34

SEMICONDUCTOR DEVICES

34.1 INTRODUCTION

In the previous lesson, you have learnt about the p-type and the n-type semiconductors. Now, the most obvious question, what will happen if we join the p-type and the n-type semiconductor under different conditions. A p-n junction diode is the result which may be applied forward and reverse biasing. Some special diodes like Zener diode, light emitting diode (LED), photo diode, solar cell etc. are also semiconductor devices with many applications in electronics.

If we join another p-type or n-type semiconductor to a n-p junction or a p-n junction respectively, then what we get is a revolutionary semiconductor device, known as transistor. The junction p-n-p or n-p-n transistors form the key element in computers, space vehicles and satellites and in all modern communication and power systems. In this lesson you will learn about mechanism of current flow in a transistor. You will also learn about characteristics of a transistor in different configurations.

34.2 OBJECTIVES

After studying this lesson, you should be able to,

- *explain the formation of a p-n junction and define the terms 'depletion region' and 'potential barrier';*
- *explain the terms 'forward biasing' and 'reverse biasing' of a p-n junction;*
- *draw the current-voltage characteristics for the forward and reverse biasing of a p-n junction diode;*
- *explain the functioning of Zener diode, LED, photo diode and a solar cell;*
- *describe the structure of a transistor and differentiate between p-n-p and n-p-n transistors, and represent them by their schematic symbols;*
- *give reasons for making the base of a transistor very thin and lightly doped;*
- *distinguish between the three different transistor configurations, i.e. common base (CB), common emitter (CE) and common collector (CC) and draw their characteristics; and*
- *explain the working of p-n-p and n-p-n transistors.*

34.3 p-n JUNCTION

You have learnt about the p-type and n-type semiconductors in the previous lesson. As a matter of fact. the p-type and n-type semiconductors, taken separately, are of little use in actual practice. If we join a p-type semiconductor suitably to n-type semiconductor such that the crystal structure remains continuous at the boundary as shown in Fig.34.1, a p-n juncion is formed. The p-n junction is of great importance in modern electronic applications. It forms the basis of semiconductor devices like diodes. transistors etc.

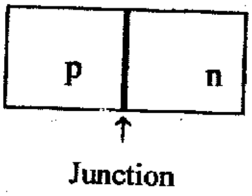


Fig. 34.1 : p-n junction

34.3.1 Formation of p-n Junction

It should be noted that a useful p-n junction cannot be formed by simply joining or welding the p-type and n-type pieces together because it will produce a discontinuous crystal structure. Special fabrication techniques are used to prepare p-n junctions. We will not go into the details of various techniques. In short, you can understand the formation of a p-n junction as follows:

A small block of a trivalent impurity, say indium, is placed on n-type germanium slab. The combination is heated to a high temperature of about $500^{o}C$ for a short duration. During this process, indium melts and gets into some of the germanium. The temperature is then lowered. Under proper conditions, the atoms of indium will be suitably adjusted in a portion of the molten germanium to form a single crystal. The addition of indium overomes the excess of electrons in the n-type germanium to such an extent that it creates a p-type region over a portion of the semiconductor and forms a p-n junction.

34.3.2 Properties of p-n junction

To understand the properties of a p-n junction, we start with the two types of materials p-type and n-type separately, as shown in Fig.34.2.

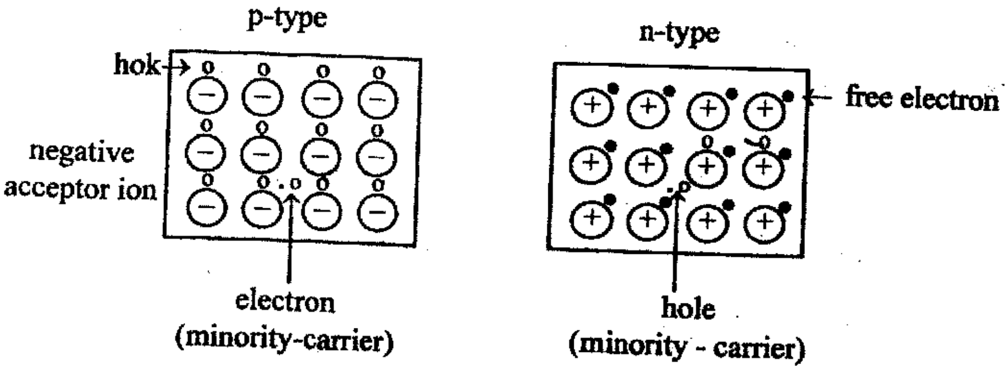


Fig. 34.2 : Charge distribution in p-type and n-type region

As explained earlier, p-type material contains negative acceptor ions and positively charged holes. These holes are large in number and are majority carriers. In addition, there is a small number of thermally generated electron-hole pairs (as shown in the Fig.34.2). These electrons are the minority carriers. Similarly, in the n-type material: there are equal number of positive donor ions and free electrons. These free electrons are large in number and act as the majority carriers, whereas, a few of the thermally generated holes act as minority carriers. It should be noted that both the p-type and n-type materials are electrically neutral on the whole.

Now, suppose that a p-n junction has just been formed. At that instant, holes are still in p-region and electrons in the n-region. However, there is greater concentration of holes in the p-region than in the n-region and similarly, there is a greater concentration of electrons in the n-region than in the p-region. This difference in concentration establishes a density gradient across the junction. Therefore, there is a tendency for holes to cross the junction and move to the n-region and for the electrons to move towards the p-region. This process is called the **diffusion** of charge carriers across the junction ***of the movement of charge carriers from a region of higher concentration to a region of lower concentration.***

Depletion Layer

As the electrons and holes move across the junction, they meet and recombine on both sides of the junction. In the process of recombination, the free electrons fill the holes in the valence band and both the charge carriers disappear. As a result of this, the negative acceptor ions on the p-side of the junction are left uncovered, i.e., they are robbed of holes. Similarly, the positive donor ions on the n-side of the junction are uncovered; or robbed of free electrons. Hence, a positive charge is built on the n-side of the junction and a negative charge on the p-side. Note that these uncovered ions are immobile and hence remain where they were. When a sufficient number of donor and acceptor ions are uncovered, further diffusion of free charge carriers is prevented. It is because now positive charge on n-side repels holes to cross from p-type to n-type and the negative charge on p-side repels the electrons to diffuse from n-type to p-type. The region containing the uncovered acceptor and donor ions, in the vicinity of the junction, is called ***depletion layer*** (Fig.34.3). It is called so because the mobile charge carriers (i.e. free electrons and holes) have been depleted. (i.e. emptied) in this region. ***The region in the junction containing no mobile charge carriers, but only immobile charges of opposite kind on its two sides is known depletion layer*** ......

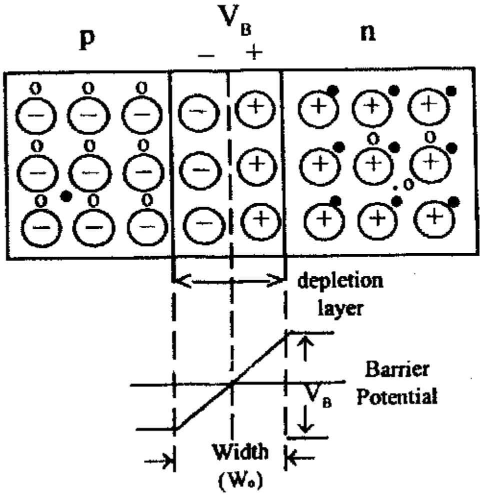


Fig. 34.3 : Formation of dopletion layer in p-n junction

The width of the depletion layer depends on the doping level. For heavy doping, depletion layer is thin because the p-n junction contains a large number of free electrons and holes and a diffusing charge carrier has not to travel far across the junction for recombination.

Opposite is the case for light doping. But, generally, the width of the depletion layer is of the order of a few μ m (10^{-6} m). It should be noted that outside this layer, on each side of the junction, the material is still neutral.

Potential Barrier

The depletion layer thus sets up a barrier against further diffusion of charge carriers. This is called potential barrier or junction barrier. The magnitude of this electric potential is represented as V_B. At room temperature, V_B is about 0.3 V for germanium and 0.7 V for Si. Its value depends on doping density, electronic charge and temperature. ***The potential in a region where the force exerted on a carrier is such as to oppose the passage of the carrier through the region is known as* Potential barrier.**

It should be noted that the barrier potential V_B is established across the junction automatically, as soon as the p-n junction is formed, even when the junction is not connected to any external source of e.m.f (Fig.34.3).

INTEXT QUESTIONS 34.1

1. Fill in the blanks with suitable word(s) or numerical value(s):

i) A--------------------------potential is developed across a p-n junction whose value for silicon is----------------.

ii) Depletion region exists on --------------------- sides of a p-n junction.

iii) Depletion layer has no ----------------- charge carriers, but only immobile --------.

iv) The width of the depletion layer in an unbiased p-n junction depends on ----------------- level.

v) The process of transfer of mobile charge carriers across the p-n junction when no external voltage is applied to it is called --------------------- process.

