the amplifying capability of the transistor. We shall discuss the amplifying property of transistor later in this chapter.

Note. There are two basic transistor types : the **bipolar junction transistor** (*BJT*) and **field-effect transistor** (*FET*). As we shall see, these two transistor types differ in both their operating characteristics and their internal construction. **Note that when we use the term transistor, it means bipolar junction transistor (*BJT*).** The term comes from the fact that in a bipolar transistor, there are *two* types of charge carriers (*viz*. electrons and holes) that play part in conductions. Note that bi means two and polar refers to polarities. The field-effect transistor is simply referred to as *FET*.

8.5 Transistor Symbols

In the earlier diagrams, the transistors have been shown in diagrammatic form. However, for the sake of convenience, the transistors are represented by schematic diagrams. The symbols used for *npn* and *pnp* transistors are shown in Fig. 8.6.

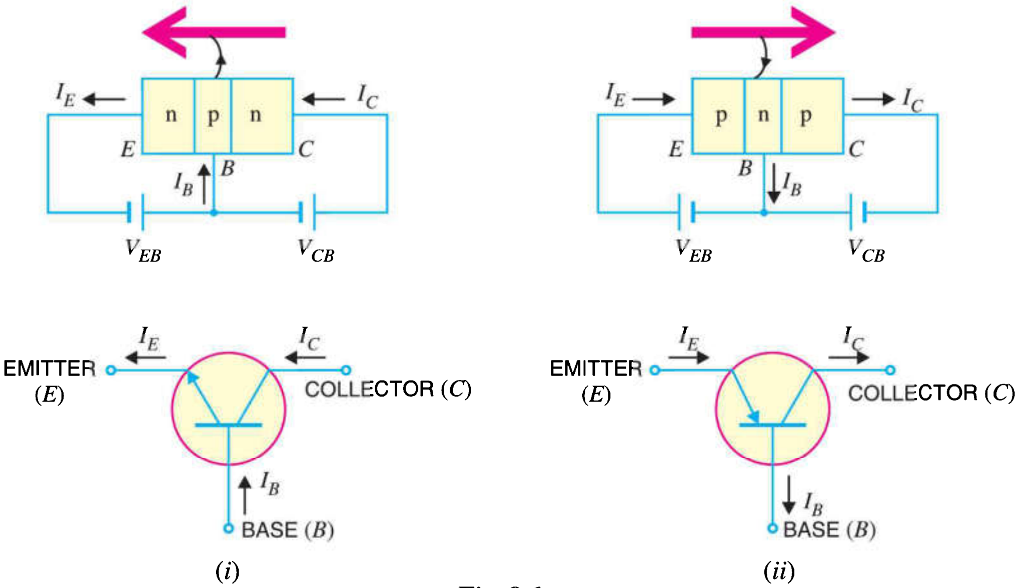

Fig. 8.6

Note that emitter is shown by an arrow which indicates the direction of conventional current flow with forward bias. For *npn* connection, it is clear that conventional current flows out of the emitter as indicated by the outgoing arrow in Fig. 8.6 (*i*). Similarly, for *pnp* connection, the conventional current flows into the emitter as indicated by inward arrow in Fig. 8.6 (*ii*).

8.6 Transistor Circuit as an Amplifier

A transistor raises the strength of a weak signal and thus acts as an amplifier. Fig. 8.7 shows the basic circuit of a transistor amplifier. The weak signal is applied between emitter-base junction and output is taken across the load R_C connected in the collector circuit. In order to achieve faithful amplification, the input circuit should always remain forward biased. To do so, a d.c. voltage V_{EE} is applied in the input circuit in addition to the signal as

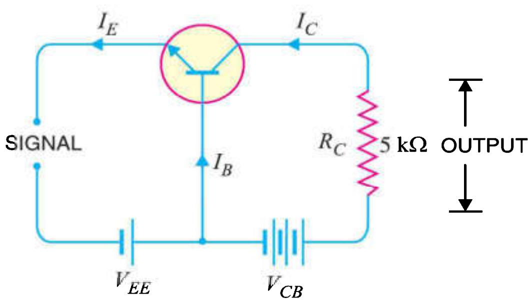

Fig. 8.7

shown. This d.c. voltage is known as bias voltage and its magnitude is such that it always keeps the input circuit forward biased regardless of the polarity of the signal.

