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 (< 1V). 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.

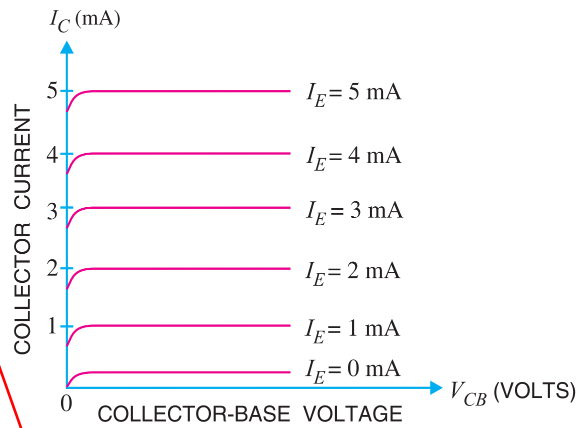

Fig. 8.15

(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.

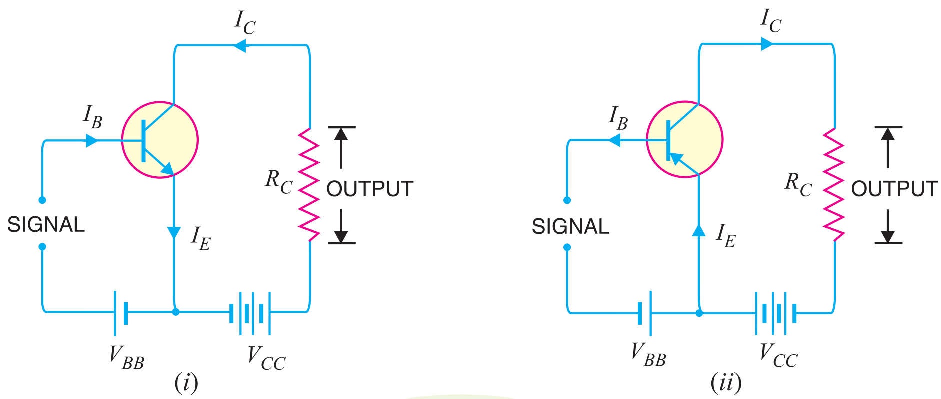

Fig. 8.16

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,

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

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

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.

$$\text{We know } I_E = I_B + I_C \quad ...(i)$$

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

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

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}.

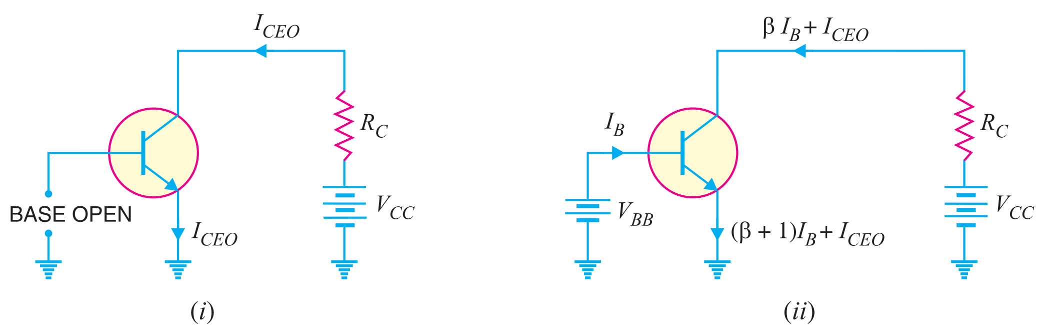

Fig. 8.17

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

$$\text{Base current} = I_B$$
$$\text{Collector current} = \beta I_B + I_{CEO}$$
$$\text{Emitter current} = \text{Collector current} + \text{Base current}$$
$$= (\beta I_B + I_{CEO}) + I_B = (\beta + 1) I_B + I_{CEO}$$

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

($I_B = 0$), the transistor is in cut off. Ideally, $I_C = 0$ but actually there is a small current from collector to emitter due to minority carriers. It is called I_{CEO} (collector-to-emitter current with base open). This current is usually in the nA range for silicon. A faulty transistor will often have excessive leakage current.