2. Select one of the items lettered a,b,c or d that correctly completes the statement:

i) When a hole diffuses from p-region to n-region, it
a) becomes a majority carrier in the n-region
b) becomes a minority carrier in the n-region
c) lowers the potential barrier
d) raises the potential barrier

ii) Depletion layer is
a) positively charged
b) negatively charged
c) completely neutral and has no charge
d) a charged region of positive and negative ions.

iii) In an unbiased p-n junction, the junction current at equilibrium is
a) due to diffusion of majority carriers only
b) due to diffusion of minority carriers only
c) zero, because no charges are crossing the junction
d) zero, because equal but opposite currents are crossing the junction.

34.4 BIASING OF p-n JUNCTION

We have seen that as a p-n junction is formed, a barrier potential is set up which does not permit the current to flow across the junction. Such a p-n junction is called unbiased junction and is of no use in actual practice. A p-n junction. connected to an external voltage source (i.e. battery) is called a biased p-n junction. Such a p-n junction finds a variety of applications in semiconductor devices.
There are two ways of applying external voltage to a p-n junction:

34.4.1 Forward Biasing

In this case, positive terminal of the battery is connected to the p-side and negative terminal to the n-side (Fig.34.4). This type of biasing permits easy flow of current across the junction.

As soon as battery connection is made, holes in the p-region are repelled by the positive battery terminal and electrons in the n-region are repelled by the negative battery terminal. As a result, both holes and electrons move *towards* the junction. Because of their acquired energy (from the voltage source), they enter the depletion region and recombine. ***This reduces the width as well as height of the potential barrier (V_B)as shown in Fig.34.4.*** As V_B is very small, a small forward voltage is sufficient to completely eliminate the barrier. In other words, the forward bias establishes a low resistance path (called forward resistance, R_f) and as a result a large current flows through the junction. This is called forward current. The magnitude of current depends upon the applied forward voltage. ***In forward biasing – the external voltage is applied to the junction in such a direction that it cancels the potential barrier, thus permitting current flow.***

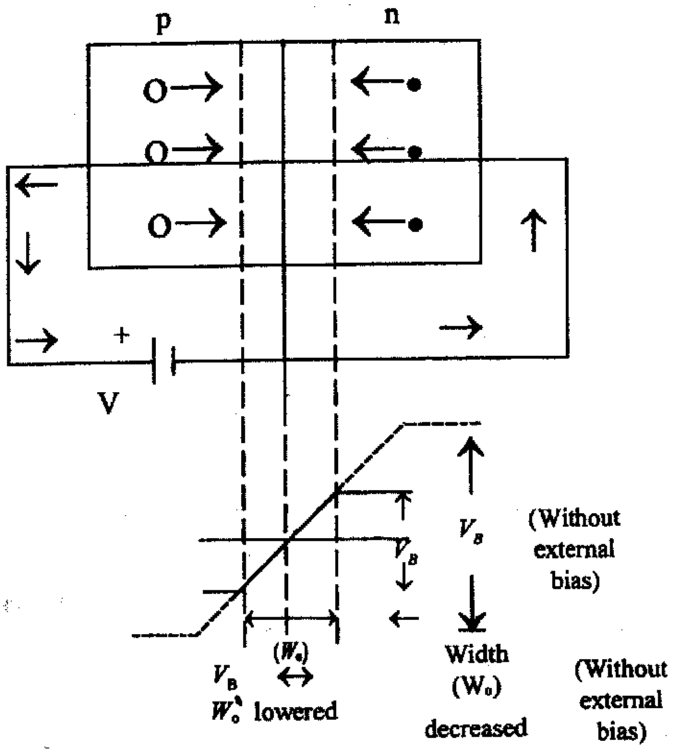


Fig. 34.4: Forward biasing in p-n junction

The mechanism of current flow in a forward bias can be understood as follows:

i) The free electrons in the n-region move towards the junction and more electrons from the negative battery terminal enter the n-region.

ii) The electrons travel through the n-region as free-electrons.

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

iv) The electrons travel through the p-region as valence electrons, ve. current in p-region is by holes.

v) When these valence electrons reach the left end of the crystal, they flow into the positive terminal of battery (creating new holes which will move towards the junction).

It can be now understood that the current within the junction is the sum of the electron current (in the n-region) and the hole current (in the p-region. The current through the external circuit is due to the movement of electrons only. This current continues to flow as long as the battery is present in the circuit.

34.4.2 Reverse Biasing

In this case, positive terminal of the battery is connected to the n-side and negative terminal to the p-side (Fig.34.5). This type of biasing prevents the easy current flow across the junction.

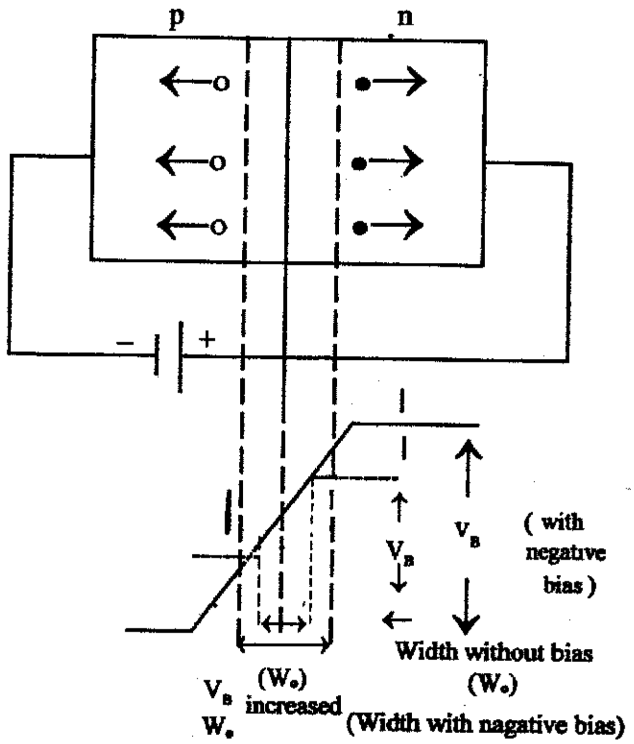


Fig. 34.5 Reverse biasing in p-n junction

With the reverse bias, the holes in the p-region are attracted towards the negative battery terminal and electrons in the n-region are attracted towards the positive battery terminal. Thus the majority carriers are drawn *away* from the junction. ***This widens the depletion layer and increases the height of the potential barrier (V_B)*** as shown in Fig.34.5. The increased potential barrier makes it very difficult for the majority carriers to diffuse across the junction. Thus a high resistance (called reverse resistance, R_r) path is established and hence current does not flow. *In reverse biasing the external voltage applied to the junction is in such a direction that it increases the potential barrier, thus preventing the current flow*

34.5 SEMICONDUCTOR DIODE

It has already been discussed in the previous section that a p-n junction conducts current easily when forward biased and practically no current flows when it is reverse biased. This unilateral conduction characteristic of p-n junction is similar to that of a vacuum diode. Further, it also consists of two electrodes (the contact points to the p and n-regions) just as a vacuum diode has. Thus, a p-n junction is called a *semiconductor diode*. It may also be called a *junction diode* or a *crystal diode*.

Fig. 34.6(a): p-n junction

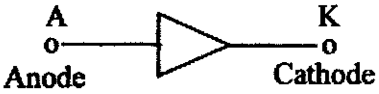


Fig.34.6(b): Symbolic resresentation of p-n junction

Thus, a p-n junction diode consists of a p-n junction, formed either in germanium or silicon crystal [Fig.34.6(a)]. It has two terminals, namely anode and cathode. The p-type region is referred to as anode and the n-type region as cathode. The circuit symbol is shown in Fig.[34.6(b)]. The arrow-head in the circuit symbol points in the direction of conventional current flow, when the diode is forward biased. It is the same direction in which hole flow takes place.

Semiconductor diodes are generally small in size (about 3 mm long) with a colour-band towards cathode end or symbol of diode painted on the body; or colour dots representing the anode and cathode of the diode (Fig.34.7).

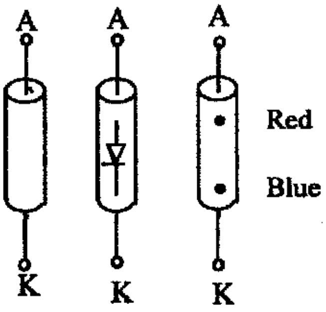


Fig. 34.7: Identification of diode terminals

34.5.1 Characteristics of p-n Junction Diode

We have seen that the current flow through the p-n junction diode is different in forward and reverse bias. Also, the current will be different for different external bias. A curve representing the variation of current with the applied external bias is called the V-I characteristics of the p-n junction diode. Fig.34.8 shows the circuit arrangement for determining the V-I characteristics of the diode. The characteristics can be studied in two parts – under the forward bias and the reverse bias. When the external bias is zero the potential barrier at the junction does not permit current flow. Therefore, the circuit current is zero as indicated by point O in the characteristic curves of Fig.34.9.