As the input circuit has low resistance, therefore, a small change in signal voltage causes an appreciable change in emitter current. This causes almost the *same change in collector current due to transistor action. The collector current flowing through a high load resistance R_C produces a large voltage across it. Thus, a weak signal applied in the input circuit appears in the amplified form in the collector circuit. It is in this way that a transistor acts as an amplifier.

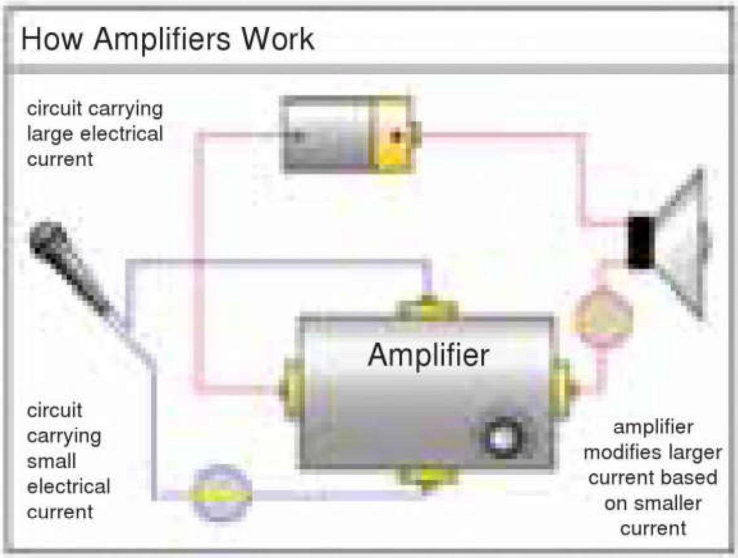

Illustration. The action of a transistor as an amplifier can be made more illustrative if we consider typical circuit values. Suppose collector load resistance R_C = 5 kΩ. Let us further assume that a change of 0.1V in signal voltage produces a change of 1 mA in emitter current. Obviously, the change in collector current would also be approximately 1 mA. This collector current flowing through collector load R_C would produce a voltage = 5 kΩ × 1 mA = 5 V. Thus, a change of 0.1 V in the signal has caused a change of 5 V in the output circuit. In other words, the transistor has been able to raise the voltage level of the signal from 0.1 V to 5 V *i.e.* voltage amplification is 50.

Example 8.1. *A common base transistor amplifier has an input resistance of 20 Ω and output resistance of 100 kΩ. The collector load is 1 kΩ. If a signal of 500 mV is applied between emitter and base, find the voltage amplification. Assume* α_{ac} *to be nearly one.*

Solution. **Fig. 8.8 shows the conditions of the problem. Note that output resistance is very high as compared to input resistance. This is not surprising because input junction (base to emitter) of the transistor is forward biased while the output junction (base to collector) is reverse biased.

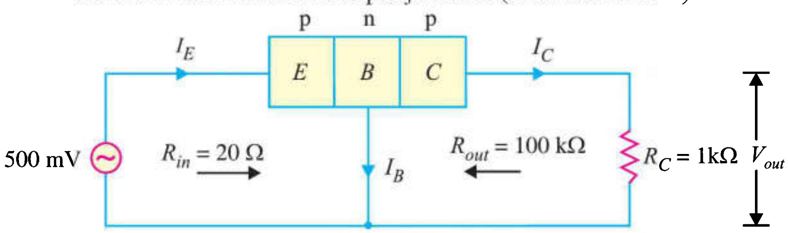

Fig. 8.8

* The reason is as follows. The collector-base junction is reverse biased and has a very high resistance of the order of mega ohms. Thus collector-base voltage has little effect on the collector current. This means that a large resistance R_C can be inserted in series with collector without disturbing the collector current relation to the emitter current *viz.* $I_C = \alpha I_E + I_{CBO}$. Therefore, collector current variations caused by a small base-emitter voltage fluctuations result in voltage changes in R_C that are quite high—often hundreds of times larger than the emitter-base voltage.

