SEMICONDUCTOR DEVICES AND CIRCUITS

8.1 Transistor

A **transistor** *consists of two pn junctions formed by *sandwiching either p-type or n-type semiconductor between a pair of opposite types.* Accordingly ; there are two types of transistors, namely;

(*i*) *n-p-n* transistor (*ii*) *p-n-p* transistor

An *n-p-n* transistor is composed of two *n*-type semiconductors separated by a thin section of *p*-type as shown in Fig. 8.1 (*i*). However, a *p-n-p* transistor is formed by two *p*-sections separated by a thin section of *n*-type as shown in Fig. 8.1 (*ii*).

Fig. 8.1

In each type of transistor, the following points may be noted :

(*i*) These are two *pn* junctions. Therefore, a transistor may be regarded as a combination of two diodes connected back to back.

(*ii*) There are three terminals, one taken from each type of semiconductor.

(*iii*) The middle section is a very thin layer. This is the most important factor in the function of a transistor.

8.2 Naming the Transistor Terminals

A transistor (*pnp* or *npn*) has three sections of doped semiconductors. The section on one side is the *emitter* and the section on the opposite side is the *collector*. The middle section is called the *base* and forms two junctions between the emitter and collector.

(*i*) Emitter. The section on one side that supplies charge carriers (electrons or holes) is called the *emitter*. *The emitter is always forward biased w.r.t. base* so that it can supply a large number of *majority carriers. In Fig. 8.2 (*i*), the emitter (*p*-type) of *pnp* transistor is forward biased and supplies hole charges to its junction with the base. Similarly, in Fig. 8.2 (*ii*), the emitter (*n*-type) of *npn* transistor has a forward bias and supplies free electrons to its junction with the base.

(*ii*) Collector. The section on the other side that collects the charges is called the *collector*. *The collector is always reverse biased.* Its function is to remove charges from its junction with the base. In Fig. 8.2 (*i*), the collector (*p*-type) of *pnp* transistor has a reverse bias and receives hole charges that flow in the output circuit. Similarly, in Fig. 8.2 (*ii*), the collector (*n*-type) of *npn* transistor has reverse bias and receives electrons.

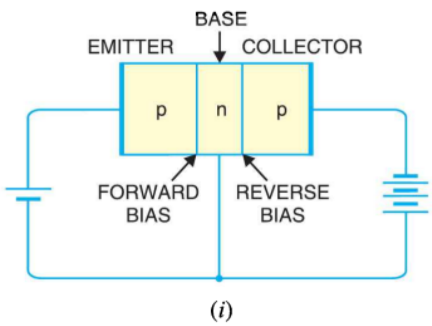
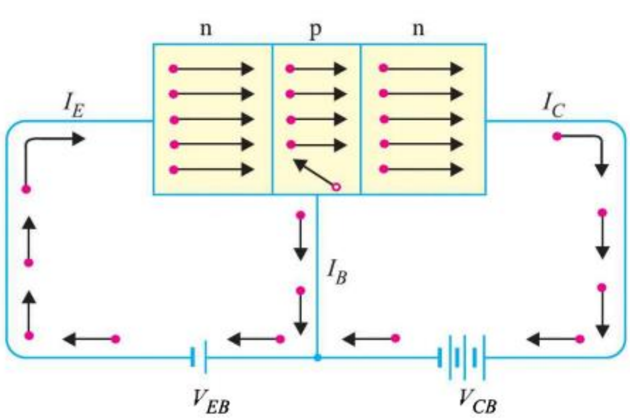


Fig. 8.2

(*iii*) Base. The middle section which forms two *pn*-junctions between the emitter and collector is called the *base*. The base-emitter junction is forward biased, allowing low resistance for the emitter circuit. The base-collector junction is reverse biased and provides high resistance in the collector circuit.

