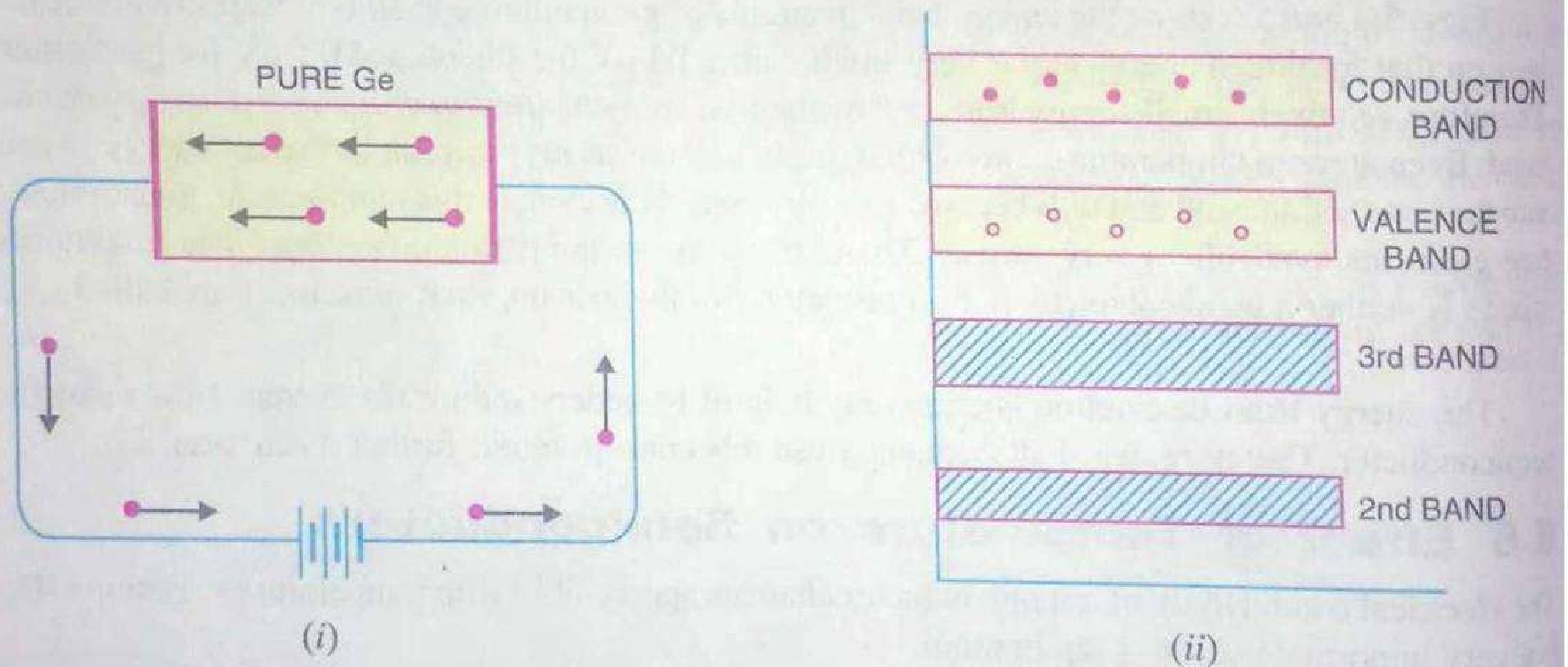


Fig. 5.7

Fig. 5.7 (*ii*) shows the energy band diagram. As the temperature is raised, some of the valence electrons acquire sufficient energy to enter into the conduction band and thus become free electrons. Under the influence of electric field, these free electrons will constitute electric current. It may be noted that each time a valence electron enters into the conduction band, a *hole* is created in the valence band. As we shall see in the next article, holes also contribute to current. In fact, hole current is the most significant concept in semiconductors.

5.7 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 t 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*, there being as many holes as the free electrons. The current conduction by holes can be explained as follows :

The hole shows a missing electron. Suppose the valence electron at *L* (See Fig. 5.8) has become free electron due to thermal energy. This creates a hole in the co-valent bond at *L*. The hole is a strong centre of attraction **for the electron. A valence electron (say at *M*) from nearby co-valent bond comes to fill in the hole at *L*. This results in the creation of hole at *M*. Another valence electron (say at *N*) in turn may leave its bond to fill the hole at *M*, thus creating a hole at *N*. Thus the hole having a positive charge has moved from *L* to *N i.e.* towards the negative terminal of supply. This constitutes *hole current*.

It may be noted that hole current is due to the movement of ***valence electrons from one co-valent bond to another bond. The reader may wonder why to call it a hole current when the conduction is again by electrons (of course *valence electrons* !). The answer is that the basic reason for current flow is the presence of holes in the co-valent bonds. Therefore, it is more appropriate to consider the current as the movement of holes.

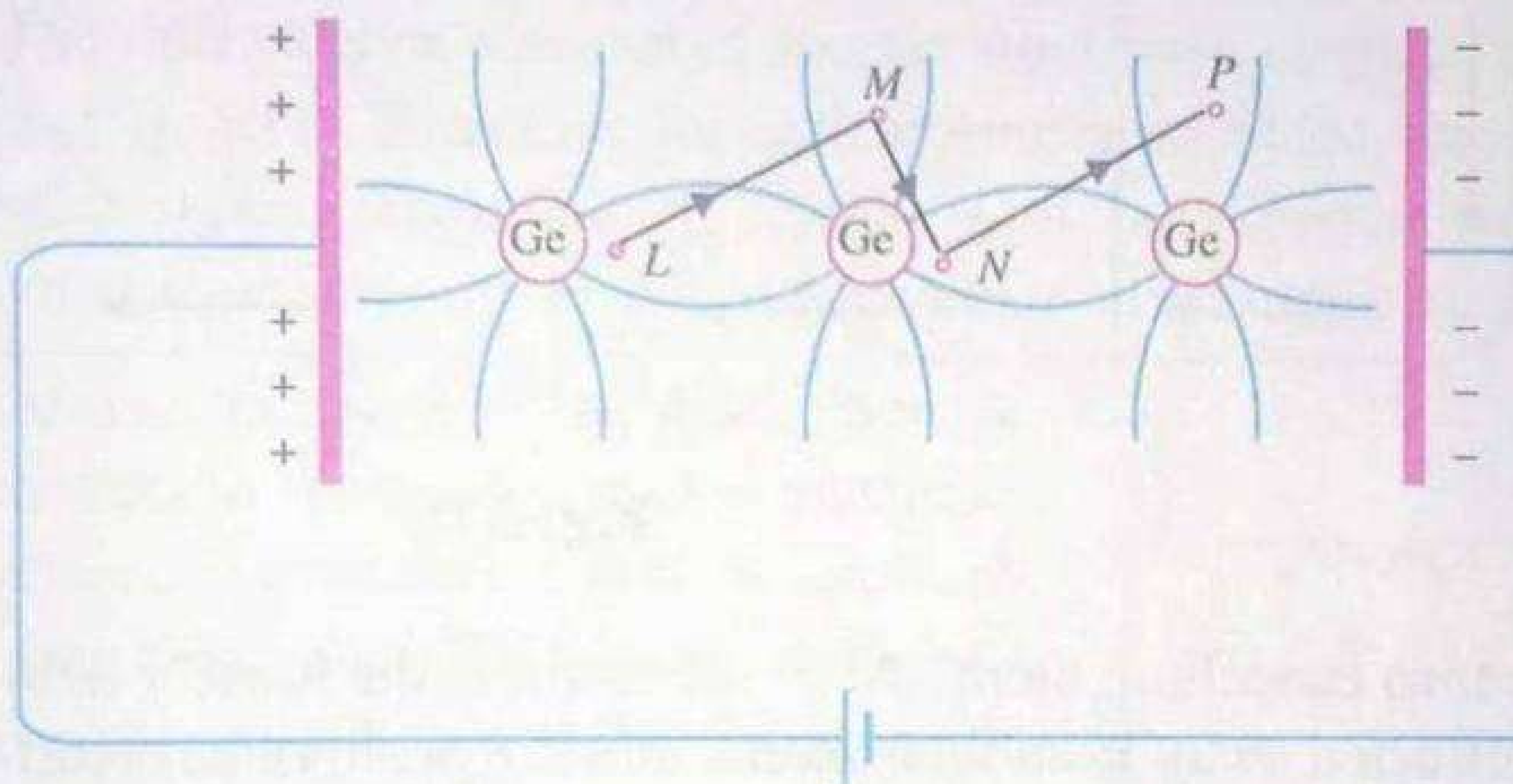


Fig. 5.8

Energy band description. The hole current can be beautifully explained in terms of energy bands. Suppose due to thermal energy, an electron leaves the valence band to enter into the conduction band as shown in Fig. 5.9.

This leaves a vacancy at *L*. Now the valence electron at *M* comes to fill the hole at *L*. The result is that hole disappears at *L* and appears at *M*. Next, the valence electron at *N* moves into the hole at *M*. Consequently, hole is created at *N*. It is clear that valence electrons move along the path *PNML* whereas holes move in the opposite direction *i.e.* along the path *LMNP*.

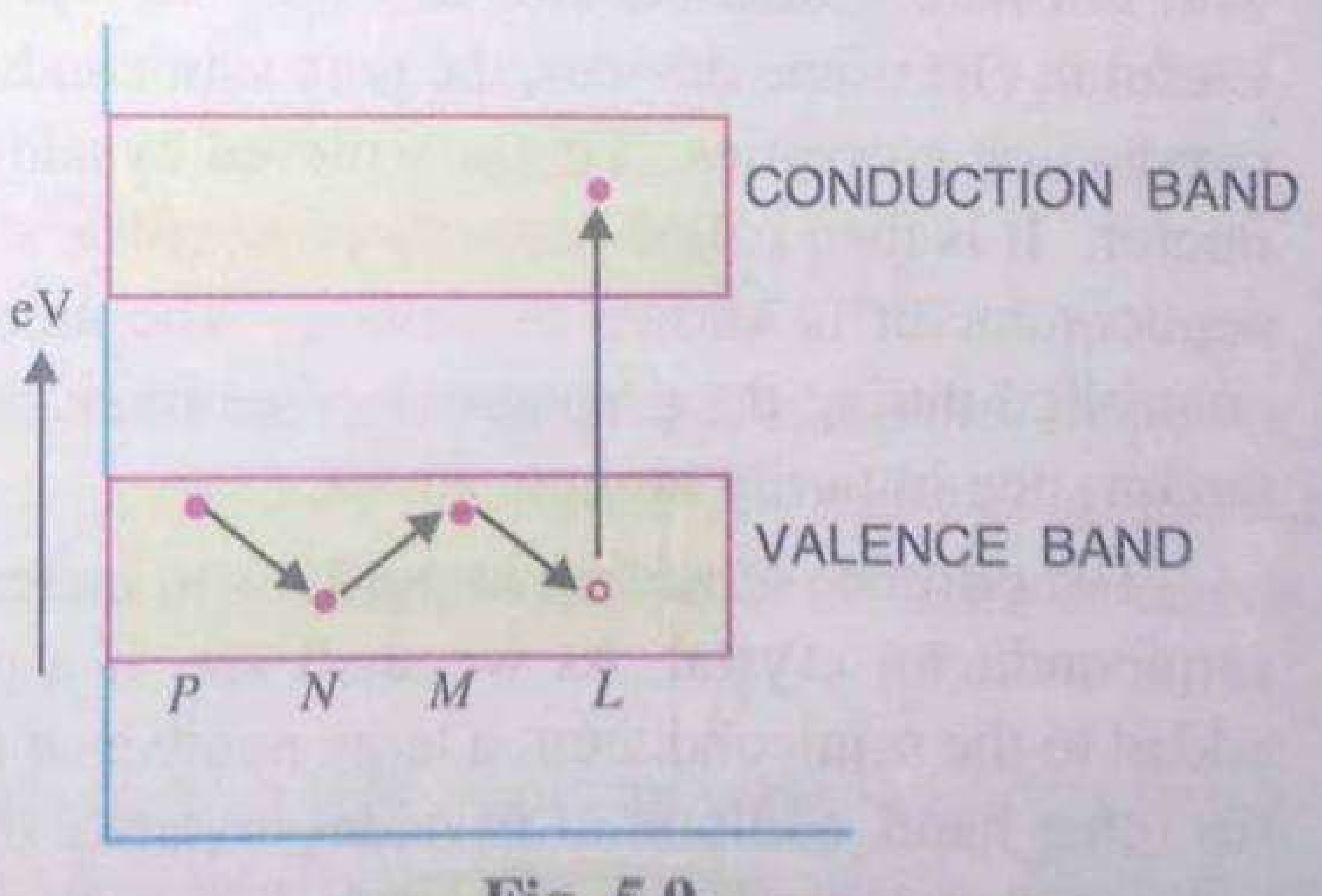


Fig. 5.9

* Note that hole acts as a virtual charge, although there is no physical charge on it.

** There is a strong tendency of semiconductor crystal to form co-valent bonds. Therefore, a hole attracts an electron from the neighbouring atom.

*** Unlike the normal current which is by free electrons.

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.

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.

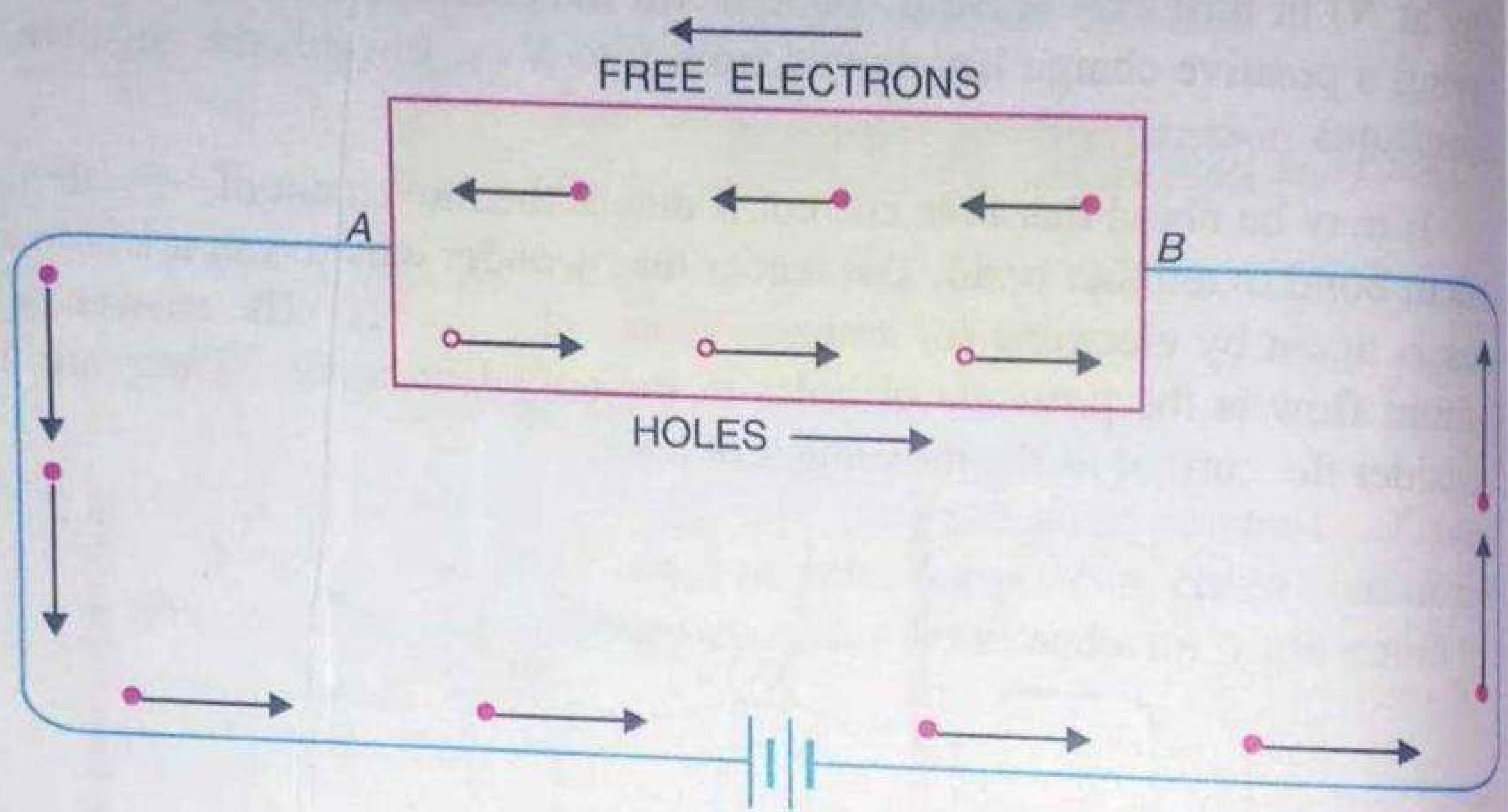


Fig. 5.10

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.**

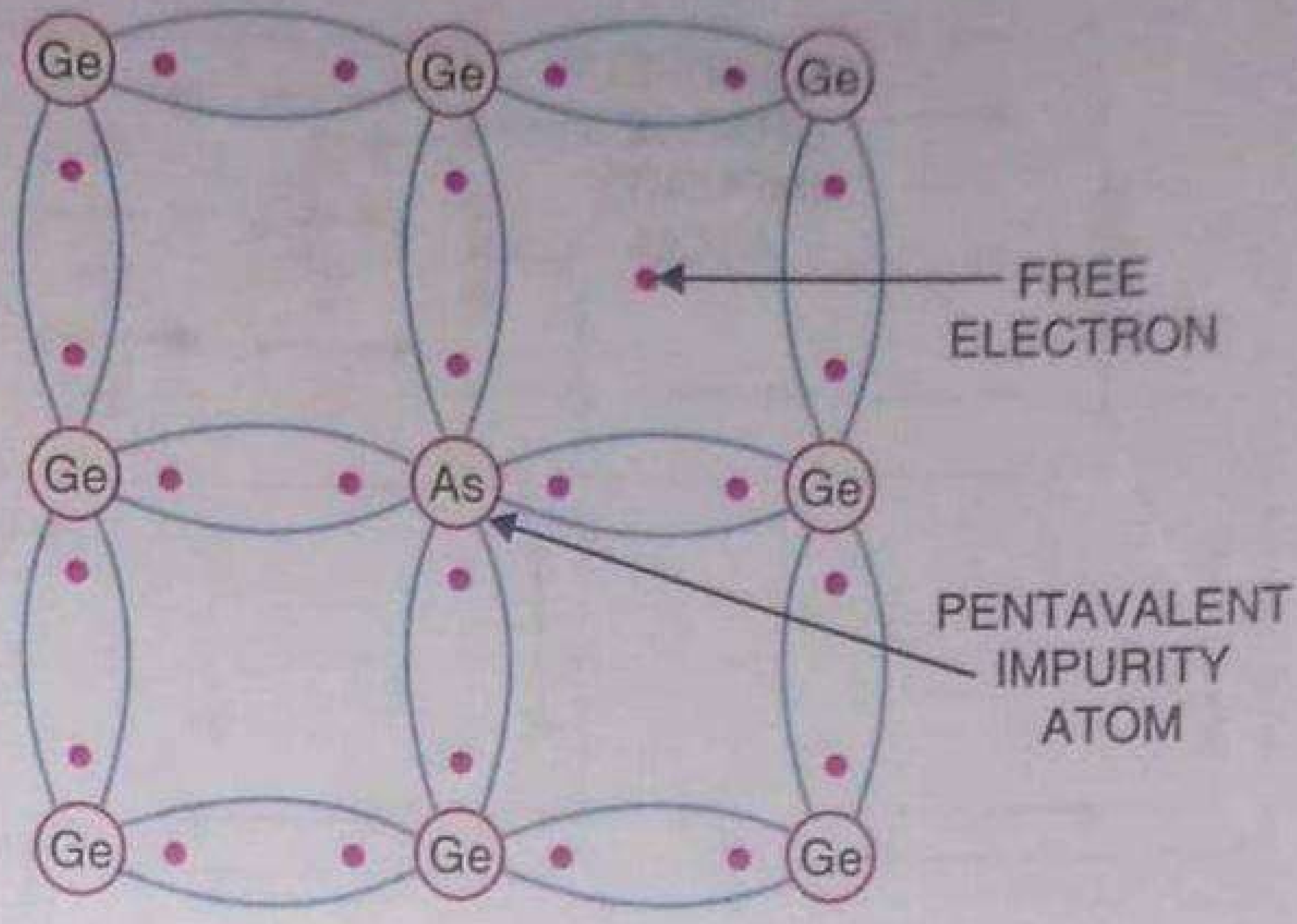


Fig. 5.11

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.

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.

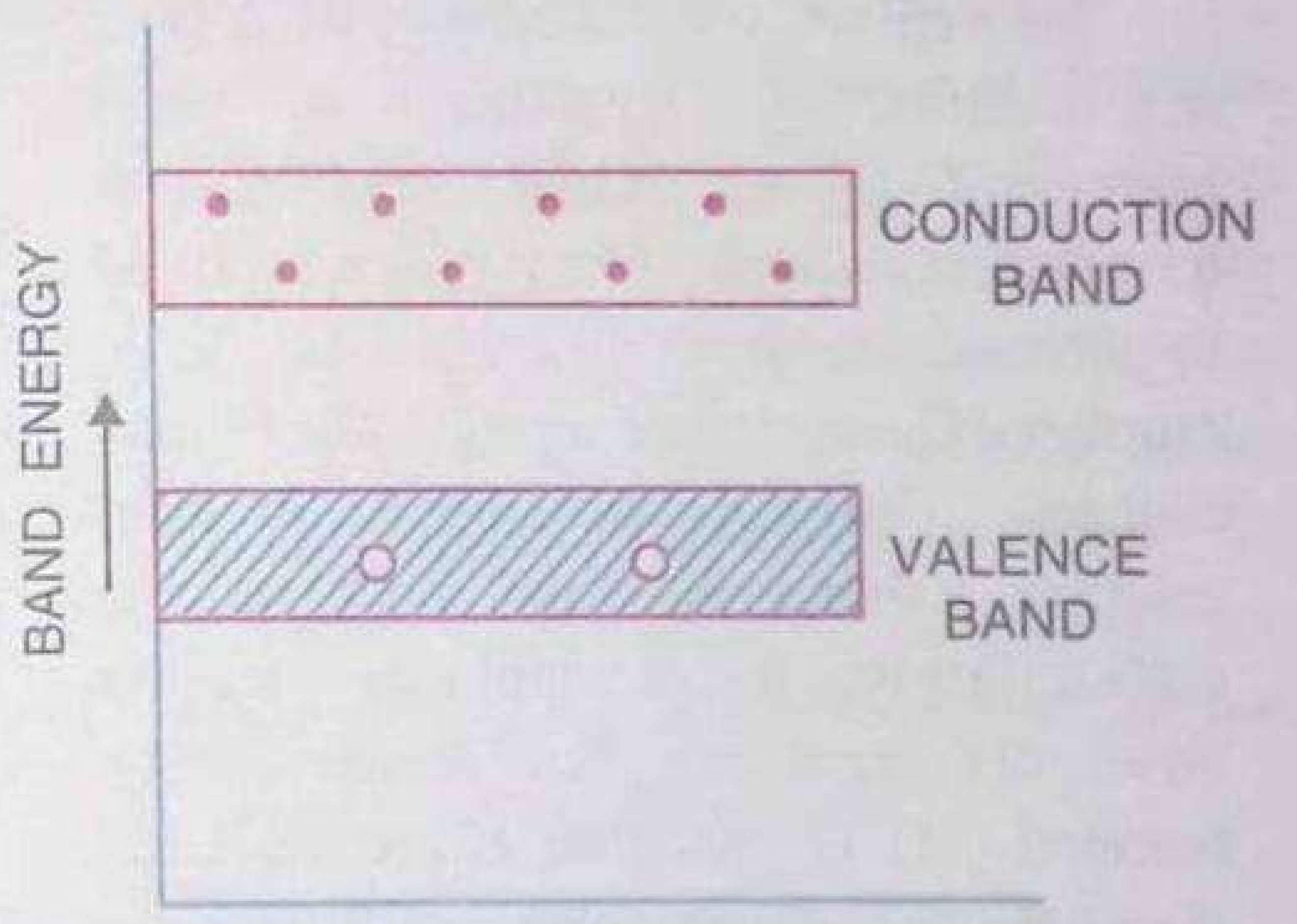


Fig. 5.12

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 :

(*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.