** The d.c. biasing is omitted in the figure because our interest is limited to amplification.

Input current, $I_E = \frac{\text{Signal}}{R_{in}} = \frac{500 \text{ mV}}{20\ \Omega} = 25 \text{ mA}$. Since α_{ac} is nearly 1, output current, $I_C = I_E =$ 25 mA.

$$\text{Output voltage, } V_{out} = I_C R_C = 25 \text{ mA} \times 1 \text{ k}\Omega = 25 \text{ V}$$

$$\therefore \quad \text{Voltage amplification, } A_v = \frac{V_{out}}{\text{signal}} = \frac{25\ V}{500\ mV} = \mathbf{50}$$

Comments. The reader may note that basic amplifying action is produced by transferring a current from a *low-resistance* to a *high-resistance* circuit. Consequently, the name transistor is given to the device by combining the two terms given in magenta letters below :

Transfer + Re**sistor** ⟶ **Transistor**

8.7 Transistor Connections

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

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

(*iii*) common collector connection

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

8.8 Common Base Connection

In this circuit arrangement, input is applied between emitter and base and output is taken from collector and base. Here, base of the transistor is common to both input and output circuits and hence the name common base connection. In Fig. 8.9 (*i*), a common base *npn* transistor circuit is shown whereas Fig. 8.9 (*ii*) shows the common base *pnp* transistor circuit.

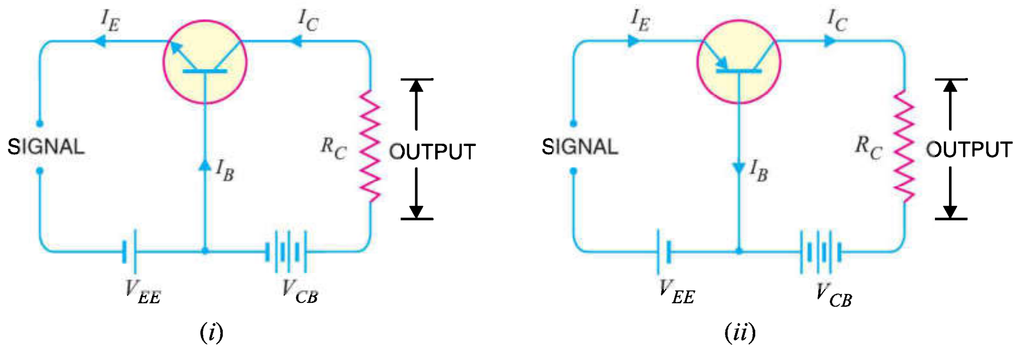

Fig. 8.9

1. Current amplification factor (α). It is the ratio of output current to input current. In a common base connection, the input current is the emitter current I_E and output current is the collector current I_C.

The ratio of change in collector current to the change in emitter current at constant collector-base voltage V_{CB} is known as **current amplification factor** *i.e.*

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

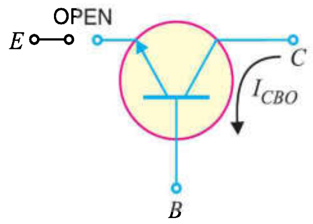

Fig. 8.10

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

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

(*i*) That part of emitter current which reaches the collector terminal *i.e.* ***αI_E.

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

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

It is clear that if $I_E = 0$ (*i.e.*, emitter circuit is open), a small leakage current still flows in the collector circuit. This $I_{leakage}$ is abbreviated as I_{CBO}, meaning collector-base current with emitter open. The I_{CBO} is indicated in Fig. 8.10.

$$\therefore \quad I_C = \alpha I_E + I_{CBO} \qquad ...(i)$$

$$\text{Now} \quad I_E = I_C + I_B$$

$$\therefore \quad I_C = \alpha (I_C + I_B) + I_{CBO}$$

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

$$\text{or} \quad I_C = \frac{\alpha}{1-\alpha} I_B + \frac{I_{CBO}}{1-\alpha} \qquad ...(ii)$$

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

Fig. 8.11 shows the concept of I_{CBO}. In *CB* configuration, a small collector current flows even when the emitter current is zero. This is the leakage collector current (*i.e.* the collector current when emitter is open) and is denoted by I_{CBO}. When the emitter voltage V_{EE} is also applied, the various currents are as shown in Fig. 8.11 (*ii*).

Note. Owing to improved construction techniques, the magnitude of I_{CBO} for general-purpose and low-powered transistors (especially silicon transistors) is usually very small and may be neglected in calculations. However, for high power applications, it will appear in microampere range. Further, I_{CBO} is very much temperature dependent; it increases rapidly with the increase in temperature. Therefore, at higher temperatures, I_{CBO} plays an important role and must be taken care of in calculations.