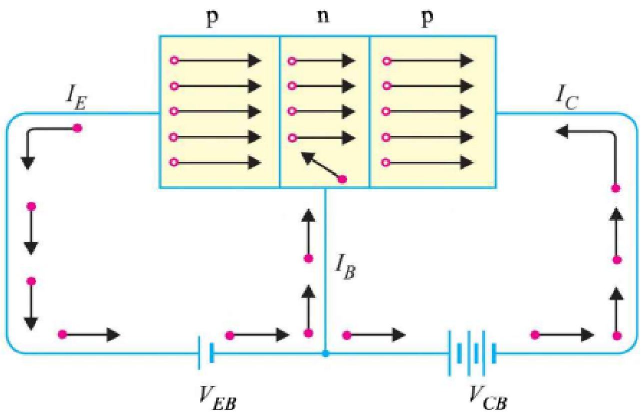
(*i*) Working of npn transistor. Fig. 8.4 shows the *npn* transistor with forward bias to emitter-base junction and reverse bias to collector-base junction. The forward bias causes the electrons in the *n*-type emitter to flow towards the base. This constitutes the emitter current I_E. As these electrons flow through the *p*-type base, they tend to combine with holes. As the base is lightly doped and very thin, therefore, only a few electrons (less than 5%) combine with holes to constitute base** current I_B. The remainder (***more than 95%) cross over into the collector region to constitute collector current I_C. In this way, almost the entire emitter current flows in the collector circuit. It is clear that emitter current is the sum of collector and base currents *i.e.*

$$I_E = I_B + I_C$$



Basic connection of *npn* transistor

(*ii*) **Working of pnp transistor.** Fig. 8.5 shows the basic connection of a *pnp* transistor. The forward bias causes the holes in the *p*-type emitter to flow towards the base. This constitutes the emitter current I_E. As these holes cross into *n*-type base, they tend to combine with the electrons. As the base is lightly doped and very thin, therefore, only a few holes (less than 5%) combine with the



Basic connection of *pnp* transistor

Fig. 8.5

electrons. The remainder (more than 95%) cross into the collector region to constitute collector current I_C. In this way, almost the entire emitter current flows in the collector circuit. It may be noted that current conduction within *pnp* transistor is by holes. However, in the external connecting wires, the current is still by electrons.

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.

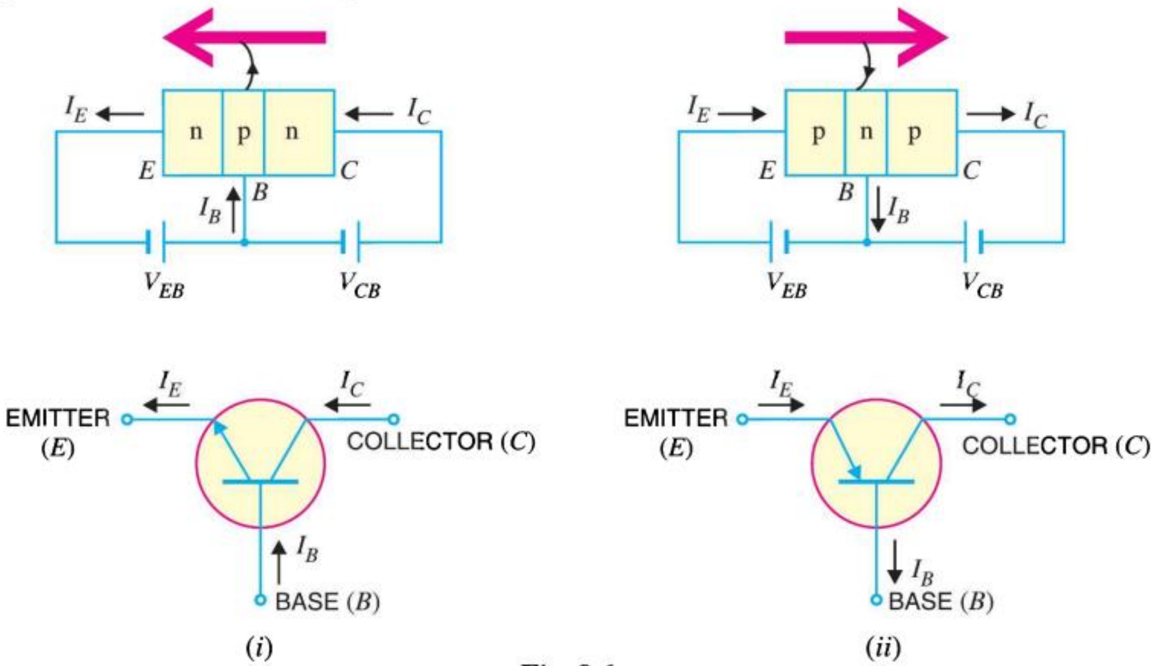


Fig. 8.6

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 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.

