CHAPTER

5 SEMI-CONDUCTOR DIODE AND TRANSISTOR

5.1. INTRODUCTION

The P type and N type semiconductors by themself are of limited use. However a PN-junction makes a useful device which is the head of all the electronic components and devices. It is possible to manufacture a simple piece of semiconductor material one half of which is doped by P impurity and other by N impurity. Such a system is shown in Fig. 5.1.

During the formation of a junction, following two phenomenon take place.

(*a*) A thin **depletion layer** is set on both sides of the junction. It is so called because this layer is depleted of free charge carriers.

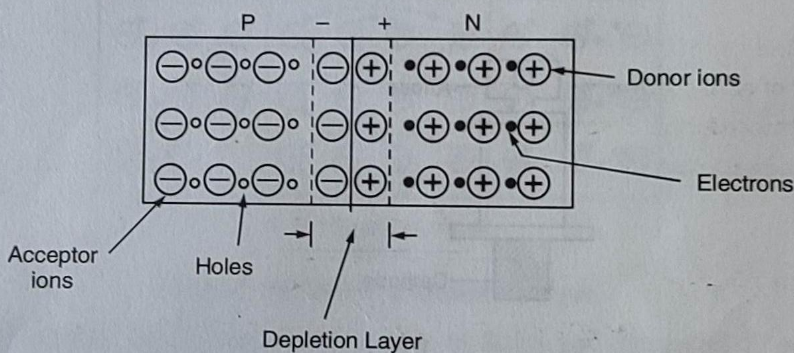


Fig. 5.1. PN-Junction

(*b*) A **junction or barrier voltage** is developed across the junction whose value depends upon the semiconductor (*i.e.* 0·3 V for Ge and 0·7 V for Si).

The essential characteristics of the PN-junction is that it contributes a diode which permits flow of current in one direction but restricts it in the other direction. When the PN-junction is forward biased, it conducts current easily and when reverse biased, practically no or very small current flows through it. The device accomplishing this property is called diode. Hence **PN-junction** *is also called a semiconductor diode or crystal diode*. It is called crystal diode because it is grown out of a crystal *i.e.* Silicon or Germanium. The circuit symbol of diode is shown in Fig. 5.2 (*a*). The arrow head indicates the conventional direction of flow of current, when forward biased. It is same as that of flow of holes.

Commercially available diodes have some means to identify which lead is P and which lead is N. The P lead is known as anode and N as cathode. The standard notation consists of type number prefixed by IN such as IN 4001.

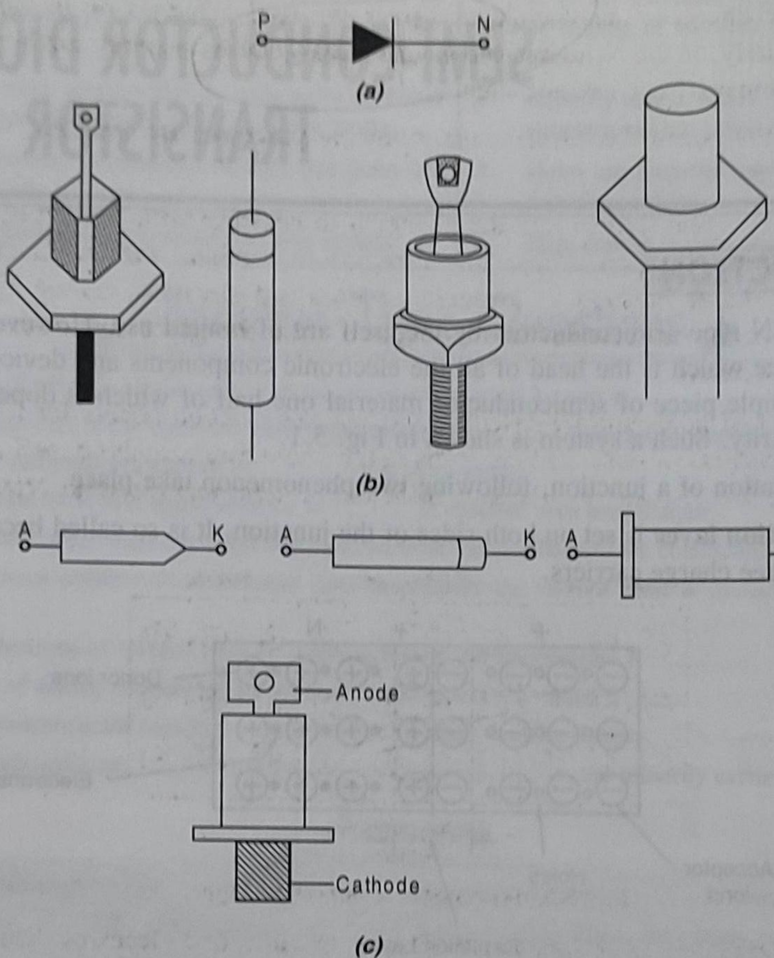


Fig. 5.2. Various types of diodes.

Fig. 5.2 (*b*) shows typical diodes having different physical sizes and 3.2 (*c*) shows terminal identification.

5.2. MECHANISM OF CURRENT CONDUCTION IN PN JUNCTION (JUNCTION THEORY)

PN-junction is extensively used in electronic circuits due to its property of conducting current in one direction only. In the other direction (reverse direction) it offers very high resistance. This happens as explained below :

5.2.1. PN-Junction Without External Voltage

Fig. 5.3 shows a PN-junction just formed. It is a single crystal having left half as P-type and right half as N-type. The P-region has holes and negatively charged impurity ions, where as the N-region has free electrons and positively charged impurity ions. The ions are immobile particles, where as holes and electrons can move and are referred to as mobile charges. Both P and N type regions are considered separately, because the junction as a whole is electrically neutral. Therefore in the P region, the charge of moving holes equals the total charges on its free electrons and immobile ions. Similarly, in the N-region, the negative charge of its majority carriers is compensated by the charge of its minority carriers and immobile ions.

As soon as the PN-junction is formed, the following processes are initiated, when no external voltage is applied to it.

(*a*) Holes from P-region diffuse into the N-region to combine with free electrons of N-region and free electrons from N-region diffuse into P-region to combine with holes of P-region. This diffusion takes place due to haphazard movement of holes and electrons, caused by thermal energy and difference of their concentrations in two regions. The P-regions has more holes where as N-region has more electrons.

(*b*) The diffusion of holes and free electrons across the junction occurs for a very short time. After a few recombinations of holes and electrons in the immediate neighbourhood of the junction, a **barrier (restraining force)** is set up. Further, diffusion of holes and electrons from one side to the other is stopped by this barrier.

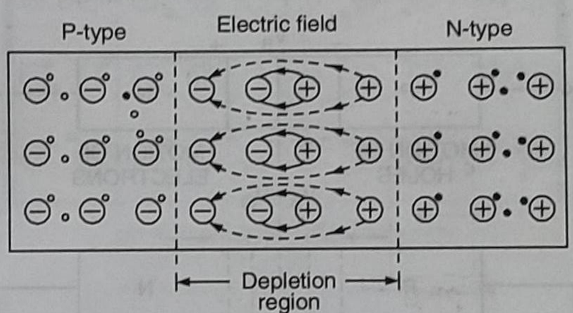


Fig. 5.3. Formation of depletion layer.

The barrier is developed as during recombination of holes and electrons. They are eliminated and the acceptor and donor ions of the P and N-region remain uncompensated. Consequently, the holes from P-region and electrons from N-region are reflected back by the uncompensated ions in the opposite regions. Thus, only a small region can exchange holes and ions as shown in Fig. 5.3.

(*c*) The region containing the uncompensated acceptor and donor ions is called **depletion region.** There is a depletion of mobile charges (holes and free electrons) in this region. Since this region has immobile (fixed) ions which are electrically charged, it is also called the **space-charge region.** The electric field between the acceptor and the donor ions is called a **barrier.** With no external batteries, for a silicon PN-junction, the barrier potential is about 0·7 V, whereas for a germanium PN-junction it is approximately 0·3 V.

5.2.2. Effect of Forward Biasing in a PN Junction

When +ve terminal of the battery is connected to P side and –ve terminal to N side of the PN junction, the junction is said to be forward biased. With forward bias, the applied potential acts in such a way that both the holes and electrons move towards the depletion layer. The depletion layer width is, thus, decreased and the barrier potential reduces from the initial value V_B to $V_B - V$, where V is the applied voltage. This reduced barrier potential allows increased flow of majority carriers across the junction. Only small voltage is sufficient to overcome the barrier voltage. Once the barrier voltage is overcome, a conducting path is established allowing flow of large current. This current is called **forward current**.

The flow of minority carriers, however, remains unaffected due to forward biasing. Fig. 5.4 shows the PN-junction under forward bias. The following points are worth noting for a forward biased PN-junction.

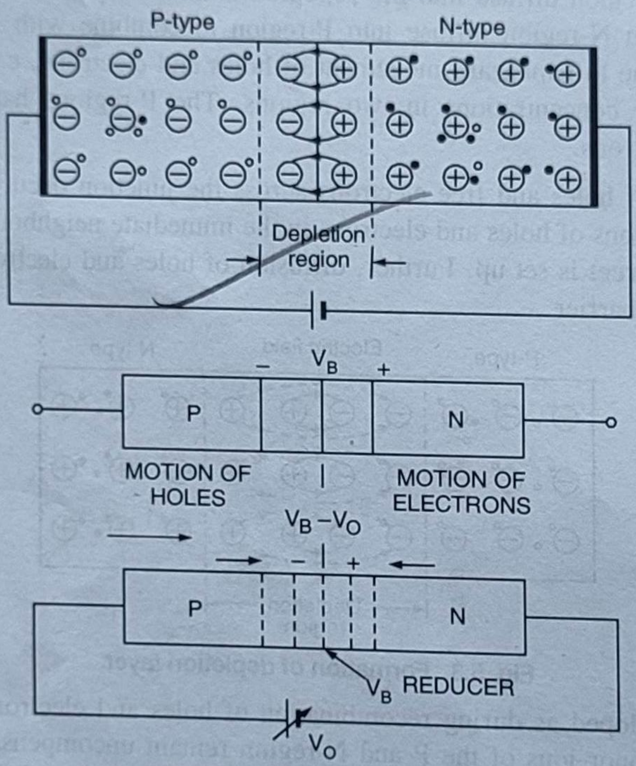


Fig. 5.4. PN-junction under forward bias.