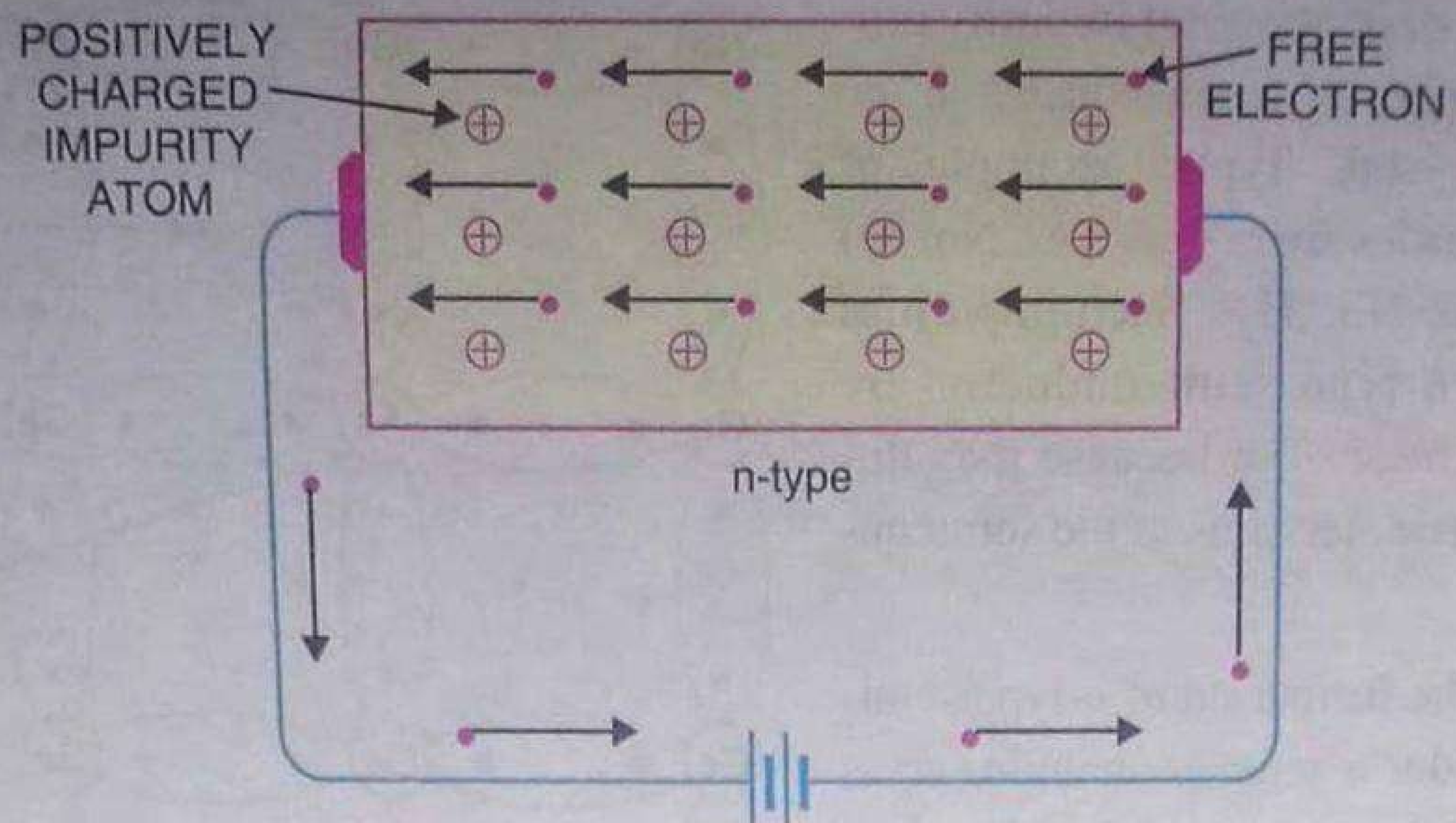


Fig. 5.13

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.

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.

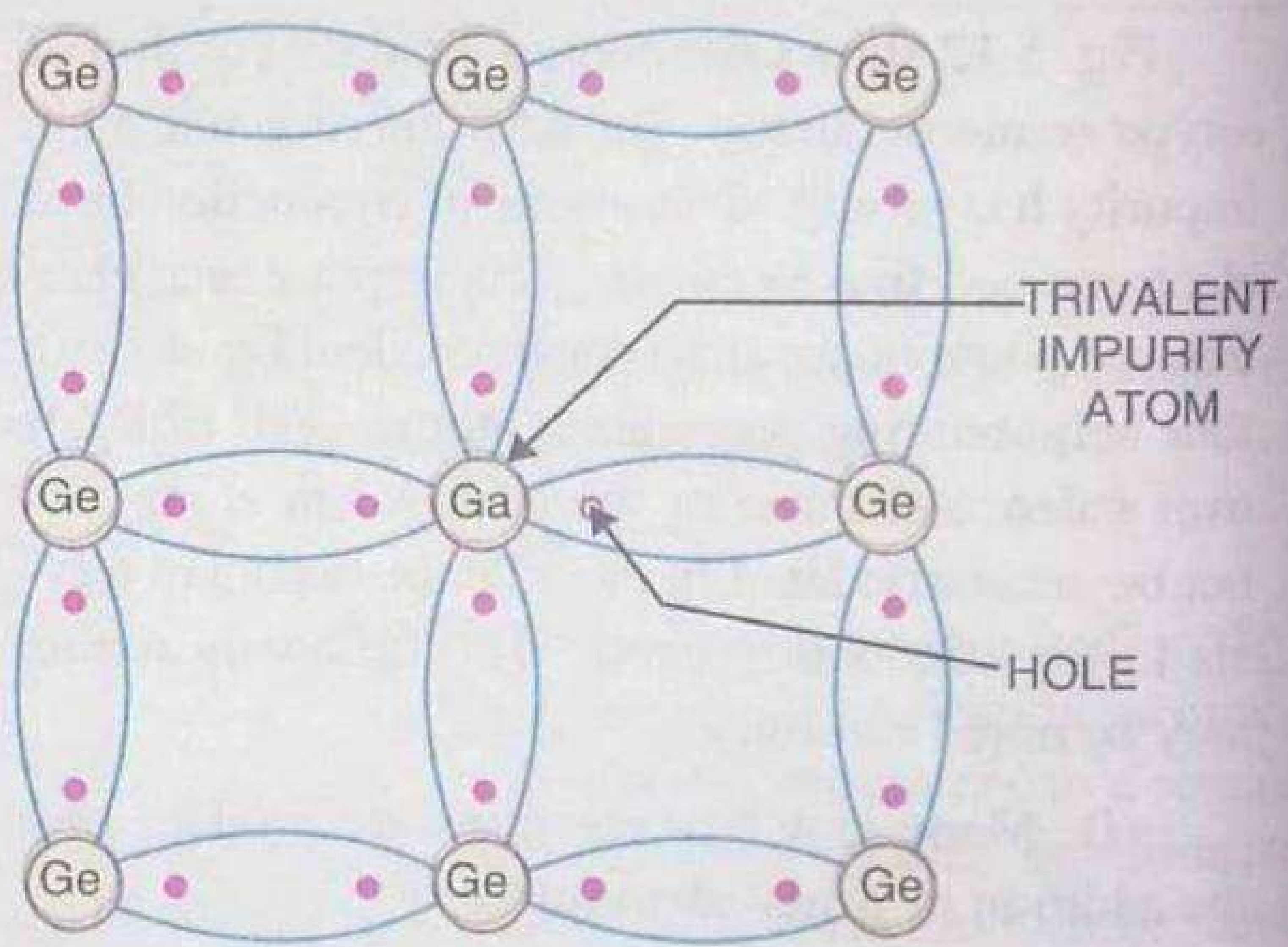


Fig. 5.14

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).

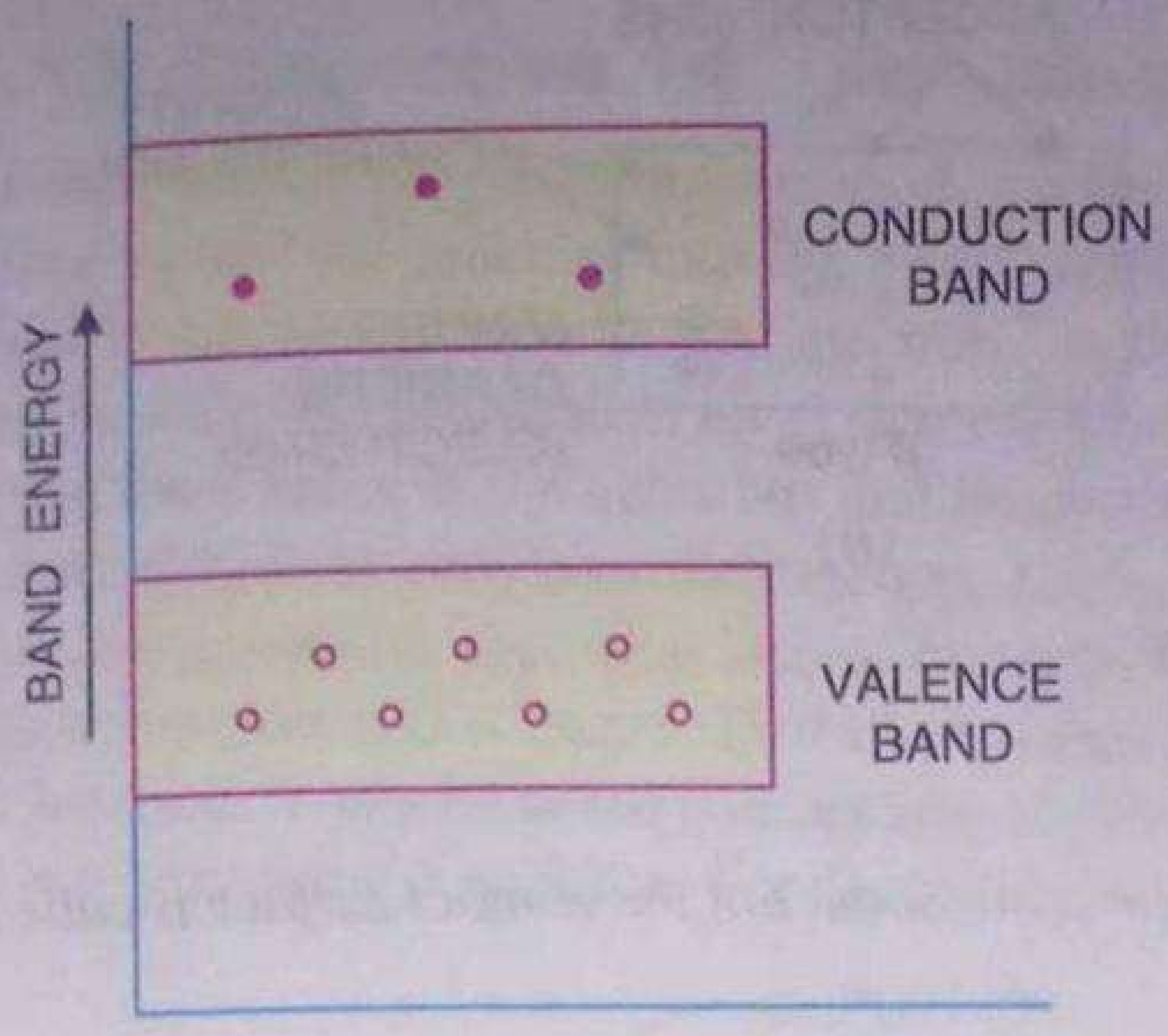


Fig. 5.15

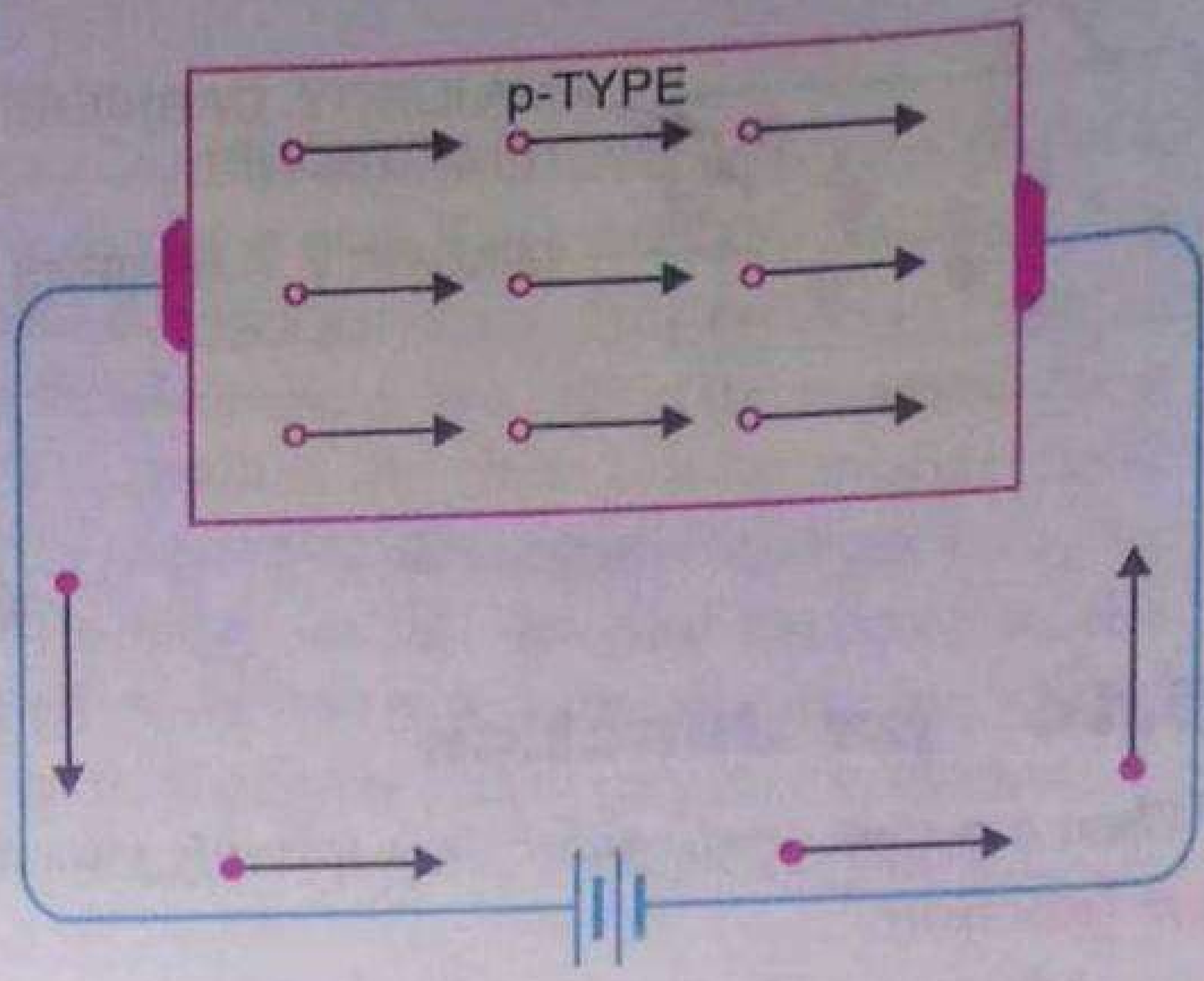


Fig. 5.16

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.

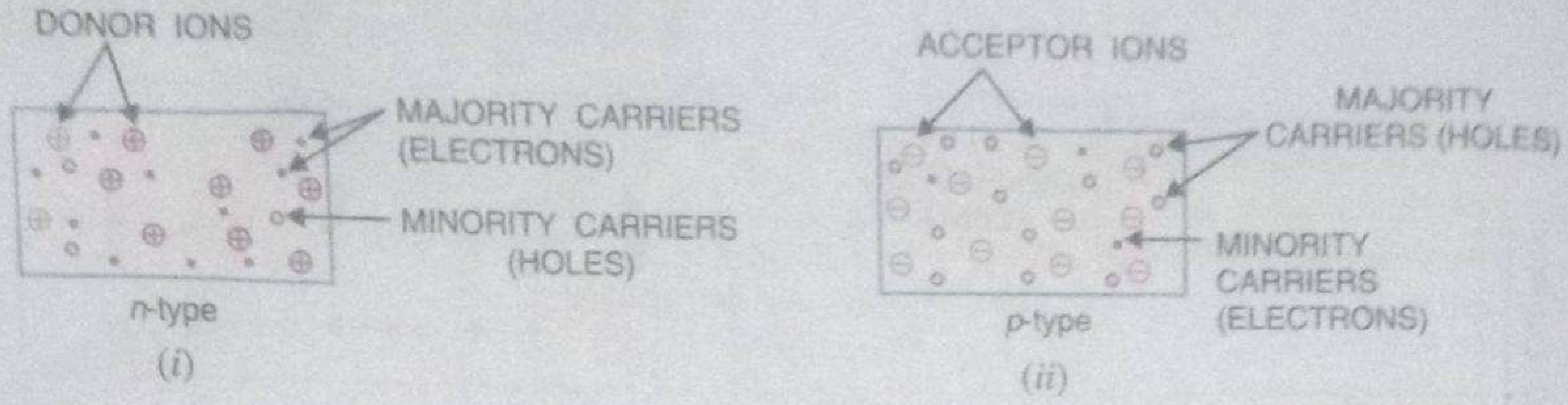


Fig. 5.17

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 500°C. 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.

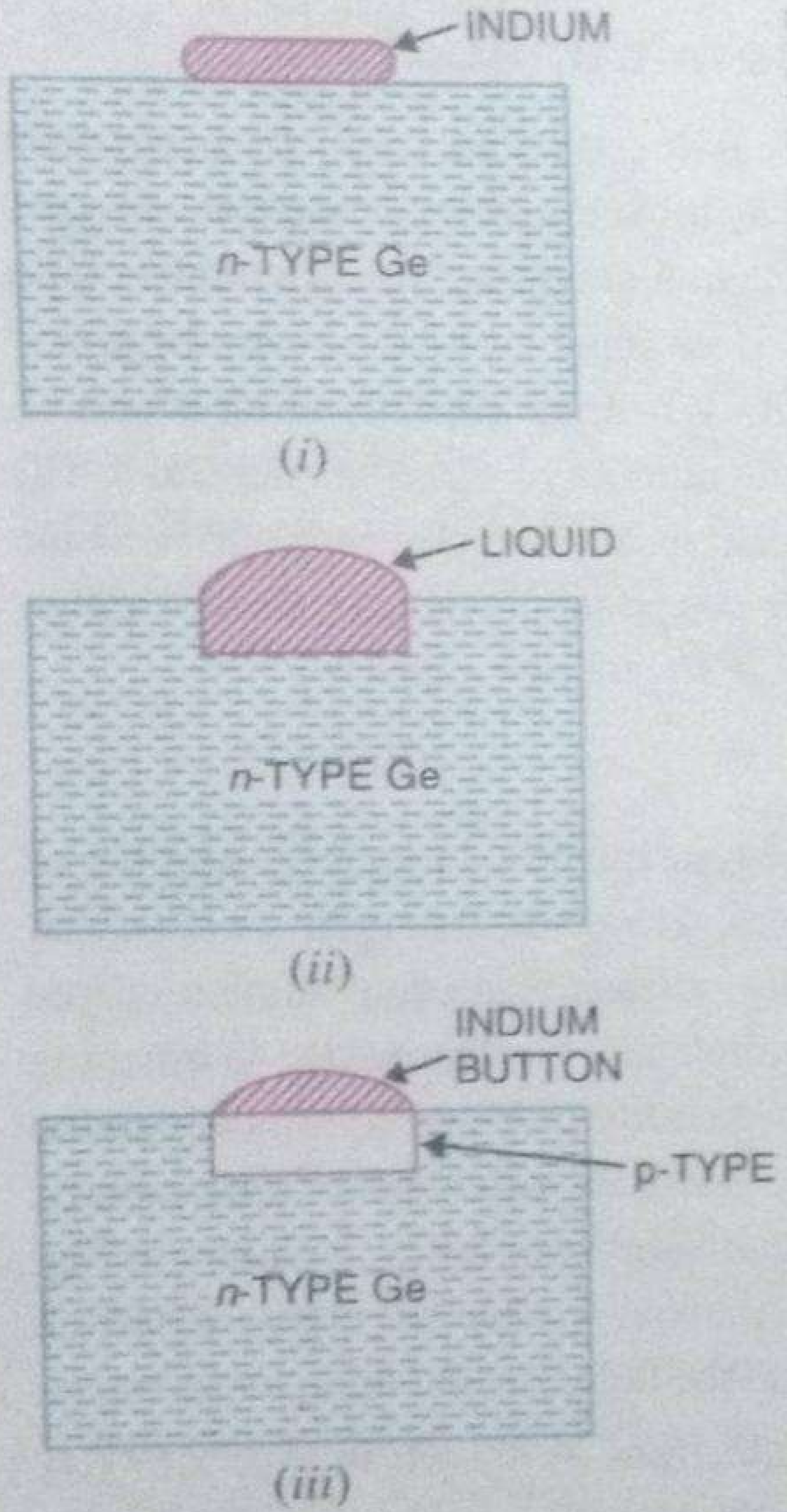
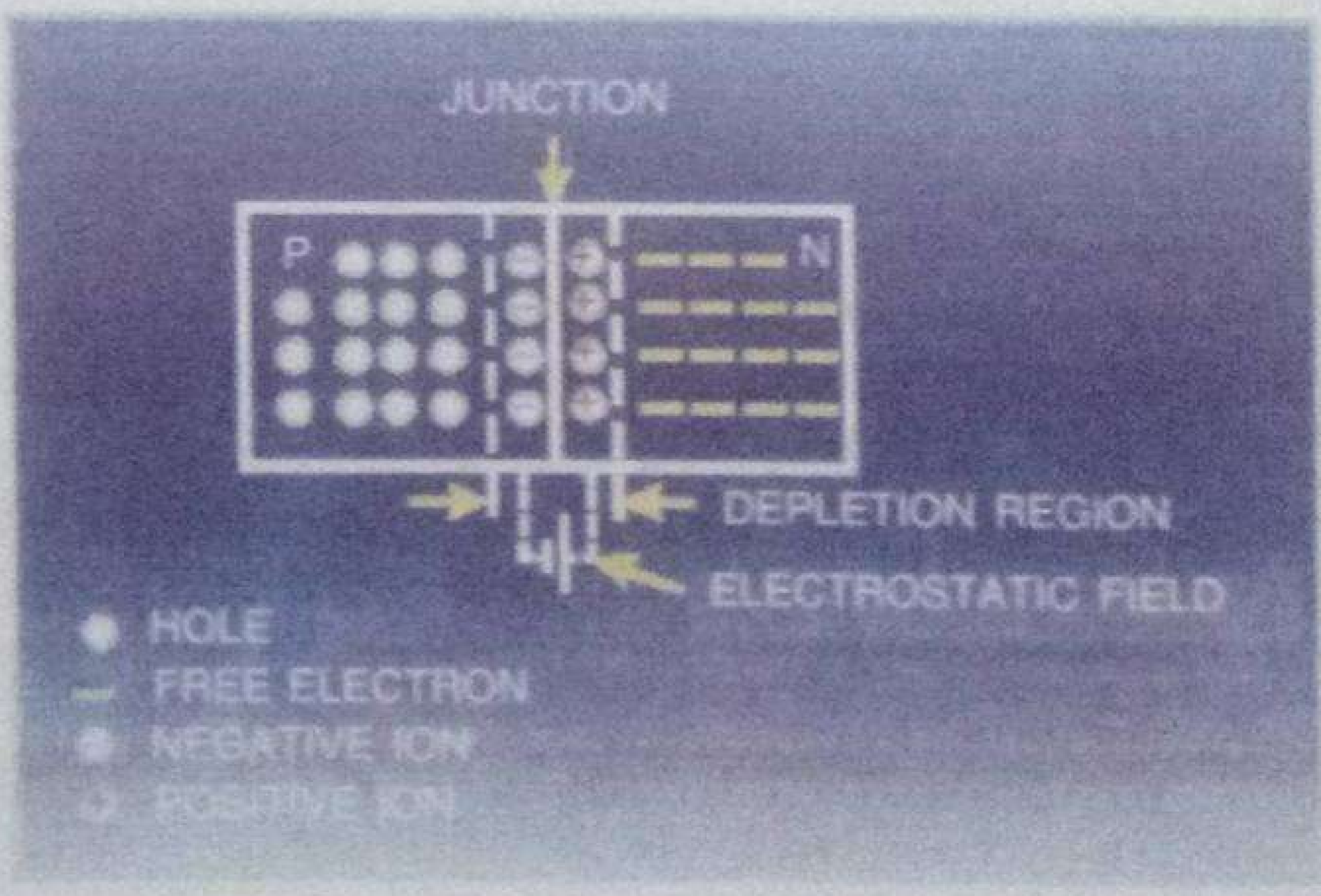


Fig. 5.18



5.16 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.