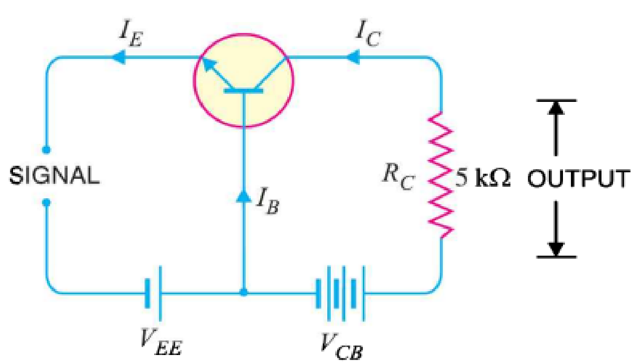


Fig. 8.7

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.

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.

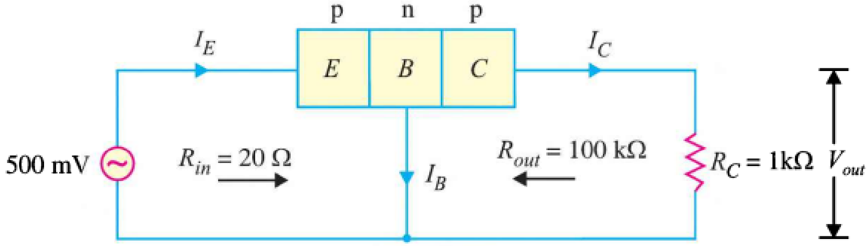


Fig. 8.8

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

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

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

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.

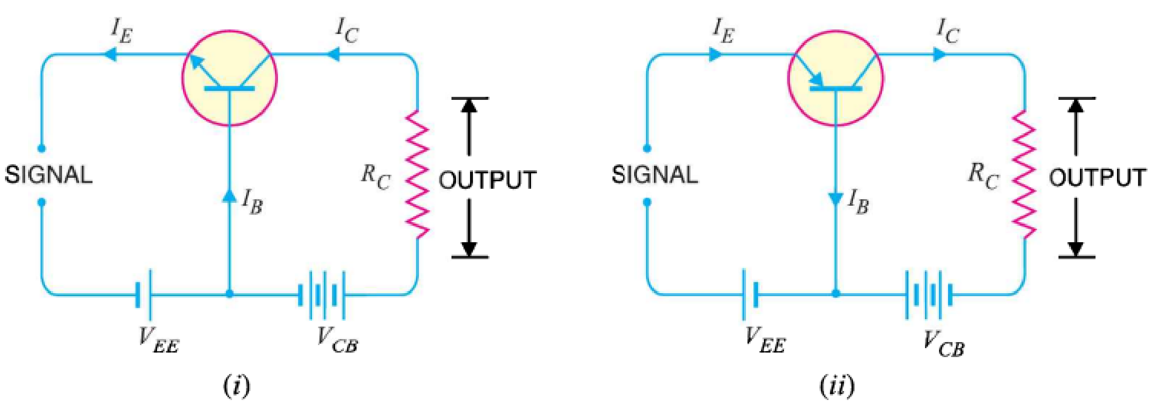
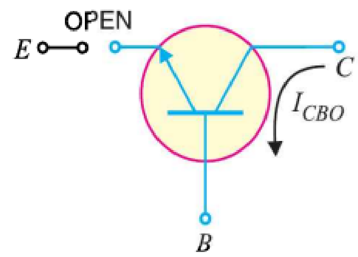


Fig. 8.9

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.*

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



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.

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.