(*a*) The barrier potential is reduced and is completely eliminated to 0·3 V for Ge and 0·7 for Si.

(*b*) The junction then offers low resistance to the flow of current.

(*c*) The forward current then depends upon the applied voltage.

(*d*) The current due to minority carriers remains unchanged and is overcome by the forward current.

(*e*) The current at any stage, through the PN-junction in forward bias is equal to

$$I = I_F - I_0$$

Where, I_F = forward current

and I_0 = current due to minority carriers.

5.2.3. Effect of Reverse Biasing in a PN Junction

When –ve terminal of battery is connected to P side and +ve terminal to N side of the PN-junction, it is said to be reverse biased. With the reverse bias the applied potential acts in such a way that both holes and electrons move away from the junction and the width of depletion layer is, thus, increased. This increased width of depletion layer results in increase of potential barrier to $V_0 + V$, where V is the applied voltage. This increased barrier potential stops the majority carriers to flow through the junction. Thus, a high resistive path is established and hence no current due to majority carriers can flow.

The net result is that even for a small value of applied reverse voltage the majority carrier current drops to zero, leaving only reverse saturation current caused due to flow of minority carriers.

Since the minority carriers are thermally generated, the reverse saturation current does not depend ordinarily on the reverse bias.

Fig. 5.5 shows the PN-junction under reverse bias.

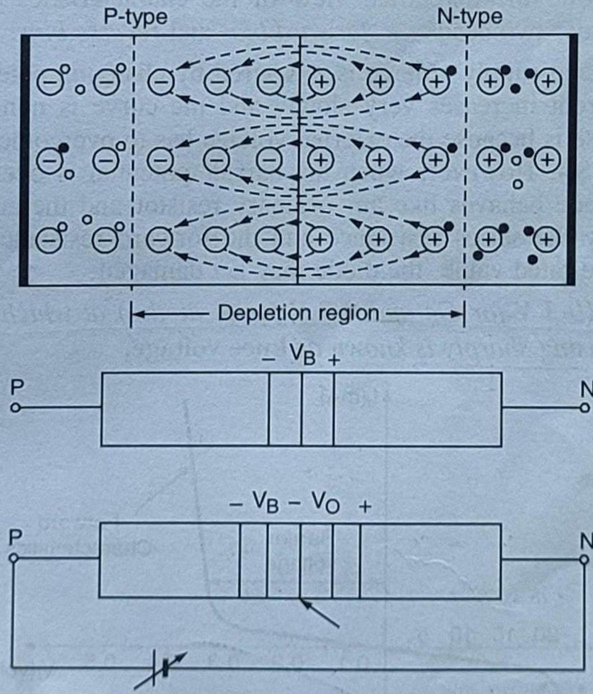


Fig. 5.5. PN-junction under reverse bias.

Following points are worth noting for reverse biased PN-junction.

(i) The depletion width is increased, hence potential barrier increases.

(ii) The junction offers very high resistance to the flow of current.

(iii) Practically, no current flows due to majority carriers. However, the reverse saturation current flows but remains constant.

5.3. CHARACTERISTICS OF ORDINARY DIODE

The volt ampere characteristics, typically known as V-I characteristics, is a curve between voltage across the diode and current through it. This characteristic shows us the behaviour of a diode under different conditions of biasing and applied voltage.

To obtain the V-I characteristic a circuit shown in Fig. 5.6 is used. In the circuit, the d.c. battery V_{AA} is connected through potentiometer P to the anode of the diode. Hence the diode is forward biased. A resistance R is included in the circuit so as to limit the current. The potentiometer helps in varying the voltage applied to the diode. The voltage is measured by means of the voltmeter. The milliammeter is used to measure the current. For reverse biasing of the diode, the polarity of the battery may be reversed. Fig. 5.7 shows the magnified view of the characteristics curve of the diode. The characteristic is studied under two heads *i.e. forward bias* and *reverse bias*.

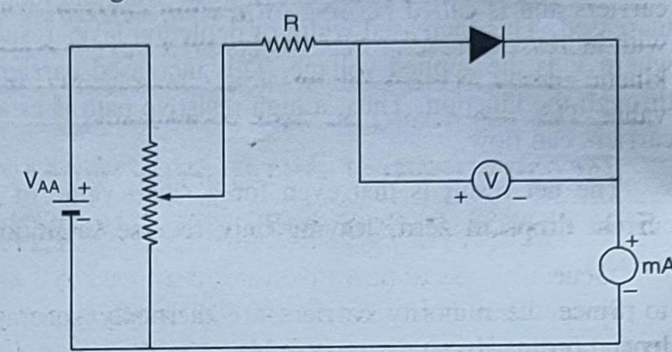


Fig. 5.6.

(a) Forward bias. When supply voltage is measured by changing potentiometer P from 0 volts to higher values, the current increases very slowly and the curve is non-linear. The slow rise in current of diode in this case is because the external voltage has to overcome the barrier potential (0·3 V for Ge and 0·7 V for Si). However, when the barrier potential is overcome and the voltage is increased, further, the diode behaves like an ordinary resistor and the current rises very sharply. This current is limited by the series resistance and the forward resistance R_f of the diode. If the current rises more than the rated value, the diode may get damaged.

The forward voltage (0·3 V for Ge and 0·7 V for Si diodes) at which the current through PN-junction or diodes starts rising sharply is known as **knee voltage.**

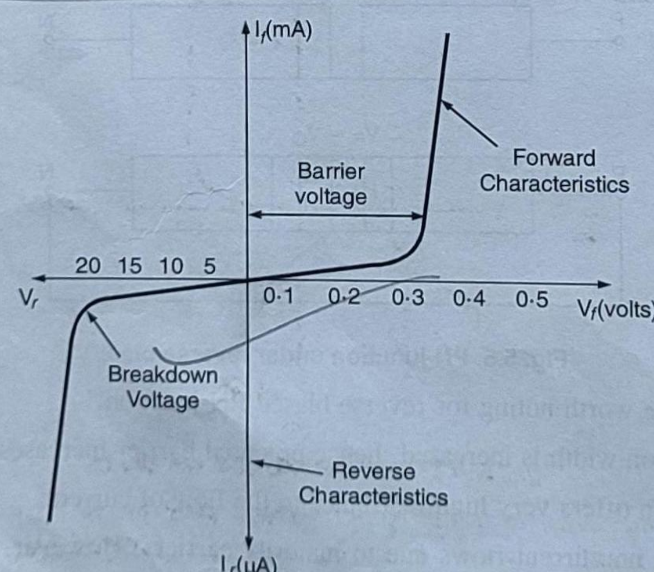


Fig. 5.7. V-I characteristics of a diode.

(*b*) **Reverse bias.** To obtain the reverse bias characteristics, the polarity of the battery is reversed *i.e.* the –ve terminal gets connected to anode and vice-versa. Under this condition the potential barrier at the junction is increased. Thus, practically no current flows. However in actual practice a very small current (μA) flows in the circuit. This current is caused due to the minority carriers and is called **reverse saturation current.** The reverse saturation current increases slightly with increase in reverse bias voltage till a stage is reached when the minority carriers attain sufficient kinetic energy to break the junction. Consequently, the reverse current increases abruptly to a large value. This may destroy the diode permanently.

The reverse voltage at which PN-junction breaks is known as **breakdown voltage.**

5.4. ZENER DIODE AND ITS CHARACTERISTICS

Generally, the ordinary diodes are not operated in reverse bias breakdown region. This is done to prevent them from burning off. The breakdown region's phenomenon was discussed successfully by C. Zener. Hence such breakdown is sometimes called zener breakdown. The breakdown or Zener voltage depends upon the amount of doping. Heavier the doping, thinner is the depletion layer and lesser will be the breakdown voltage. Such a diode is called **zener diode.** Hence, *a zener diode is a heavily doped crystal diode which is optimised to operate in breakdown region.*

Fig. 5.8 (*a*) shows the schematic symbol of zener diode. Fig. 5.8 (*b*) shows the V-I characteristics of such diode.

Following points are worth noting for the characteristics of zener diode :

(*i*) Its characteristic is almost similar to the ordinary diode except that it has a sharp reverse breakdown.

(*ii*) The voltage after reverse breakdown is almost constant.

(*iii*) During the reverse breakdown, the zener diode does not burn off until the external circuit limits the current through it.

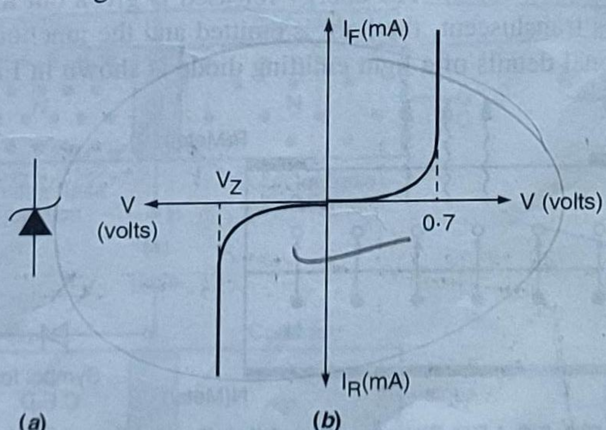


Fig. 5.8. V-I characteristic of Zener diode.