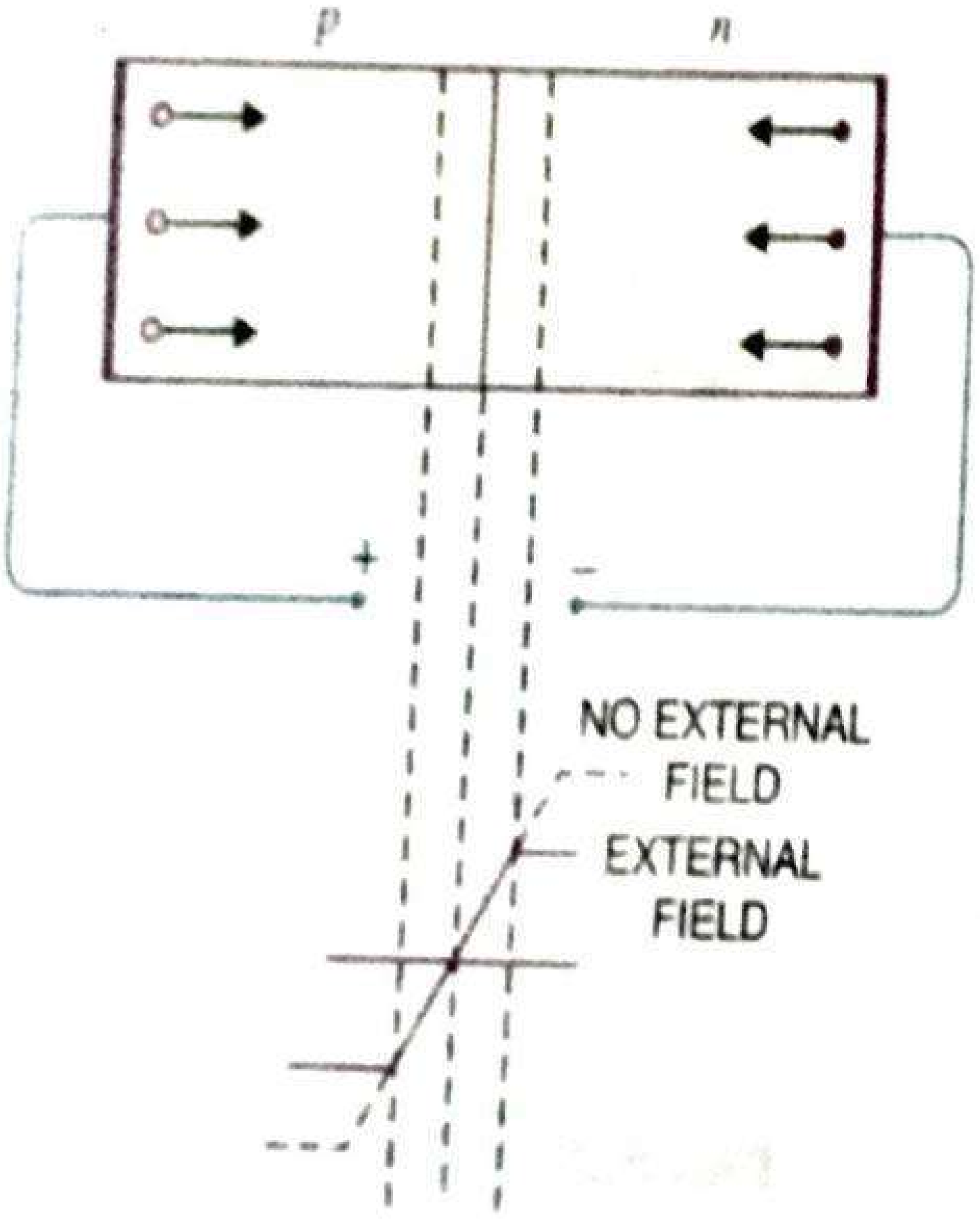


Fig. 5.21

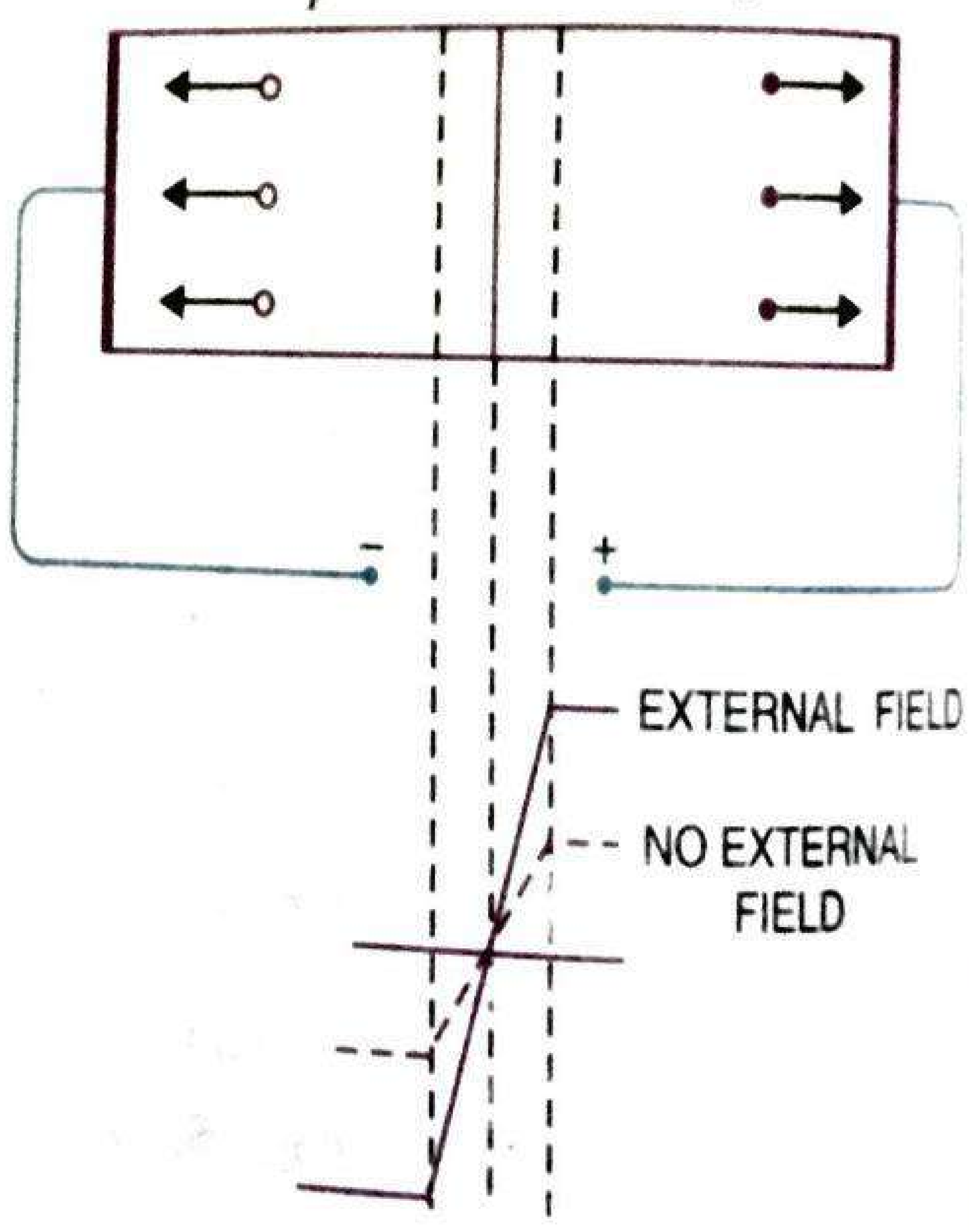


Fig. 5.22

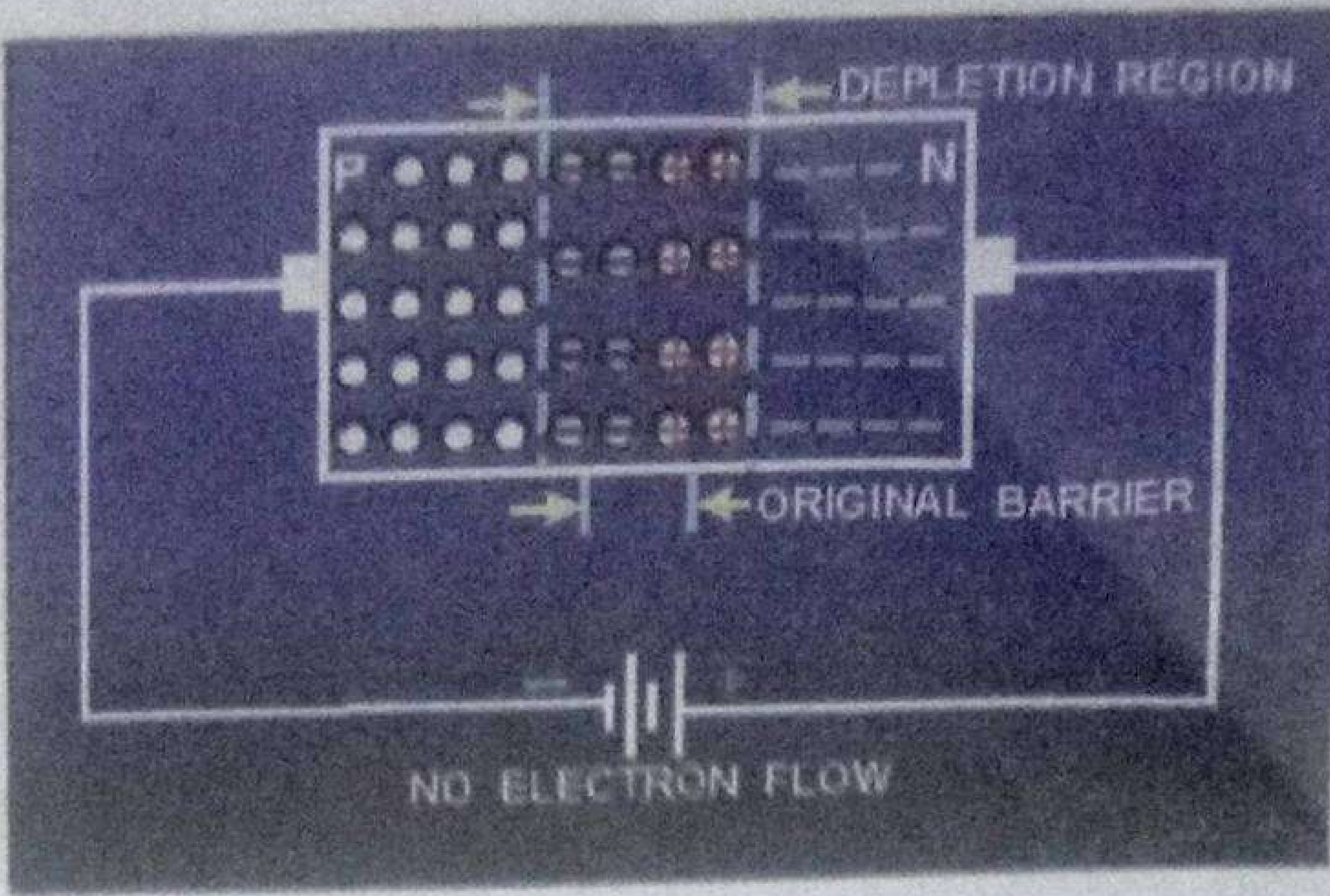
2. Reverse biasing. *When the external d.c. voltage applied to the junction is in such a direction that potential barrier is increased, it is called* **reverse biasing.**

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.

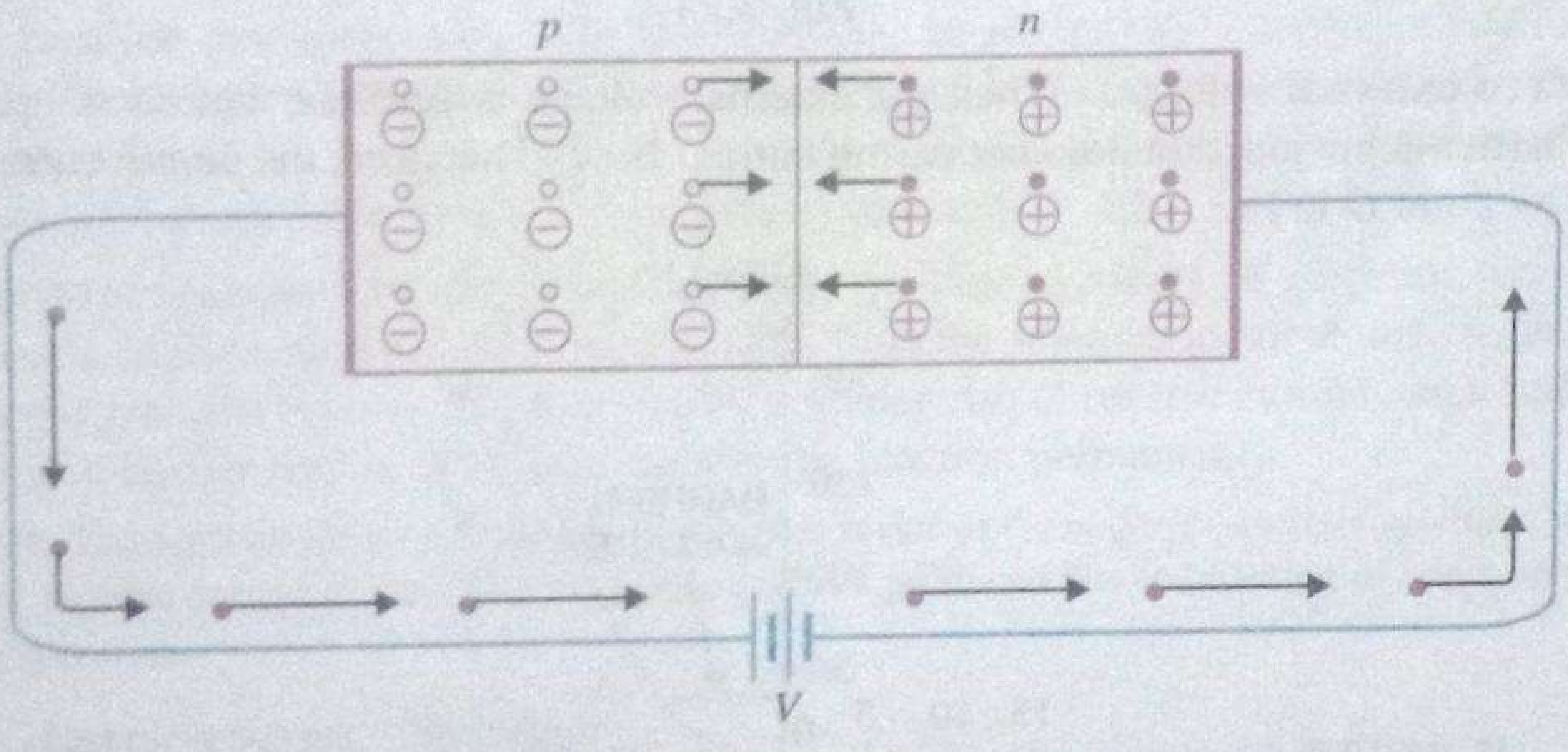


Fig. 5.23

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.

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*.

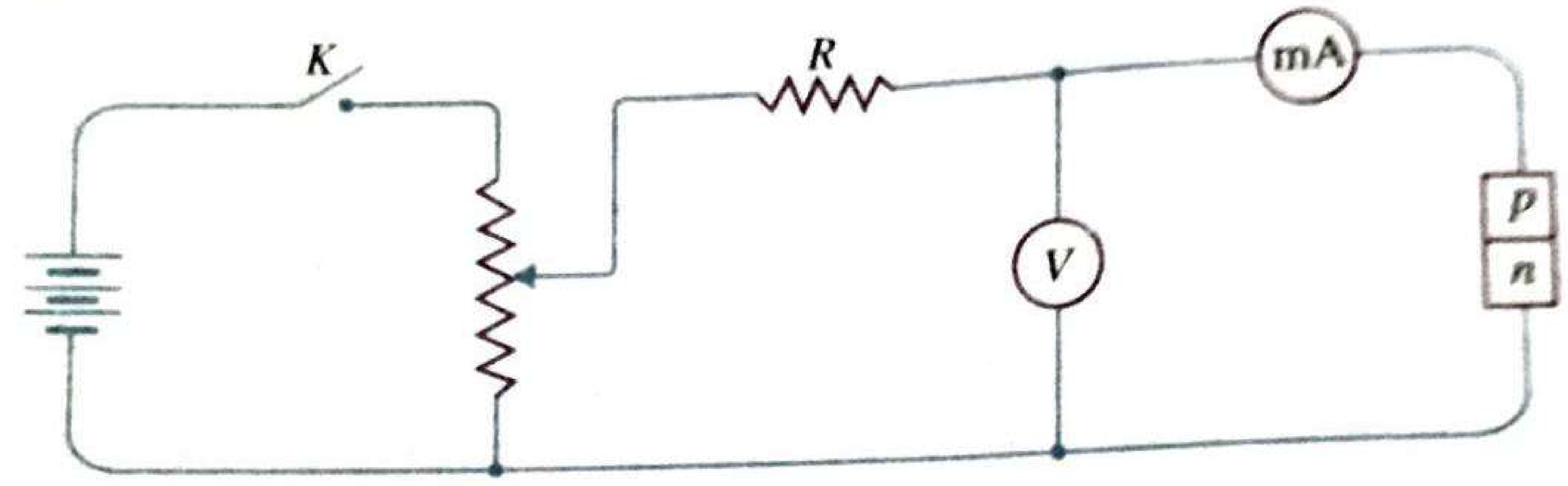


Fig. 5.24

(*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.

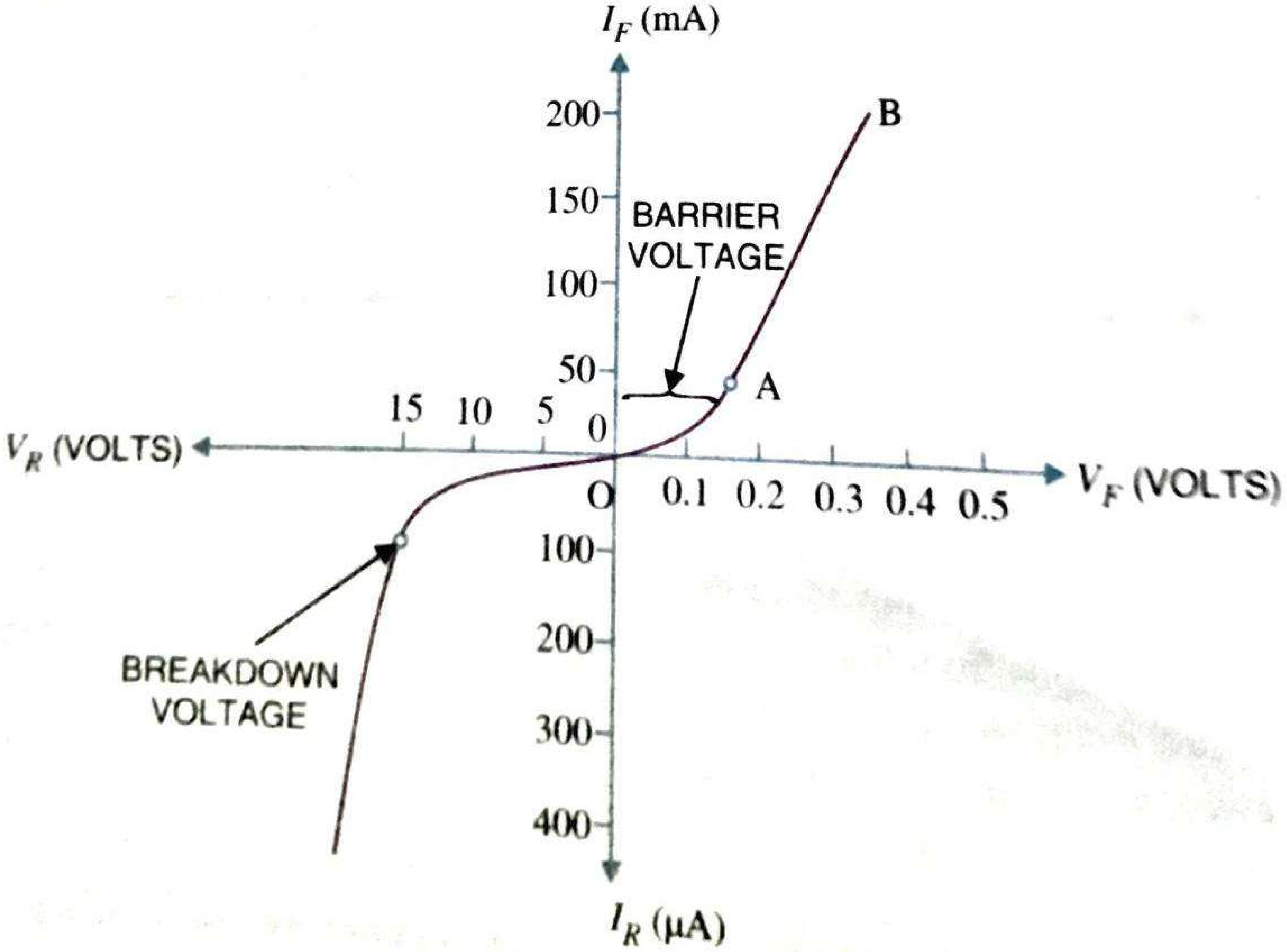


Fig. 5.25

* *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 μA) 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.

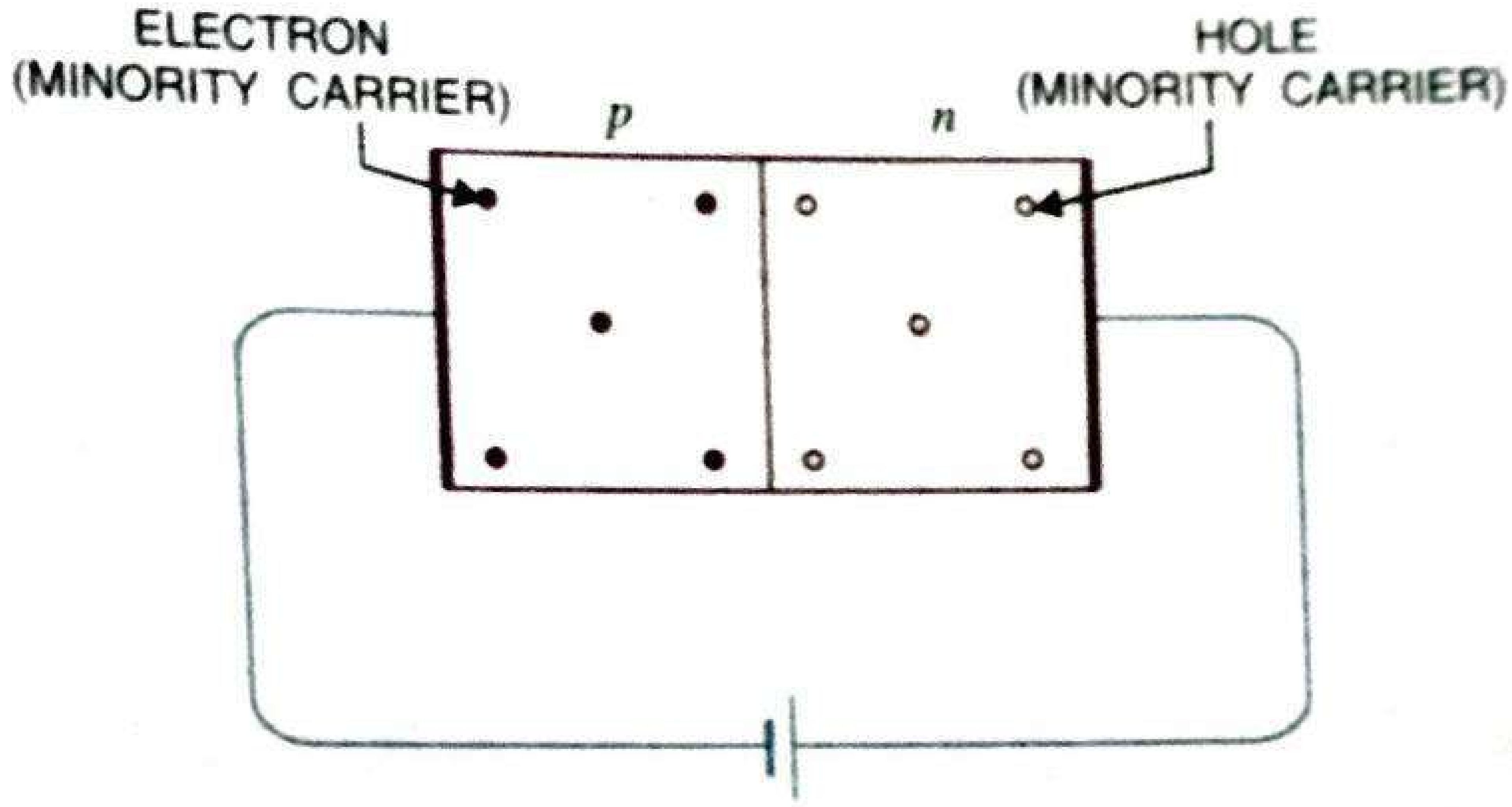


Fig. 5.26

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.