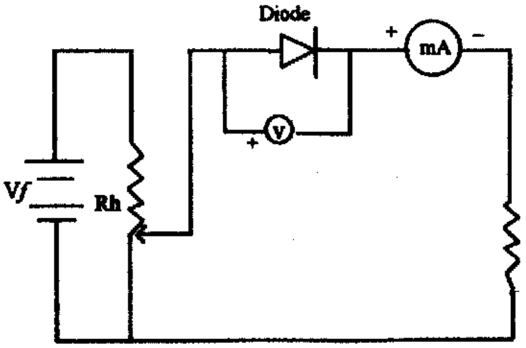


Fig. 34.8: Circuit diagram for forward characterists of a p-n junction diode.

(i) Forward Bias: Forward bias can be applied to the diode as shown in Fig.34.8. The diode is connected to a d.c. battery (V_f) through a rheostat (R_h). The rheostat helps in varying the voltage applied across the diode. The resistance R is included in the circuit so as to limit the current through the diode. Voltmeter (V) and milliammeter (mA) measure the voltage and current respectively.

Let us now increase the voltage in small steps of about 0.1 V and record the corresponding values of diode current. If a graph is plotted with voltage across the diode along the horizontal axis and diode current along the vertical axis, a curve OAB, shown in Fig.34.9, will be obtained. This is the ***forward characteristic*** curve of the diode.

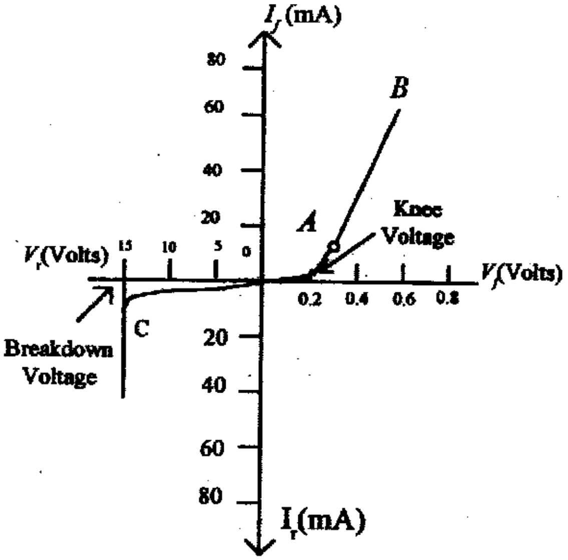


Fig. 34.9: I-V characteristics of a p-n junction diode

It can be seen that at first (region OA), the current increases very slowly and the curve is non-linear. It is because the external voltage is used up in overcoming the potential barrier. However, once the external voltage exceeds the barrier potential, the p-n junction behaves like an ordinary conductor. Therefore, the current rises very sharply with increase in external voltage (region AB of the curve). The curve is almost linear in this portion. The voltage corresponding to point A of the forward characteristic curve is known as **Knee voltage.** ***It is defined as the forward voltage at which the current through the junction starts to increase rapidly.***

It may be added here that in order to get useful current through a p-n junction, the applied voltage must be more than the knee voltage.

It has been observed that a voltage of about 1 volt produces a forward current of about 50 mA to 100 mA. Hence, the forward resistance of the diode (R_f) is quite small. It is of the order of 10 to 100 ohms. The applied forward voltage should not be increased beyond a certain safe limit, otherwise the diode will burn out.

ii) Reverse Bias: For the reverse bias to be applied to the diode, the circuit connection will remain the same as in Fig.34.8 except that the diode terminals (i.e. the anode and the cathode) are to be interchanged. Moreover, the milliameter will have to be changed by a microammeter. As already discussed in Section 34.4(b), the majority carriers are not able to cross the junction due to the increased barrier potential. So, practically no current flows through the circuit. However, in practice, a very small current (of the order of μA) flows in the circuit. It is due to the minority carriers and is called leakage current or reverse saturation current (I_r). It may be recalled that there are a few free electrons in p-type material and a few holes in n-type material. To these minority carriers, the applied reverse bias appears as forward bias. Therefore, a very small reverse current flows in the reverse direction (as shown by the curve OC in the negative voltage region of Fig.34.9. This small current can generally be regarded as negligible over the working range of voltages.

If reverse voltage is increased continuously, the kinetic energy of the minority electrons may become high enough to knock out electrons from the semiconductor atoms. The newly liberated electrons in turn free other valence electrons. In this way, we get an *avalanche* (i.e. flood) of free electrons. This is called *breakdown* of the junction. Due to this, the reverse current rises suddenly with a sudden fall of the resistance of the barrier region. This voltage corresponding to the point C of the reverse characteristic curve is called the **Breakdown voltage.** ***It is the reverse voltage at which the p-n junction breaks down with sudden rise in reverse current.***

Breakdown of the junction may be due to an another effect also. This effect is different from the avalanche effect. In a general purpose diode, the doping is light. This results in a high breakdown voltage which is due to the avalanche effect. If the p and n regions in a diode are heavily doped, the breakdown voltage can be reduced. Heavy doping reduces the width of the depletion region and the electric field at the barrier will be very high even for low voltage. The field is so strong that the electrons in the covalent bond can break away from the bonds. This effect is known as ***Zener effect.*** This also leads to the sudden fall of junction resistance and a sharp rise in 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 p-n junction is always less than the breakdown voltage.

INTEXT QUESTIONS 34.2

1. Fill in the blanks by appropriate word(s):

i) When reverse bias of a junction diode is increased beyond a certain limit, a ----------------- occurs.

ii) When a junction is forward biased for majority carriers, it is --------------- biased for---------------carriers.

iii) Reverse saturation current consists of----------------------- carriers.

iv) A junction offers almost ------------------- resistance in the breakdown region.

v) Avalanche breakdown is initiated by------------------ carriers.

vi) Zener breakdown occurs in junctions which are -------------------- doped and have -------------- depletion layer.

vii) Zener breakdown involves ---------------------- of covalent bonds under the influence of a ----------------- electric field.

34.6 SPECIAL DIODES

In the last sections, you studied about an ordinary p-n junction diode. Now, we will discuss some special semiconductor diodes, which are used for specific applications.

(a) Zener Diode

It is a ***reverse biased heavily doped*** silicon (or germanium) p-n junction diode which is operated in the breakdown region. The reverse current is limited by the external resistance in the circuit and power dissipation of the diode. Silicon is preferred to germanium because of its higher temperature stability and current capability.

At reverse voltage less than 6 V, Zener effect predominates whereas above 6V, avalanche effect is predominant. But, in both the cases, the diode is called a Zener diode. Zener diodes are designed to operate at voltages ranging from a few volts to few hundred volts.

The voltage across the diode remains practically constant at the Zener breakdown voltage V_Z. Hence it is also called a breakdown diode or voltage regulator diode. The Zener voltage V_Z can be set by carefully controlling the doping level of p and n regions during manufacturing.

V-I Characteristics: The reverse current due to minority carriers remains negligibly small upto the knee point (K). At this point (K), the breakdown voltage (Zener voltage V_Z) remains practically constant over a range of Zener current values (Fig.34.10). These are:

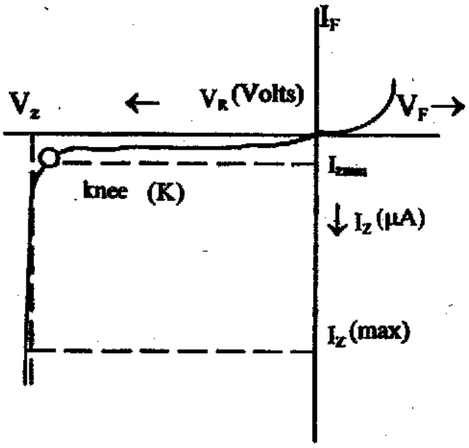


Fig. 34.10: Reverse charecteristics of a zener diode

i) $I_{Z,min}$ - *The minimium value of Zener current which must be maintained to keep the diode in the breakdown region.*
ii) $I_{Z,max}$ - *The maximum value of Zener current above which the diode may be damaged.*

The value of this current is given by the maximum power rating (provided by the manufacturer), and can be controlled by suitable external load. As long as this limit is not crossed, the diode is not damaged and comes out of the breakdown region on reducing the voltage below V_Z. The schematic symbol of a Zener diode is represented in Fig.34.11(a). It is similar to that of a normal diode except that the line representing cathode is bent at both ends to look like the letter Z. It has an equivalent circuit like that in Fig.34.11(b), where it looks like a battery of V_Z volts.