The zener diode maintains constant output voltage after breakdown and, thus, is used for voltage stabilization in rectifier circuits. It can be operated in forward bias mode as well. But it is rarely used for rectification because of its heavy cost.

Important terms and Applications of zener diode : Some commonly used terms or ratings of zener diode are as given below :

(*a*) **Zener voltage.** Zener voltage is the reverse voltage at which a zener diode breaks *i.e. the voltage at which a zener diode breaks in the reverse bias condition is known as zener voltage.* Generally, the zener diodes are available with zener voltage rating from 3 to 200 volts.

The value of breakdown voltage depends upon the doping, more the doping, lesser is the breakdown voltage. Zener voltage is denoted by V_Z.

(*b*) **Tolerance :** *The voltage at which a zener diode conducts in reverse direction is called* **tolerance.** Tolerance is infact over a range of breakdown voltage instead of a fixed value. Tolerance is expressed in % of given fixed value, *e.g.* Zener marked 5 volts, 10% tolerance means, breakdown voltage ranging from 4·5 volts to 5·5 volts.

(*c*) **Power rating :** *The maximum power a zener diode can dissipate or work at without being damaged is known as its power rating.* Generally, zener diodes are available having power rating ranging from 1/4 watts to 50 watts. Power rating of a zener is denoted by P_{ZM}.

(*d*) **Maximum current rating :** *The maximum value of current which a zener diode can handle at its rated voltage without damage is known as* **Maximum current rating.** It is denoted by I_{ZM}.

(*e*) **Zener Resistance or Zener Impedance :** *The opposition offered to the current flow by the zener diode in the operating region is known as* **Zener resistance.** Zener diode has a very small value of this resistance operating at a.c. voltages. It is denoted by R_Z or Z_Z.

5.5. LIGHT EMITTING DIODE (LED)

It is a diode which emits light when energised. As discussed earlier, the charge recombination takes place when a diode is forward biased. The recombination results in release of energy. For silicon or germanium diodes, this energy is wasted as heat. But in case of other semiconductor materials like gallium arsenide (GaAs). The energy released is given out in the form of light. If the semi-conductor material is transluscent, the light is emitted and the junction becomes a light source. The schematic constructional details of a light emitting diode is shown in Fig. 5.9.

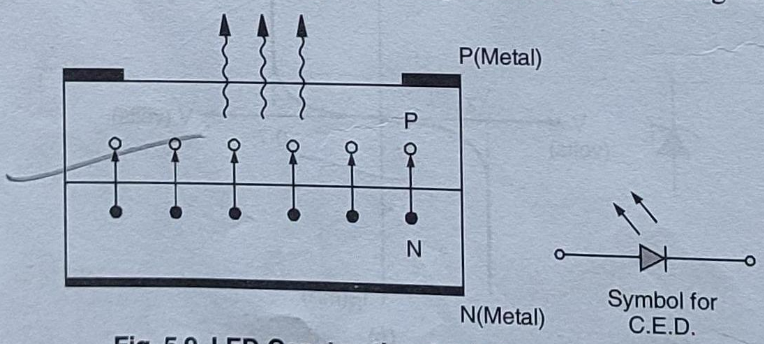


Fig. 5.9. LED-Constructional details and its symbol.

The colour of light emitted depends upon the type of semiconductor material. While GaAs emits infrared radiations, gallium phosphide (GaP) emits red or green light and gallium arsenic phosphide (GaAsP) emits red or yellow (amber) light. The LEDs are always operated in forward bias and require 1·5 to 2 volts for the full glow.

Applications. The infrared LEDs are used in remote controlling devices, while other diodes are used in various types of displays such as seven segment displays (numeric displays), advertisement displays etc.

5.6. BIPOLAR JUNCTION TRANSISTOR (BJT)

The transistor was invented by the Bell Laboratories in America in the year 1948. This invention single handedly revolutionised the electronics industry. Since then there has been rapid strides in the electronics industry. They have replaced the bulky tubes in performing many tasks. Today transistors are used in almost all modern electronics and electrical devices. It has got a wide variety of applications including televisions, automatic control devices, satellite instrumentation, test and measurement instrumentations, medical electronics etc. Its ability to amplify makes it extensively useful in almost all electronics devices. Following are a few reasons of its preference over vacuum tubes :

(*a*) It operates/works instantaneously as no filament/heating is required causing delay in operation.

(*b*) Transistors are much smaller in size and light in weight.

(*c*) They can be used at very low operating voltages.

(*d*) Being made up of semiconductors exhibits longer life without any aging effects.

(*e*) They yield higher efficiency as they consume little power.

Basically the transistor consists of two back to back PN junction diodes manufactured in a single piece of semiconductor crystal. These two junctions give rise to three regions called emitter, base and collector. The two junctions are called the emitter-base junction and collecter base junction respectively. As shown in fig. 5.10, a transistor can be assumed of having been manufactured by sandwitching a thin piece of one type of semiconductor between two pieces of other type of semiconductor (N into P or vice-versa).

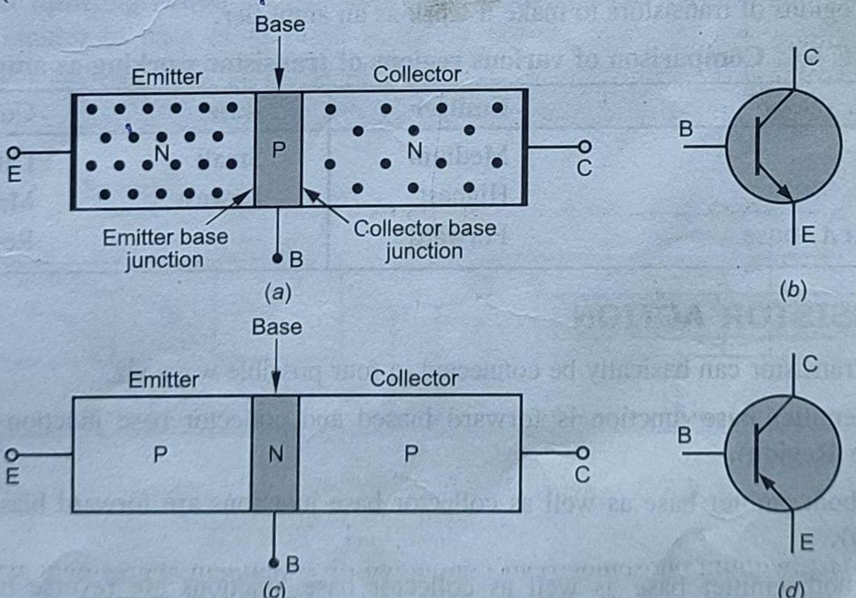


Fig. 5.10. Trasistor (a) NPN type (b) its symbol (c) PNP type (d) its symbol.

The symbols of the transistor are also shown in fig. 5.10. The arrowhead is always on the emitter terminal and indicates the direction of flow of conventional current. The conventional current is always assumed to be opposite to the flow of electrons. Every transistor has three regions called emitter, collector and base. The characteristics and functions of three regions are as under :

(i) EMITTER

This is the region which injects the majority carriers (holes in PNP transistor and electrons in NPN transistor) into transistor. The emitter is heavily doped region and has a medium width.

(ii) BASE

It is the middle portion of the transistor and is made up of semiconductor of other type than the collector and emitter. It is the thinnest of the three regions and is lightly doped. The carriers injected by the emitter recombine with the carriers in base and constitute the base current. Majority of the carriers pass through it as such. It will be discovered later on that it is the base, which introduces the transistor characteristics in, otherwise, simple semiconductor.

(iii) COLLECTOR

The function of the collector is to collect the majority carriers which were injected by the emitter into the transistor minus those which recombined in the 'base' region. The collector region is mediumly doped and largest in area. The area is largest because the majority carriers are collected here and they release energy producing heat. The larger area helps in proper heat dissipation.

Since the emitter has to inject electrons into the transistor, it should be biased in such a way that 'battery' repels the majority carriers into the base region. Thus, it is forward biased. Similarly, the collector should attract the majority carriers and hence it is reverse biased. For a PNP transistor the (emitter) should be made +ve and collector –ve *w.r.t.* the base region, making 'emitter' base junction 'forward biased' collector base junction 'reverse biased.' Table 8.1 shows the characteristics of the various regions of transistors to make it work as an amplifier.

TABLE 5.1. Comparison of various regions of transistor working as amplifier.

Region	Emitter	Base	Collector
Width	Medium	Small	Large
Doping	Highest	Lowest	Medium
Biasing w.r.t. base	Forward	—	Reverse

5.7. TRANSISTOR ACTION

A bipolar transistor can basically be connected in four possible ways viz.

(*a*) When emitter base junction is forward biased and collector base junction reverse biased **(Active Region)**.

(*b*) When both emitter base as well as collector base junctions are forward biased **(Saturation Region)**.

(*c*) When both emitter base as well as collector base junctions are reverse biased **(Cut-Off Region)**.

(*d*) When emitter base junction is reverse biased and collector base junction is forward biased **(Inverted Region).**

Out of the above four modes of transistor operation, the transistor is mostly used in *active region i.e.* EB junction forward biased and CB-junction reverse biased. For this purpose, connections of an NPN-transistor are as shown in Fig. 5.11, where emitter base junction is forward biased, through battery V_{EE} and collector base junction is reverse biased through battery V_{CC}. To understand the operations of both the junctions separately two switches S_1 (at EB junction) and S_2 (at CB junctions) are provided.