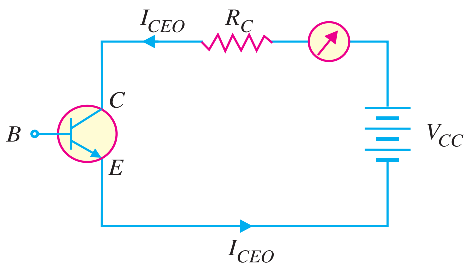

Fig. 8.18

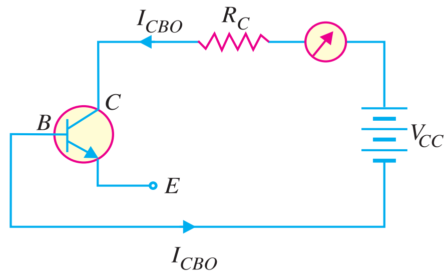

Fig. 8.19

(*ii*) Circuit for I_{CBO} test. Fig. 8.19 shows the circuit for measuring I_{CBO}. Since the emitter is open ($I_E = 0$), there is a small current from collector to base. This is called I_{CBO} (collector-to-base current with emitter open). This current is due to the movement of minority carriers across base-collector junction. The value of I_{CBO} is also small. If in measurement, I_{CBO} is excessive, then there is a possibility that collector-base is shorted.

Example 8.8. *Find the value of β if (i) α = 0.9 (ii) α = 0.98 (iii) α = 0.99.*

Solution. (*i*) $$\beta = \frac{\alpha}{1-\alpha} = \frac{0.9}{1-0.9} = \mathbf{9}$$

(*ii*) $$\beta = \frac{\alpha}{1-\alpha} = \frac{0.98}{1-0.98} = \mathbf{49}$$

(*iii*) $$\beta = \frac{\alpha}{1-\alpha} = \frac{0.99}{1-0.99} = \mathbf{99}$$

Example 8.9. *Calculate I_E in a transistor for which β = 50 and I_B = 20 μA.*

Solution. Here $\beta = 50, \quad I_B = 20\mu A = 0.02$ mA

Now $$\beta = \frac{I_C}{I_B}$$

$$\therefore \quad I_C = \beta I_B = 50 \times 0.02 = 1 \text{ mA}$$

Using the relation, $$I_E = I_B + I_C = 0.02 + 1 = \mathbf{1.02\ mA}$$

Example 8.10. *Find the α rating of the transistor shown in Fig. 8.20. Hence determine the value of I_C using both α and β rating of the transistor.*

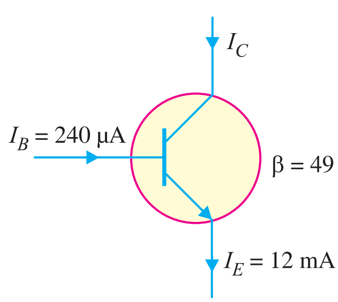

Fig. 8.20

Solution. Fig. 8.20 shows the conditions of the problem.

$$\alpha = \frac{\beta}{1+\beta} = \frac{49}{1+49} = \mathbf{0.98}$$

The value of I_C can be found by using either α or β rating as under :

$$I_C = \alpha I_E = 0.98 \text{ (12 mA)} = \mathbf{11.76\ mA}$$

Also $$I_C = \beta I_B = 49 \text{ (240 μA)} = \mathbf{11.76\ mA}$$

Example 8.11. *For a transistor, β = 45 and voltage drop across 1kΩ which is connected in the collector circuit is 1 volt. Find the base current for common emitter connection.*

Solution. Fig. 8.21 shows the required common emitter connection. The voltage drop across R_C (= 1 kΩ) is 1volt.