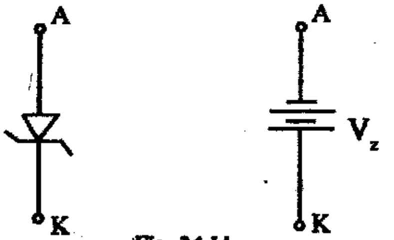


Fig. 34.11

(a) :Symbolic representation of zener diode *(b) :Ideal equivalent circuits for Zener diode.*

Uses: Zener diodes have a number of applications in semiconductor circuits. Some of their common uses are:

i) As voltage regulators;
ii) As a fixed reference voltage for biasing;
iii) For protecting meters against damage from accidental application of high voltage.

(b) Light Emitting Diode (LED)

It is a ***forward biased*** p-n junction which ***emits light*** when energised. You have learnt that forward biasing of a p-n junction gives forward current due to recombination of electrons.

and holes. When a conduction electron combines with a hole in the valence band, it falls from the higher energy level to a lower energy level. The difference of energy is released out. In the ordinary diodes (Si and Ge) greater percentage of this energy is given up in the form of heat. There are some other semiconductors which are inter-metallic compounds of group III and group V elements, like gallium arsenide (GaAs), gallium phosphide (GaP), Gallium nitride (GaN) etc. In the diodes made from these semiconductors, a greater percentage of energy released during recombination is in the form of light. If the semiconductor material is transluscent, light is emitted out of it. The colour of the light emitted depends on the type of material used. The Schematic symbol of a light emitting diode is shown in Fig.34.12. The arrows represent the light emitted by the diode.

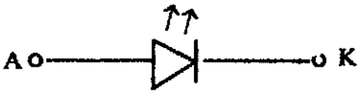


Fig. 34.12 : Symbolic reprisentection of LED

Uses: LED is a very important electronic device and finds widespread applications. A few of them are:

i) In 7-segment display used in calculators, digital clocks, stereo tuners etc.;
ii) For indicating power ON/OFF conditions in many instruments;
iii) In burgler alarm systems;
iv) In solid state video displays;
v) In the field of optical communication.

c) Photo - diode

It is a ***reverse biased*** p-n junction diode which gives useful current when light falls on it. The current produced varies almost linearly with the light intensity. It is made from light sensitive semiconductor with a very thin and transparent p-region which allows incident light to reach the junction easily. The incident light carries photons having energy $E = h\nu$ where h is the Planck's constant and ν is the frequency of light. If this energy is greater than the forbidden gap energy, the valence electrons will absorb this energy and jump to the conduction band, producing electron-hole pairs. The number of such pairs produced depends upon the intensity of the incident light. These carriers are minority carriers and produce current called photo-current when the junction is reverse biased. This photo-current is much larger than the reverse-saturation current which is much smaller in the ordinary p-n junction diode. A photodiode can turn its current ON and OFF in nano (10^{-9}) seconds. The schematic symbol for the photo-diode is shown in Fig.34.13. The inward arrows represent the light falling on the diode.

Fig. 34.13 : Symbolic reprisentection of a photo diode

Uses: Some of the important applications of photo-diodes are:

i) In detection of light (both visible and invisible)
ii) In light operated switches
iii) In reading of computer punched cards and tapes
iv) In optical communication systems.

d) Solar Cell

It is a type of photo-voltaic cell which is used to convert light energy of the sun to the electric energy. It is basically a photo-diode which is in open circuit. It is generally made of silicon or germanium with an extremely thin p-layer on n-layer, to allow the incident photons reach the junction easily. It is designed to have more exposed area to get more of incident light. The minority – carriers are produced as in the photo-diode. These move down the hill [Fig.34.14(a)] formed by a barrier - potential (electrons in p-side move to the n-side and holes in the n-side move towards the p-side). In the open circuit, this leads to the accumulation of electrons on n-side and of holes on p-side (Fig.34.14b) giving rise to an *open-circuit voltage* V_{OC} (against the potential barrier). This is called photo-voltaic e.m.f. and is of the order of 0.5 V for a silicon cell and 0.1 V for a germanium cell. The schematic symbol of the solar-cell is shown in Fig.34.15. It basically represents a cell operated by light.

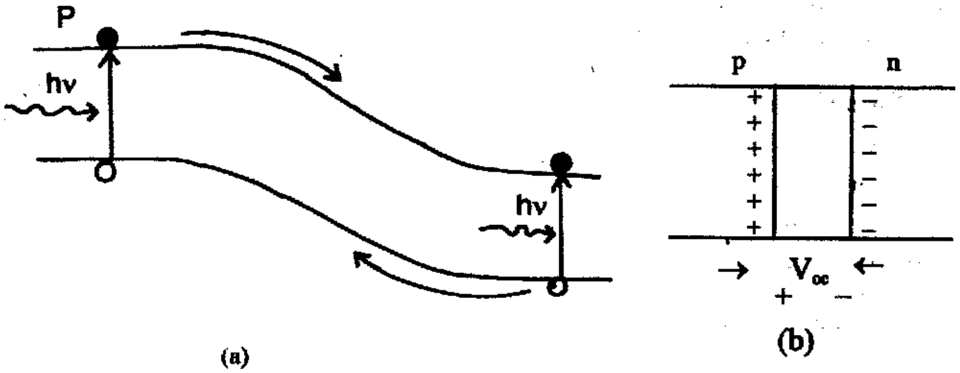


Fig. 34.14 : (a) Generation and movement of charge carriers by photons,
(b) Open circuit voltage across the junction of a photo - voltaic cell

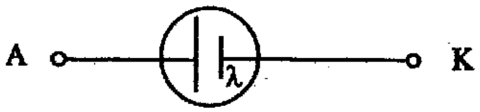


Fig. 34.15 : Symbolic representation of a solar cell.

Uses: Solar cells are extensively used to power the instruments of satellites and space vehicles. They are also used in other similar purposes such as in unmanned radio stations, light houses and telephone repeaters.

INTEXT QUESTIONS 34.3

1. *Fill in the blanks with suitable word(s).*
   - i) *A semiconductor diode designed to operate in the breakdown region is called a ——————— diode.*
   - ii) *LEDs emit light only when ——————— biased.*
   - iii) *Devices which convert light energy directly into electric energy are called ——————— devices.*
   - iv) *The open circuit voltage of a silicon solar cells is ——————— than that of a germanium solar cell.*
   - v) *Zener diodes are commonly used as ——————— regulators.*

2. Write 'True' or 'False' against the following statements:

i) Once in breakdown, a Zener diode keeps its voltage practically constant.
ii) Light emission by LED is due to recombination of electrons and holes.
iii) A photodiode is a junction device needing forward bias.
iv) Higher the illumination level, greater the reverse current of a photodiode.
v) Solar cell converts sun's heat energy directly into electric energy.

3. Select one of the items lettered a,b,c or d that correctly completes the statement:

i) The colour of light emitted by a LED depends on
  a) its forward bias — *b) its reverse bias*
  c) the amount of forward current — *d) the type of semiconductor material used*

ii) A p-n junction photo-diode is
  a) operated in forward direction — *b) encased in an opaque package*
  c) a very fast photo-detector — *d) depending on thermally-generated minority carriers*

34.7 TRANSISTOR - STRUCTURE AND TYPES

This device was invented in 1948 by W.J.Brattain and J.Bardeen of Bell Telephone Laboratories, USA. They gave it the name transistor *(transfer-resistor)* and demonstrated its important amplifying action.

Transistor

The transistor is a semiconductor crystal which has three doped regions and two p-n junctions. It has a very thin n-type or p-type region sandwiched between a pair of opposite type regions. Accordingly, there are two types of transistors, namely (i) p-n-p transistor and (ii) n-p-n transistor.

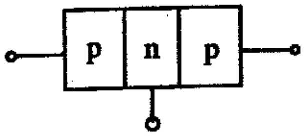


Fig. 34.16 (a): p-n-p transistor

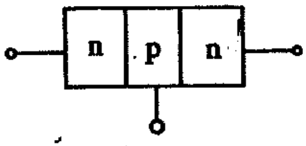


Fig. 34.16 (b): n-p-n transistor

A p-n-p transistor is composed of two p-type semiconductors separated by a very thin n-type section [Fig.34.16(a)], whereas, a n-p-n transistor is composed of two n-type semiconductors separated by a thin p-type section [Fig.34.16(b)].

In practice, a transistor is created by growing three different regions in the same semiconductor crystal by using special processes of adding corresponding imourities in turn. A transistor, thus, may be considered as consisting of two p-n junctions connected back-to-back. But, it should be noted that two *discrete* diodes connected back to back cannot act like a transistor because it will have four sections instead of three and the middle region will not be very thin, as required for a transistor.