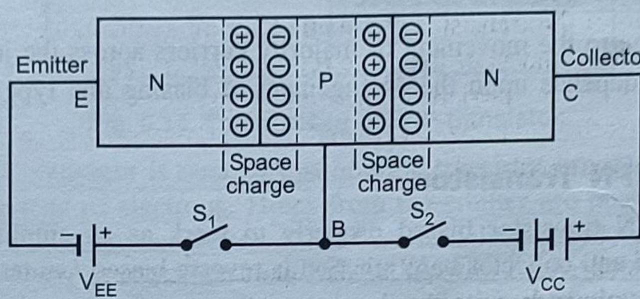


Fig. 5.11. Biasing of NPN Transistor in Active region.

Biasing of NPN Transistor in Active region : When both the switches *i.e.* S_1 and S_2 are open as shown in fig., the transistor is in unbiased condition and space change regions or depletion layer develops at both the junctions.

When switch S_1 is closed and S_2 is kept open. The EB junction will be forward biased and it acts as a **PN-diode** resulting in flow of large current under forward biasing. This current consists of majority carriers diffusing across the junction. The major contents of this current are electrons diffusing from emitter to base as the base is lightly doped. Thus, the emitter current and base currents are equal and are quite large, at this stage the collector current I_c is zero as shown in Fig. 5.12 (*a*).

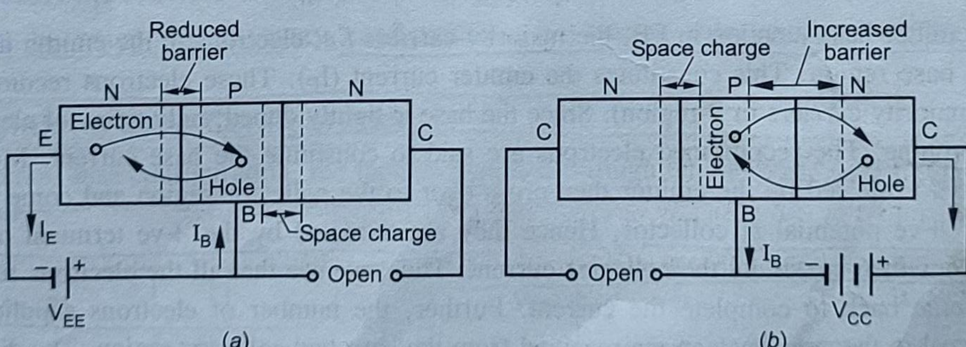


Fig. 5.12. (a) EB-Junction forward biased results in flow of large current
(b) CB-Junction reverse biased results in flow of small leakage current.

When the switch S_2 is closed and S_1 is kept open as shown in Fig. 5.12 (*b*), the CB junction is reverse biased and again behaves as a PN-diode under reverse biased condition and a small leakage current flows through the junction. This leakage current flows into the collector lead and out of this base lead. This collector leakage current is written as I_{CBO} and it is temperature dependent.

When both the switches are closed *i.e.* the transistor works in active region, the emitter and collector current both comes out to be large where base current is negligible in this case. Practically,

$$I_E = I_B + I_C$$

5.8. WORKING OF A TRANSISTOR

A transistor works due to the movement of majority carriers across the junction, the movement of these current carriers depends upon the arrangement of biasing and type of transistor used *i.e.* NPN or PNP.

5.8.1. Working of NPN Transistor

Fig. 8.13 shows NPN transistor biased properly to work as an amplifier. The emitter base junction is forward biased and collector base junction is reverse biased *i.e.* transistor works in active region. The forward bias voltage is quite small, whereas the reverse bias voltage is 'higher'.

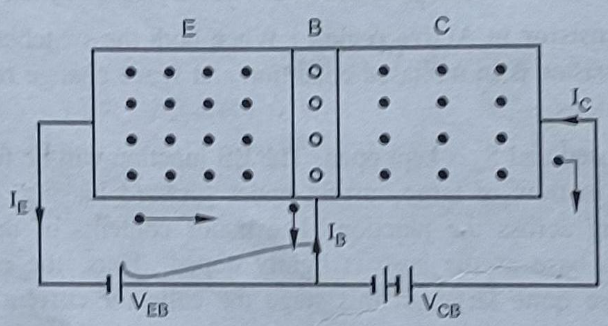


Fig. 5.13. Working of a NPN transistor.

As the emitter base junction in FB, the majority carriers *i.e.* electrons in the emitter are pushed towards the base region. This constitutes the emitter current (I_E). These electrons recombine with the holes (majority carriers in P-region). Since the base is lightly doped, only a few of electrons are able to recombine. The recombined electrons are said to constitute the base current. Most of the electrons (95%) injected by the emitter then cross over to the collector region and come under the influence of +ve potential at collector. Hence they are attracted by the +ve terminal of battery. These electrons then constitute the collector current. Thus, we see that all the electrons repelled by +ve V_{EB} come back to complete the current. Further, the number of electrons supplied by the emitter is equal to the sum of electrons received from the base and collector region. The direction of conventional current is opposite to flow of electrons and is shown in the fig. We note that,

$$I_E = I_C + I_B$$

5.8.2. Working of PNP-transistor

Fig. 5.14 shows a PNP transistor biased property in the active region, the emitter base junction is forward biased and the collector base junction reverse biased.

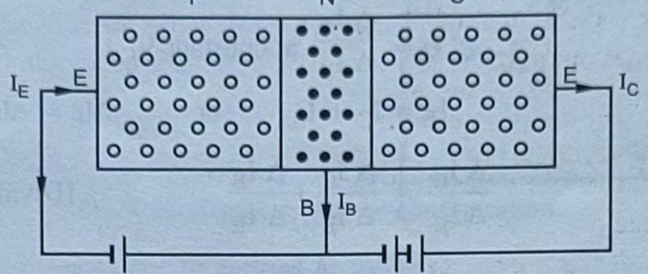


Fig. 5.14. The working of PNP-transistor.

The working of PNP transistor is same as that of NPN transistor except that the majority carriers in this case are holes instead of electrons. Holes from the emitter are pushed to the base region to diffuse with the electrons in N-region (Base). Since base is lightly doped, only a few electrons (less than 5%) combine with holes to constitute base current I_B. Rest of the holes (over 95%) cross over to the collector region, thus, constituting the collector current I_C. Again, we see that

$$I_E = I_C + I_B$$

5.9. CONCEPT OF CONFIGURATIONS

A transistor has three terminals, emitter, base and collector. So far we supplied input through the emitter, and took the output from collector. The base terminal acted common between the input and output. Such a 'configuration' is called common base configuration. Similarly, we can have emitter or collector as common between the input and output. Thus, three transistor configurations exist. They are

(*i*) Common base 'configuration' (CB).

(*ii*) Common emitter 'configuration' (CE).

(*iii*) Common collector 'configuration' (CC).

It must be noted that in every configuration, the biasing rule applies (*i.e.* they work as 'amplifiers').

5.9.1. Common Base Configuration

In common base configuration, the input is supplied through emitter and output is taken through the collector.

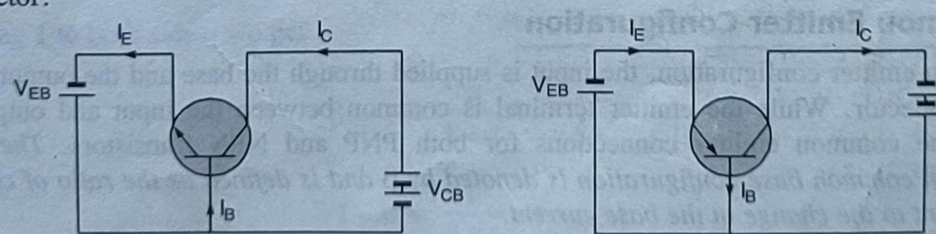


Fig. 5.15. Common base configuration.

Fig. 5.15 shows the common base connections for both PNP and NPN transistor. The input current is denoted as I_E and output current as I_C. The ratio of collector current to emitter current is denoted as α. *Rather α may be defined as "The ratio of change in collector current to the change in emitter current at constant output voltage (V_{CB})".*

i.e.

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

Now

$$I_E = I_C + I_B \quad \text{or} \quad \Delta I_E = \Delta I_C + \Delta I_B$$

$$\Rightarrow \quad \frac{\Delta I_E}{\Delta I_E} = \frac{\Delta I_C}{\Delta I_E} + \frac{\Delta I_B}{\Delta I_E} \quad \text{[Dividing throughout by } \Delta I_E]$$

or

$$1 = \alpha + \frac{\Delta I_B}{\Delta I_A}$$

Hence,

$$\alpha = \mathbf{1} - \frac{\mathbf{\Delta I_B}}{\mathbf{\Delta I_E}}$$

It implies that the value of α is always less than unity. As α is less than unity one may think that the configuration does not work as amplifier. However as discussed earlier, the input impedance of this circuit *i.e.* the impedance of EB junction is low and the output impedance that of CB junction is high.

The voltage gain,

$$A_V = \frac{I_C \times R_{out}}{I_E \times R_{in}} = \alpha . \frac{R_{out}}{R_{in}}$$

Since, the value of $\frac{R_{out}}{R_{in}}$ is very high (typically 100). So, its voltage gain is quite high.