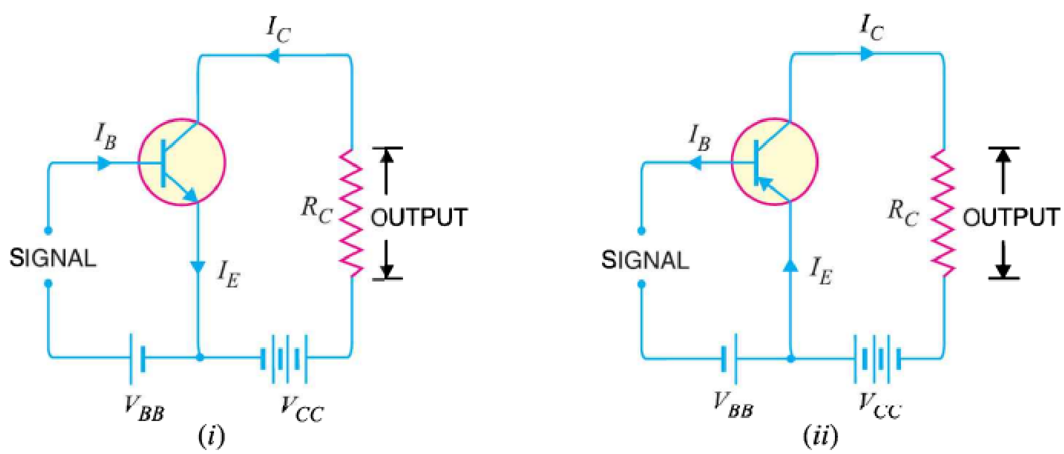


Fig. 8.16

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 :

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

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

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,

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

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

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

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

Example 8.12. *A transistor is connected in common emitter (CE) configuration in which collector supply is 8V and the voltage drop across resistance R_C connected in the collector circuit is 0.5V. The value of R_C = 800 Ω. If α = 0.96, determine :*

(i) collector-emitter voltage

(ii) base current

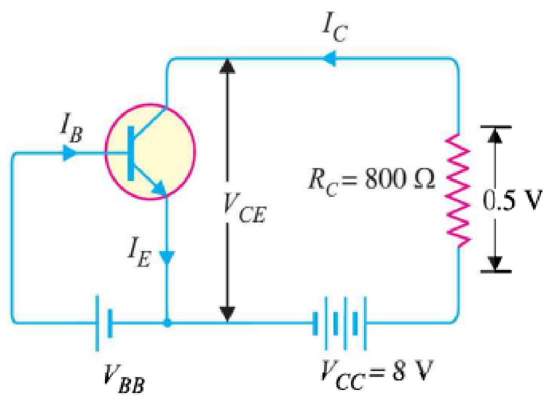


Fig. 8.22

Solution. Fig. 8.22 shows the required common emitter connection with various values.

(*i*) Collector-emitter voltage,

$$V_{CE} = V_{CC} - 0.5 = 8 - 0.5 = \mathbf{7.5\ V}$$

(***ii***) The voltage drop across R_C (= 800 Ω) is 0.5 V.

$$\therefore \quad I_C = \frac{0.5\ \text{V}}{800\ \Omega} = \frac{5}{8}\ \text{mA} = 0.625\ \text{mA}$$

Now $$\beta = \frac{\alpha}{1-\alpha} = \frac{0.96}{1-0.96} = 24$$

$$\therefore \quad \text{Base current,} \quad I_B = \frac{I_C}{\beta} = \frac{0.625}{24} = \mathbf{0.026\ mA}$$

Example 8.17 *Determine V_{CB} in the transistor * circuit shown in Fig. 8.26 (i). The transistor is of silicon and has $\beta = 150$.*