The following points may be noted about the *structure* and functioning of a transistor:

i) There are three sections and three terminals are taken out from them.
ii) The middle section is very thin (10^{-6} m) and is called the *base*.

iii) The section on one side of the base the supplies the charge carriers (electrons or holes) is called the ***emitter***. For proper functioning of a transistor. the emitter is always forward biased with respect to the base (Fig.34.17).

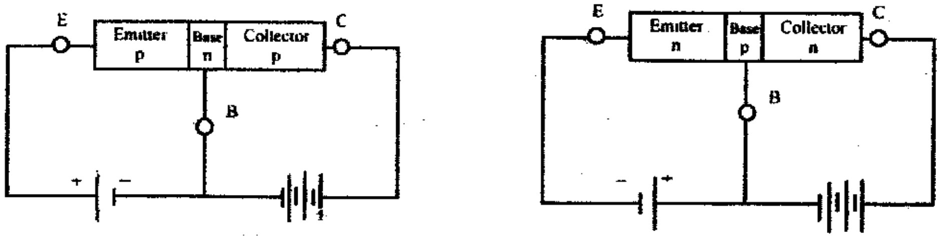


Fig. 34.17 : (a) Biasing of p-n-p transistor (b) Biasing of n-p-n transistor

iv) The section on the other side of the base that collects the charge carriers is called the ***collector***. The collector is always reverse biased with respect to the base (Fig.34.17).

v) The emitter is heavily doped, so that it supplies a large number of charge carriers to the base. The base is very highly doped, so that it does not offer much carriers to combine with the carriers from the emitter. The collector is moderately doped.

vi) The junction between emitter and base is called emitter – base diode whereas, the junction between collector and base is called the collector – base diode.

vii) The resistance offered by the emitter diode is low, as it is forward biased. The resistance offered by the collector diode is high, as it is reverse biased.

viii) The forward bias applied to the emitter diode is very small whereas reverse bias applied to the collector diode is much higher.

ix) The collector region is larger than the emitter region because it is required to dissipate more heat generated. But it is customary to show emitter and collector to be of equal size. Because of this difference, there is no possibility of inverting the transistor, i.e. making its collector the emitter and vice-versa.

Transistor Symbols

The schematic symbols of the two types of transistors are shown in Fig.34.18.

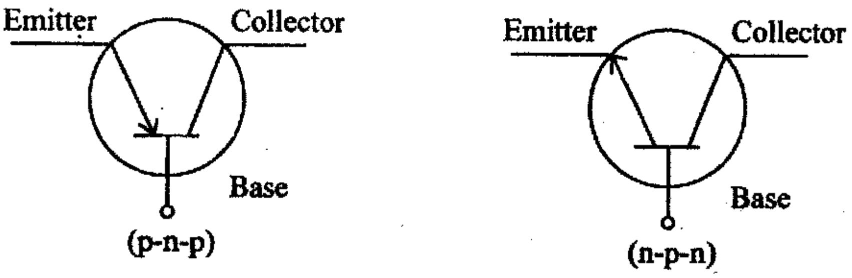


Fig. 34.18: Symbolic representation of transistor

Note that there is an arrow on the emitter leg. The direction of this arrow indicates the conventional current flow with forward bias. The conventional current flows into the emitter (towards the base) in the p-n-p transistor, represented by the inward arrow. In the n-p-n transistor, electrons will flow towards the base from the n-type emitter under forward bias. Hence, the conventional current flows out of the emitter, as indicated by the outward arrow.

Meaning of the word 'Transistor'

Amplification is the important basic function of a transistor (you will learn about this in detail in the next chapter). For this purpose, a weak signal is introduced in the input circuit of the transistor which is forward biased and has a low resistance. The output is taken from the output circuit, which is reverse biased and has high resistance. Therefore, a transistor *transfers* a signal from a low resistance to high resistance. Moreover, transistor is a solid element in the same general family with *resistors*. Hence the name transistor, made from the combination of the prefix 'trans' and the suffix 'istor' from these two words.

34.7.1 Working of a transistor

It has already been said that the emitter-base junction is forward biased. It is so, since the function of emitter is to supply charge carriers to the base. This will be possible only under forward – bias which makes the charge carriers move *towards the junction.* Similarly, the collector base junction is reverse-biased, since collector's function is to receive the supply of charge carriers coming from the emitter, through the base. Hence, it needs to remove the charge from its junction with the base, i.e. *away from the junction.* It should be noted that the current in the collector terminal is not because of the flow of charges either of the collector or the base region (as this junction is reverse-biased); but it is mainly because of the carriers coming from the emitter junction (as this junction is forward-biased). That is, the emitter current almost entirely flows into the collector circuit. This is the basic transistor action. Let us examine this action for the two types of transistors.

a) Working of n-p-n transistor

Fig.34.19 shows the n-p-n transistor with the battery V_{EB} supplying forward bias to the emitter-base junction and the battery V_{CB} supplying reverse bias to the collector-base junction. Under the action of the forward bias, the electrons in the n-type emitter move towards the base. This constitutes the emitter current I_E. As these electrons flow through the base, they tend to combine with the holes. But, since the base is very lightly doped and very thin, only a small fraction of electrons (less than 5%) are able to combine with the holes in the base region. These electrons move through the holes to the outer circuit and constitute base current I_B. The majority of electrons (more than

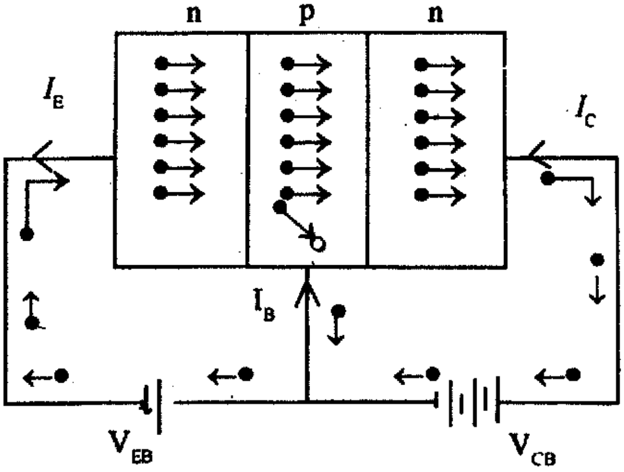


Fig. 34.19: Working of n-p-n transistor

95%) injected into the base from the emitter are able to cross the base-collector junction. This is because they have not combined with the holes in the base region and the reverse bias on collector is quite high and exerts an attractive force on these electrons. Hence, these electrons flow into the collector terminal and constitute collector current I_C. In this way, almost entire emitter current flows in the collector circuit. It is clear that the emitter current is the sum of collector and base currents, i.e.

$$I_E = I_B + I_C$$

The electrons from the collector end move in the outer circuit towards the positive battery terminal V_{CB}. At the same time, more electrons flow into the emitter terminal from the negative terminal of the battery V_{EB}. Hence, the current will keep flowing in the circuit as long as the two batteries are connected in the circuit. It should be noted that the conventional currents are in the opposite direction to the flow of electrons; i.e., the collector current and base current flow into the respective regions whereas the emitter current flows out of the emitter region.

b) Working of p-n-p transistor

Fig.34.20 shows the p-n-p transistor with the forward biasing battery V_{EB} connected to the emitter-base junction and reverse biasing battery V_{CB} connected to the collector-base junction. Here, under the action of the forward bias, holes in the p-type emitter region move towards the n-type base. Their flow constitutes the emitter current I_E. As they reach the base region, most of them (more than 95%) cross the base-collector junction and reach the collector under the action of the reverse biased collector junction and a few of them (less than 5%) recombine with free electrons in the very lightly doped and very thin base region. This recombination constitutes a small base current I_B which flows out of the base terminal. The holes which move towards the collector terminal, constitute collector current I_C. As a hole reaches the collector electrode, an electron comes from the negative battery terminal V_{CB} and recombines with it. For each recombination taking place at the collector electrode, a covalent bond is broken at the emitter electrode, the electron produced moves in the outer circuit towards the positive battery terminal V_{EB} and the hole again moves towards the base. In this way, emitter current flows into the emitter terminal and collector and base currents out of the respective regions. Again

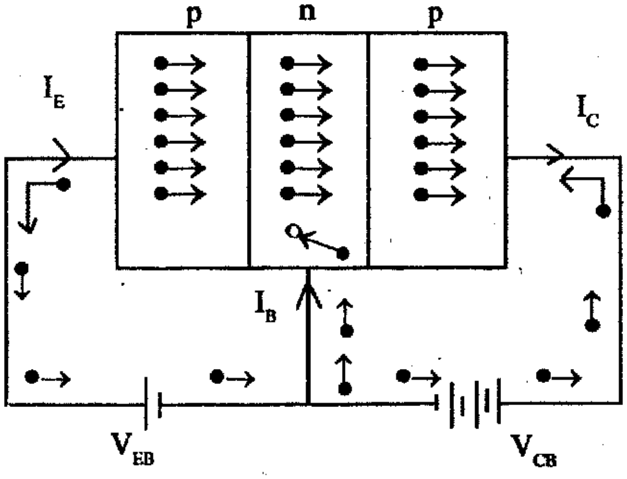


Fig. 34.20: Working of p-n-p transistor

$$I_E = I_B + I_C$$

INTEXT QUESTIONS 34.4

1. State whether the following statements are 'True' or 'False':

i) A transistor has two leads.

ii) A transistor has three p-n junctions

iii) Two discrete diodes connected back to back cannot act like a transistor.

iv) In n-p-n transistor, collector is positive with respect to the base.