* If only d.c. values are considered, then $\alpha = I_C/I_E$.

** At first sight, it might seem that since there is no current gain, no voltage or power amplification could be possible with this arrangement. However, it may be recalled that output circuit resistance is much higher than the input circuit resistance. Therefore, it does give rise to voltage and power gain.

*** $$\alpha = \frac{I_C}{I_E} \quad \therefore \quad I_C = \alpha I_E$$

In other words, αI_E part of emitter current reaches the collector terminal.

change in emitter current (ΔI_E) at constant collector-base voltage (V_{CB}) *i.e.*

$$\text{Input resistance, } r_i = \frac{\Delta V_{BE}}{\Delta I_E} \text{ at constant } V_{CB}$$

In fact, input resistance is the opposition offered to the signal current. As a very small V_{EB} is sufficient to produce a large flow of emitter current I_E, therefore, input resistance is quite small, of the order of a few ohms.

2. Output characteristic. It is the curve between collector current I_C and collector-base voltage V_{CB} at *constant emitter current I_E. Generally, collector current is taken along *y*-axis and collector-base voltage along *x*-axis. Fig. 8.15 shows the output characteristics of a typical transistor in *CB* arrangement.

The following points may be noted from the characteristics :

(*i*) The collector current I_C varies with V_{CB} only at very low voltages (< 1 V). The transistor is *never* operated in this region.

(*ii*) When the value of V_{CB} is raised above 1 – 2 V, the collector current becomes constant as indicated by straight horizontal curves. It means that now I_C is independent of V_{CB} and depends upon I_E only. This is consistent with the theory that the emitter current flows *almost* entirely to the collector terminal. The transistor is *always* operated in this region.

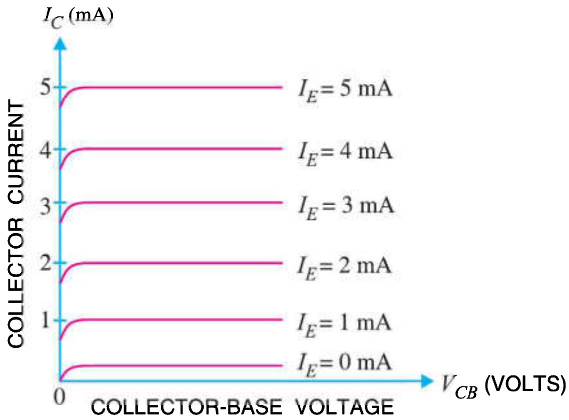

Fig. 8.15

(*iii*) A very large change in collector-base voltage produces only a tiny change in collector current. This means that output resistance is very high.

Output resistance. It is the ratio of change in collector-base voltage (ΔV_{CB}) to the resulting change in collector current (ΔI_C) at constant emitter current *i.e.*

$$\text{Output resistance, } r_o = \frac{\Delta V_{CB}}{\Delta I_C} \text{ at constant } I_E$$

The output resistance of *CB* circuit is very high, of the order of several tens of kilo-ohms. This is not surprising because the collector current changes very slightly with the change in V_{CB}.

8.10 Common Emitter Connection

In this circuit arrangement, input is applied between base and emitter and output is taken from the collector and emitter. Here, emitter of the transistor is common to both input and output circuits and hence the name common emitter connection. Fig. 8.16 (*i*) shows common emitter *npn* transistor circuit whereas Fig. 8.16 (*ii*) shows common emitter *pnp* transistor circuit.

* I_E has to be kept constant because any change in I_E will produce corresponding change in I_C. Here, we are interested to see how V_{CB} influences I_C.