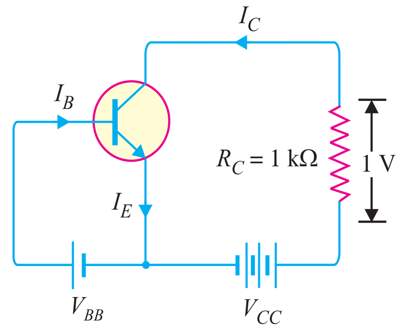

Fig. 8.21

$$\therefore \qquad I_C = \frac{1\ V}{1\ k\Omega} = 1\ mA$$

$$\text{Now} \qquad \beta = \frac{I_C}{I_B}$$

$$\therefore \qquad I_B = \frac{I_C}{\beta} = \frac{1}{45} = \mathbf{0.022\ mA}$$

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

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

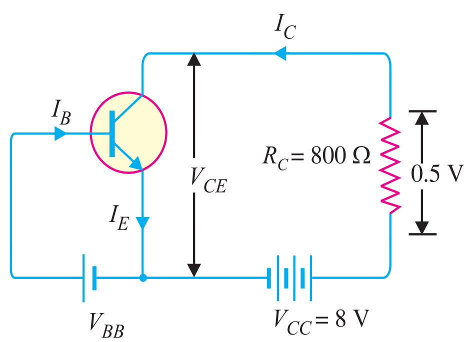

Fig. 8.22

(*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.

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

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

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

Example 8.13. *An n-p-n transistor at room temperature has its emitter disconnected. A voltage of 5V is applied between collector and base. With collector positive, a current of 0.2 µA flows. When the base is disconnected and the same voltage is applied between collector and emitter, the current is found to be 20 µA. Find α, I_E and I_B when collector current is 1mA.*

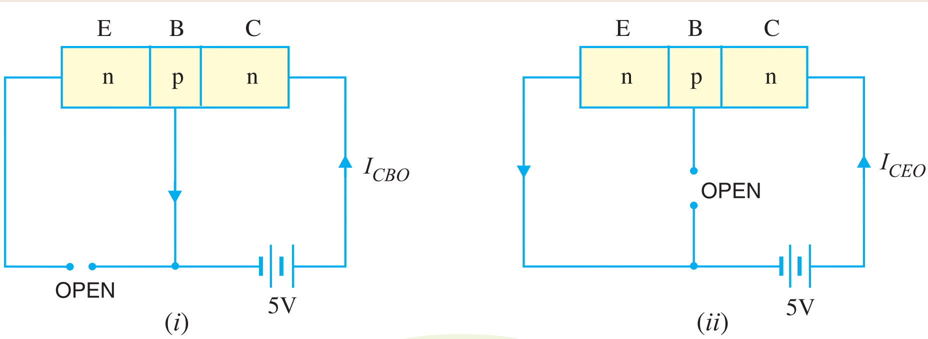

Fig. 8.23

Solution. When the emitter circuit is open [See Fig. 8.23 (*i*)], the collector-base junction is reverse biased. A small leakage current I_{CBO} flows due to minority carriers.

$\therefore \quad I_{CBO} = 0.2\ \mu A$ ...*given*

When base is open [See Fig. 8.23 (*ii*)], a small leakage current I_{CEO} flows due to minority carriers.

$\therefore \quad I_{CEO} = 20\ \mu A$ . . . *given*

We know $\quad I_{CEO} = \dfrac{I_{CBO}}{1-\alpha}$

or $\quad 20 = \dfrac{0.2}{1-\alpha}$

$\therefore \quad \alpha = \mathbf{0.99}$

Now $\quad I_C = \alpha I_E + I_{CBO}$

Here $\quad I_C = 1\text{mA} = 1000\ \mu A\ ;\ \alpha = 0.99\ ;\ I_{CBO} = 0.2\ \mu A$

$\therefore \quad 1000 = 0.99 \times I_E + 0.2$

or $\quad I_E = \dfrac{1000 - 0.2}{0.99} = \mathbf{1010\ \mu A}$

and $\quad I_B = I_E - I_C = 1010 - 1000 = \mathbf{10\ \mu A}$

Example 8.14. *The collector leakage current in a transistor is 300 μA in CE arrangement. If now the transistor is connected in CB arrangement, what will be the leakage current? Given that β = 120.*

Solution. $\quad I_{CEO} = 300\ \mu A$

$$\beta = 120\ ;\ \alpha = \frac{\beta}{\beta+1} = \frac{120}{120+1} = 0.992$$

Now, $\quad I_{CEO} = \dfrac{I_{CBO}}{1-\alpha}$

$\therefore \quad I_{CBO} = (1-\alpha)\, I_{CEO} = (1 - 0.992) \times 300 = \mathbf{2.4\ \mu A}$

Note that leakage current in *CE* arrangement (*i.e.* I_{CEO}) is much more than in *CB* arrangement (*i.e.* I_{CBO}).