Since, the CB junction is reverse biased, quite a small amount of the current due to minority carriers will also flow in the collector circuit. This current is denoted by I_{CBO} and is defined as the current that will be flowing in the collector circuit when the input circuit is open (no forward bias). The total collector current is, thus, given as,

I_C = collector current due to emitter current and current due to minority carriers.

or

$$\mathbf{I_C = \alpha I_E + I_{CBO}}$$

Sometimes I_{CBO} is also denoted by I_{CO}. In that case,

$$\mathbf{I_C = \alpha I_E + I_{CO}}$$

5.9.2. Common Emitter Configuration

In common emitter configuration, the input is supplied through the base and the output is taken through the collector. While the emitter terminal is common between the input and output. Fig. 5.16 shows the common emitter connections for both PNP and NPN transistors. *The current amplification in common base configuration is denoted by β and is defined as the ratio of change in collector current to the change in the base current.*

The current amplification, $\beta = \dfrac{\Delta I_C}{\Delta I_B}$

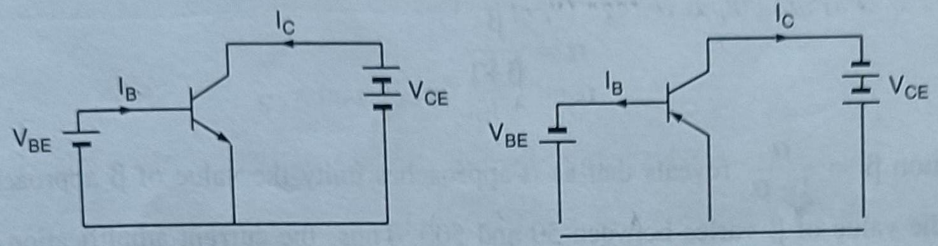


Fig. 5.16. Common emitter configuration.

The relation between β and α may be derived as follows,

We know, $$\beta = \frac{\Delta I_C}{\Delta I_B} \quad \ldots(i)$$

and $$\alpha = \frac{\Delta I_C}{\Delta I_E} \quad \ldots(ii)$$

Also $$I_E = I_C + I_B \text{ or } \Delta I_E = \Delta I_C + \Delta I_B$$

$$\Rightarrow \quad \Delta I_B = \Delta I_E - \Delta I_C$$

Substituting this value of ΔI_B in equation (*i*), we get

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

Dividing numerator and denominator by ΔI_E

$$\beta = \frac{\dfrac{\Delta I_C}{\Delta I_E}}{\dfrac{\Delta I_E}{\Delta I_E} - \dfrac{\Delta I_C}{\Delta I_E}}$$

$$\beta = \frac{\alpha}{1-\alpha} \quad \text{as} \quad \frac{\Delta I_C}{\Delta I_E} = \alpha$$

Adding 1 to both sides, we get

$$\beta + 1 = \frac{\alpha}{1-\alpha} + 1 = \frac{1}{1-\alpha}$$

$$\Rightarrow \quad 1 - \alpha = \frac{1}{\beta+1}$$

or
$$\alpha = 1 - \frac{1}{\beta+1} = \frac{\beta+1-1}{\beta+1}$$

or
$$\alpha = \frac{\beta}{\beta+1}.$$

The relation $\beta = \frac{\alpha}{1-\alpha}$ reveals that as α approaches unity the value of β approaches infinity. Practically, the value of β varies between 50 and 500. Thus, the current amplification of common emitter configuration is fairly high. The expression for collector current can also be derived as follows,

We know,
$$I_E = I_C + I_B \quad \ldots(i)$$

also
$$I_C = \alpha I_E + I_{CBO} \quad ..(ii) \text{ as in case of CB configuration}$$

Substituting equation (*i*) in equation (*ii*), we get,
$$I_C = \alpha(I_B + I_C) + I_{CBO} \text{ or } I_C = \alpha I_B + \alpha I_C + I_{CBO}$$

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

$\Rightarrow$
$$I_C = \frac{\alpha}{1-\alpha} I_B + \frac{I_{CBO}}{1-\alpha} \quad \ldots(iii)$$

The leakage current in the common emitter configuration is denoted by I_{CEO} and its value can be determined from the equation (*iii*)

When $I_B = 0$, then $I_C = I_{CEO} = \frac{I_{CBO}}{1-\alpha}$

Substituting the value of $\frac{I_{CBO}}{1-\alpha}$ as I_{CEO}, the equation (*iii*) may be rearranged as

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

Now
$$\frac{\alpha}{1-\alpha} = \beta$$

$\therefore$
$$I_C = \beta I_B + I_{CEO}$$

5.9.3. Common Collector Configuration

In case of common collector configuration, the input is supplied through the base and the output taken through the emitter, while the collector terminal is common. Fig. 5.17 shows the common collector configuration for both NPN and PNP transistors, with correct polarities of voltage and currents. It must be noted that in all the configurations, the biasing rule is applicable.

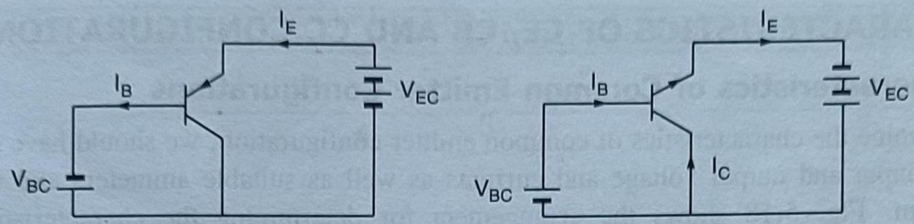


Fig. 5.17. Common collector configuration.

The current amplification in this configuration is denoted by γ and is given as

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

The relation between γ and α may be derived as follows :

We know, $$\gamma = \frac{\Delta I_E}{\Delta I_B} \quad \ldots(i) \qquad \text{and} \qquad \alpha = \frac{\Delta I_C}{\Delta I_E} \quad \ldots(ii)$$

We know that, $$I_E = I_C + I_B \quad \text{or} \quad \Delta I_E = \Delta I_C + \Delta I_B$$

$$\Rightarrow \quad \Delta I_B = \Delta I_E - \Delta I_C$$

Substituting in (i) $$\gamma = \frac{\Delta I_E}{\Delta I_E - \Delta I_C}$$

Dividing numerator and denominator by ΔI_E, we get

$$\gamma = \frac{1}{1 - \frac{\Delta I_C}{\Delta I_E}} = \frac{1}{1-\alpha} \quad \text{as} \quad \frac{\Delta I_C}{\Delta I_E} = \alpha$$

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

The relation between α and β may also be derived as follows :

$$\gamma - 1 = \frac{1}{1-\alpha} - 1 \qquad \text{[Subtracting 1 on both sides]}$$

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

$$\Rightarrow \quad \gamma - 1 = \frac{\alpha}{1-\alpha} \quad \text{Also we know that} \quad \frac{\alpha}{1-\alpha} = \beta$$

$$\therefore \quad \gamma - 1 = \beta \text{ or } \gamma = \beta + 1$$

The above relation shows that the current gain of common collector configuration is fairly high $(\sim \beta)$. However, this configuration is not used as amplifier as its input impedance is very high and the output impedance is very low.

5.10. CHARACTERISTICS OF CE, CB AND CC CONFIGURATIONS

5.10.1. Characteristics of Common Emitter Configurations

To determine the characteristics of common emitter configuration, we should have provision for variation of input and output voltage and currents as well as suitable ammeters and voltmeters to measure them. Fig. 5.18 shows the arrangement for determining the characteristics of a CE amplifier using NPN transistor. To determine the characteristics of PNP transistor, same arrangement would work, but we will have to reverse the polarities of the voltage source and the ammeters and voltmeters.

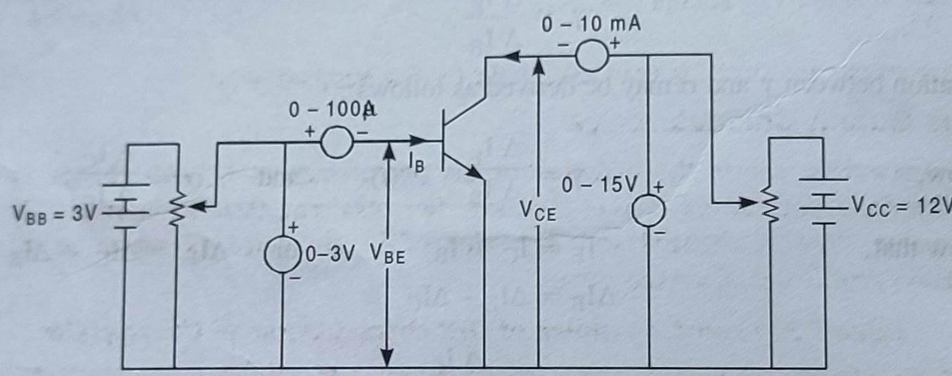


Fig. 5.18. Current arrangement to determine characteristics of CE configuration.

(a) Input Characteristics

The input characteristics shows the variation of I_B w.r.t. variation V_{BE} when V_{CE} is kept constant. The characteristics curve is drawn by keeping V_{CE} constant at a particular values, V_{BE} is varied and the values of I_B plotted as shown in the chart below. The overall shape of the input characteristics resembles with the shape of VI characteristics of PN junction diode in forward bias. Several curves may be drawn by setting the value of V_{CE} at other voltages as shown in fig. 5.19.

TABLE 5.2. Table for readings of input characteristics of CE amplifier.

S.No.	$V_{CE} = 0$ V		$V_{CE} = 10$ V	
	V_{BE}	I_B	V_{BE}	I_B
1.				
2.				
3.				
4.				
5.				
6.				

The variation of V_{CE} does not have much impact on the shape of input characteristics. The characteristic curve may be used to find out the input resistance of the configuration while the static resistance is given as :

$R_{in} = \frac{V_{BE}}{I_B}$ in the linear portion of the characteristic curves.

The dynamic resistance may be calculated as :

$r_{in} = \frac{\Delta V_{BE}}{\Delta I_B}$ when V_{CE} is kept constant.