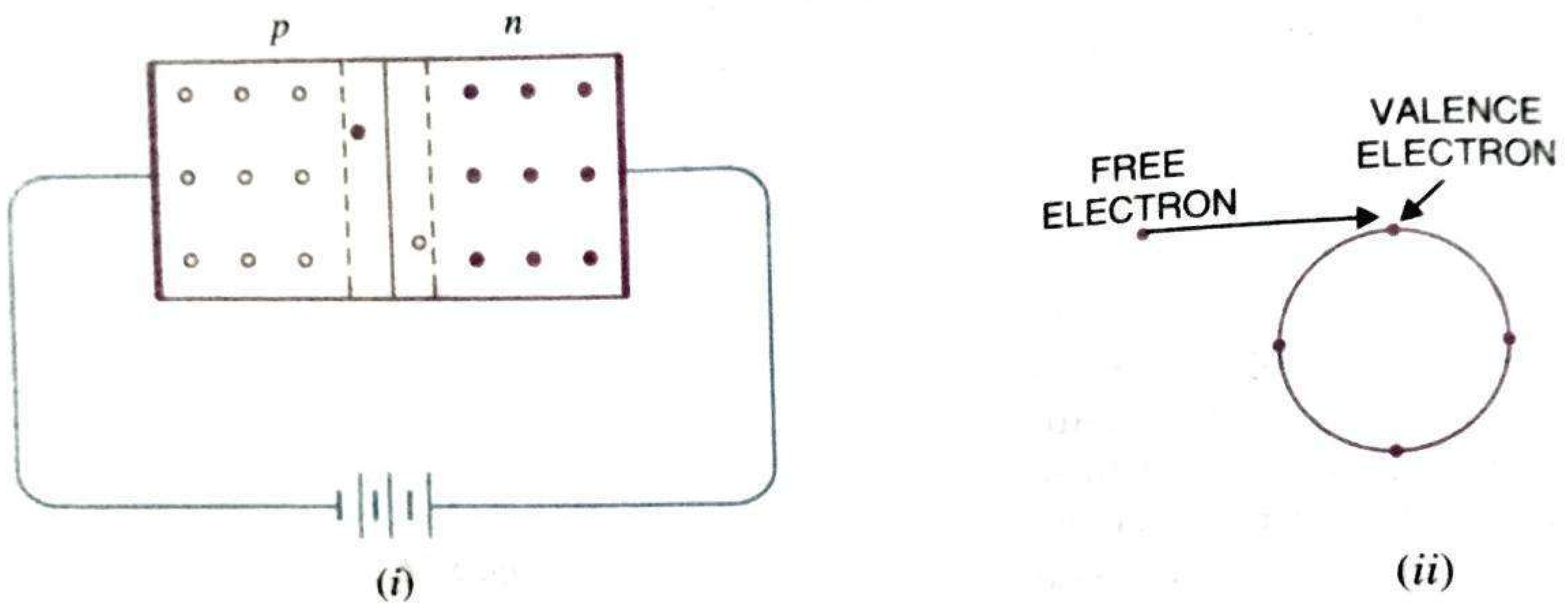


Fig. 5.27

(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.

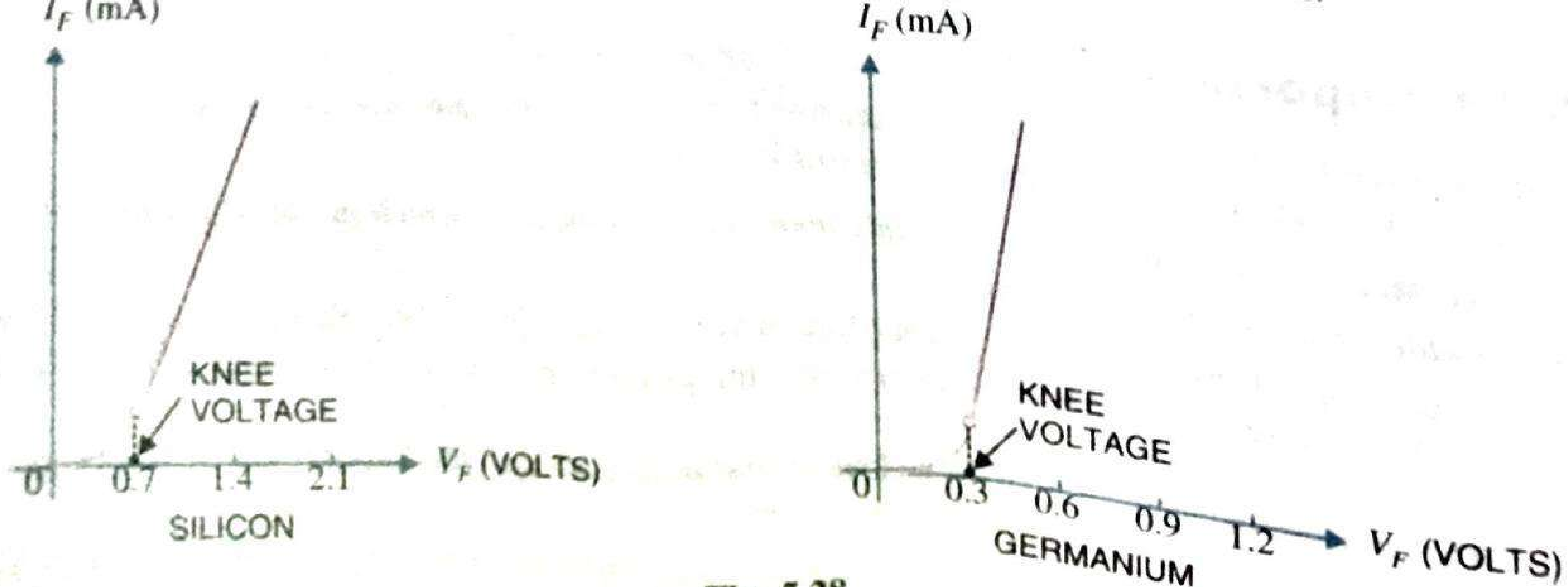


Fig. 5.28

(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.

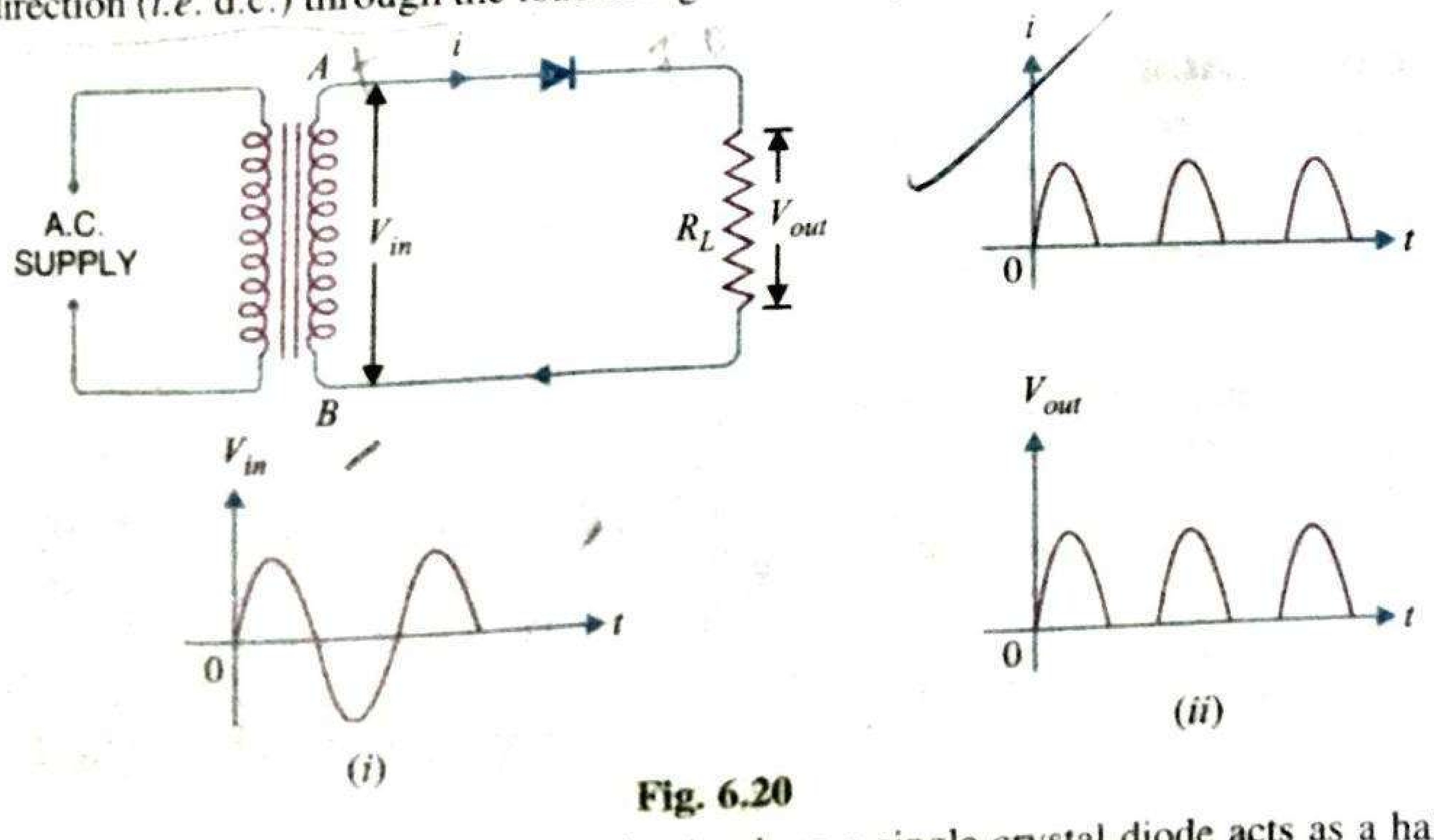


Fig. 6.20

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.

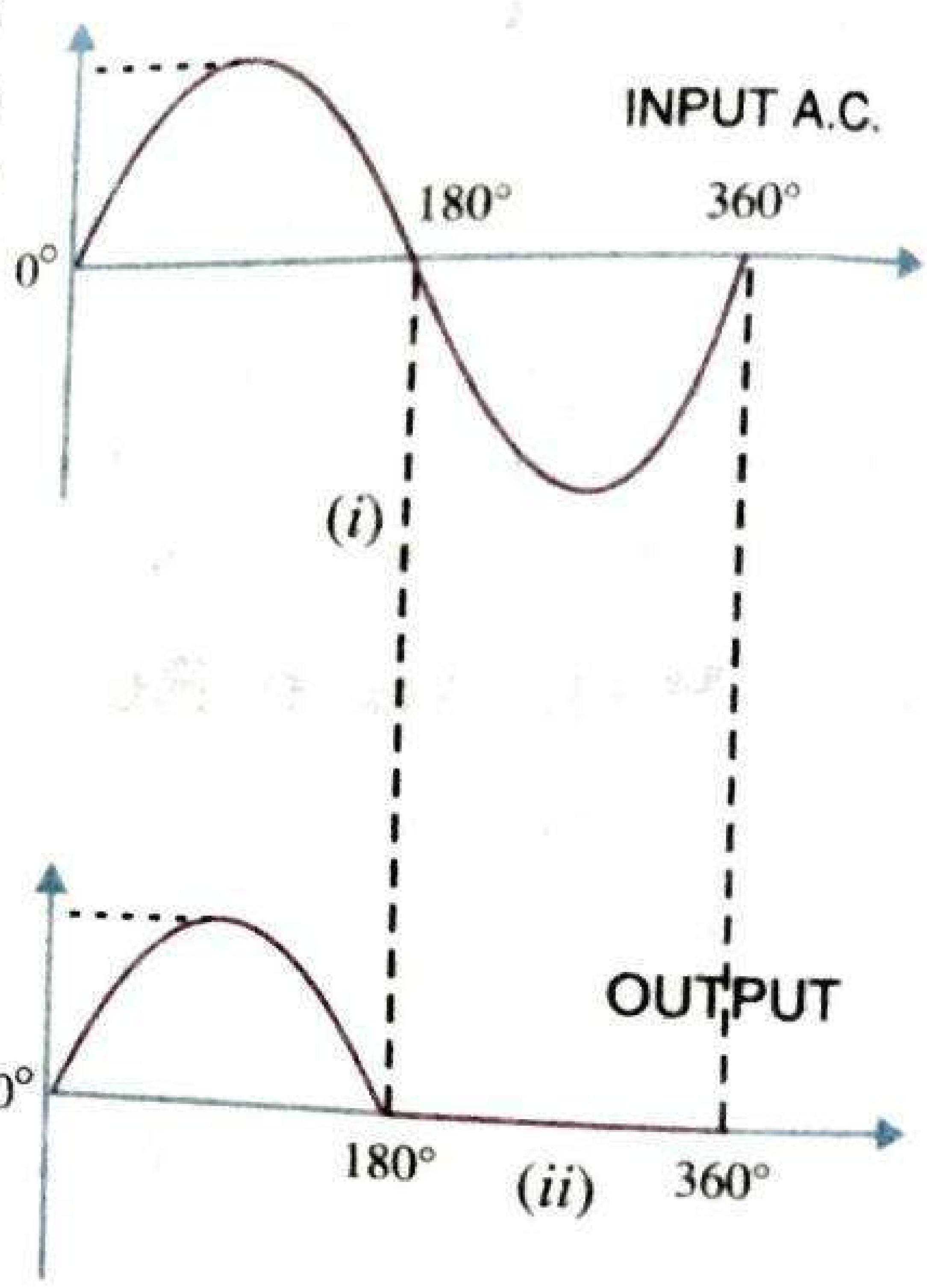


Fig. 6.21

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.*

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

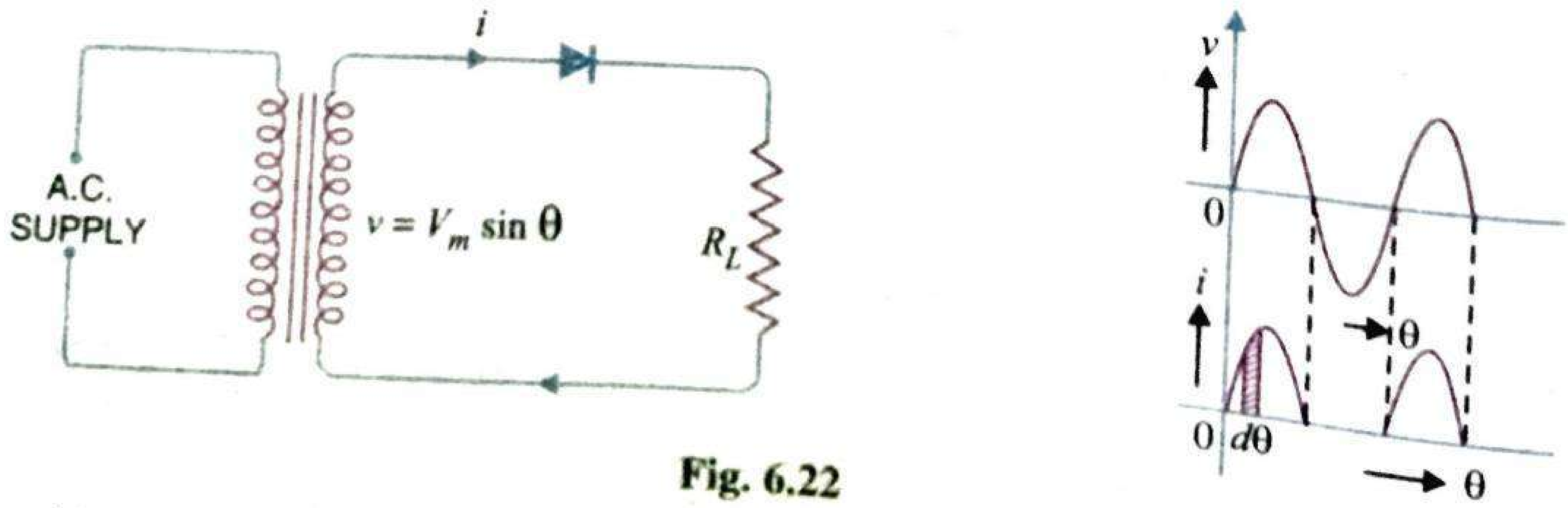


Fig. 6.22

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, $I_{rms} = I_m/2$

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

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

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

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.

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.

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.

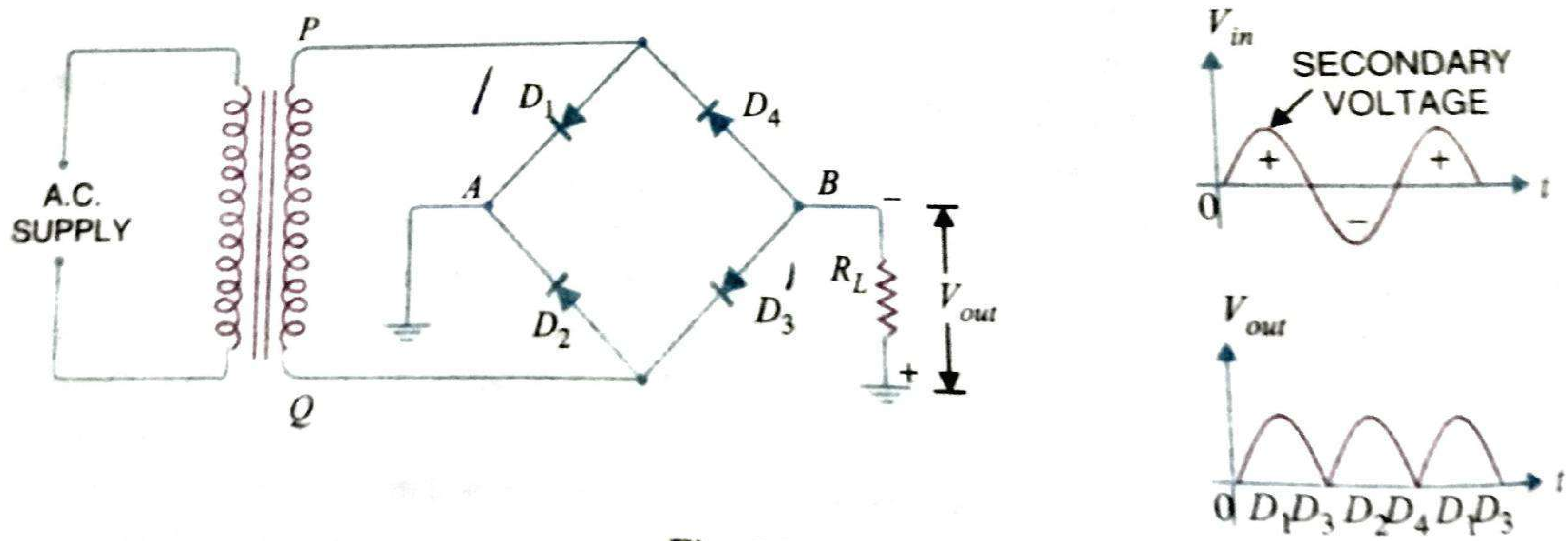


Fig. 6.26

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.

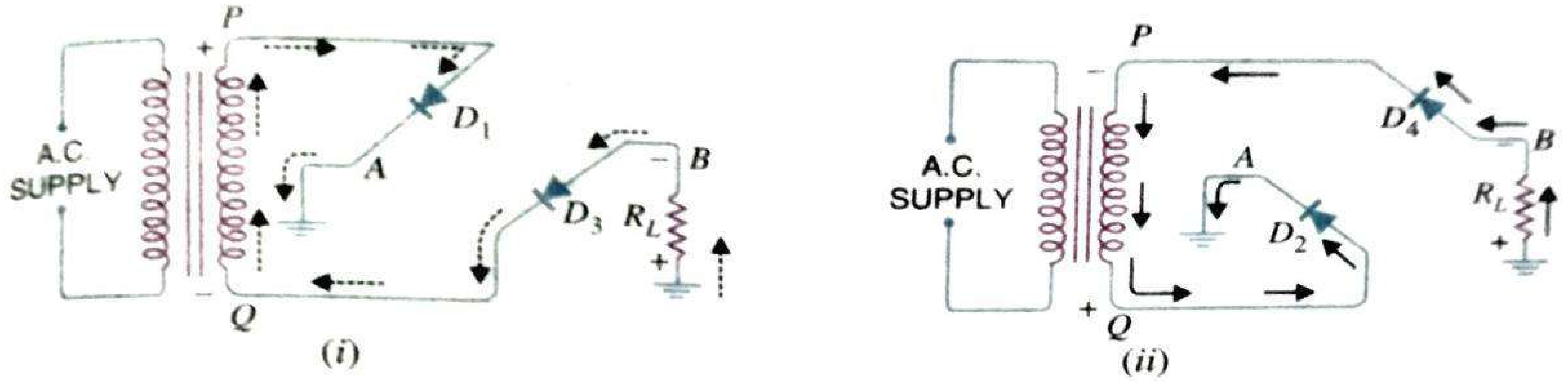


Fig. 6.27

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*).

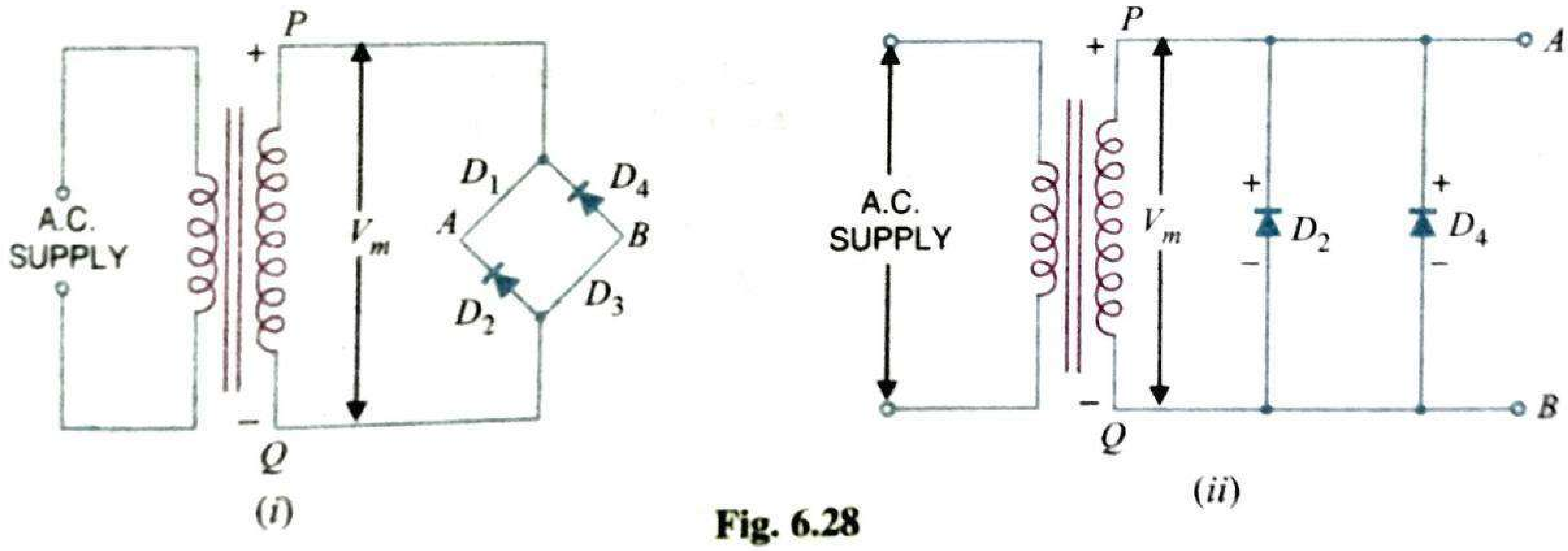


Fig. 6.28

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.*

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

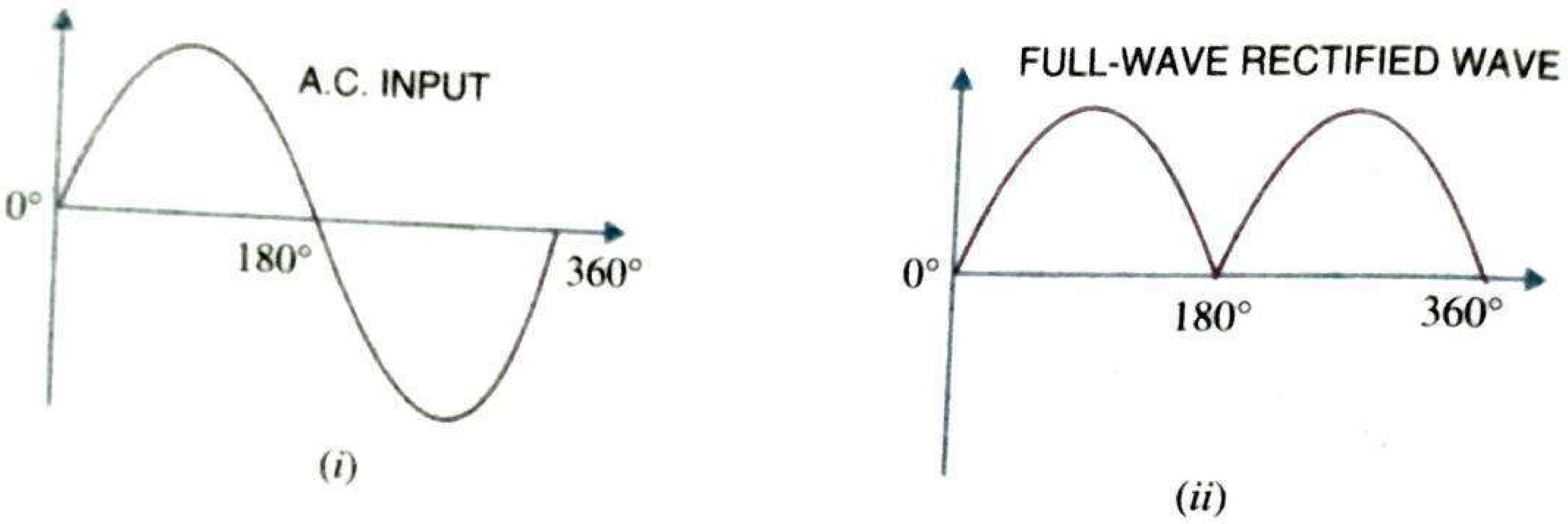


Fig. 6.29

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 :