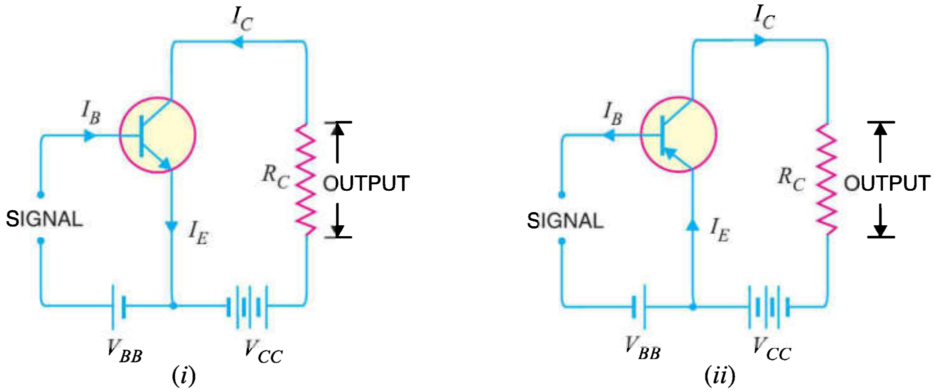

Fig. 8.16

1. Base current amplification factor (β). In common emitter connection, input current is I_B and output current is I_C.

The ratio of change in collector current (ΔI_C) *to the change in base current* (ΔI_B) *is known as* **base current amplification factor** *i.e.*

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

In almost any transistor, less than 5% of emitter current flows as the base current. Therefore, the value of β is generally greater than 20. Usually, its value ranges from 20 to 500. This type of connection is frequently used as it gives appreciable current gain as well as voltage gain.

Relation between β and α. A simple relation exists between β and α. This can be derived as follows :

$$\beta = \frac{\Delta I_C}{\Delta I_B} \quad \text{...}(i)$$

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

Now $\quad I_E = I_B + I_C$

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

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

Substituting the value of ΔI_B in exp. (*i*), we get,

$$\beta = \frac{\Delta I_C}{\Delta I_E - \Delta I_C} \quad \text{...}(iii)$$

Dividing the numerator and denominator of R.H.S. of exp. (*iii*) by ΔI_E, we get,

$$\beta = \frac{\Delta I_C / \Delta I_E}{\frac{\Delta I_E}{\Delta I_E} - \frac{\Delta I_C}{\Delta I_E}} = \frac{\alpha}{1-\alpha} \qquad \left[\because \quad \alpha = \frac{\Delta I_C}{\Delta I_E}\right]$$

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

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

* If d.c. values are considered, $\beta = I_C/I_B$.

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

We know $I_E = I_B + I_C$ ...(*i*)

and $I_C = \alpha I_E + I_{CBO}$ ...(*ii*)

From exp. (*ii*), we get, $I_C = \alpha I_E + I_{CBO} = \alpha (I_B + I_C) + I_{CBO}$

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

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

From exp. (*iii*), it is apparent that if $I_B = 0$ (*i.e.* base circuit is open), the collector current will be the current to the emitter. This is abbreviated as I_{CEO}, meaning collector-emitter current with base open.

$$\therefore \quad I_{CEO} = \frac{1}{1-\alpha} I_{CBO}$$

Substituting the value of $\frac{1}{1-\alpha} I_{CBO} = I_{CEO}$ in exp. (*iii*), we get,

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

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

Concept of I_{CEO}. In *CE* configuration, a small collector current flows even when the base current is zero [See Fig. 8.17 (*i*)]. This is the collector cut off current (*i.e.* the collector current that flows when base is open) and is denoted by I_{CEO}. The value of I_{CEO} is much larger than I_{CBO}.

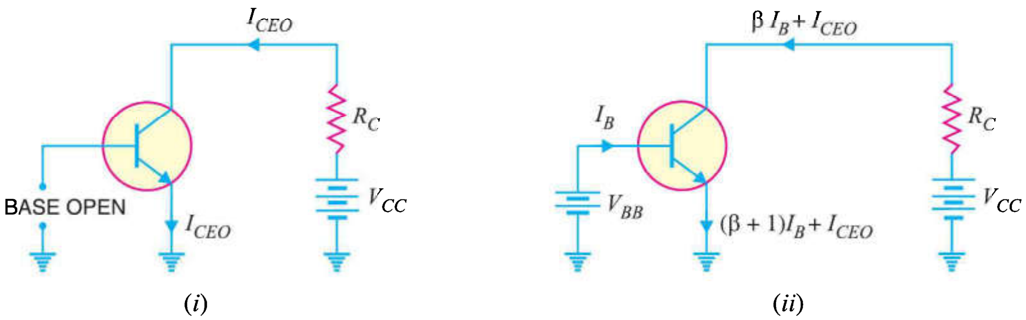

Fig. 8.17

When the base voltage is applied as shown in Fig. 8.17 (*ii*), then the various currents are :