Example 8.15. *For a certain transistor, I_B = 20 μA; I_C = 2 mA and β = 80. Calculate I_{CBO}.*

Solution.

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

or $\quad 2 = 80 \times 0.02 + I_{CEO}$

$\therefore \quad I_{CEO} = 2 - 80 \times 0.02 = 0.4\ \text{mA}$

Now $\quad \alpha = \dfrac{\beta}{\beta+1} = \dfrac{80}{80+1} = 0.988$

$\therefore \quad I_{CBO} = (1-\alpha)\, I_{CEO} = (1 - 0.988) \times 0.4 = \mathbf{0.0048\ mA}$

Example 8.16. *Using diagrams, explain the correctness of the relation $I_{CEO} = (\beta + 1)\, I_{CBO}$.*

Solution. The leakage current I_{CBO} is the current that flows through the base-collector junction when emitter is open as shown is Fig. 8.24. When the transistor is in *CE* arrangement, the *base current (*i.e.* I_{CBO}) is multiplied by β in the collector as shown in Fig. 8.25.

$\therefore \quad I_{CEO} = I_{CBO} + \beta I_{CBO} = (\beta + 1)\, I_{CBO}$

* The current I_{CBO} is amplified because it is forced to flow across the base-emitter junction.

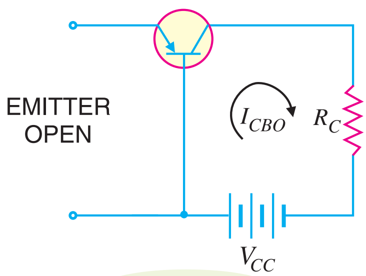

Fig. 8.24

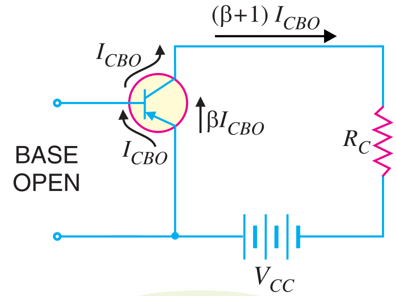

Fig. 8.25

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

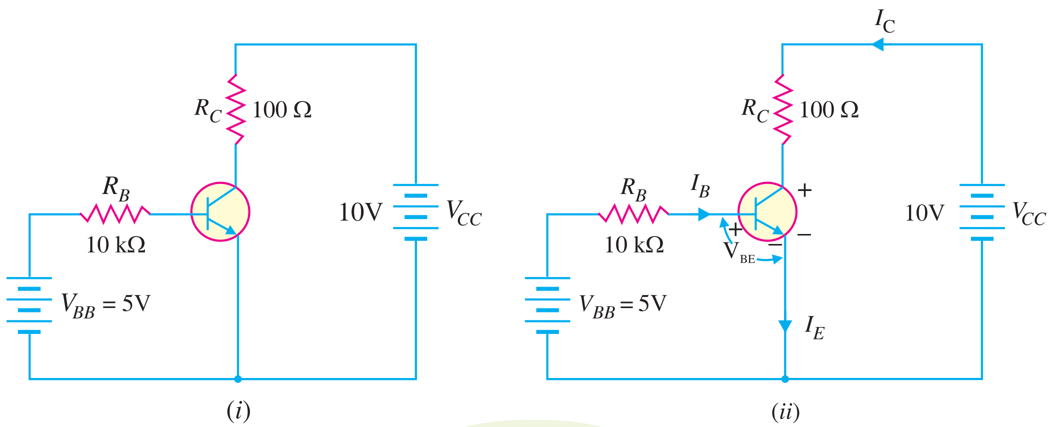

Fig. 8.26

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

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

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

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

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

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

Example 8.18. *In a transistor, I_B = 68 μA, I_E = 30 mA and β = 440. Determine the α rating of the transistor. Then determine the value of I_C using both the α rating and β rating of the transistor.*

Solution.

$$\alpha = \frac{\beta}{\beta+1} = \frac{440}{440+1} = \mathbf{0.9977}$$

* The resistor R_B controls the base current I_B and hence collector current I_C (= βI_B). If R_B is increased, the base current (I_B) decreases and hence collector current (I_C) will decrease and vice-versa.