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

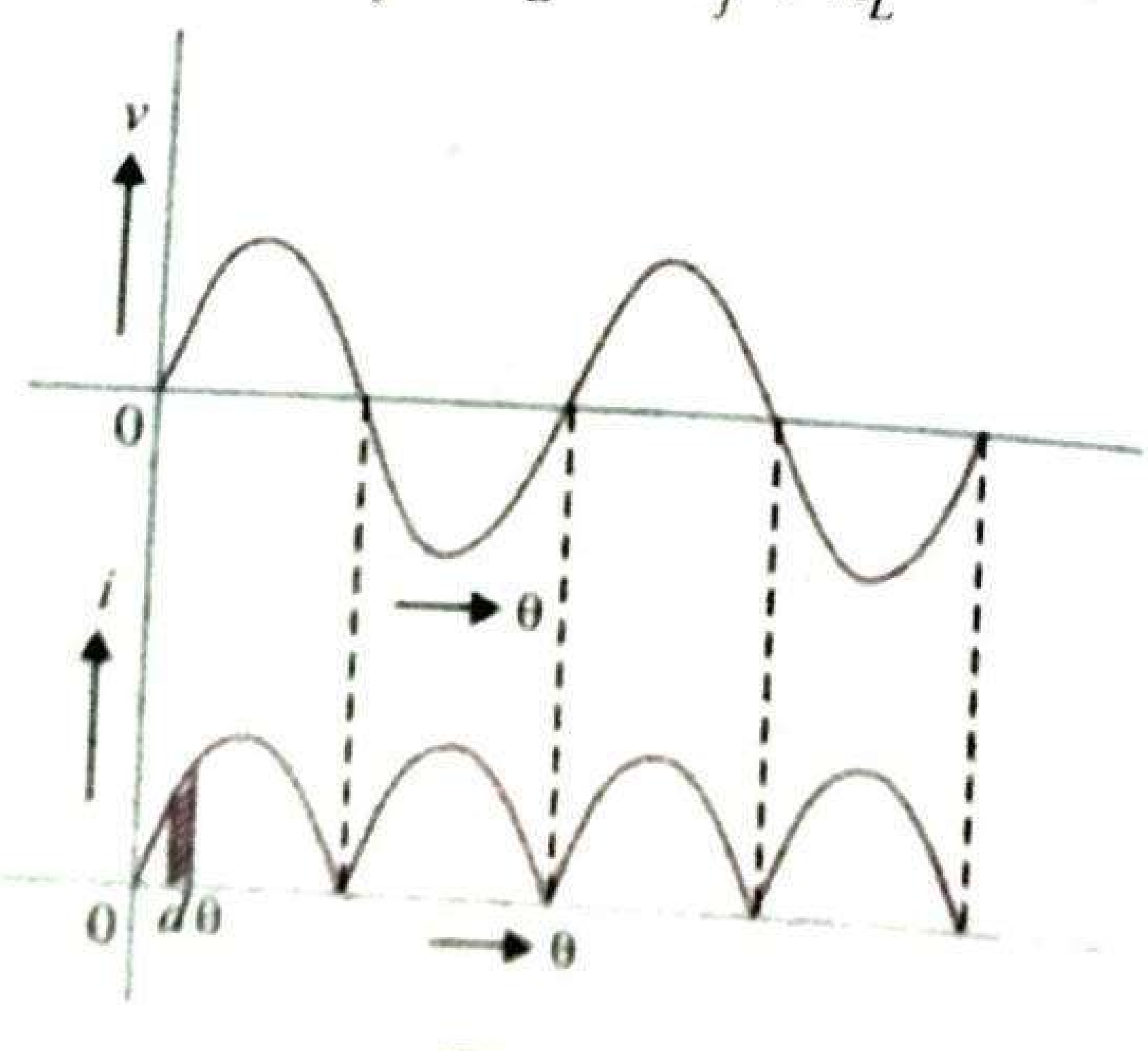


Fig. 6.30

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,

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

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

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

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

$\therefore$ Full-wave rectification efficiency is

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

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

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

$\therefore$ Maximum efficiency = 81.2%

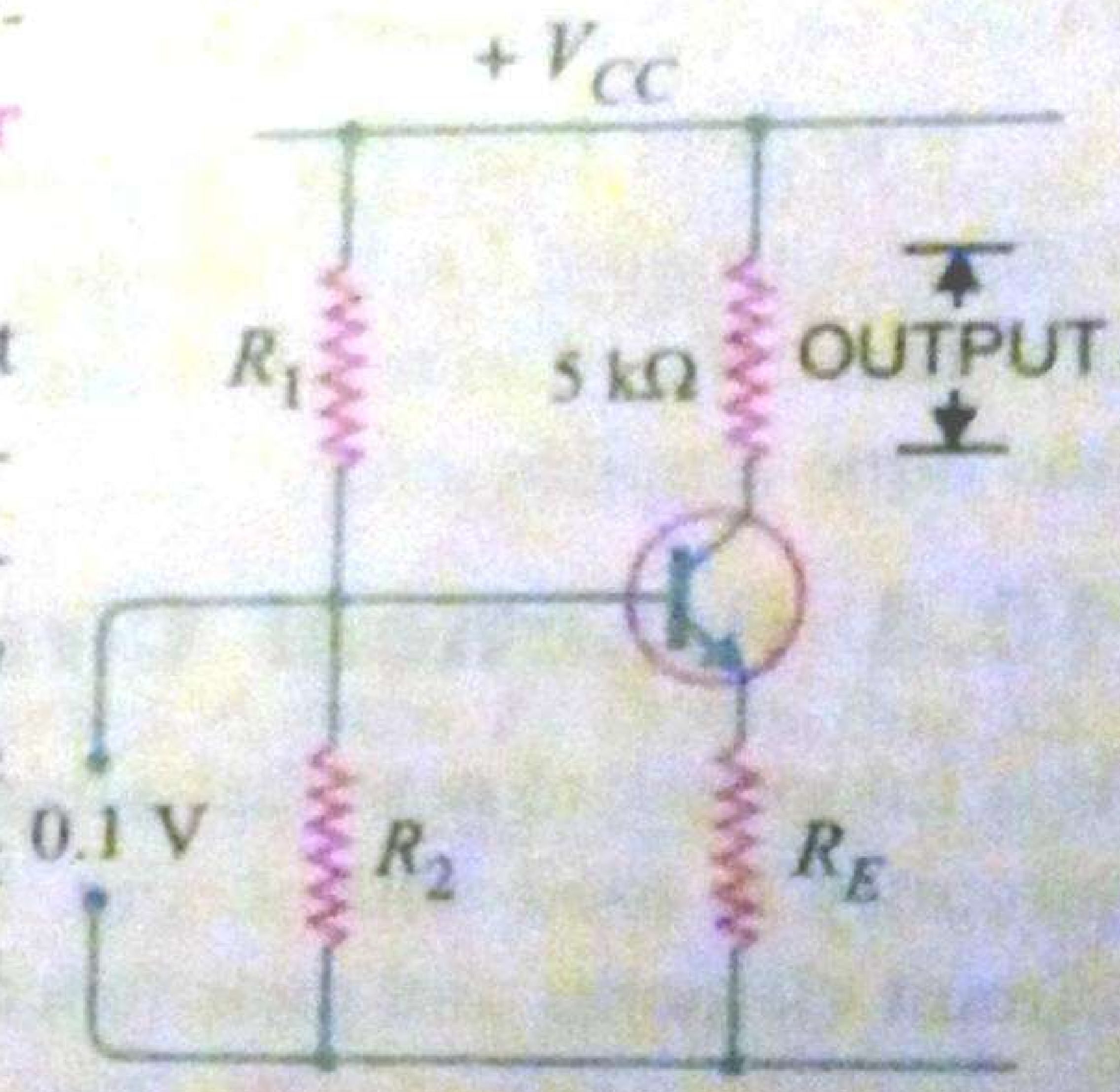
This is double the efficiency due to half-wave rectifier. Therefore, a full-wave rectifier is twice as effective as a half-wave rectifier.

Unit - III: Amplifiers and Oscillators

10.1 Single Stage Transistor Amplifier

When only one transistor with associated circuitry is used for amplifying a weak signal, the circuit is known as **single stage transistor amplifier.**

A single stage transistor amplifier has one transistor, bias circuit and other auxiliary components. Although a practical amplifier consists of a number of stages, yet such a complex circuit can be conveniently split up into separate single stages. By analysing carefully only a single stage and using this single stage analysis repeatedly, we can effectively analyse the complex circuit. It follows, therefore, that single stage amplifier analysis is of great value in understanding the practical amplifier circuits.



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10.7 D.C. And A.C. Equivalent Circuits

In a transistor amplifier, both d.c. and a.c. conditions prevail. The d.c. sources set up d.c. currents and voltages whereas the a.c. source (*i.e.* signal) produces fluctuations in the transistor currents and voltages. Therefore, a simple way to analyse the action of a transistor is to split the analysis into two parts *viz.* a d.c. analysis and an a.c. analysis. In the d.c. analysis, we consider all the d.c. sources at the same time and work out the d.c. currents and voltages in the circuit. On the other hand, for a.c. analysis, we consider all the a.c. sources at the same time and work out the a.c. currents and voltages. By adding the d.c. and a.c. currents and voltages, we get the total currents and voltages in the circuit. For example, consider the amplifier circuit shown in Fig. 10.8. This circuit can be easily analysed by splitting it into *d.c. equivalent circuit* and *a.c equivalent circuit.*

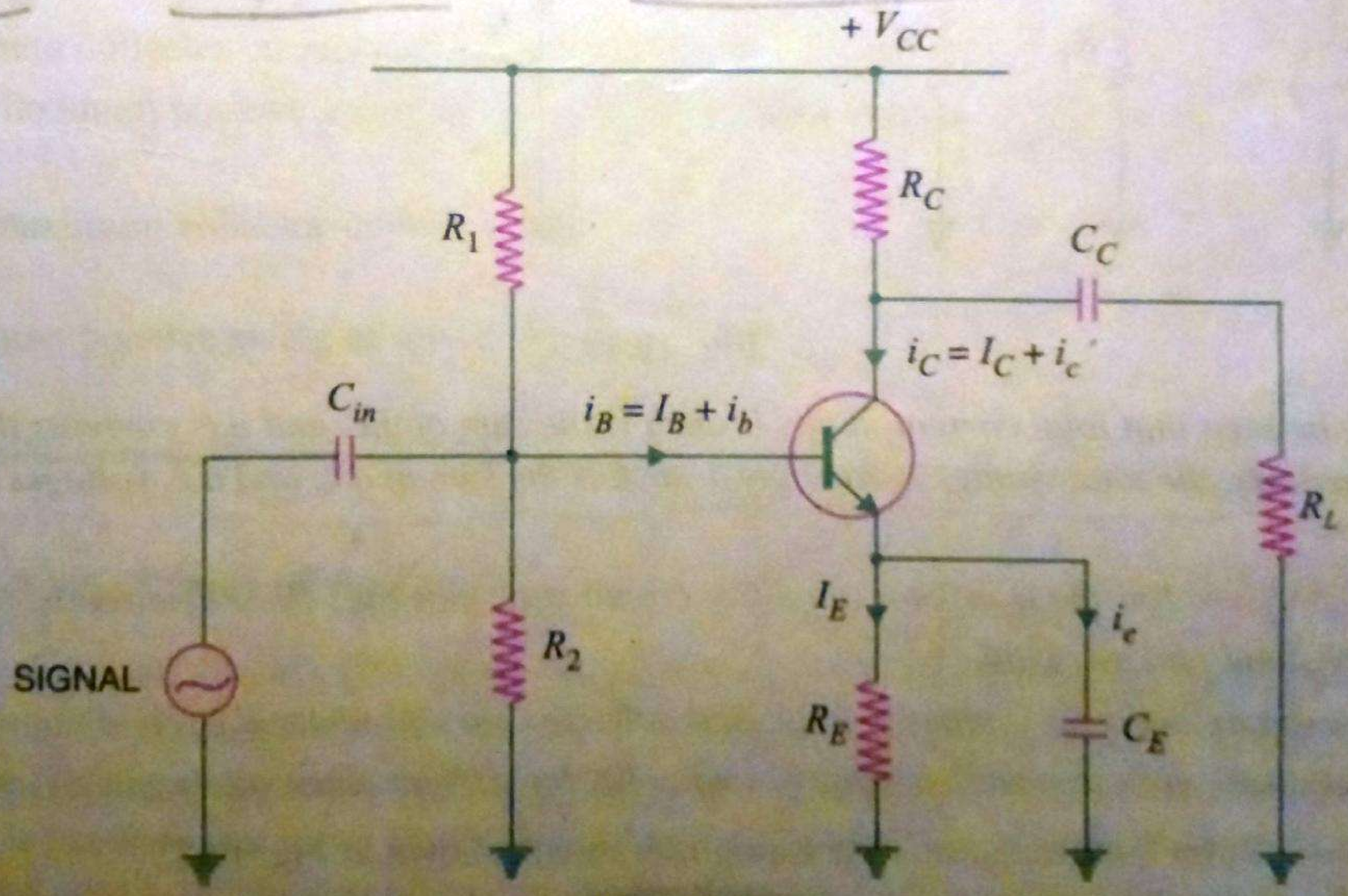

Fig. 10.8

(*i*) **D. C. equivalent circuit.** In the d.c. equivalent circuit of a transistor amplifier, only d.c. conditions are to be considered *i.e.* it is presumed that no signal is applied. As direct current cannot flow through a capacitor, therefore, *all the capacitors look like open circuits in the d.c. equivalent circuit.* It follows, therefore, that in order to draw the equivalent d.c. circuit, the following two steps are applied to the transistor circuit :

(*a*) **Reduce all a.c. sources to zero.**

(*b*) **Open all the capacitors.**

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Applying these two steps to the circuit shown in Fig. 10.8, we get the d.c. equivalent circuit shown in Fig. 10.9. We can easily calculate the d.c. currents and voltages from this circuit.

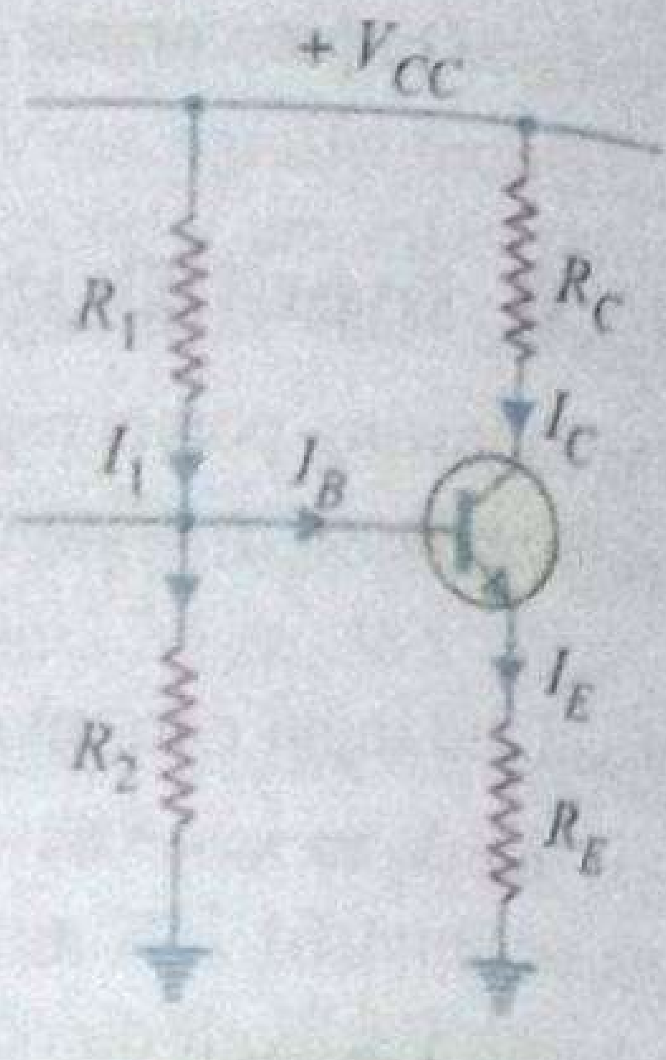


Fig. 10.9

(ii) A.C. equivalent circuit. In the a.c. equivalent circuit of a transistor amplifier, only a.c. conditions are to be considered. Obviously, the d.c. voltage is not important for such a circuit and may be considered zero. The capacitors are generally used to couple or bypass the a.c. signal. The designer intentionally selects capacitors that are large enough to appear as *short* circuits to the a.c. signal. It follows, therefore, that in order to draw the a.c. equivalent circuit, the following two steps are applied to the transistor circuit :

(*a*) Reduce all d.c. sources to zero (*i.e.* $V_{CC} = 0$).

(*b*) Short all the capacitors.

Applying these two steps to the circuit shown in Fig. 10.8, we get the a.c. *equivalent circuit shown in Fig. 10.10. We can easily calculate the a.c. currents and voltages from this circuit.

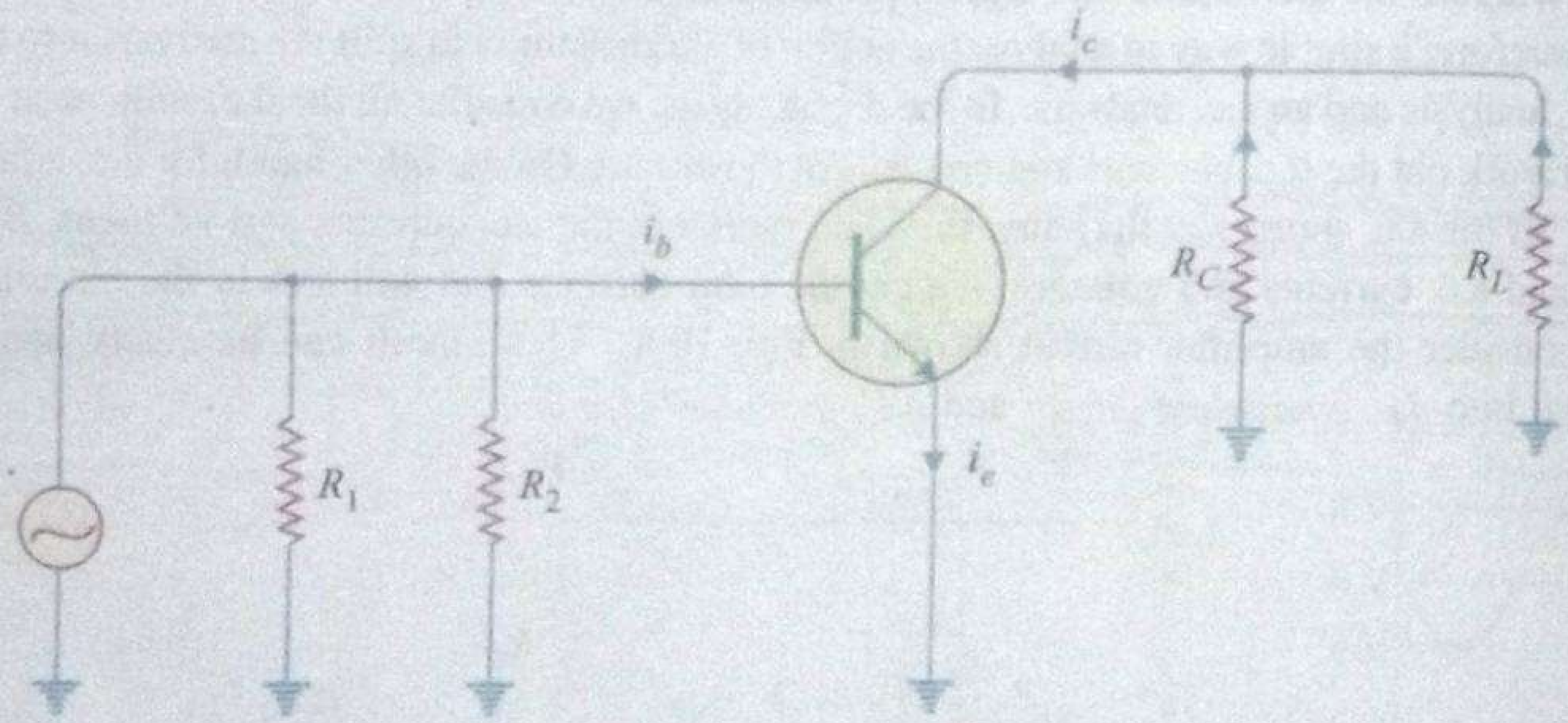


Fig. 10.10

It may be seen that total current in any branch is the sum of d.c. and a.c. currents through that branch. Similarly, the total voltage across any branch is the sum of d.c. and a.c. voltages across that branch.

Example 10.4. *For the transistor amplifier circuit shown in Fig. 10.8, determine :*

(i) d.c. load and a.c. load

(ii) maximum collector-emitter voltage and collector current under d.c. conditions

(iii) maximum collector-emitter voltage and collector current when a.c. signal is applied

Solution. Refer back to the transistor amplifier circuit shown in Fig. 10.8.

(*i*) The d.c. load for the transistor is Thevenin's equivalent resistance as seen by the collector and emitter terminals. Thus referring to the d.c. equivalent circuit shown in Fig. 10.9, Thevenin's equivalent resistance can be found by shorting the voltage source (*i.e.* V_{CC}) as shown in Fig. 10.11. Because a voltage source looks like a short, it will bypass all other resistances except R_C and R_E which will appear in series. Consequently, transistor amplifier will see a d.c. load of $R_C + R_E$ *i.e.*

* Note that R_1 is also in parallel with transistor input so far as signal is concerned. Since R_1 is connected from the base lead to V_{CC} and V_{CC} is at "ac ground", R_1 is effectively connected from the base lead to ground as far as signal is concerned.

d.c. load = $\mathbf{R_C + R_E}$

Referring to the a.c. equivalent circuit shown in Fig. 10.10, it is clear that as far as a.c. signal is concerned, resistance R_C appears in parallel with R_L. In other words, transistor amplifier sees an a.c. load equal to $R_C \parallel R_L$ *i.e.*

a.c. load, $R_{AC} = R_C \parallel R_L$

$$= \frac{R_C\ R_L}{R_C + R_L}$$

(ii) Referring to d.c. equivalent circuit of Fig. 10.9,

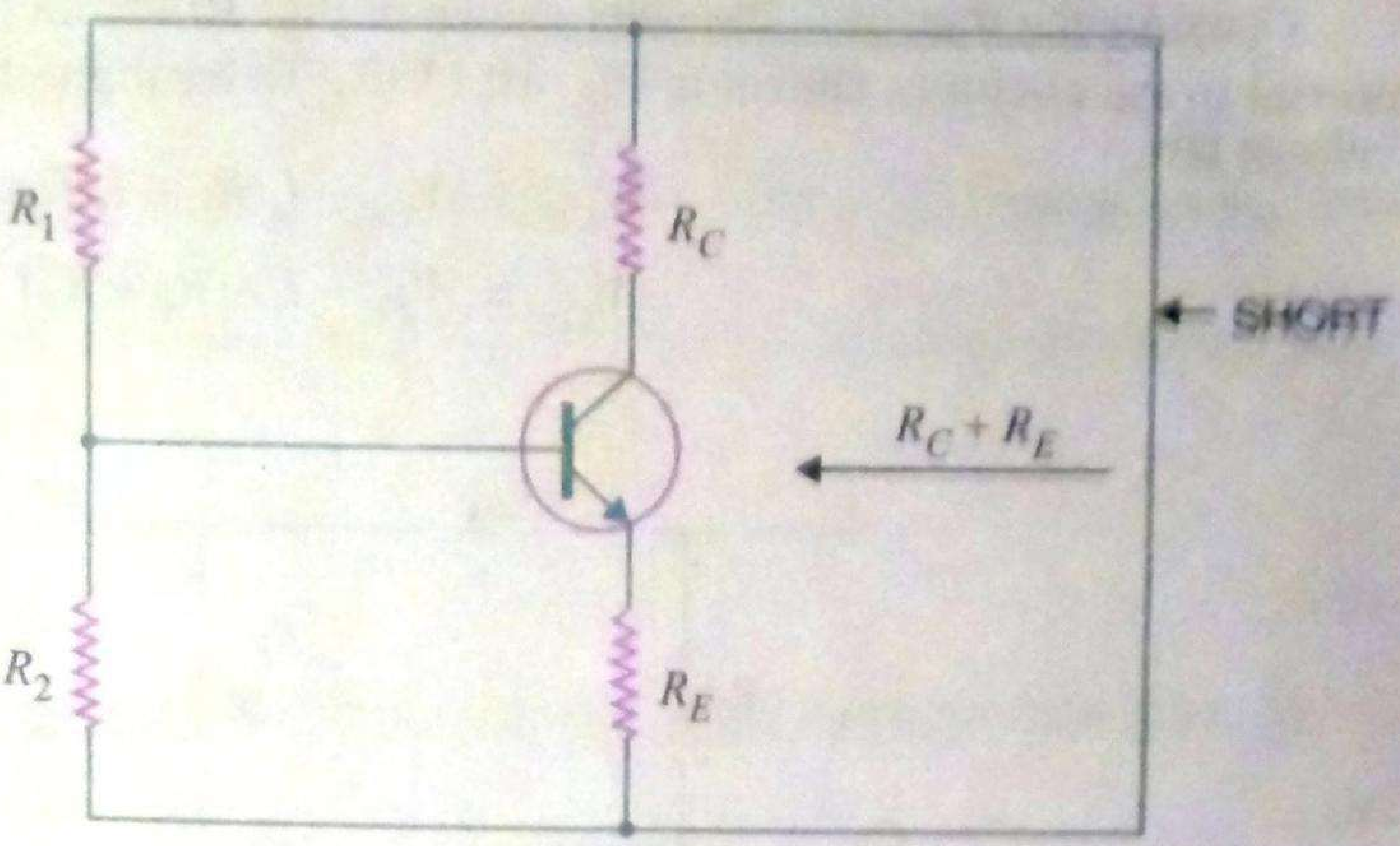


Fig. 10.11

$$V_{CC} = V_{CE} + I_C (R_C + R_E)$$

The maximum value of V_{CE} will occur when there is no collector current *i.e.* $I_C = 0$.