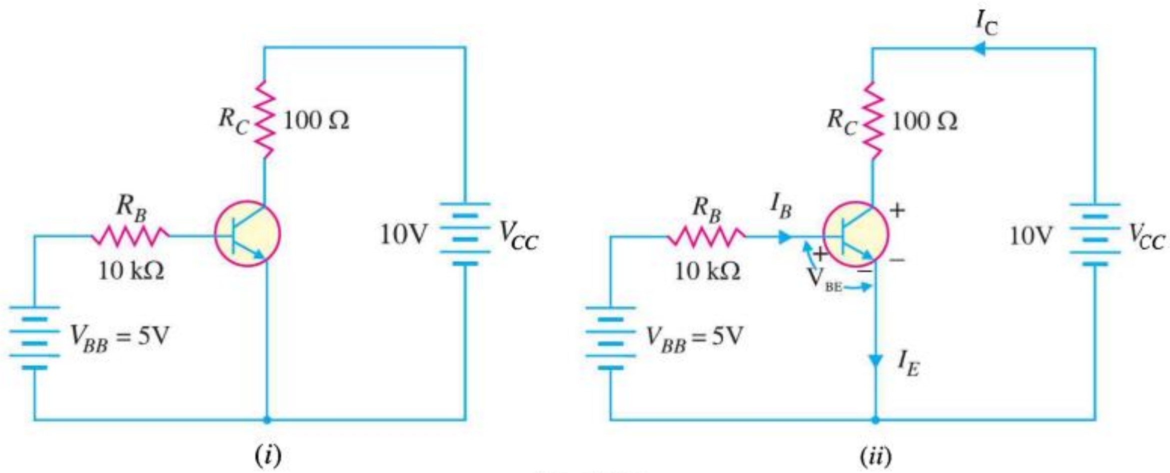


Fig. 8.26

Solution. Fig. 8.26 (*i*) shows the transistor circuit while Fig. 8.26 (*ii*) shows the various currents and voltages along with polarities.

Applying Kirchhoff's voltage law to base-emitter loop, we have,

$$V_{BB} - I_B R_B - V_{BE} = 0$$

or $$I_B = \frac{V_{BB} - V_{BE}}{R_B} = \frac{5V - 0.7V}{10\ k\Omega} = 430\ \mu A$$

∴ $$I_C = \beta I_B = (150)(430\ \mu A) = 64.5\ mA$$

Now $$V_{CE} = V_{CC} - I_C R_C$$

$$= 10V - (64.5\ mA)\ (100\Omega) = 10V - 6.45V = 3.55V$$

We know that : $$V_{CE} = V_{CB} + V_{BE}$$

∴ $$V_{CB} = V_{CE} - V_{BE} = 3.55 - 0.7 = \mathbf{2.85V}$$

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.

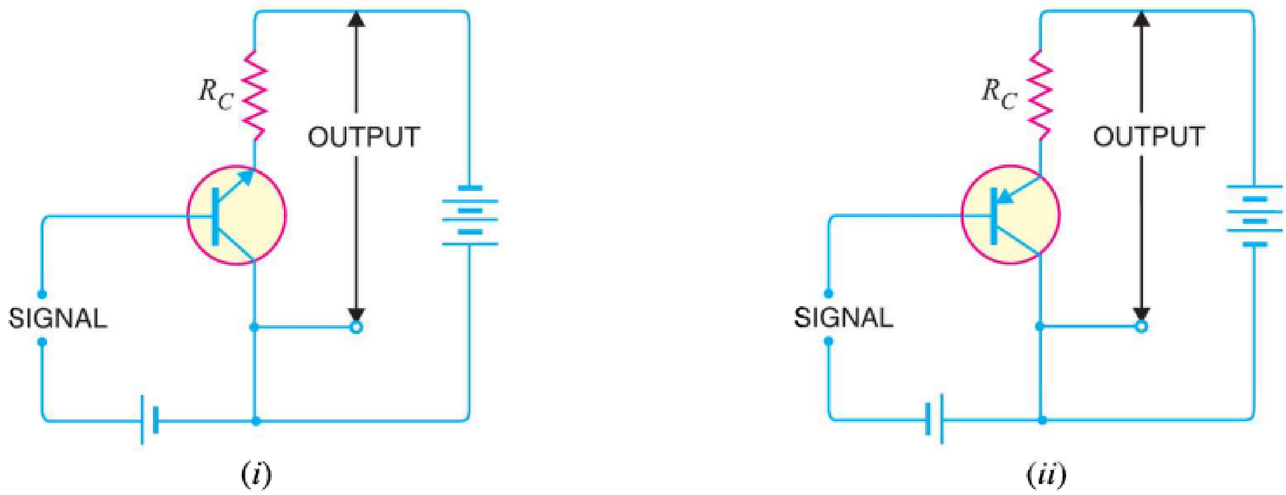


Fig. 8.32

(*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.

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,

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

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

(*iv*) Current gain. *It is the ratio of change in collector current* (ΔI_C) *to the change in base current* (ΔI_B) *i.e.*

$$\text{Current gain, } \beta = \frac{\Delta I_C}{\Delta I_B}$$

The value of β ranges from 20 to 500. The current gain indicates that input current becomes β times in the collector circuit.