$$I_C = \alpha\, I_E = (0.9977)\,(30\text{ mA}) = \textbf{29.93 mA}$$

Also $$I_C = \beta\, I_B = (440)\,(68\ \mu\text{A}) = \textbf{29.93 mA}$$

Example 8.19. *A transistor has the following ratings : $I_{C\,(max)}$ = 500 mA and β_{max} = 300. Determine the maximum allowable value of I_B for the device.*

Solution.

$$I_{B\,(max)} = \frac{I_{C\,(max)}}{\beta_{max}} = \frac{500\text{ mA}}{300} = \textbf{1.67 mA}$$

For this transistor, if the base current is allowed to exceed 1.67 mA, the collector current will exceed its maximum rating of 500 mA and the transistor will probably be destroyed.

Example 8.20. *Fig. 8.27 shows the open circuit failures in a transistor. What will be the circuit behaviour in each case ?*

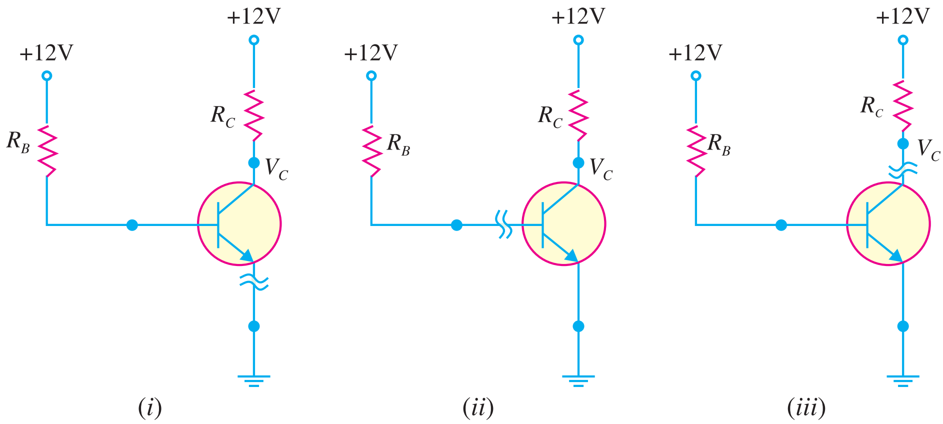

Fig. 8.27

Solution. *Fig 8.27 shows the open circuit failures in a transistor. We shall discuss the circuit behaviour in each case.

(*i*) Open emitter. Fig. 8.27 (*i*) shows an open emitter failure in a transistor. Since the collector diode is not forward biased, it is *OFF* and there can be neither collector current nor base current. Therefore, there will be no voltage drops across either resistor and the voltage at the base and at the collector leads of the transistor will be 12V.

(*ii*) Open-base. Fig. 8.27 (*ii*) shows an open base failure in a transistor. Since the base is open, there can be no base current so that the transistor is in *cut-off*. Therefore, all the transistor currents are 0A. In this case, the base and collector voltages will both be at 12V.

Note. It may be noted that an open failure at either the base or emitter will produce similar results.

(*iii*) Open collector. Fig. 8.27 (*iii*) shows an open collector failure in a transistor. In this case, the emitter diode is still *ON*, so we expect to see 0.7V at the base. However, we will see 12V at the collector because there is no collector current.

Example 8.21. *Fig. 8.28 shows the short circuit failures in a transistor. What will be the circuit behaviour in each case ?*

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* The collector resistor R_C controls the collector voltage V_C ($= V_{CC} - I_C R_C$). When R_C increases, V_C decreases and vice-versa.