2. Select one of the items littered a.b.c or d that correctly completes the statement.

i) In n-p-n transistor, the electrons flow

a) into the transistor at the emitter and base leads

b) into the transistor at the collector and base leads

c) out of the transistor at the emitter and base leads

d) out of the transistor at the collector and base leads.

ii) In a properly biased n-p-n transistor, most of the electrons from the emitter

a) recombine with holes in the base *b) rewcombine in the emitter itself*

c) are stopped by the junction barrier *d) pass through the base to the collector*

iii) In a properly biased n-p-n transistor. most of the electrons from the emitter.

(a) recombine with holes in the base

(b) re combine in the emitter itself

(c) are stopped by the junction barrier

(d) pass through the base to the collector

3. In p-n-p transistor, name the

i) majority carriers in the emitter *ii) majority carriers in the collector*

iii) minority carriers in the emitter *iv) minority carriers in the base*

34.8 TRANSISTOR CIRCUIT CONFIGURATIONS AND CHARACTERISTIC CURVES

We know that a transistor has three terminals or leads namely emitter (E), base (B) and collector (C). However, when a transistor is connected in a circuit, we require four terminals. i.e. two terminals for input and two for output. This difficulty is overcome by using one of the three circuits. Any one of the three terminals can be used as a common terminal. Hence, the transistor can operate under any one of the three different types of circuit connections

a) Common-base (CB) configuration

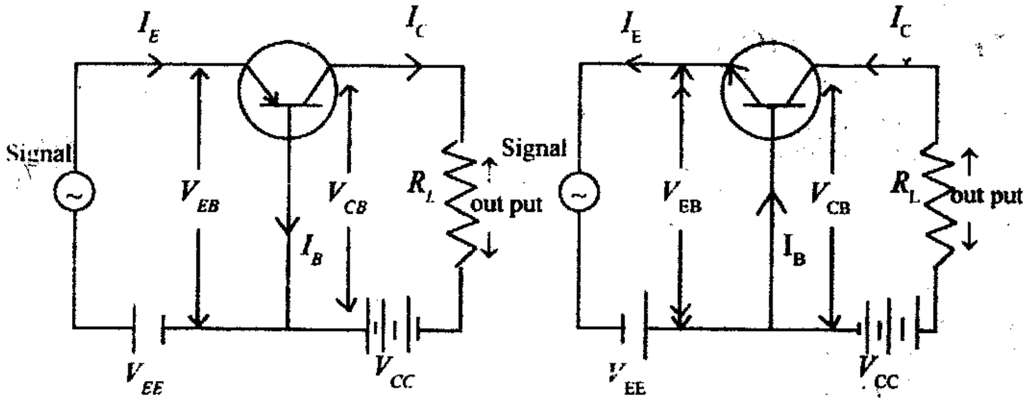
b) Common-emitter (CE) configuration

c) Common-collector (CC) configuration

Let us now consider these circuit configurations one by one and discuss some of the features about them.

34.8.1 Common-Base (CB) Configuration

In this configuration, the transistor is connected with the base as a common terminal as shown in Figs.34.21 (a) and 34.21(b) for the p-n-p and n-p-n transistor respectively. The input is applied between the emitter and base terminals. The output is taken between the collector and base terminals.



(a) p-n-p (a) n-p-n

Fig. 34.21 :Common base circuits of a transistor

In this configuration, emitter current I_E is the input current and collector current I_C is the output current. A d.c. voltage source V_{EE} is connected to the input circuit which provides forward bias to the emitter with respect to the base. An a.c. signal source may also be connected to the input circuit (for the purpose of amplification). The voltage drop between the emitter and base terminals is designated as V_{EB}. Similarly, a d.c. voltage source V_{CC} is connected in the output circuit, to make the collector reverse biased with respect to the base. Here a load resistance R_L is connected across which output can be taken. The voltage drop between the collector and base terminals is designated as V_{CB}. Thus V_{EB} is the input voltage and V_{CB} is the output voltage.

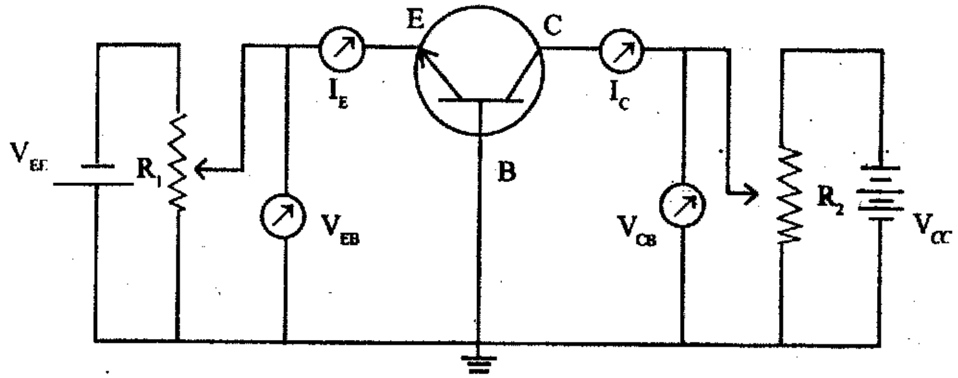


Fig. 34.22 Circuit arragement chardeteristic curves of a transistor in common base configrations

Characteristic Curves

The different d.c. voltage and currents in a transistor circuit are related to one-another. The curves which represent relationship between different d.c. voltage and currents of a transistor are known as characteristics of transistor. The complete electrical behaviour of a transistor can be described by these graphical representations. The circuit arrangement shown in Fig.34.22 is used to obtain the characteristic curves for the common base configuration for a n-p-n transistor. If the transistor is p-n-p, the terminals of input and output d.c. voltage sources will have to be interchanged. The two potentiometer resistors R_1 and R_2 supply variable voltages from the collector and emitter d.c. supplies. Voltmeters are connected between E and B to measure voltage V_{EB} and between C and B to measure voltage V_{CB}. Milliammeters are included in series with the emitter and collector circuits to measure I_E and I_C.

There are two important sets of characteristic curves:

i) **Input characteristics:** These are the curves which show the relationship between the input current and input voltage for a given output voltage. For the common base configuration, these curves are obtained by plotting corresponding values of input voltage i.e. emitter-base voltage V_{EB} and input current i.e. emitter current I_E along the x and y axis respectively. First, the collector-base voltage V_{CB} is adjusted to a suitable value with the help of R_1 (Fig.34.22). Next, voltage V_{BE} is increased in small steps (i.e. of the order of 0.1 V or so) and the corresponding values of I_E are noted from the milliammeter connected in the emitter circuit. When plotted, we get the input characteristics shown in Fig.34.23, one for Ge and the other for Si. Both the curves are exactly similar to the forward characteristics of a p-n diode (what eventually the emitter-base junction is). The presence of knee voltage V_K can be seen, below which the emitter current is negligibly small. It is approximately 0.2 V for Ge and 0.5 V for Si transistors. Beyond the knee voltage, I_E increases rapidly with a small increase in V_{EB}. It means that ***input resistance*** (R_i) of a transistor in CB configuration is very small. Its value is given by the reciprocal of the slope of the input characteristic curve.