$\therefore$ Maximum $V_{CE} = \mathbf{V_{CC}}$

The maximum collector current will flow when $V_{CE} = 0$.

$$\therefore \quad \text{Maximum } I_C = \frac{\mathbf{V_{CC}}}{\mathbf{R_C + R_E}}$$

(iii) When no signal is applied, V_{CE} and I_C are the collector-emitter voltage and collector current respectively. When a.c. signal is applied, it causes changes to take place above and below the operating point Q (*i.e.* V_{CE} and I_C).

Maximum collector current due to a.c. signal = $^*I_C$

$\therefore$ Maximum positive swing of a.c. collector-emitter voltage

$$= I_C \times R_{AC}$$

Total maximum collector-emitter voltage

$$= V_{CE} + I_C R_{AC}$$

Maximum positive swing of a.c. collector current

$$= V_{CE}/R_{AC}$$

$\therefore$ Total maximum collector current

$$= I_C + V_{CE}/R_{AC}$$

11.3 Important Terms

In the study of multistage amplifiers, we shall frequently come across the terms *gain, frequency response, decibel gain* and *bandwidth*. These terms stand discussed below :

(*i*) **Gain.** *The ratio of the output *electrical quantity to the input one of the amplifier is called its* **gain.**

* Accordingly, it can be current gain or voltage gain or power gain.

The gain of a multistage amplifier is equal to the product of gains of individual stages. For instance, if G_1, G_2 and G_3 are the individual voltage gains of a three-stage amplifier, then total voltage gain G is given by :

$$*G = G_1 \times G_2 \times G_3$$

It is worthwhile to mention here that in practice, total gain G is less than $G_1 \times G_2 \times G_3$ due to the loading effect of next stages.

(ii) Frequency response. The voltage gain of an amplifier varies with signal frequency. It is because reactance of the capacitors in the circuit changes with signal frequency and hence affects the output voltage. The curve between voltage gain and signal frequency of an amplifier is known as *frequency response*. Fig. 11.4 shows the frequency response of a typical amplifier. The gain of the amplifier increases as the frequency increases from zero till it becomes maximum at f_r, called *resonant frequency*. If the frequency of signal increases beyond f_r, the gain decreases.

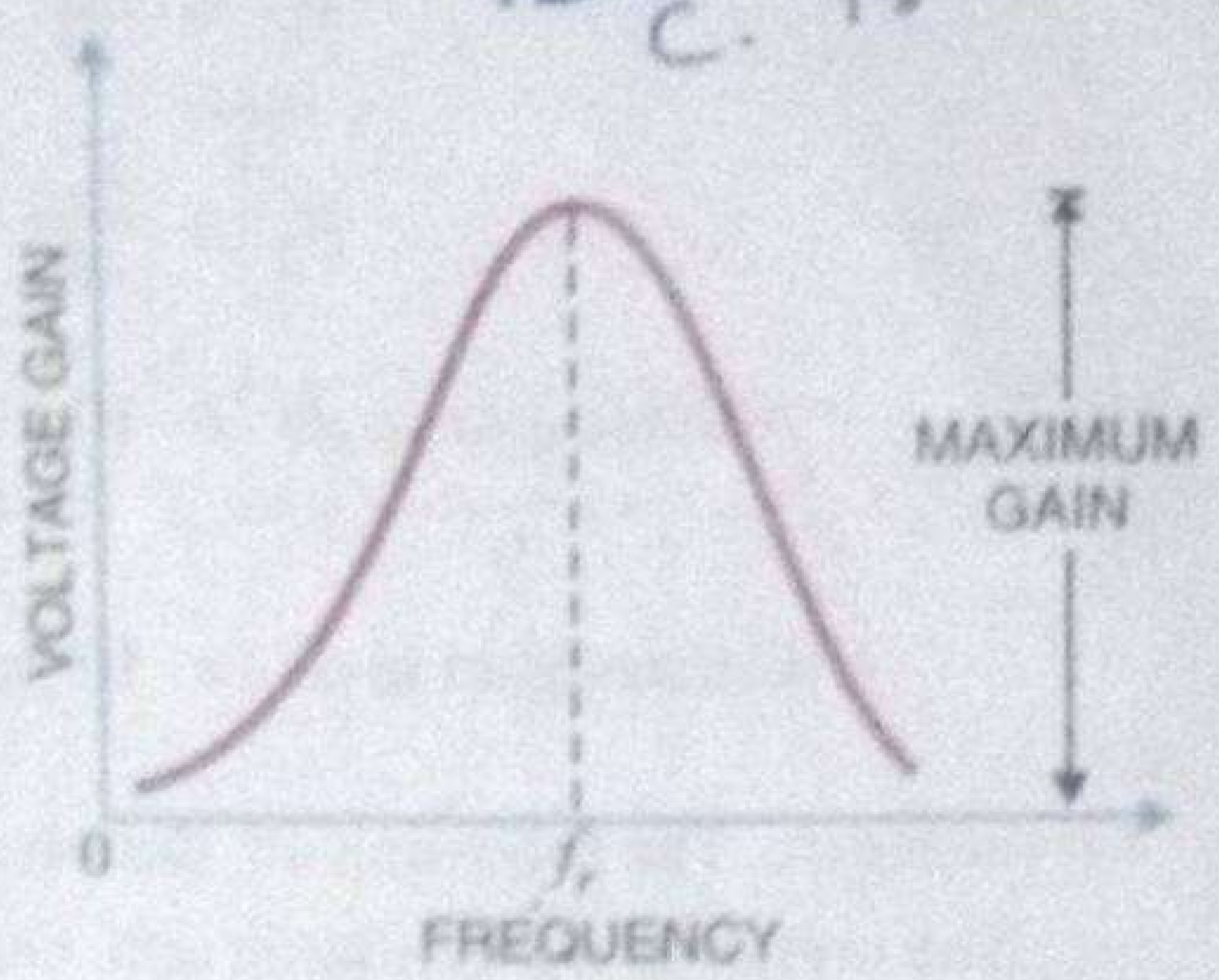


Fig. 11.4

The performance of an amplifier depends to a considerable extent upon its frequency response. While designing an amplifier, appropriate steps must be taken to ensure that gain is essentially uniform over some specified frequency range. For instance, in case of an audio amplifier, which is used to amplify speech or music, it is necessary that all the frequencies in the sound spectrum (*i.e.* 20 Hz to 20 kHz) should be uniformly amplified otherwise speaker will give a distorted sound output.

(iii) Decibel gain. Although the gain of an amplifier can be expressed as a number, yet it is of great practical importance to assign it a unit. The unit assigned is *bel or decibel (db)*.

The common logarithm (log to the base 10) of power gain is known as **bel power gain** *i.e.*

$$\text{Power gain} = \log_{10} \frac{P_{out}}{P_{in}} \; bel$$

$$1 \text{ bel} = 10 \; db$$

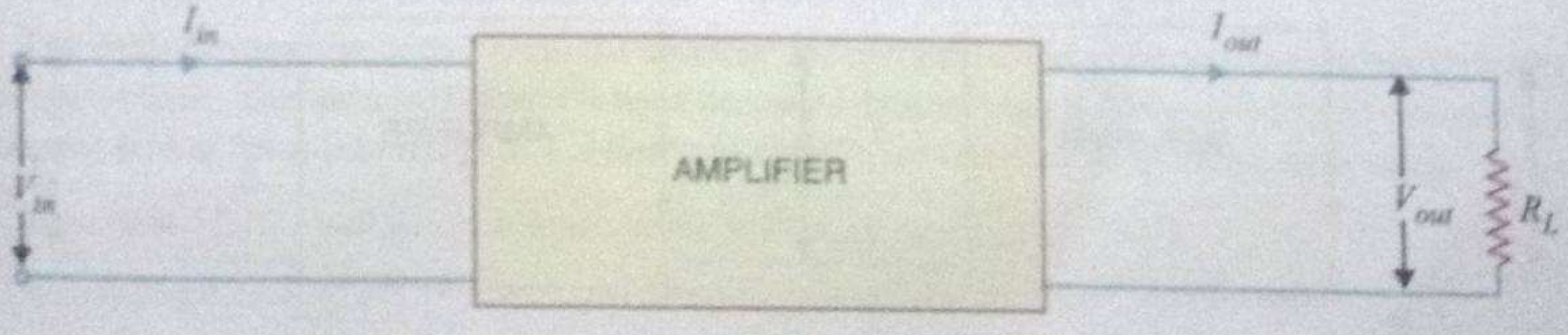


Fig. 11.5

* This can be easily proved. Supporse the input to first stage is V.

$$\text{Output of first stage} = G_1 V$$

$$\text{Output of second stage} = (G_1 V)\, G_2 = G_1 G_2 V$$

$$\text{Output of third stage} = (G_1 G_2 V) G_3 = G_1 G_2 G_3 V$$

$$\text{Total gain, } G = \frac{\text{Output of third stage}}{V}$$

or

$$G = \frac{G_1 G_2 G_3 V}{V} = G_1 \times G_2 \times G_3$$

$$\therefore \quad \text{Power gain} = 10 \log_{10} \frac{P_{out}}{P_{in}} \ db$$

If the two powers are developed in the same resistance or equal resistances, then,

$$P_1 = \frac{V_{in}^2}{R} = I_{in}^2 R$$

$$P_2 = \frac{V_{out}^2}{R} = I_{out}^2 R$$

$$\therefore \quad \text{Voltage gain in } db = 10 \log_{10} \frac{V_{out}^2 / R}{V_{in}^2 / R} = 20 \log_{10} \frac{V_{out}}{V_{in}}$$

$$\text{Current gain in } db = 10 \log_{10} \frac{I_{out}^2 R}{I_{in}^2 R} = 20 \log_{10} \frac{I_{out}}{I_{in}}$$

Advantages. The following are the advantages of expressing the gain in *db* :

(*a*) The unit *db* is a logarithmic unit. Our ear response is also logarithmic *i.e.* loudness of sound heard by ear is not according to the intensity of sound but according to the log of intensity of sound. Thus if the intensity of sound given by speaker (*i.e.* power) is increased 100 times, our ears hear a doubling effect ($\log_{10} 100 = 2$) *i.e.* as if loudness were doubled instead of made 100 times. Hence, this unit tallies with the natural response of our ears.

(*b*) When the gains are expressed in *db*, the overall gain of a multistage amplifier is the sum of gains of individual stages in *db*. Thus referring to Fig. 11.6,

$$\text{Gain as number} = \frac{V_2}{V_1} \times \frac{V_3}{V_2}$$

$$\text{Gain in } db = 20 \log_{10} \frac{V_2}{V_1} \times \frac{V_3}{V_2}$$

$$= 20 \log_{10} \frac{V_2}{V_1} + 20 \log_{10} \frac{V_3}{V_2}$$

$$= \text{1st stage gain in } db + \text{2nd stage gain in } db$$

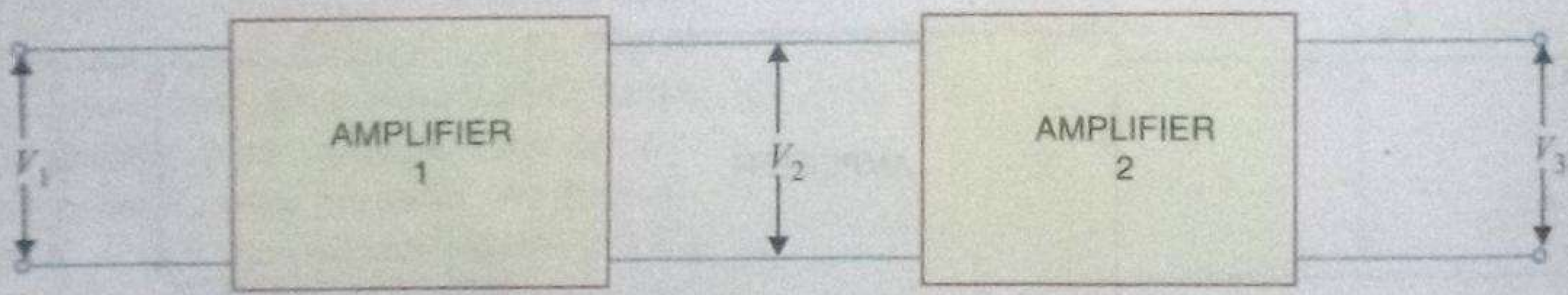


Fig. 11.6

However, absolute gain is obtained by multiplying the gains of individual stages. Obviously, it is easier to add than to multiply.

(*iv*) **Bandwidth.** *The range of frequency over which the voltage gain is equal to or greater than *70.7% of the maximum gain is known as* **bandwidth.**

* The human ear is not a very sensitive hearing device. It has been found that if the gain falls to 70.7% of maximum gain, the ear cannot detect the change. For instance, if the gain of an amplifier is 100, then even if the gain falls to 70.7, the ear cannot detect the change in intensity of sound and hence no distortion will be heard. However, if the gain falls below 70.7, the ear will hear clear distortion.

The voltage gain of an amplifier changes with frequency. Referring to the frequency response in Fig. 11.7, it is clear that for any frequency lying between f_1 and f_2, the gain is equal to or greater than 70.7% of the maximum gain. Therefore, $f_1 - f_2$ is the bandwidth. It may be seen that f_1 and f_2 are the limiting frequencies. The former (f_1) is called *lower cut-off frequency* and the latter (f_2) is known as *upper cut-off frequency*. For distortionless amplification, it is important that signal frequency range must be within the bandwidth of the amplifier.

40 decibels phone

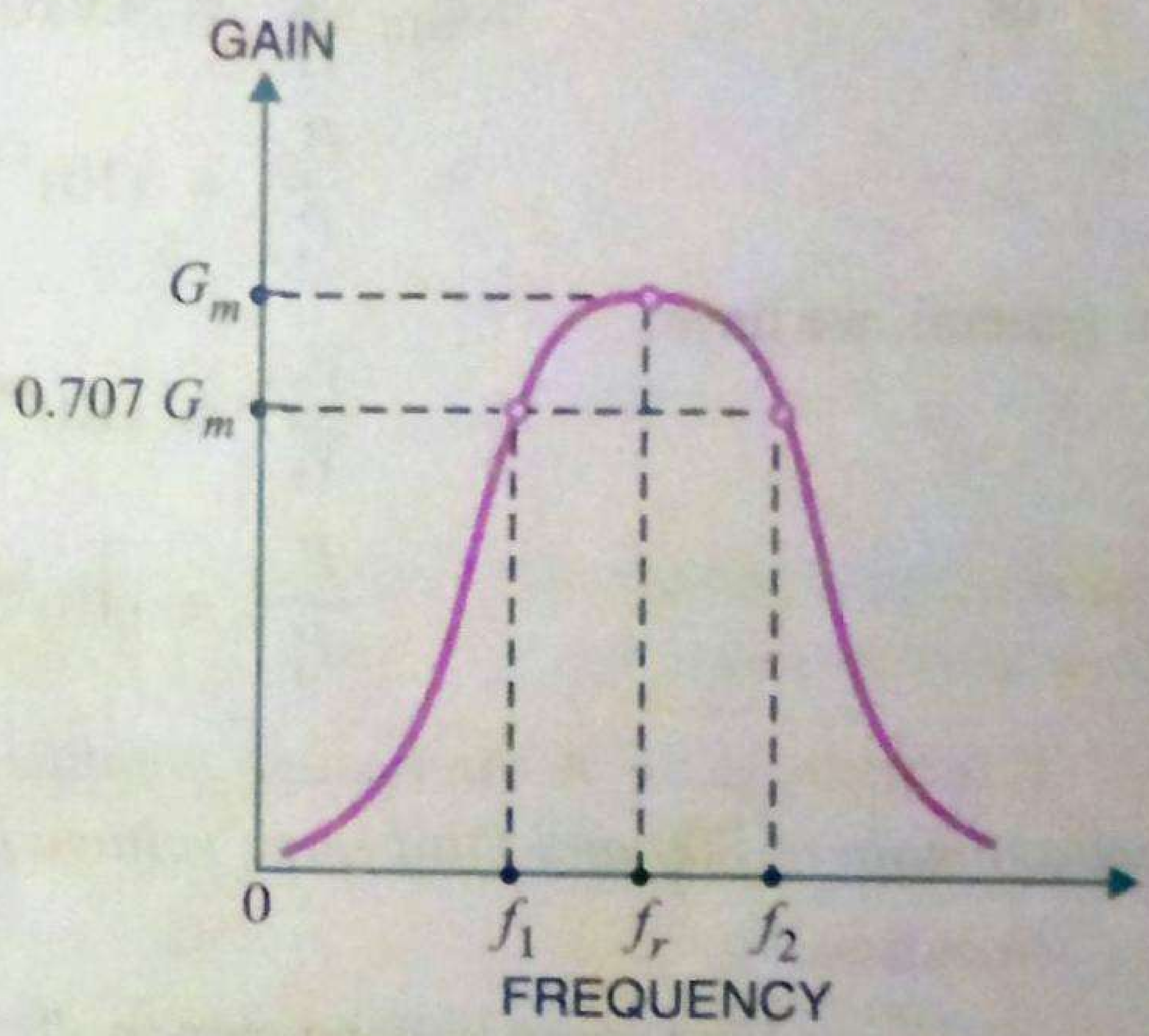


Fig. 11.7

The bandwidth of an amplifier can also be defined in terms of *db*. Suppose the maximum voltage gain of an amplifier is 100. Then 70.7% of it is 70.7.

∴ Fall in voltage gain from maximum gain

$$= 20 \log_{10} 100 - 20 \log_{10} 70.7$$

$$= 20 \log_{10} \frac{100}{70.7} \; db$$

$$= 20 \log_{10} 1.4142 \; db = 3 \; db$$

Hence **bandwidth** *of an amplifier is the range of frequency at the limits of which its voltage gain falls by 3 db from the maximum gain.*

The frequency f_1 or f_2 is also called *3-db frequency* or *half-power frequency*.

The 3-*db* designation comes from the fact that voltage gain at these frequencies is 3*db* below the maximum value. The term half-power is used because when voltage is down to 0.707 of its maximum value, the power (proportional to V^2) is down to $(0.707)^2$ or one-half of its maximum value.

11.1 Multistage Transistor Amplifier

A transistor circuit containing more than one stage of amplification is known as **multistage transistor amplifier.**

In a multistage amplifier, a number of single amplifiers are connected in **cascade arrangement* *i.e.* output of first stage is connected to the input of the second stage through a suitable *coupling device* and so on. The purpose of coupling device (*e.g.* a capacitor, transformer etc.) is (*i*) to transfer a.c. output of one stage to the input of the next stage and (*ii*) to isolate the d.c. conditions of one stage from the next stage. Fig. 11.1 shows the block diagram of a 3-stage amplifier. Each stage consists of one transistor and associated circuitry and is coupled to the next stage through a coupling device. The name of the amplifier is usually given after the type of coupling used. *e.g.*

Name of coupling	*Name of multistage amplifier*
RC coupling	R-C coupled amplifier
Transformer coupling	Transformer coupled amplifier
Direct coupling	Direct coupled amplifier

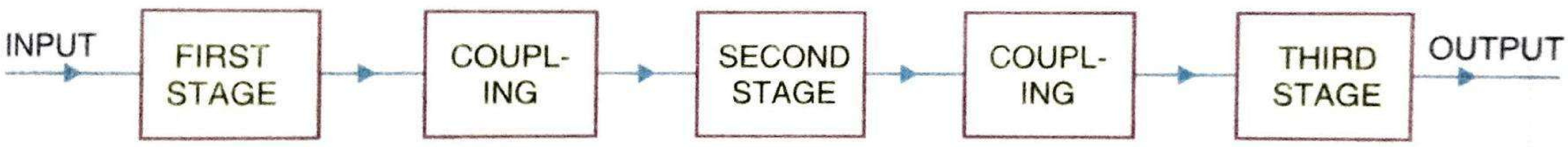


Fig. 11.1

(*i*) In *RC* coupling, a capacitor is used as the coupling device. The capacitor connects the output of one stage to the input of the next stage in order to pass the a.c. signal on while blocking the d.c. bias voltages.

(*ii*) In transformer coupling, transformer is used as the coupling device. The transformer coupling provides the same two functions (*viz.* to pass the signal on and blocking d.c.) but permits in addition impedance matching.

(*iii*) In direct coupling or d.c. coupling, the individual amplifier stage bias conditions are so designed that the two stages may be directly connected without the necessity for d.c. isolation.

11.5 RC Coupled Transistor Amplifier

This is the most popular type of coupling because it is cheap and provides excellent audio fidelity over a wide range of frequency. It is usually employed for voltage amplification. Fig. 11.9 shows two stages of an *RC* coupled amplifier. A coupling capacitor C_C is used to connect the output of first stage to the base (*i.e. input*) of the second stage and so on. As the coupling from one stage to next is achieved by a coupling capacitor followed by a connection to a shunt resistor, therefore, such amplifiers are called *resistance - capacitance coupled amplifiers*.

The resistances R_1, R_2 and R_E form the biasing and stabilisation network. The emitter bypass capacitor offers low reactance path to the signal. Without it, the voltage gain of each stage would be lost. The coupling capacitor C_C transmits a.c. signal but blocks d.c. This prevents d.c. interference between various stages and the shifting of operating point.

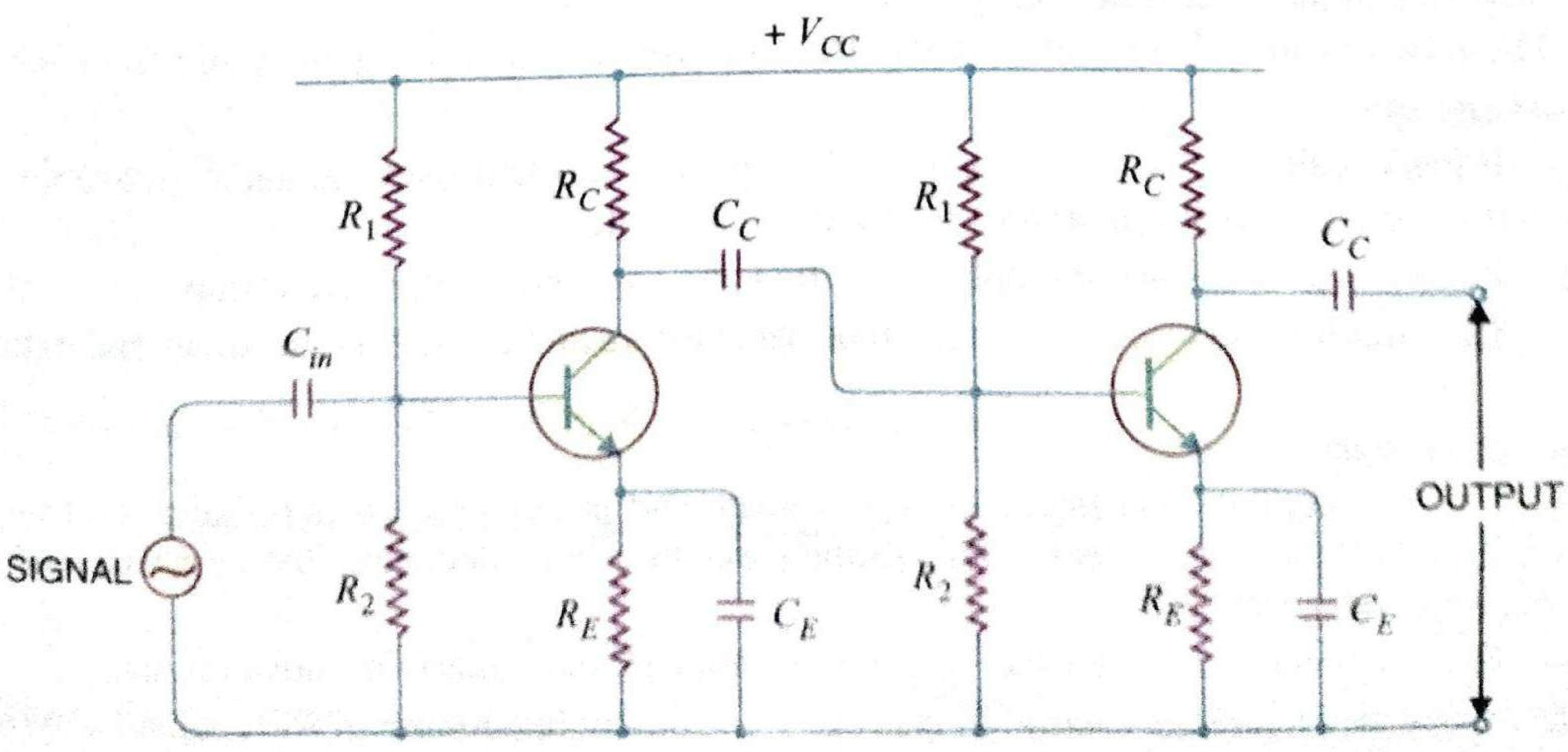


Fig. 11.9

Operation. When a.c. signal is applied to the base of the first transistor, it appears in the amplified form across its collector load R_C. The amplified signal developed across R_C is given to base of next stage through coupling capacitor C_C. The second stage does further amplification of the signal. In this way, the *cascaded* (one after another) stages amplify the signal and the overall gain is considerably increased.