Base current $= I_B$

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

Emitter current $=$ Collector current + Base current

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

It may be noted here that :

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

8.11. Measurement of Leakage Current

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

(*i*) **Circuit for I_{CEO} test.** Fig. 8.18 shows the circuit for measuring I_{CEO}. Since base is open

1. Input characteristic. *It is the curve between base current I_B and base-emitter voltage V_{BE} at constant collector-emitter voltage V_{CE}.*

The input characteristics of a *CE* connection can be determined by the circuit shown in Fig. 8.29. Keeping V_{CE} constant (say at 10 V), note the base current I_B for various values of V_{BE}. Then plot the readings obtained on the graph, taking I_B along *y*-axis and V_{BE} along *x*-axis. This gives the input characteristic at V_{CE} = 10V as shown in Fig. 8.30. Following a similar procedure, a family of input characteristics can be drawn. The following points may be noted from the characteristics :

(*i*) The characteristic resembles that of a forward biased diode curve. This is expected since the base-emitter section of transistor is a diode and it is forward biased.

(*ii*) As compared to *CB* arrangement, I_B increases less rapidly with V_{BE}. Therefore, input resistance of a *CE* circuit is higher than that of *CB* circuit.

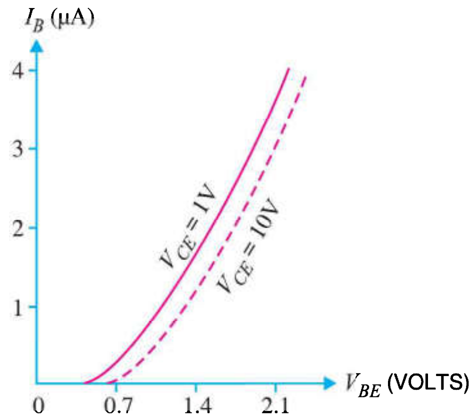

Fig. 8.30

Input resistance. It is the ratio of change in base-emitter voltage (ΔV_{BE}) to the change in base current (ΔI_B) at constant V_{CE} *i.e.*

$$\text{Input resistance,} \quad r_i = \frac{\Delta V_{BE}}{\Delta I_B} \text{ at constant } V_{CE}$$

The value of input resistance for a *CE* circuit is of the order of a few hundred ohms.

2. Output characteristic. *It is the curve between collector current I_C and collector-emitter voltage V_{CE} at constant base current I_B.*

The output characteristics of a *CE* circuit can be drawn with the help of the circuit shown in Fig. 8.29. Keeping the base current I_B fixed at some value say, 5 µA, note the collector current I_C for various values of V_{CE}. Then plot the readings on a graph, taking I_C along *y*-axis and V_{CE} along *x*-axis. This gives the output characteristic at I_B = 5 µA as shown in Fig. 8.31 (*i*). The test can be repeated for I_B = 10 µA to obtain the new output characteristic as shown in Fig. 8.31 (*ii*). Following similar procedure, a family of output characteristics can be drawn as shown in Fig. 8.31 (*iii*).

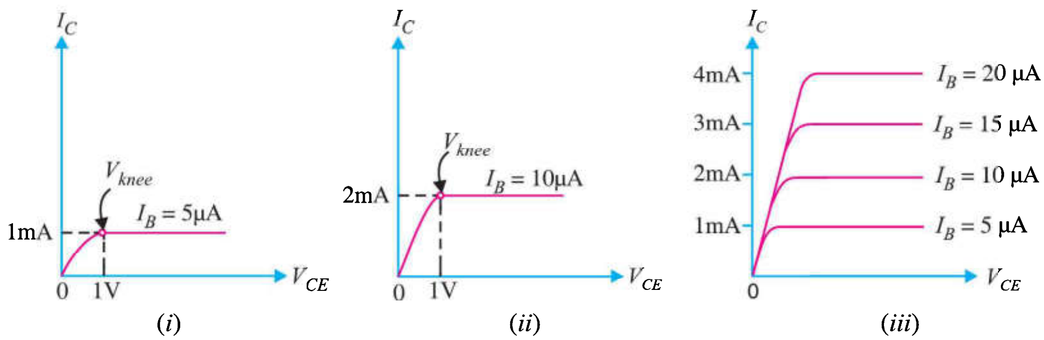

Fig. 8.31

The following points may be noted from the characteristics:

(*i*) The collector current I_C varies with V_{CE} for V_{CE} between 0 and 1 V only. After this, collector current becomes *almost* constant and independent of V_{CE}. This value of V_{CE} upto which collector current I_C changes with V_{CE} is called the *knee voltage* (V_{knee}). *The transistors are always operated in the region above knee voltage.*

(ii) Above knee voltage, I_C is almost constant. However, a small increase in I_C with increasing V_{CE} is caused by the collector depletion layer getting wider and capturing a few more majority carriers before electron-hole combinations occur in the base area.