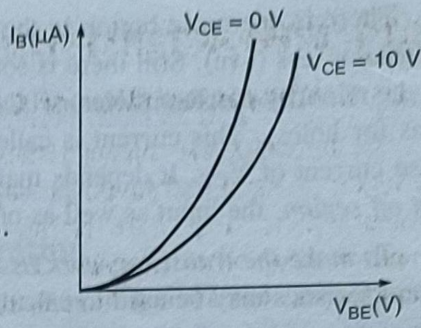


Fig. 5.19. Input characteristics of CE config.

The value of this resistance is very less, typically few hundred ohms.

(b) The Output Characteristics

This characteristic shows the variation of the output current I_C with change in the output voltage, when the input current is kept constant. For obtaining this characteristic, I_B is set to a convenient value, V_{CE} is changed and the value of I_C are noted as shown in the table 5.3. Fig. 5.20 shows typical characteristic curves.

Table 5.3. Table for reading of O/P characteristics of CE amplifier

S.No.	V_{CE} (V)	$I_B = 0\mu A$ I_C (mA)	$I_B = 10\mu A$ I_C (mA)	$I_B = 20\mu A$ I_C (mA)	$I_B = 50\mu A$ I_C (mA)

As seen from the fig. 5.19, when V_{CE} increases from zero, I_C rapidly increases to a near saturation value for fixed value of I_B or it may be said otherwise that after active conduction, when V_{CE} is reduced below a fraction of volts (0·2 V), the collector current I_C does not reduce. This state of transistor characteristic is called **Saturation region.** In saturation region, the input junction is forward biased as well as the output junction is forward biased.

However when V_{CE} is increased further (*i.e.* the output junction is reverse biased), the transistor operates in active region and I_C increases proportionally to V_{CE} for fixed value of I_B. This state of transistor characteristic is called **Active region.** In active region, the input junction is forward biased and output junction is reverse biased. The value of I_C can be changed by changing the value of I_B as shown in Fig. 5.20.

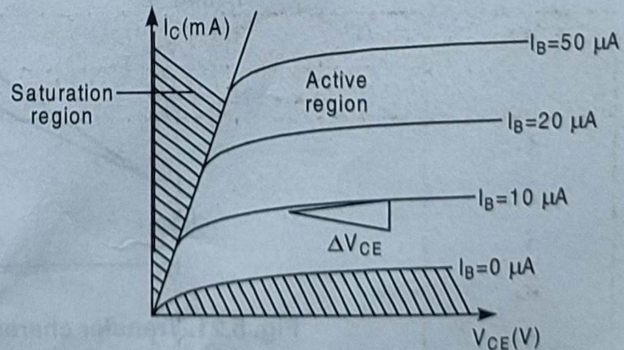


Fig. 5.20. Output characteristic of CE amplifier.

There is one more region in the characteristic *i.e.* **Cut off region.** In this case, the base current is zero or less (–ve). Still there is some current that flows in the collector circuit. This current is due to the minority carriers (holes) which are subjected to high reverse bias voltage (V_{CE} that is forward bias for holes). This current is called *reverse saturation current* I_{CEO} and is almost independent of base current of V_{CE}. It depends mainly on the temperature and increases w.r.t. temperature. In the *cut off region,* the input as well as output junctions are reverse biased.

To make the transistor work as an amplifier, it should be operated in active region. The output characteristics may be used to calculate the output resistance of the transistor in CE configuration.

The static output resistance is given as :

$$R_{out} = \frac{V_{CE}}{I_C} \text{ at constant } I_B$$

and the dynamic output resistance is given as

$$r_{out} = \frac{\Delta V_{CE}}{\Delta I_C} \text{ at constant } I_B.$$

The dynamic output resistance is equal to the inverse of the slope of output characteristic.

i.e.
$$r_{out} = \frac{1}{\text{slope of output characteristic}} \text{ at constant } I_B.$$

In the active region, the change in collector current is very small (~ 1 mA) for 5 V change in V_{CE}. Therefore, the output resistance of CE configuration is high ($\sim$ 100 kΩ).

(c) Transfer Characteristic

This characteristic is drawn by varying the input current and noting the corresponding values of output current while keeping the values of V_{CE} constant. It is seen that when the input current is zero, even then there is some constant output current (reverse saturation current I_{CEO}). Further, the output current increases rapidly w.r.t. change in input current. The typical transfer characteristics is shown in Fig. 5.21.

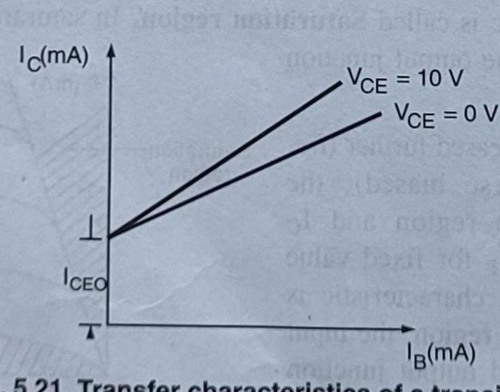


Fig. 5.21. Transfer characteristics of a transistor.

The ratio of change in output current to the change in input current is defined as current amplification β.

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

Further, the equation of collector current can be derived from the transfer characteristics and is given as

$$I_C = \beta I_B + I_{CEO} \; (y = mx + C)$$

5.10.2. Characteristics of Common Base Configuration

The circuit for determining the characteristics of CB configuration of a NPN transistor is shown in Fig. 5.22. In this case, the base terminal is common to both the input and the output. The input junction is biased by a battery V_{EE} and the output junction by another battery V_{CC}. The same circuit is recommended for PNP transistor except that the polarities of batteries and meters are required to be reverse biased.

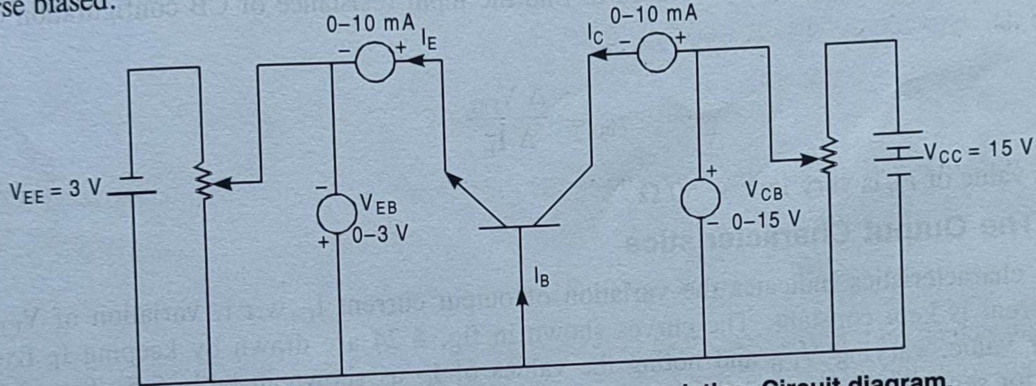


Fig. 5.22. Common base configuration characteristics- Circuit diagram.

(a) Input Characteristics

This characteristics shows the variation of I_E w.r.t. V_{EB} when V_{CB} is kept constant. The curve is plotted by keeping V_{CB} constant at a particular value, varying V_{EB} and noting the values of I_E as shown in table 5.4. The value of V_{CB} is then set to another value and same set of readings is repeated. Fig. 5.23 shows such a characteristic curve. It is seen that for certain input voltage (0·2 V for Ge and 0·4 V for Si), the emitter current is zero. The value of this voltage is called **Cut in voltage.**

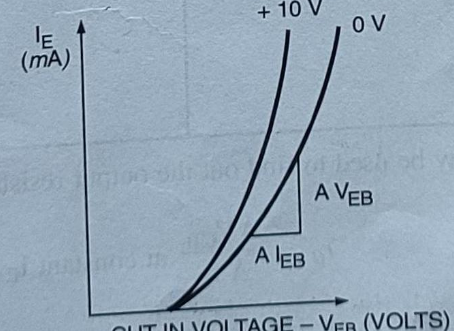


Fig. 5.23. Input characteristics of CB-configuration

TABLE 5.4. Table for finding input characteristics of CB configuration

S.No.	V_{EB} – ve(V)	$V_{CB} = 0$ V	$V_{CB} = 10$ V
		I_E (mA)	I_E(mA)
1.			
2.			
3.			
4.			
5.			
6.			

The input characteristics may be used to find the input resistance of CB configuration which is given as

$$r_{in} = \frac{\Delta V_{EB}}{\Delta I_E}$$

This value of r_{in} is very low ~ 50 Ω

(b) The Output Characteristics

This characteristics indicates the variation of output current I_C w.r.t. variation of V_{CB} when input current is kept constant. The curves shown in fig. 5.24 are drawn by keeping I_E fixed at a particular value, varying V_{CB} and noting the values of I_C as shown in table 5.5. The curves are repeated for several values of I_E.

TABLE 5.5. Readings for CB output characteristics.

S.No.	V_{CB} (V)	$I_E = 0, I_C$ (mA)	$I_E = 2$mA, I_C	$I_E = 4$ mA, I_C
1.				
2.				
3.				
4.				
5.				
6.				
7.				

The characteristic curves may be used to find out the output resistance which is given as

$$r_0 = \frac{\Delta V_{CB}}{\Delta I_C} \text{ at constant } I_E$$

Since, the change in I_C is very small per unit change in V_{CB} (curves are flat). The output impedance is very large (~ MΩ). It is the highest of all the configurations.