It may be mentioned here that total gain is less than the product of the gains of individual stages. It is because when a second stage is made to follow the first stage, the *effective load resistance* of first stage is reduced due to the shunting effect of the input resistance of second stage. This reduces the gain of the stage which is loaded by the next stage. For instance, in a 3-stage amplifier, the gain of first and second stages will be reduced due to loading effect of next stage. However, the gain of the third stage which has no loading effect of subsequent stage, remains unchanged. The overall gain shall be equal to the product of the gains of three stages.

Frequency response. Fig.11.10 shows the frequency response of a typical *RC* coupled amplifier. It is clear that voltage gain drops off at low (< 50 Hz) and high (> 20 kHz) frequencies whereas it is uniform over *mid-frequency* range (50 Hz to 20 kHz). This behaviour of the amplifier is briefly explained below :

(*i*) *At low frequencies* (< 50 Hz), the reactance of coupling capacitor C_C is quite high and hence very small part of signal will pass from one stage to the next stage. Moreover, C_E cannot shunt the emitter resistance R_E effectively because of its large reactance at low frequencies. These two factors cause a falling of voltage gain at low frequencies.

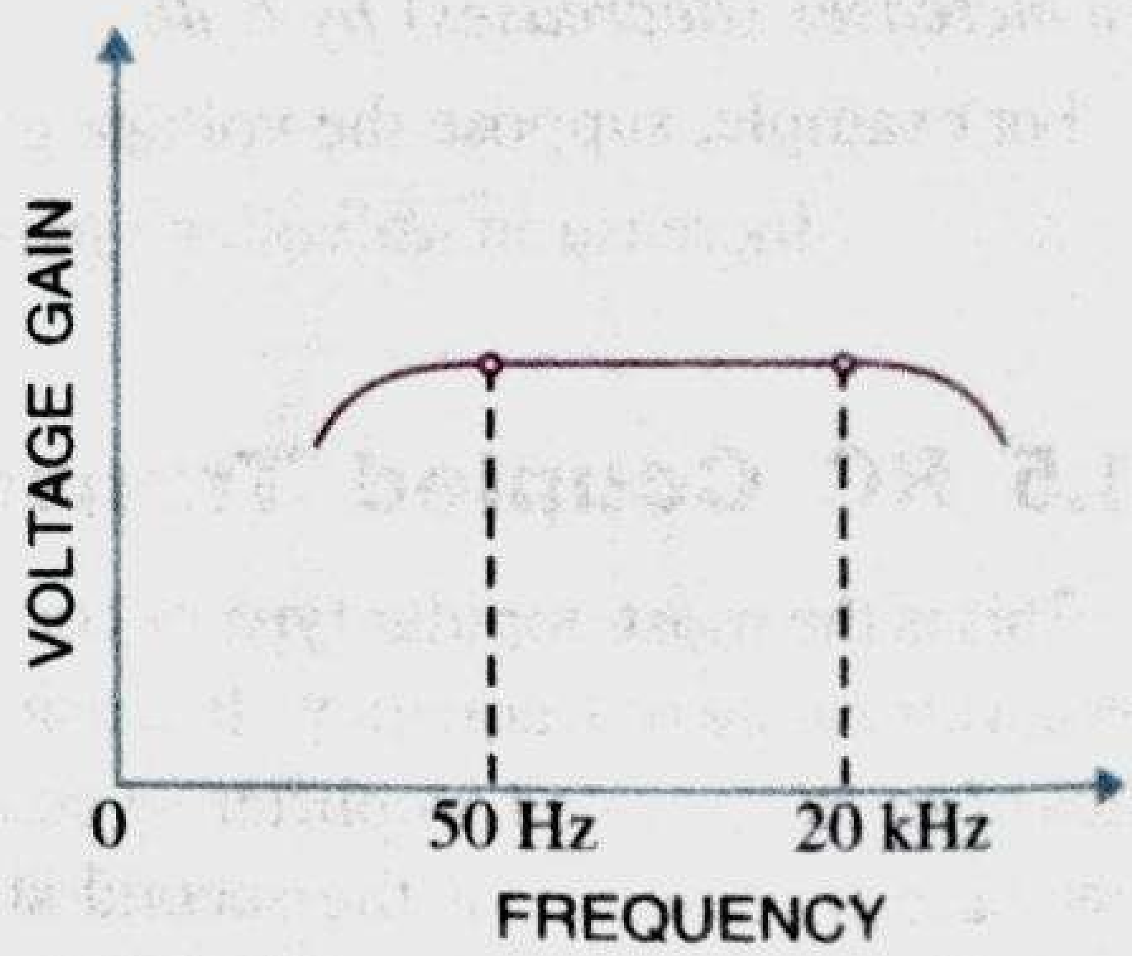


Fig. 11.10

(*ii*) *At high frequencies* (> 20 kHz), the reactance of C_C is very small and it behaves as a short circuit. This increases the loading effect of next stage and serves to reduce the voltage gain. Moreover, at high frequency, capacitive reactance of base-emitter junction is low which increases the base current. This reduces the current amplification factor β. Due to these two reasons, the voltage gain drops off at high frequency.

(*iii*) *At mid-frequencies* (50 Hz to 20 kHz), the voltage gain of the amplifier is constant. The effect of coupling capacitor in this frequency range is such so as to maintain a uniform voltage gain. Thus, as the frequency increases in this range, reactance of C_C decreases which tends to increase the gain. However, at the same time, lower reactance means higher loading of first stage and hence lower gain. These two factors almost cancel each other, resulting in a uniform gain at mid-frequency.

Advantages

(*i*) It has excellent frequency response. The gain is constant over the audio frequency range which is the region of most importance for speech, music etc.

(*ii*) It has lower cost since it employs resistors and capacitors which are cheap.

(*iii*) The circuit is very compact as the modern resistors and capacitors are small and extremely light.

Disadvantages

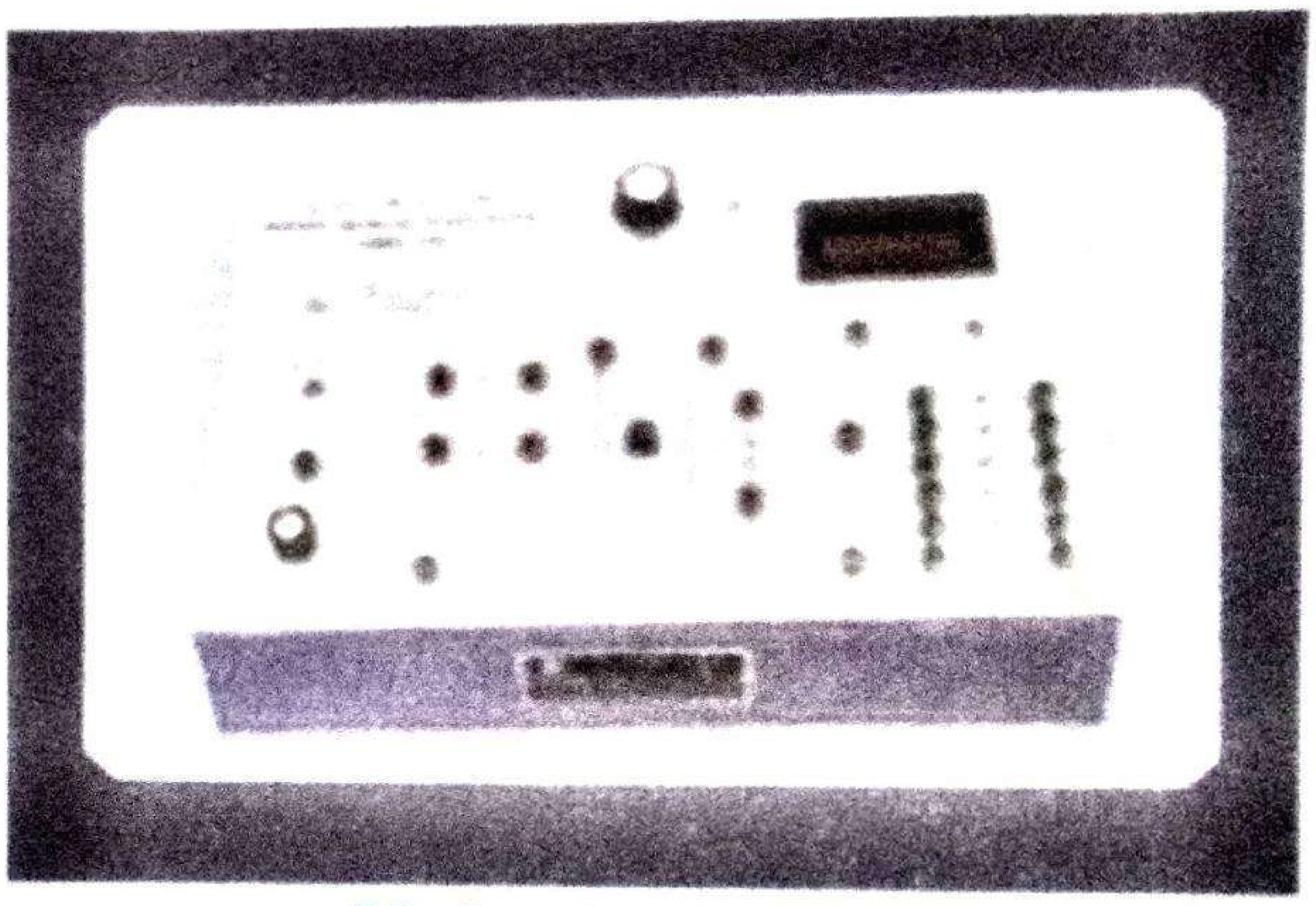
(*i*) The *RC* coupled amplifiers have low voltage and power gain. It is because the low resistance presented by the input of each stage to the preceding stage decreases the effective load resistance (R_{AC}) and hence the gain.

(*ii*) They have the tendency to become noisy with age, particularly in moist climates.

(*iii*) Impedance matching is poor. It is because the output impedance of *RC* coupled amplifier is several hundred ohms whereas the input impedance of a speaker is only a few ohms. Hence, little power will be transferred to the speaker.

Applications.

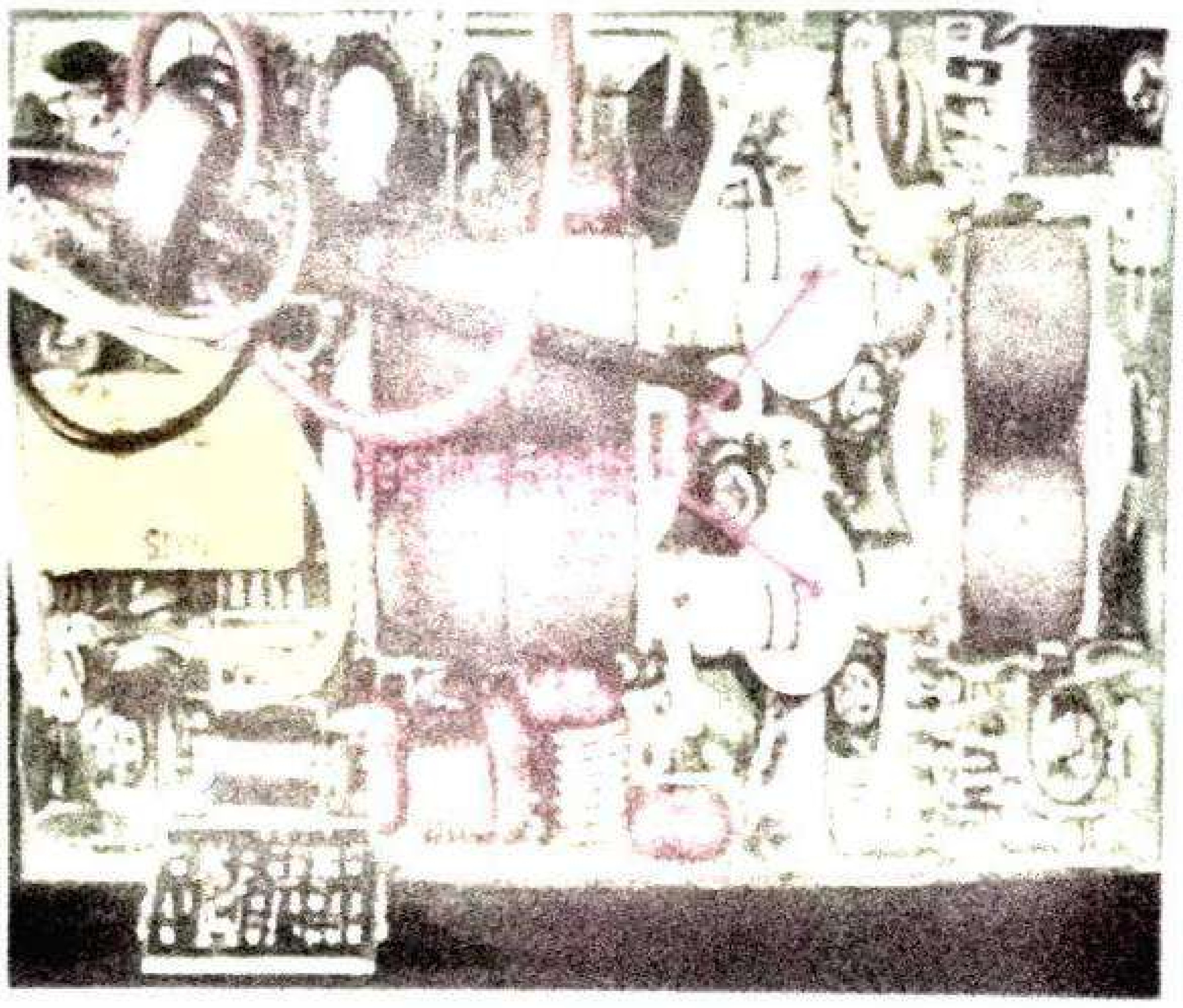
The *RC* coupled amplifiers have excellent audio fidelity over a wide range of frequency. Therefore, they are widely used as voltage amplifiers *e.g.* in the initial stages of public address system. If other type of coupling (*e.g.* transformer coupling) is employed in the initial stages, this results in frequency distortion which may be amplified in next stages. However, because of poor impedance matching, *RC* coupling is rarely used in the final stages.



RC Coupled Amplifiers

Note. When there is an even number of cascaded stages (2, 4, 6 etc), the output signal is not inverted from the input. When the number of stages is odd (1, 3, 5 etc.), the output signal is inverted from the input.

Amplifiers with Negative Feedback



INTRODUCTION

A practical amplifier has a gain of nearly one million *i.e.* its output is one million times the input. Consequently, even a casual disturbance at the input will appear in the amplified form in the output. There is a strong tendency in amplifiers to introduce *hum* due to sudden temperature changes or stray electric and magnetic fields. Therefore, every high gain amplifier tends to give noise along with signal in its output. The noise in the output of an amplifier is undesirable and must be kept to as small a level as possible.

The noise level in amplifiers can be reduced considerably by the use of *negative feedback i.e.* by injecting a fraction of output in phase opposition to the input signal. The object of this chapter is to consider the effects and methods of providing negative feedback in transistor amplifiers.

13.1 Feedback

The process of injecting a fraction of output energy of *some device back to the input is known as* **feedback**.

The principle of feedback is probably as old as the invention of first machine but it is only some 50 years ago that feedback has come into use in connection with electronic circuits. It has been found very useful in reducing noise in amplifiers and making amplifier operation stable. Depending upon whether the feedback energy aids or opposes the input signal, there are two basic types of feedback in amplifiers *viz positive feedback* and *negative feedback*.

(*i*) **Positive feedback.** When the feedback energy (voltage or current) is in phase with the input signal and thus aids it, it is called *positive feedback*. This is illustrated in Fig. 13.1. Both amplifier and feedback network introduce a phase shift of 180°. The result is a 360° phase shift around the loop, causing the *feedback voltage* V_f to be in phase with the input signal V_{in}.

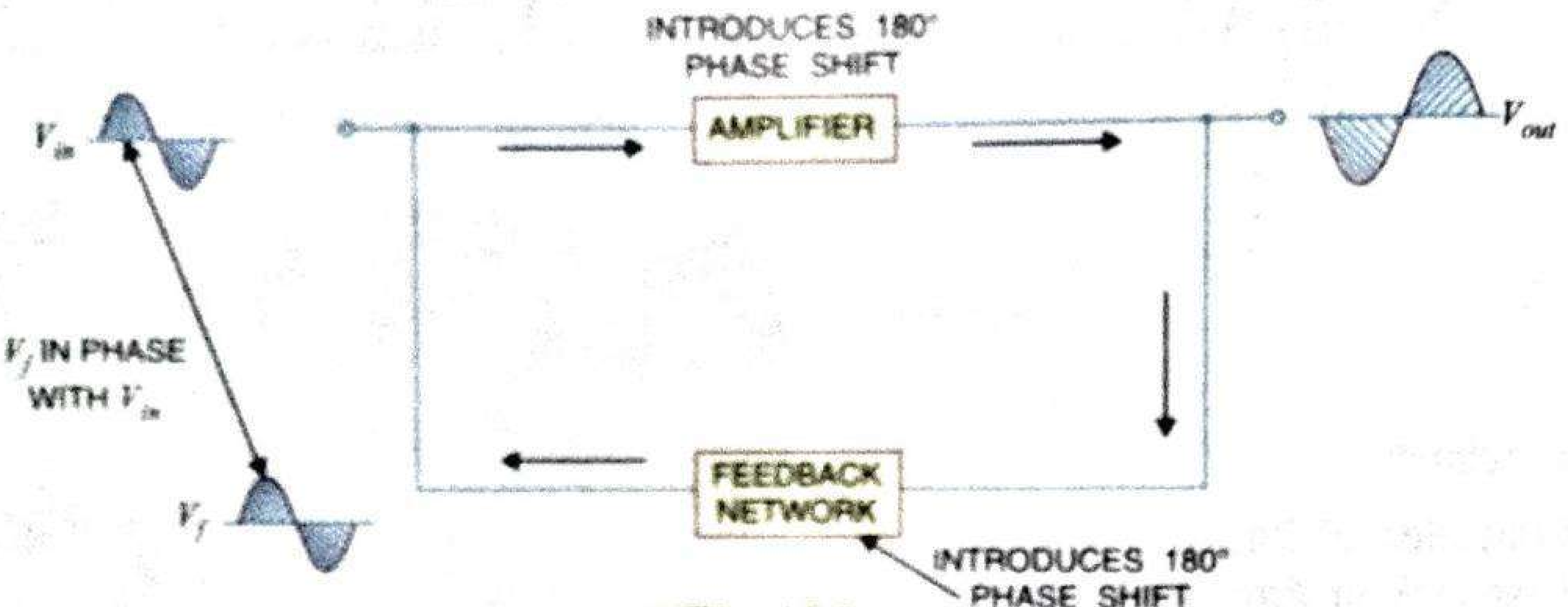


Fig. 13.1

The positive feedback increases the gain of the amplifier. However, it has the disadvantages of increased distortion and instability. Therefore, positive feedback is seldom employed in amplifiers. One important use of positive feedback is in oscillators. As we shall see in the next chapter, if positive feedback is sufficiently large, it leads to oscillations. As a matter of fact, an oscillator is a device that converts d.c. power into a.c. power of any desired frequency.

(*ii*) **Negative feedback.** When the feedback energy (voltage or current) is out of phase with the input signal and thus opposes it, it is called *negative feedback*. This is illustrated in Fig. 13.2. As you can see, the amplifier introduces a phase shift of 180° into the circuit while the feedback network is so designed that it introduces no phase shift (*i.e.*, 0° phase shift). The result is that the *feedback voltage* V_f is 180° out of phase with the input signal V_{in}.

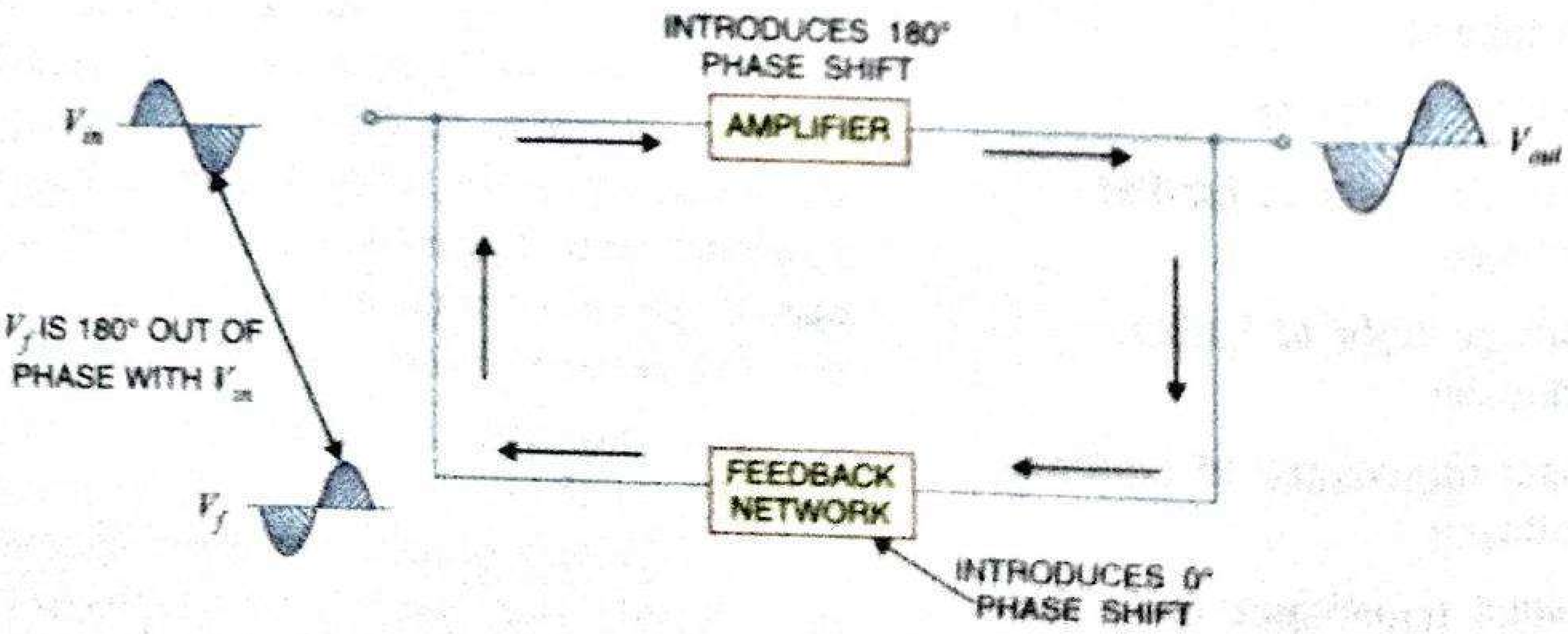


Fig. 13.2

Negative feedback reduces the gain of the amplifier. However, the advantages of negative feedback are: reduction in distortion, stability in gain, increased bandwidth and improved input and output impedances. It is due to these advantages that negative feedback is frequently employed in amplifiers.