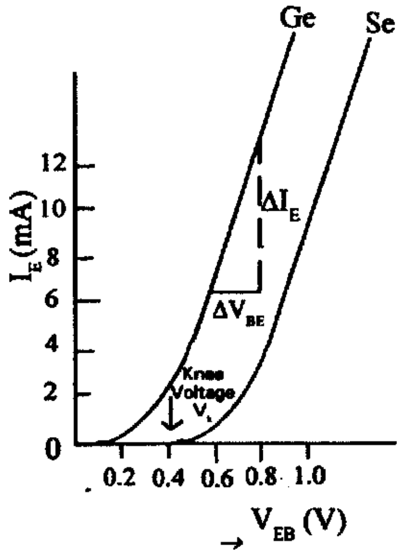


Fig. 34.23: Input Characteristics of a transistor in common base configuration

$$R_i = (\Delta V_{EB}/\ I_E) - V_{CB}\text{ constant}$$

Its value over linear part of the characteristic is about 50 Ω . The input characteristic curve is hardly affected by changes either in V_{CB} or in temperature.

ii) **Output characteristics:** These are the curves which show the relationship between the output voltage and output current for a given input current. These curves are thus obtained by plotting the corresponding values of output voltage i.e. collector-base voltage V_{CB} and output current i.e. collector current I_C along the x- and y-axis respectively. The circuit of Fig.34.22 is again used. First movable contact on R_2 is changed to get a suitable value of V_{BE} and hence I_E. While keeping I_E constant at this value, V_{CB} is increased from zero in a number of steps and the corresponding collector current I_C is noted. Next V_{CB} is reduced to zero, I_E is increased to a value a little higher than before and the whole process is repeated. In this way, the whole family of the output characteristic curves is obtained (as shown in Fig.34.24). The following points can be noted from these curves:

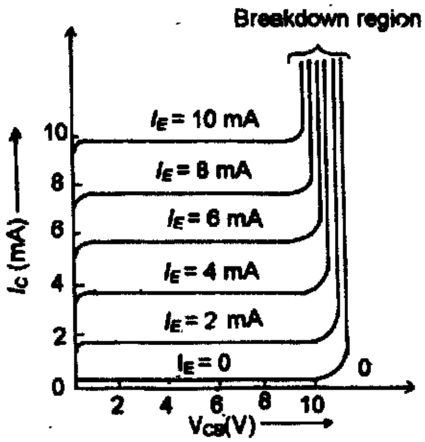


Fig. 34.24: Output characteristics of a transistor in common base configuration

1. *It is seen that I_C flows even when $V_{CB} = 0$. It is due to the fact that the charge carriers are injected into the base under the action of forward biased E-B junction and are being collectd by the collector under the action of the internal junction potential at C-B junction.*

2. *A small amount of collector current ($I_C = I_{leakage}$) flows even when emitter current $I_E = 0$. As you know [Section 34.6(ii)] it is the leakage current under the reverse biased CB junction.*

3. *I_C is practically independent of V_{CB} over the working range of the transistor. Yet, if V_{CB} is increased beyond a certain value, I_C increases due to avalanche breakdown as shown in Fig.34.24.*

4. *The output resistance (R_o) of the transistor in CB configuration is very high (as I_C is almost constant with respect to V_{CB}). Its value is given by the reciprocal of the slope of the horizontal part of the characteristics i.e.*

$$R_o = (\Delta V_{CB}/ I_C) - I_E \text{ constant}$$

Its value is very high, of the order of 500 k Ω.

34.8.2 Common Emitter (CE) Configuration

In this configuration, the transistor is connected with the emitter as a common terminal as shown in Fig.34.25(a) and Fig.34.25(b), for the p-n-p and n-p-n transistors respectively. The input is applied between the base and emitter terminals and the output is taken between the collector and emitter terminals.

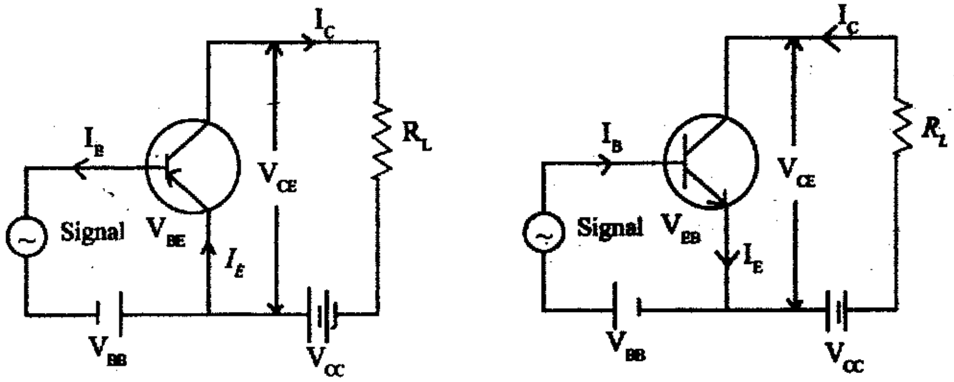


Fig. 34.25 (Common emitter circuits of a transistor (a) p-n-p (b) n-p-n)

In this configuration, base current I_B is the input current and collector current I_C is the output current. D.C. voltage sources V_{BB} and V_{CC} are used to forward bias the input circuit (B-E circuit) and reverse bias the output circuit (C-E circuit) respectively. V_{BE} and V_{CE} are the respective input and output voltages.

Characteristic Curves

As stated earlier, these are the curves representing the relationship between different d.c. voltages and currents of the input and output circuits. The circuit arrangement shown in Fig.34.26 is used to obtain the characteristic curves for a n-p-n transistor in the CE configuration. For the p-n-p transistor, the polarities of the two voltage sources V_{BB} and V_{CC} will have to be interchanged. A microammeter is connected in the input circuit and a milliammeter in the output circuit to measure the input and output currents. The d.c. voltages in the input and output circuits can be varied by changing the positions of the potentiometers R_1 and R_2 respectively and can be measured by the voltmeters connected in the respective circuits.

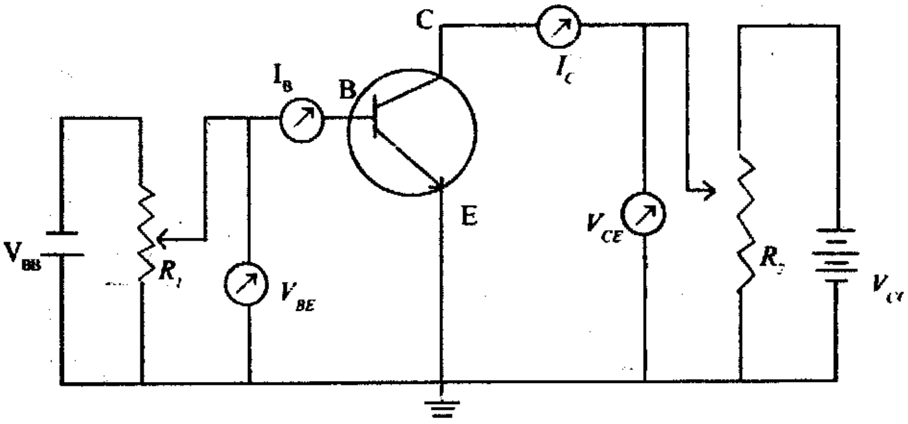


Fig. 34.26 : Circuit arrangement for characteristics curves of a transistor in Common emitter Configeration

Again, we will study the two important sets of characteristic curves for this circuit configuration. These are

i) Input Characteristics: These curves give the relationship between the base current (I_B) and the base-to-emitter voltage (V_{BE}) for a constant collector-to-emitter voltage (V_{CE}). To obtain these curves, voltage V_{CE} is maintained constant at a convenient value and then V_{BE} is increased in small steps. The procedure is then repeated for a different but constant value of V_{CE}. A typical input characteristic curve is shown in Fig.34.27 where the corresponding values of V_{BE} and I_B are plotted along the x- and y-axis respectively. Like the C-B connection, the overall slope resembles the forward characteristic of a p-n diode. Again, there exists a knee voltage below which the base current is negligibly small, Beyond the knee, the base current I_B increases with the increase in V_{BE}. However, the base current does not increase as rapidly as the input current in the CB transistor. It means that the input resistance of a CE configuration is higher as compared to the common base configuration. It is given as shown in fig. 34.27.