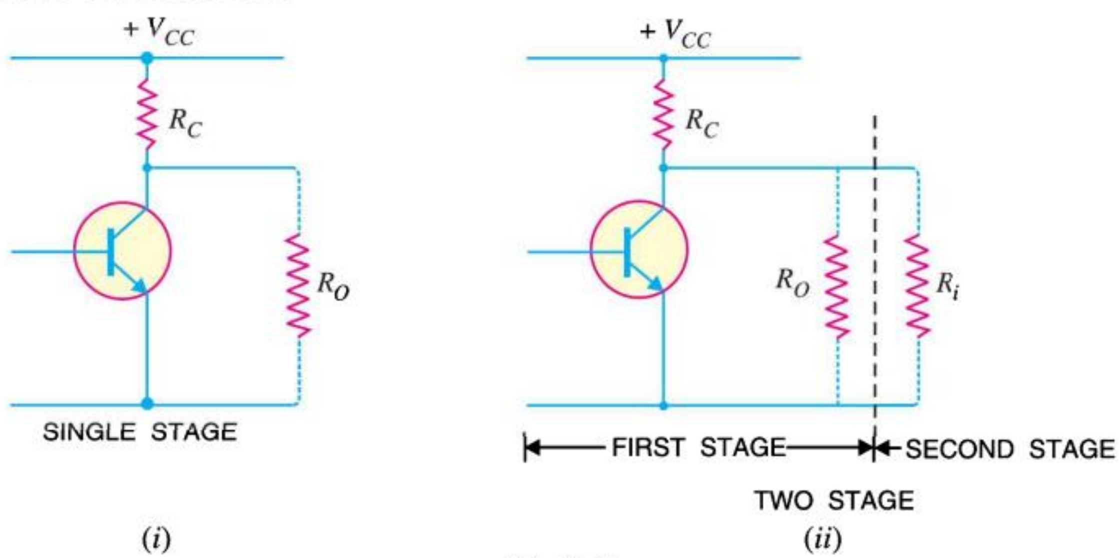


Fig. 8.48

(*v*) Voltage gain. *It is the ratio of change in output voltage* (ΔV_{CE}) *to the change in input voltage* (ΔV_{BE}) *i.e.*

$$\text{Voltage gain, } A_v = \frac{\Delta V_{CE}}{\Delta V_{BE}}$$

$$= \frac{\text{Change in output current} \times \text{effective load}}{\text{Change in input current} \times \text{input resistance}}$$

$$= \frac{\Delta I_C \times R_{AC}}{\Delta I_B \times R_i} = \frac{\Delta I_C}{\Delta I_B} \times \frac{R_{AC}}{R_i} = \beta \times \frac{R_{AC}}{R_i}$$

For single stage, $R_{AC} = R_C$. However, for multistage, $R_{AC} = \dfrac{R_C \times R_i}{R_C + R_i}$ where R_i is the input resistance of the next stage.

(*vi*) Power gain. *It is the ratio of output signal power to the input signal power i.e.*

$$\text{Power gain, } A_p = \frac{(\Delta I_C)^2 \times R_{AC}}{(\Delta I_B)^2 \times R_i} = \left(\frac{\Delta I_C}{\Delta I_B}\right) \times \frac{\Delta I_C \times R_{AC}}{\Delta I_B \times R_i}$$

$$= \text{Current gain} \times \text{Voltage gain}$$

Example 8.30. *For a single stage transistor amplifier, the collector load is* $R_C = 2k\Omega$ *and the input resistance* $R_i = 1k\Omega$. *If the current gain is 50, calculate the voltage gain of the amplifier.*

Solution. Collector load, $R_C = 2\ \text{k}\Omega$

Input resistance, $R_i = 1\ \text{k}\Omega$

Current gain, $\beta = 50$

$\therefore$ Voltage gain, $A_v = \beta \times \dfrac{R_{AC}}{R_i} = \beta \times \dfrac{R_C}{R_i}$ [$\because$ For single stage, $R_{AC} = R_C$]

$= 50 \times (2/1) = \mathbf{100}$