The characteristic curves have three distinct regions viz **Saturation, Active and Cut off region.**

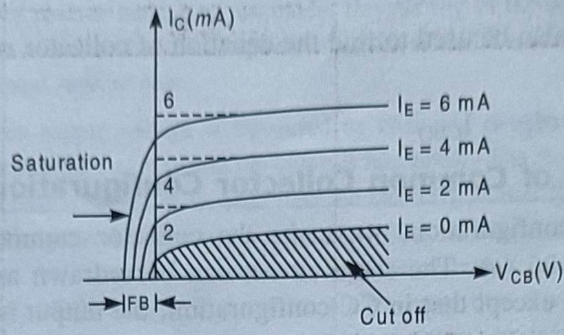


Fig. 5.24. Output characteristic of CB configuration of NPN transistor.

In saturation region both the junctions are forward biased. Actually V_{CB} is slightly negative in this case and the collector current changes quite rapidly.

In cut off region, both the collector and emitter junctions are reverse biased. There is a small amount of current that flows in collector region, but this current is due to minority carriers and is almost independent of the collector voltage.

In active region, the input junction (EB junction) is forward biased and the output junction (CB junction) is reverse biased. In active region, the collector current is almost independent of collector voltage and depends mainly upon the emitter current.

(c) Transfer Characteristics

It shows the variation of I_C *w.r.t.* change in I_E when V_{CB} is kept constant. This curve is drawn by keeping V_{CB} fixed at convenient value, the value of I_E is changed and corresponding values of I_C are noted. The transfer characteristic is as shown in Fig. 5.25. The slope of this characteristic gives the value of the common base current gain α.

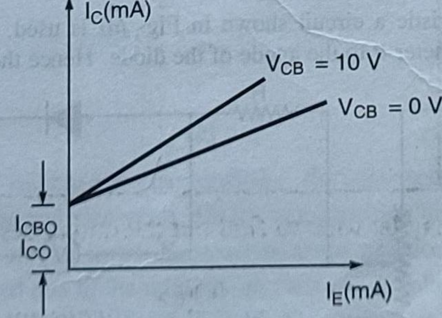


Fig. 5.25. Transfer characteristic.

i.e. Current gain, $\alpha = \frac{\Delta I_C}{\Delta I_E}$

The characteristic may also be used to find the equation of collector current of CB configuration which is then given as

$$I_C = \alpha I_E + I_{CBO} \qquad (\because Y = mx + C)$$

5.10.3. Characteristic of Common Collector Configuration

In common collector configuration, we make the collector common between the input and output as shown in Fig. 5.26 (*a*). The same circuit can be redrawn as shown in Fig. 5.26 (*b*). The two circuits look alike, except that in CC configuration, the output is taken at emitter, rather at the collector.

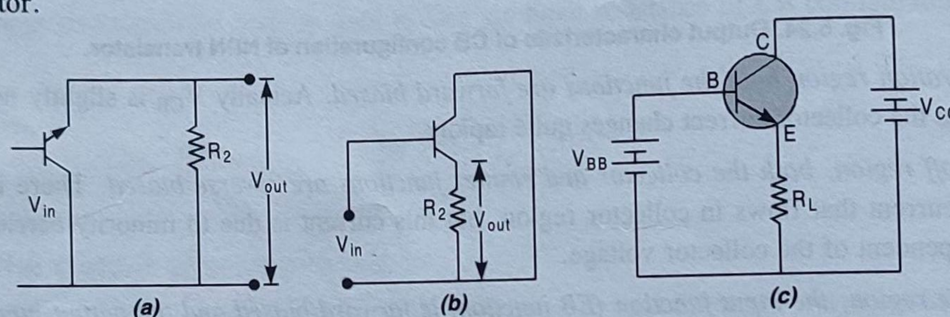


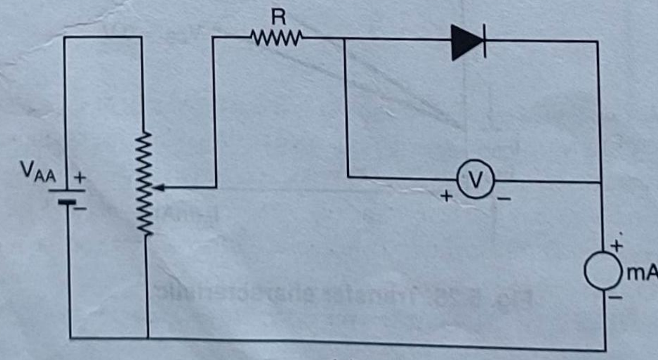
Fig. 5.26. (a) and (b) Common collector configuration for NPN transistor.

The biasing arrangement for CC configuration has been shown in Fig. 5.26 (*c*). The characteristics of CC configuration are not of any practical significance and they are not being considered. The input resistance of CC configuration is highest of all configurations and the output resistance is the lowest. The leakage current is almost same as that of common emitter configuration.

Important and Expected Questions

Q.1 Explain the characteristics of ordinary diode.

Ans. To obtain the V-I characteristic a circuit shown in Fig. (*a*) is used. In the circuit, the d.c. battery V_{AA} is connected through potentiometer P to the anode of the diode. Hence the diode is forward biased.

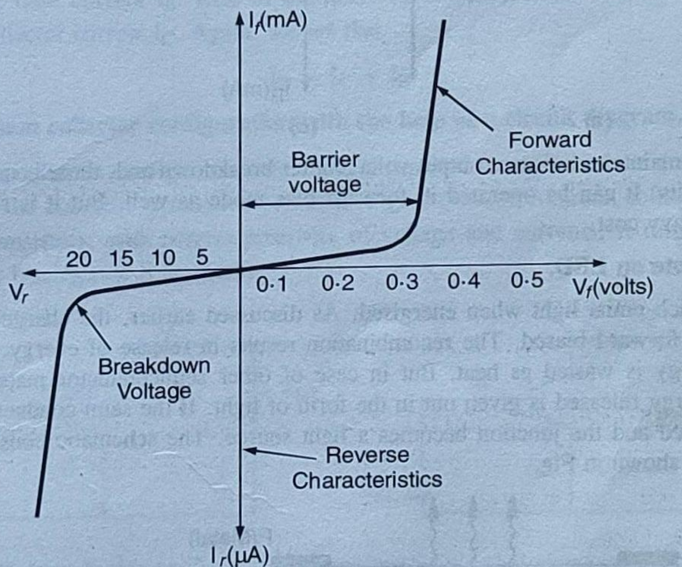


(*a*)

A resistance R is included in the circuit so as to limit the current. The potentiometer helps in varying the voltage applied to the diode. The voltage is measured by means of the voltmeter. The milliammeter is used to measure the current. For reverse biasing of the diode, the polarity of the battery may be reversed. Fig. *(b)* shows the magnified view of the characteristics curve of the diode. The characteristic is studied under two heads *i.e. forward bias* and *reverse bias*.

***(a)* Forward bias.** When supply voltage is measured by changing potentiometer P from 0 volts to higher values, the current increases very slowly and the curve is non-linear. The slow rise in current of diode in this case is because the external voltage has to overcome the barrier potential (0·3 V for Ge and 0·7 V for Si). However, when the barrier potential is overcome and the voltage is increased, further, the diode behaves like an ordinary resistor and the current rises very sharply. This current is limited by the series resistance and the forward resistance R_f of the diode. If the current rises more than the rated value, the diode may get damaged.

The forward voltage (0·3 V for Ge and 0·7 V for Si diodes) at which the current through PN-junction or diodes starts rising sharply is known as **knee voltage.**



(b)

***(b)* Reverse bias.** To obtain the reverse bias characteristics, the polarity of the battery is reversed *i.e.* the –ve terminal gets connected to anode and vice-versa. Under this condition the potential barrier at the junction is increased. Thus, practically no current flows. However in actual practice a very small current (μA) flows in the circuit. This current is caused due to the minority carriers and is called **reverse saturation current.** The reverse saturation current increases slightly with increase in reverse bias voltage till a stage is reached when the minority carriers attain sufficient kinetic energy to break the junction. Consequently, the reverse current increases abruptly to a large value. This may destroy the diode permanently.

The reverse voltage at which PN-junction breaks is known as **breakdown voltage.**

Q.2. What is a zener diode ? What are its characteristics ?

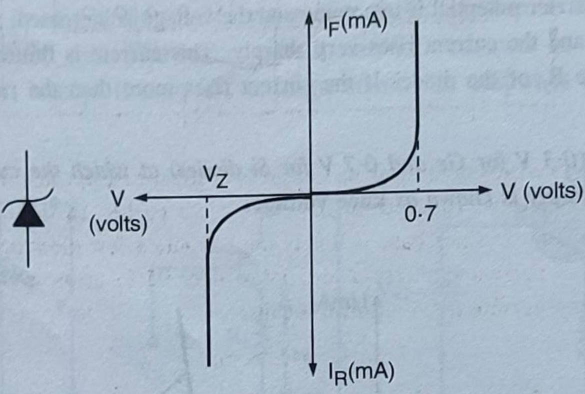
Ans. *A **Zener diode** is a heavily doped crystal diode which is optimised to operate in breakdown region.* Fig. (*a*) shows the schematic symbol of zener diode. Fig. (*b*) shows the **V-I characteristics of Zener diode.**

Following points are worth noting for the characteristics of zener diode :

(*i*) Its characteristic is almost similar to the ordinary diode except that it has a sharp reverse breakdown.

(*ii*) The voltage after reverse breakdown is almost constant.

(*iii*) During the reverse breakdown, the zener diode does not burn off until the external circuit limits the current through it.