13.2 Principles of Negative Voltage Feedback In Amplifiers

A feedback amplifier has two parts viz an amplifier and a feedback circuit. The feedback circuit usually consists of resistors and returns a fraction of output energy back to the input. Fig. 13.3 *shows the principles of negative voltage feedback in an amplifier. Typical values have been assumed to make the treatment more illustrative. The output of the amplifier is 10 V. The fraction m_v of this output *i.e.* 100 mV is fedback to the input where it is applied in series with the input signal of 101 mV. As the feedback is negative, therefore, only 1 mV appears at the input terminals of the amplifier.

Referring to Fig. 13.3, we have,

$$\text{Gain of amplifier without feedback, } A_v = \frac{10 \text{ V}}{1 \text{ mV}} = 10,000$$

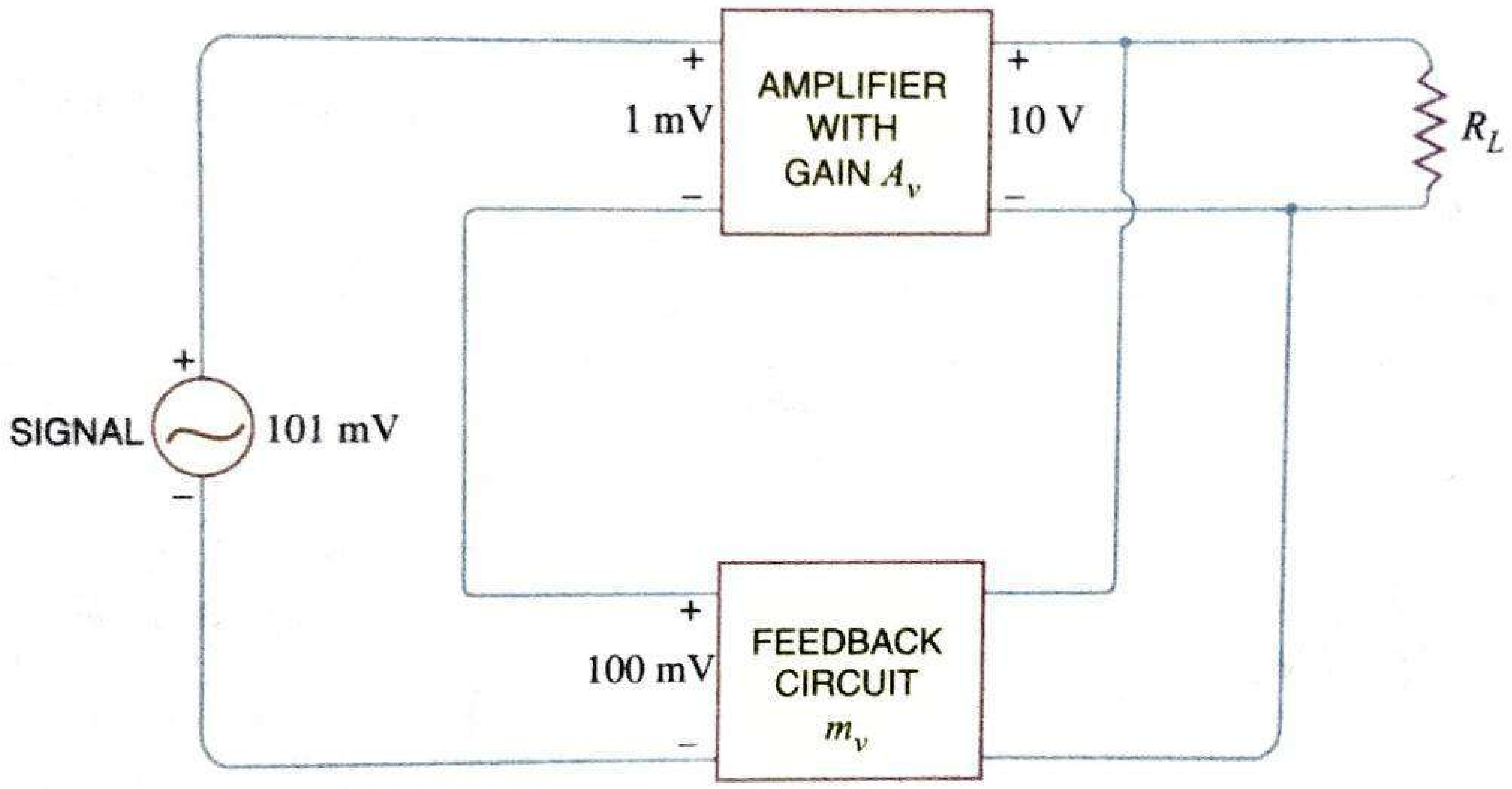


Fig. 13.3

$$\text{Fraction of output voltage fedback, } m_v = \frac{100 \text{ mV}}{10 \text{ V}} = 0.01$$

$$\text{Gain of amplifier with negative feedback, } A_{vf} = \frac{10 \text{ V}}{101 \text{ mV}} = 100$$

The following points are worth noting :

(*i*) When negative voltage feedback is applied, the gain of the amplifier is **reduced. Thus, the gain of above amplifier without feedback is 10,000 whereas with negative feedback, it is only 100.

(*ii*) When negative voltage feedback is employed, the voltage *actually* applied to the amplifier is extremely small. In this case, the signal voltage is 101 mV and the negative feedback is 100 mV so that voltage applied at the input of the amplifier is only 1 mV.

(*iii*) In a negative voltage feedback circuit, the feedback fraction m_v is always between 0 and 1.

(*iv*) The gain with feedback is sometimes called *closed-loop gain* while the gain without feedback is called *open-loop gain*. These terms come from the fact that amplifier and feedback circuits form a "loop". When the loop is "opened" by disconnecting the feedback circuit from the input, the amplifier's gain is A_v, the "open-loop" gain. When the loop is "closed" by connecting the feedback circuit, the gain decreases to A_{vf}, the "closed-loop" gain.

* Note that amplifier and feedback circuits are connected in *series-parallel*. The inputs of amplifier and feedback circuits are in *series* but the outputs are in *parallel*. In practice, this circuit is widely used.

** Since with negative voltage feedback the voltage gain is decreased and current gain remains unaffected, the power gain A_p $(= A_v \times A_i)$ will decrease. However, the drawback of reduced power gain is offset by the advantage of increased bandwidth.

13.3 Gain of Negative Voltage Feedback Amplifier

Consider the negative voltage feedback amplifier shown in Fig. 13.4. The gain of the amplifier without feedback is A_v. Negative feedback is then applied by feeding a fraction m_v of the output voltage e_0 back to amplifier input. Therefore, the actual input to the amplifier is the signal voltage e_g *minus* feedback voltage $m_v e_0$ *i.e.*,

$$\text{Actual input to amplifier} = e_g - m_v e_0$$

The output e_0 must be equal to the input voltage $e_g - m_v e_0$ multiplied by gain A_v of the amplifier *i.e.*,

$$(e_g - m_v e_0) A_v = e_0$$

or $$A_v e_g - A_v m_v e_0 = e_0$$

or $$e_0 (1 + A_v m_v) = A_v e_g$$

or $$\frac{e_0}{e_g} = \frac{A_v}{1 + A_v m_v}$$

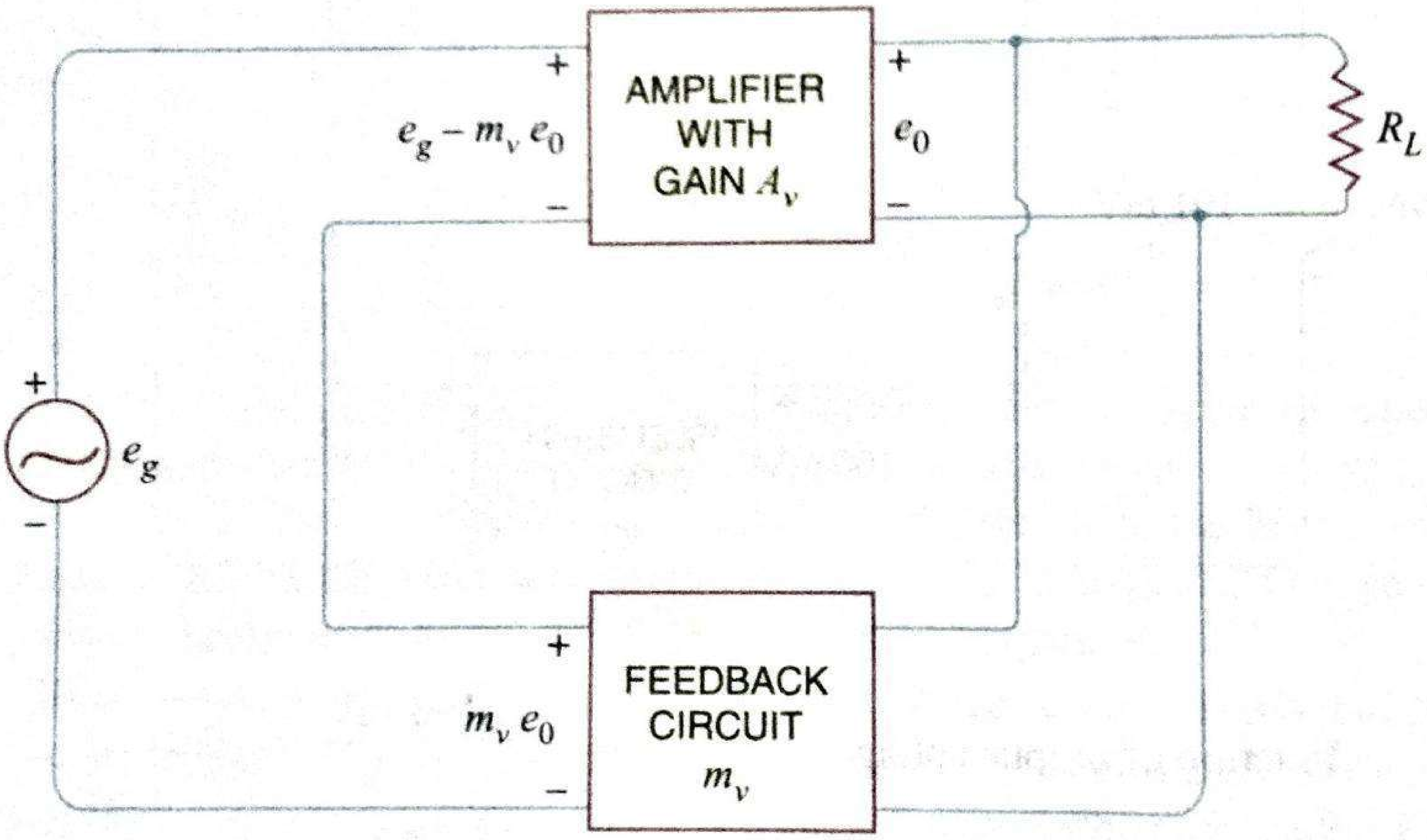


Fig. 13.4

But e_0/e_g is the voltage gain of the amplifier with feedback.

∴ Voltage gain with negative feedback is

$$A_{vf} = \frac{A_v}{1 + A_v m_v}$$

It may be seen that the gain of the amplifier without feedback is A_v. However, when negative voltage feedback is applied, the gain is reduced by a factor $1 + A_v m_v$. It may be noted that negative voltage feedback does not affect the current gain of the circuit.

13.4 Advantages of Negative Voltage Feedback

The following are the advantages of negative voltage feedback in amplifiers :

(i) **Gain stability.** An important advantage of negative voltage feedback is that the resultant gain of the amplifier can be made independent of transistor parameters or the supply voltage variations.

$$A_{vf} = \frac{A_v}{1 + A_v\, m_v}$$

For negative voltage feedback in an amplifier to be effective, the designer deliberately makes the product $A_v m_v$ much greater than unity. Therefore, in the above relation, 1 can be neglected as compared to $A_v m_v$ and the expression becomes :

$$A_{vf} = \frac{A_v}{A_v\, m_v} = \frac{1}{m_v}$$

It may be seen that the gain now depends only upon feedback fraction m_v *i.e.*, on the characteristics of feedback circuit. As feedback circuit is usually a voltage divider (a resistive network), therefore, it is unaffected by changes in temperature, variations in transistor parameters and frequency. Hence, the gain of the amplifier is extremely stable.

(ii) **Reduces non-linear distortion.** A large signal stage has non-linear distortion because its voltage gain changes at various points in the cycle. The negative voltage feedback reduces the non-linear distortion in large signal amplifiers. It can be proved mathematically that :

$$D_{vf} = \frac{D}{1 + A_v\, m_v}$$

where D = distortion in amplifier without feedback

D_{vf} = distortion in amplifier with negative feedback

It is clear that by applying negative voltage feedback to an amplifier, distortion is reduced by a factor $1 + A_v m_v$.

(iii) **Improves frequency response.** As feedback is usually obtained through a resistive network, therefore, voltage gain of the amplifier is *independent of signal frequency. The result is that voltage gain of the amplifier will be substantially constant over a wide range of signal frequency. The negative voltage feedback, therefore, improves the frequency response of the amplifier.

(iv) **Increases circuit stability.** The output of an ordinary amplifier is easily changed due to variations in ambient temperature, frequency and signal amplitude. This changes the gain of the amplifier, resulting in distortion. However, by applying negative voltage feedback, voltage gain of the amplifier is stabilised or accurately fixed in value. This can be easily explained. Suppose the output of a negative voltage feedback amplifier has increased because of temperature change or due to some other reason. This means more negative feedback since feedback is being given from the output. This tends to oppose the increase in amplification and maintains it stable. The same is true should the output voltage decrease. Consequently, the circuit stability is considerably increased.

(v) **Increases input impedance and decreases output impedance.** The negative voltage feedback increases the input impedance and decreases the output impedance of amplifier. Such a change is profitable in practice as the amplifier can then serve the purpose of impedance matching.

(a) **Input impedance.** The increase in input impedance with negative voltage feedback can be explained by referring to Fig. 13.6. Suppose the input impedance of the amplifier is Z_{in} without feedback and Z'_{in} with negative feedback. Let us further assume that input current is i_1.

Referring to Fig. 13.6, we have,

$$e_g - m_v e_0 = i_1 Z_{in}$$

Now

$$e_g = (e_g - m_v e_0) + m_v e_0$$

$$= (e_g - m_v e_0) + A_v m_v (e_g - m_v e_0) \qquad [\because e_0 = A_v (e_g - m_v e_0)]$$

$$= (e_g - m_v e_0)(1 + A_v m_v)$$

$$= i_1 Z_{in} (1 + A_v m_v) \qquad [\because e_g - m_v e_0 = i_1 Z_{in}]$$

* $A_{vf} = 1/m_v$. Now m_v depends upon feedback circuit. As feedback circuit consists of resistive network, therefore, value of m_v is unaffected by change in signal frequency.

or $$\frac{e_g}{i_1} = Z_{in}(1 + A_v m_v)$$

But $e_g/i_1 = Z'_{in}$, the input impedance of the amplifier with negative voltage feedback.

$$\therefore \quad Z'_{in} = Z_{in}(1 + A_v m_v)$$

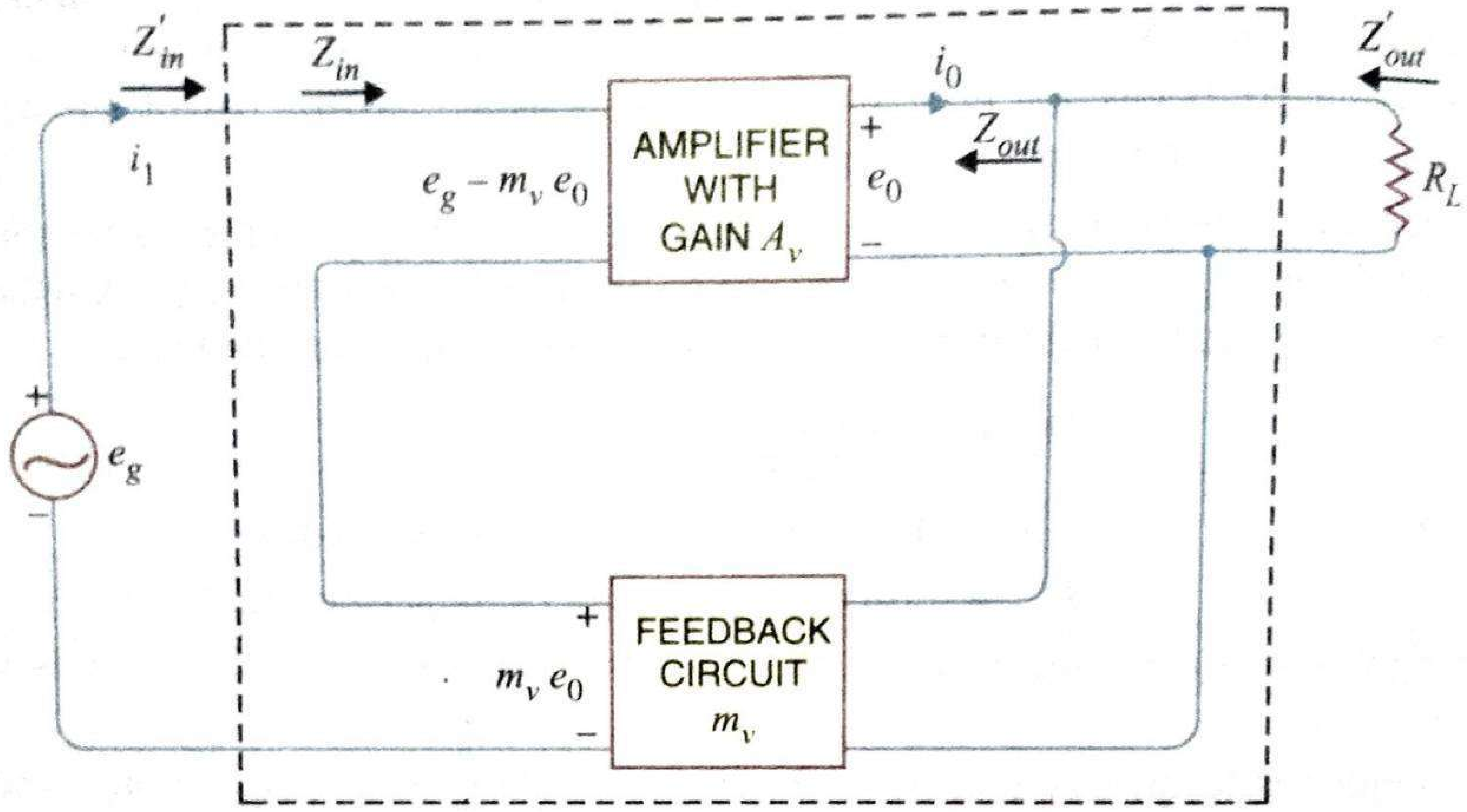


Fig. 13.6

It is clear that by applying negative voltage feedback, the input impedance of the amplifier is increased by a factor $1 + A_v m_v$. As $A_v m_v$ is much greater than unity, therefore, input impedance is increased considerably. This is an advantage, since the amplifier will now present less of a load to its source circuit.

(b) Output impedance. Following similar line, we can show that output impedance with negative voltage feedback is given by :

$$Z'_{out} = \frac{Z_{out}}{1 + A_v m_v}$$

where Z'_{out} = output impedance with negative voltage feedback

Z_{out} = output impedance without feedback

It is clear that by applying negative feedback, the output impedance of the amplifier is decreased by a factor $1 + A_v m_v$. This is an added benefit of using negative voltage feedback. With lower value of output impedance, the amplifier is much better suited to drive low impedance loads.

where BW = Bandwidth of the amplifier without feedback

$BW_{(f)}$ = Bandwidth of the amplifier with negative feedback

13.6 Principles of Negative Current Feedback

In this method, a fraction of output current is fedback to the input of the amplifier. In other words, the feedback current (I_f) is proportional to the output current (I_{out}) of the amplifier. Fig. 13.10 shows the principles of negative current feedback. This circuit is called current-shunt feedback circuit. A feedback resistor R_f is connected between input and output of the amplifier. This amplifier has a current gain of A_i without feedback. It means that a current I_1 at the input terminals of the amplifier will appear as $A_i I_1$ in the output circuit *i.e.*, $I_{out} = A_i I_1$. Now a fraction m_i of this output current is fedback to the input through R_f. The fact that arrowhead shows the feed current being fed forward is because it is *negative* feedback.

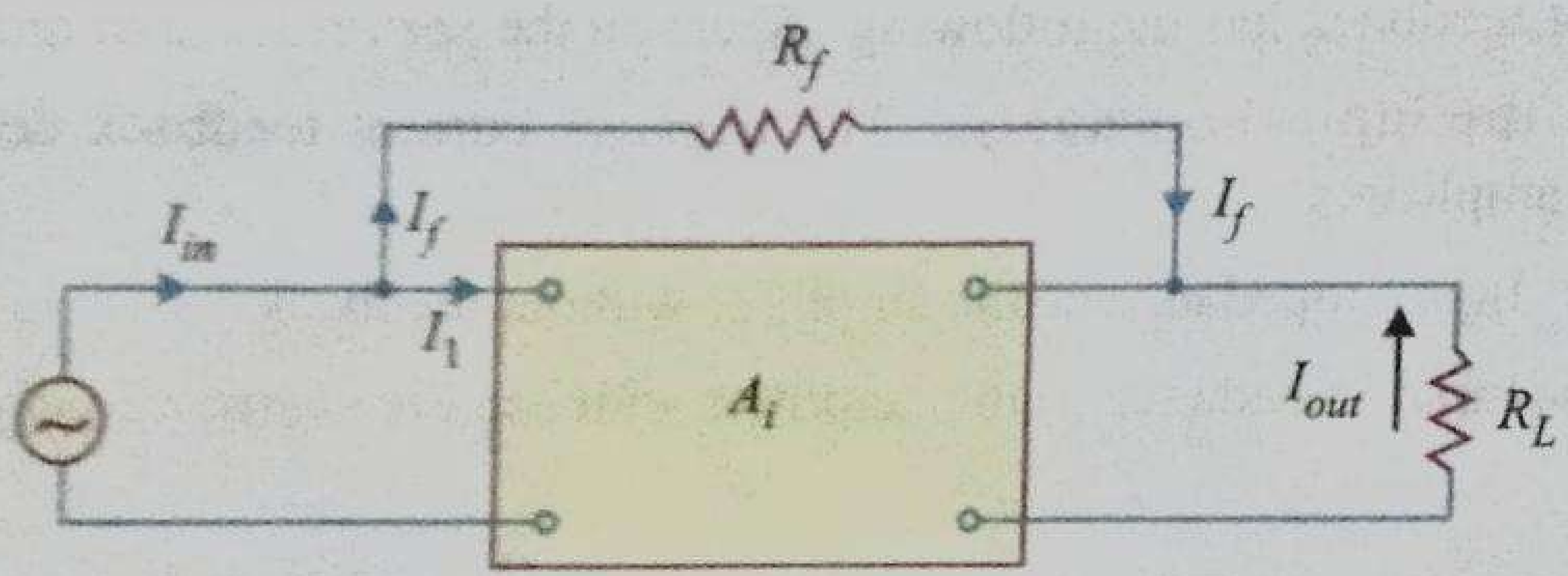


Fig. 13.10

Feedback current, $I_f = m_i I_{out}$

$\therefore$ Feedback fraction, $m_i = \dfrac{I_f}{I_{out}} = \dfrac{\text{Feedback current}}{\text{Output current}}$

Note that negative current feedback reduces the input current to the amplifier and hence its current gain.

13.7 Current Gain with Negative Current Feedback

Referring to Fig. 13.10, we have,

$$I_{in} = I_1 + I_f = I_1 + m_i I_{out}$$

But $I_{out} = A_i I_1$, where A_i is the current gain of the amplifier without feedback.

$$\therefore \quad I_{in} = I_1 + m_i A_i I_1 \qquad (\because I_{out} = A_i I_1)$$

$\therefore$ Current gain with negative current feedback is

$$A_{if} = \frac{I_{out}}{I_{in}} = \frac{A_i I_1}{I_1 + m_i A_i I_1}$$

or

$$A_{if} = \frac{A_i}{1 + m_i A_i}$$

This equation looks very much like that for the voltage gain of negative voltage feedback amplifier. The only difference is that we are dealing with current gain rather than the voltage gain. The following points may be noted carefully :

(*i*) The current gain of the amplifier without feedback is A_i. However, when negative current feedback is applied, the current gain is reduced by a factor $(1 + m_i A_i)$.

(*ii*) The feedback fraction (or current attenuation) m_i has a value between 0 and 1.

(*iii*) The negative current feedback does not affect the voltage gain of the amplifier.

Example 13.15. *The current gain of an amplifier is 200 without feedback. When negative current feedback is applied, determine the effective current gain of the amplifier. Given that current attenuation* $m_i = 0.012$.

Solution. $$A_{if} = \frac{A_i}{1 + m_i A_i}$$

Here $A_i = 200 \; ; \quad m_i = 0.012$

$$\therefore \quad A_{if} = \frac{200}{1 + (0.012)(200)} = \mathbf{58.82}$$

Scanned Book:

1. V.K.Mehta & Rohit Mehta, 2012, Principles of Electronics-S.Chand & Company, Ram Nagar, New Delhi-110 055.