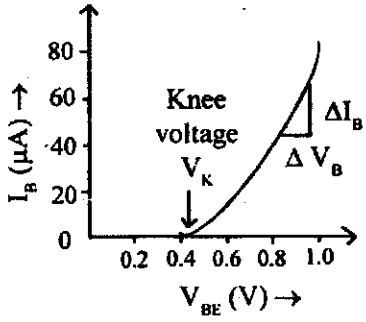


Fig. 34.27 : Input characteristics of a ttransistor in common emitter configuration

$$R_i = (V_{BE}/\Delta I_B) \text{ - constt. } V_{CE}$$

It may be noted that the input characteristic is non-linear in the lower region. Hence, the input resistance varies with the location of the operating point. Its values ranges beteen 500 Ω to 5000 Ω. There is a slight effect of the increase in V_{CE} on I_B. The curves shift downwards for higher values of V_{CE}.

ii) Output characteristics: These are the curves which show the relationship between the collector current I_C and collector-emitter volrtage V_{CE} at constant value of base current I_B. For obtaining this characteristic, first I_B is set to a convenient value (using resistance R_1 in Fig.34.26) and maintained constant and then V_{CE} is increased from zero in suitable steps (using R_2) and I_C noted at each step. Next, V_{CE} is reduced to zero and I_B increased to another convenient value and the whole procedure repeated. In this way, a family of curves (Fig.34.28) is obtained by plotting the corresponding values of V_{CE} and I_C along the x- and y-axis respectively. The following points can be noted from these curves:

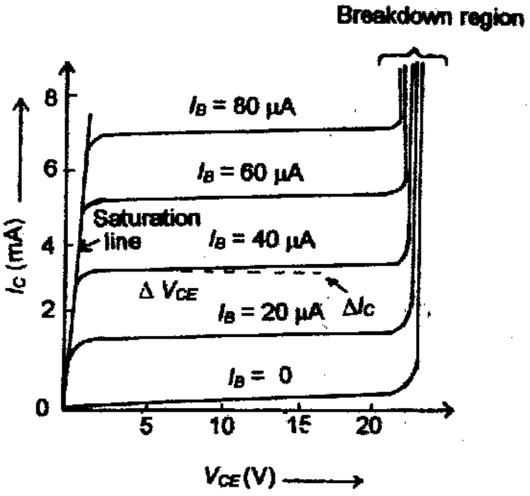


Fig. 34.28: Output characteristics of a tronsistor in common emitter configuration

1. *As V_{CE} increases from zero, I_C rapidly increases to a near saturation level for a fixed value of I_B (for V_{CE} say upto 1 V).*
2. *When V_{CE} is increased further, I_C increases slightly. This implies a large output resistance for the circuit, however, it is smaller than the corresponding resistance in the CB configuration. It is given as the increase slope of the curve, i.e.*

$$R_o = (V_{CE}/\Delta I_C) \text{ at constant } I_B$$

It ranges from 10 kΩ to 50 kΩ.

3. *When the base current is zero, a small collector current still flows. It is the leakage current.*
4. *If V_{CE} is increased beyond a certain limit, the junction will breakdown with large collector current. This is always to be avoided.*

34.8.3 Common Collector (CC) Configuration

In this type of transistor connection, collector is common to both input and output circuits. Input is applied between base and collector while output is taken between emitter and collector. Fig.34.29(a) and Fig.34.29(b) show the common collector p-n-p and n-p-n transistor circuits respectively.

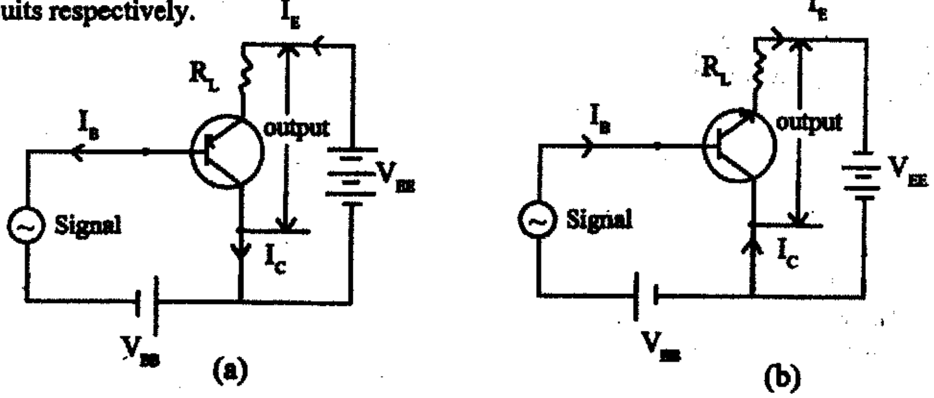


Fig. 34.29 : Common collector circuits of a transistor (a) p-n-p (b) n-p-n

Here. I_B is the input current and I_E is the output current. The voltage V_{BB} forward-biases the emitter-base junction and V_{CC} reverse-biases the collector-base junction of the transistor. An external resistance is connected to the emitter, across which the output is taken.

This type of circuit configuration is not of much practical importance. It has very high input resistance (about 750 K) and very low output resistance (about 25 Ω). This circuit is, thus, primarily used for impedance matching, e.g.. for driving a low resistance load from a high resistance source.

Both CB and CE circuits can be used for amplification purposes. However, as you will study in detail in the next chapter, the CE circuit is used in about 95% of the applications of the transistor.

INTEXT QUESTIONS 34.5

1. Select one of the items lettered a,b,c or d that correctly completes the statement:

i) A transistor connected in common-base configuration has

a) a high input resistance and a low output resistance

b) a low input resistance and a high output resistance

c) a low input resistance and a low output resistance

d) a high input resistance and a high output resistance

ii) The collector characteristics of a common-emitter connected transistor may be used to find its.

a) input resistance b) output resistance

c) base current d) voltage gain

iii) In common-collector circuit, input resistance is

a) very high b) very low

c) moderate d) zero

iv) A small increase in collector-base reverse bias will cause

a) a large increase in emitter current

b) a large increase in collector current

c) very little change in collector reverse saturation current

d) a large decrease in collector current

34.9 WHAT YOU HAVE LEARNT

- The contact surface formed on joining p-type semiconductor suitably to n-type semiconductor, is called p-n junction.
- Diffusion of electrons and holes across the junction creates a depletion layer.
- A barrier potential is developed across the junction due to the accumulation of immobile charge in the depletion layer.
- External voltage can be applied to a p-n junction in two ways which are called forward biasing and reverse biasing.
- A p-n junction behaves differently under forward and reverse biasing.
- A p-n junction is called a semiconductor diode.
- Zener diode is a special diode which operates in the breakdown region.
- Light emitting diode (LED) emits light on recombination of electrons and holes.
- Photo-diode gives useful current when light falls on it. It acts as a very fast photo-detector.

- Solar cell acts as source of electrical energy, using the light energy of sun
- The transistor is a semiconductor crystal which has two p-n junctions and three doped regions called emitter, base and collector
- In a transistor, emitter and collector are doped with the same type of impurity while the base is doped with the opposite type of impurity
- The emitter is heavily doped, base is very lightly doped and the doping level of the collector lies between that of the base and emitter
- The base in the transistor is made very thin along with having very light doping, to reduce the base current (due to recombination of charge carriers)
- Transistors are of two types viz. n-p-n and p-n-p.
- There can be three types of configuration of a transistor in a circuit, viz. common base (CB), common emitter (CE) and common collector (CC)
- The transistor shows different characteristics in different configurations.

34.10 TERMINAL QUESTIONS

1. What is a p-n junction and how is it formed?
2. What does the space charge at a p-n junction consist of?
3. What is the meaning of break-down of a p-n junction?
4. With the help of diagram, discuss the current-voltage characteristic of a p-n junction diode.
5. Discuss the effect of biasing on the height of the barrier potential at a p-n junction.
6. Why the p-n junction is called a diode? How its terminals are identified?
7. What is a Zener diode? Explain its functioning.
8. In what respect is a LED different from an ordinary p-n junction diode? State applications of LEDs.
9. Draw the notations of an ordinary p-n junction diode, Zener diode, LED, photo diode and solar cell.
10. Explain the functioning of a solar cell.
11. What is a transistor? Why is it so called?
12. Describe the working of n-p-n transistor.
13. Name the three possible transistor connections. Draw the circuit diagrams for all the three types of connections in the case of n-p-n transistor.
14. How will you determine the input and output characteristics of CE connection experimentally.

15. Select one of the items lettered a, b, c or d that correctly completes the statement:

i) The emitter of a transistor is generally doped the heaviest because it

a) has to dissipate maximum power b) has to supply the charge carriers

c) is the first region of the transistor d) must possess low resistance

ii) For proper functioning of the transistor

a) its E/B junction is always forward biased and C/B junction reverse biased.

b) its E/B junction is always reverse biased and C/B junction forward biased.

c) both the junctions are forward biased

d) both the junctions are reverse biased

16. In a transistor name the region which is

i) supplier of charge carriers ii) very lightly doped

iii) largest of the three regions iv) very thin

CHECK YOUR ANSWERS

Intext Questions - 34.1

1. (i) barrier, 0.7 V (ii) both (iii) mobile, ions (iv) diffusion
2. (i) b (ii) d (iii) c

Intext Questions - 34.2

1. (i) breakdown (ii) reverse, minority (iii) minority (iv) zero
(v) minority (vi) heavily, narrow (vii) breaking, high

Intext Questions - 34.3

1. (i) Zener (ii) forward (iii) photo-voltaic (iv) more (v) voltage
2. (i) True (ii) True (iii) False (iv) True (v) False
3. (i) d (ii) c

4. (i) b (ii) a
5. (i) emitter (ii) base (iii)collector (iv) base

Intext Questions - 34.4

1. (i) False (ii) False (ii) True (iv) True
2. (i) d (ii) a (iii) d
3. (i) holes (ii) holes (iii) electrons (iv) holes

Intext Questions - 34.5

1. (i) b (ii) b (iii)a (iv) c