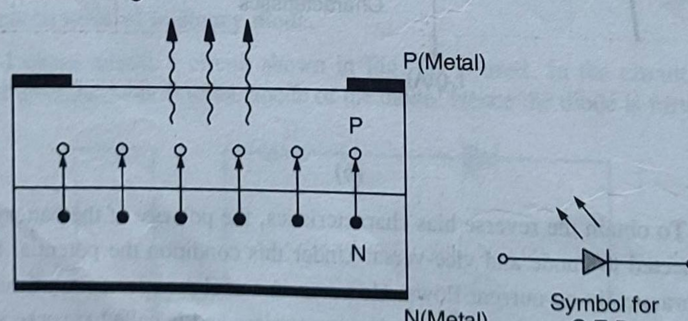


(*a*) (*b*)

The zener diode maintains constant output voltage after breakdown and, thus, is used for voltage stabilization in rectifier circuits. It can be operated in forward bias mode as well. But it is rarely used for rectification because of its heavy cost.

Q.3. Write a short note on LED.

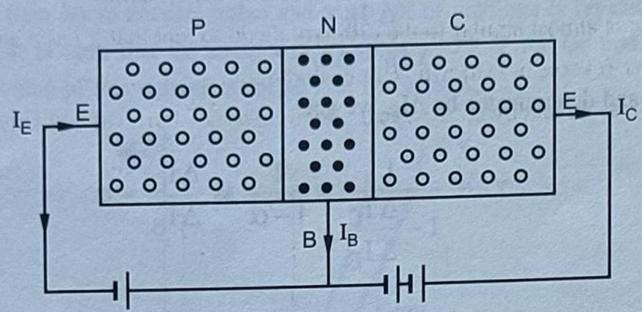
Ans. It is a diode which emits light when energised. As discussed earlier, the charge recombination takes place when a diode is forward biased. The recombination results in release of energy. For silicon or germanium diodes, this energy is wasted as heat. But in case of other semiconductor materials like gallium arsenide (GaAs). The energy released is given out in the form of light. If the semi-conductor material is transluscent, the light is emitted and the junction becomes a light source. The schematic constructional details of a light emitting diode is shown in Fig.



The colour of light emitted depends upon the type of semiconductor material. While GaAs emits infrared radiations, gallium phosphide (GaP) emits red or green light and gallium arsenic phosphide (GaAsP) emits red or yellow (amber) light. The LEDs are always operated in forward bias and require 1·5 to 2 volts for the full glow.

Q.4. Explain the working of PNP transistor with diagram.

Ans. Fig. shows a PNP transistor biased property in the active region, the emitter base junction is forward biased and the collector base junction reverse biased.

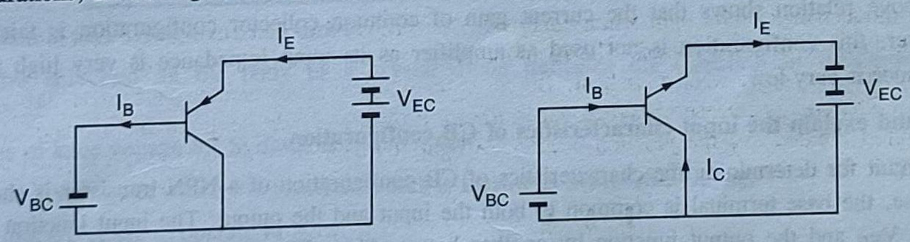


The working of PNP transistor is same as that of NPN transistor except that the majority carriers in this case are holes instead of electrons. Holes from the emitter are pushed to the base region to diffuse with the electrons in N-region (Base). Since base is lightly doped, only a few electrons (less than 5%) combine with holes to constitute base current I_B. Rest of the holes (over 95%) cross over to the collector region, thus, constituting the collector current I_C. Again, we see that

$$I_E = I_C + I_B$$

Q.5. Explain the common collector configuration with the help of a circuit diagram.

Ans. In case of common collector configuration, the input is supplied through the base and the output taken through the emitter, while the collector terminal is common. Fig. shows the common collector configuration for both NPN and PNP transistors, with correct polarities of voltage and currents. It must be noted that in all the configurations, the biasing rule is applicable.



The current amplification in this configuration is denoted by γ and is given as

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

The relation between γ and α may be derived as follows :

We know, $$\gamma = \frac{\Delta I_E}{\Delta I_B} \quad \ldots(i)$$ and

$$\alpha = \frac{\Delta I_C}{\Delta I_E} \quad \ldots(ii)$$

We know that,

$$I_E = I_C + I_B$$

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

$$\Rightarrow \quad \Delta I_B = \Delta I_E - \Delta I_C$$

Substituting in (*i*)

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

Dividing numerator and denominator by ΔI_E, we get

$$\gamma = \frac{1}{1 - \dfrac{\Delta I_C}{\Delta I_E}} = \frac{1}{1-\alpha} \text{ as } \frac{\Delta I_C}{\Delta I_E} = \alpha$$

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

The relation between α and β may also be derived as follows :

$$\gamma - 1 = \frac{1}{1-\alpha} - 1 \quad \text{[Subtracting 1 on both sides]}$$

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

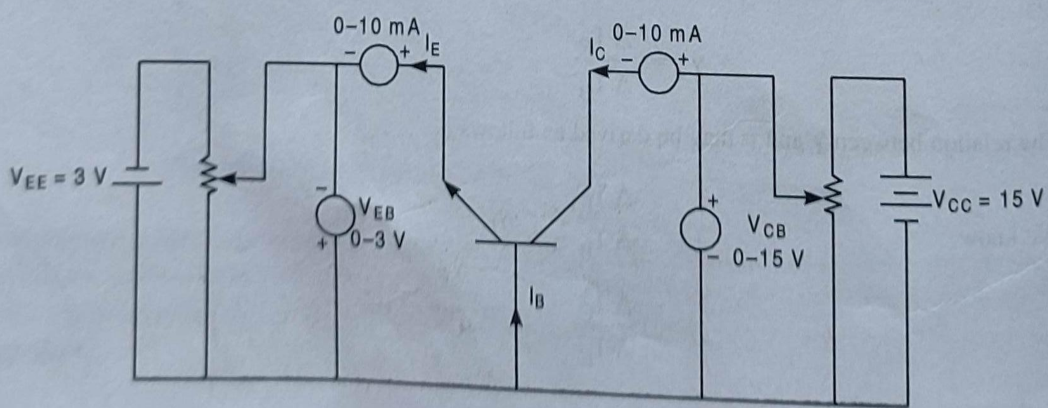
$$\Rightarrow \quad \gamma - 1 = \frac{\alpha}{1-\alpha} \text{ Also we know that } \frac{\alpha}{1-\alpha} = \beta$$

$$\therefore \quad \gamma - 1 = \beta \text{ or } \gamma = \beta + 1$$

The above relation shows that the current gain of common collector configuration is fairly high ($\sim\beta$). However, this configuration is not used as amplifier as its input impedance is very high and the output impedance is very low.

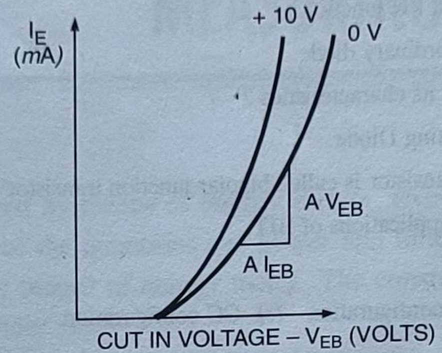
Q.6. State and explain the input characteristics of CB configuration.

Ans. The circuit for determining the characteristics of CB configuration of a NPN transistor is shown in Fig. In this case, the base terminal is common to both the input and the output. The input junction is biased by a battery V_{EE} and the output junction by another battery V_{CC}. The same circuit is recommended for PNP transistor except that the polarities of batteries and meters are required to be reverse biased.



(a) Input Characteristics

This characteristics shows the variation of I_E w.r.t. V_{EB} when V_{CB} is kept constant. The curve is plotted by keeping V_{CB} constant at a particular value, varying V_{EB} and noting the values of I_E as shown in table 5.4. The value of V_{CB} is then set to another value and same set of readings is repeated. Fig. 5.23 shows such a characteristic curve. It is seen that for certain input voltage (0·2 V for Ge and 0·4 V for Si), the emitter current is zero. The value of this voltage is called **Cut in voltage.**



The input characteristics may be used to find the input resistance of CB configuration which is given as

$$r_{in} = \frac{\Delta V_{EB}}{\Delta I_E}$$

This value of r_{in} is very low ~ 50 Ω

Objective Type Questions

1. PN-junction is also called a .... diode.
2. The arrow direction on the body of a crystal diode indicates the direction in which the diode can conduct ....
3. The value of knee voltage for Si diode is .... volt.
4. The .... voltage at which PN-junction breaks is known as breakdown voltage.
5. A zener diode is made to operate in ....
6. Usually a zener diode is used as a ....
7. LED stands for ....
8. A transistor contains .... PN-junctions.
9. In a transistor, base is made very .... and it is doped.
10. To make the transistor work as an amplifier, it should be operated in .... region.

Answers

1. semi conductor	2. conventional current	3. 0·7	4. reverse
5. breakdown	6. voltage regulator	7. Light Emitting Diode	8. two
9. thin, lightly	10. active.		

Review Questions

1. Why a PN-junction is called crystal diode ? How are the polarities of diode identified ?
2. Discuss the following :
   (a) Effect of forward biasing in a PN junction.
   (b) Effect of reverse biasing in a PN junction.
3. Explain the characteristics of an ordinary diode.
4. What is a zener diode ? What are its characteristics ?
5. Write a short note on Light Emitting Diode.
6. Explain why ordinary junction transistor is called bipolar junction transistor ?
7. Describe the characteristics and applications of BJT.
8. Explain the following :
   (a) CE configuration (b) CB configuration (c) CC configuration.

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