(iii) For any value of V_{CE} above knee voltage, the collector current I_C is approximately equal to $\beta \times I_B$.

Output resistance. It is the ratio of change in collector-emitter voltage (ΔV_{CE}) to the change in collector current (ΔI_C) at constant I_B *i.e.*

$$\text{Output resistance, } r_o = \frac{\Delta V_{CE}}{\Delta I_C} \text{ at constant } I_B$$

It may be noted that whereas the output characteristics of *CB* circuit are horizontal, they have noticeable slope for the *CE* circuit. Therefore, the output resistance of a *CE* circuit is less than that of *CB* circuit. Its value is of the order of 50 kΩ.

8.13 Common Collector Connection

In this circuit arrangement, input is applied between base and collector while output is taken between the emitter and collector. Here, collector of the transistor is common to both input and output circuits and hence the name common collector connection. Fig. 8.32 (*i*) shows common collector ***npn*** transistor circuit whereas Fig. 8.32 (*ii*) shows common collector ***pnp*** circuit.

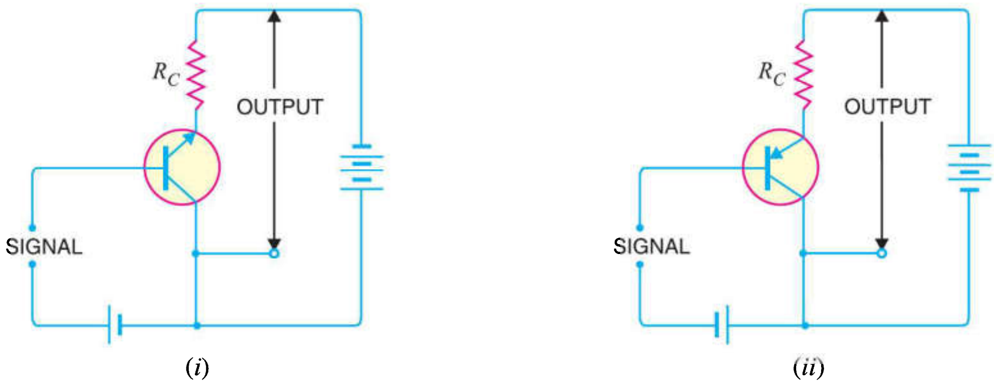

Fig. 8.32

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

The ratio of change in emitter current (ΔI_E) to the change in base current (ΔI_B) is known as **current amplification factor** *in common collector (CC) arrangement i.e.*

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

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

Relation between γ and α

$$\gamma = \frac{\Delta I_E}{\Delta I_B} \quad ...(i)$$

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

Now $$I_E = I_B + I_C$$

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

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

Substituting the value of ΔI_B in exp. (*i*), we get,

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

Dividing the numerator and denominator of R.H.S. by ΔI_E, we get,

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

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

(*ii*) Expression for collector current

We know $$I_C = \alpha I_E + I_{CBO} \qquad \text{(See Art. 8.8)}$$

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

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

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

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

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

8.14 Comparison of Transistor Connections

The comparison of various characteristics of the three connections is given below in the tabular form.

S. No.	Characteristic	Common base	Common emitter	Common collector
1.	Input resistance	Low (about 100 Ω)	Low (about 750 Ω)	Very high (about 750 kΩ)
2.	Output resistance	Very high (about 450 kΩ)	High (about 45 kΩ)	Low (about 50 Ω)
3.	Voltage gain	about 150	about 500	less than 1
4.	Applications	For high frequency applications	For audio frequency applications	For impedance matching
5.	Current gain	No (less than 1)	High (β)	Appreciable

The following points are worth noting about transistor arrangements :

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