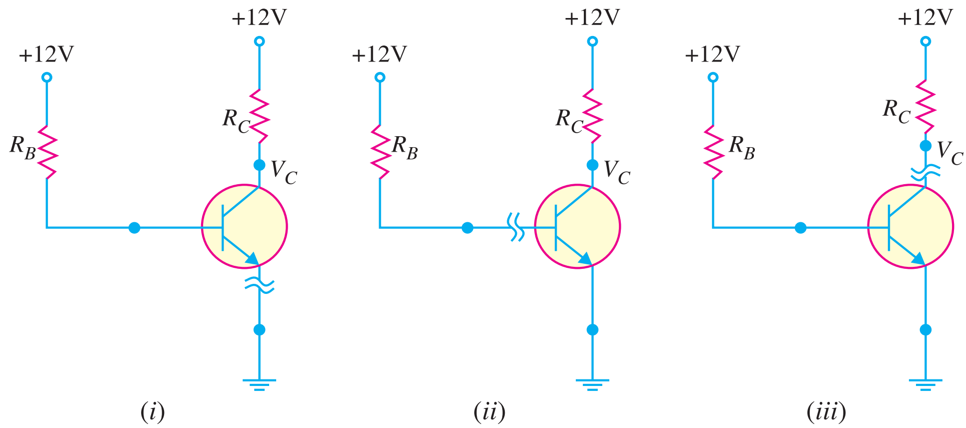


Fig. 8.28

Solution. Fig. 8.28 shows the short circuit failures in a transistor. We shall discuss the circuit behaviour in each case.

(i) **Collector-emitter short.** Fig. 8.28 (*i*) shows a short between collector and emitter. The emitter diode is still forward biased, so we expect to see 0.7V at the base. Since the collector is shorted to the emitter, $V_C = V_E = 0V$.

(ii) **Base -emitter short.** Fig 8.28 (*ii*) shows a short between base and emitter. Since the base is now directly connected to ground, $V_B = 0$. Therefore, the current through R_B will be diverted to ground and there is no current to forward bias the emitter diode. As a result, the transistor will be *cut-off* and there is no collector current. So we will expect the collector voltage to be 12V.

(iii) **Collector-base short.** Fig. 8.28 (*iii*) shows a short between the collector and the base. In this case, the emitter diode is still forward biased so $V_B = 0.7V$. Now, however, because the collector is shorted to the base, $V_C = V_B = 0.7V$.

Note. The collector-emitter short is probably the most common type of fault in a transistor. It is because the collector current (I_C) and collector-emitter voltage (V_{CE}) are responsible for the major part of the power dissipation in the transistor. As we shall see (See Art. 8.23), the power dissipation in a transistor is mainly due to I_C and V_{CE} (*i.e.* $P_D = V_{CE} I_C$). Therefore, the transistor chip between the collector and the emitter is most likely to melt first.

8.12 Characteristics of Common Emitter Connection

The important characteristics of this circuit arrangement are the *input characteristics* and *output characteristics.*

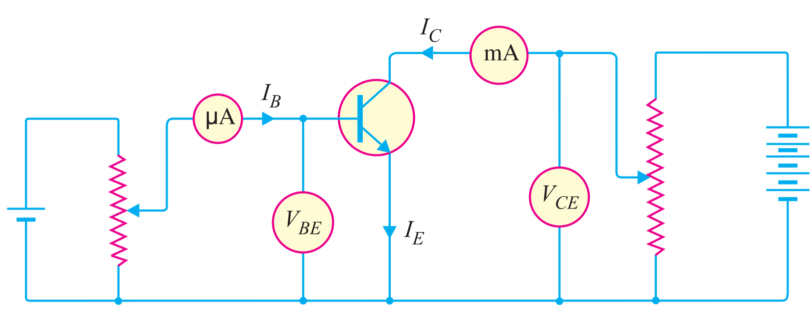


Fig. 8.29

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 :

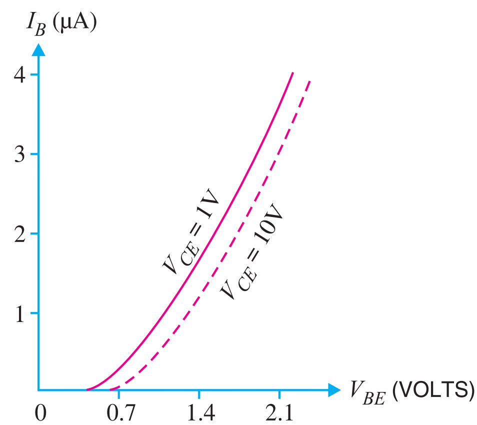


Fig. 8.30

(*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.

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*).

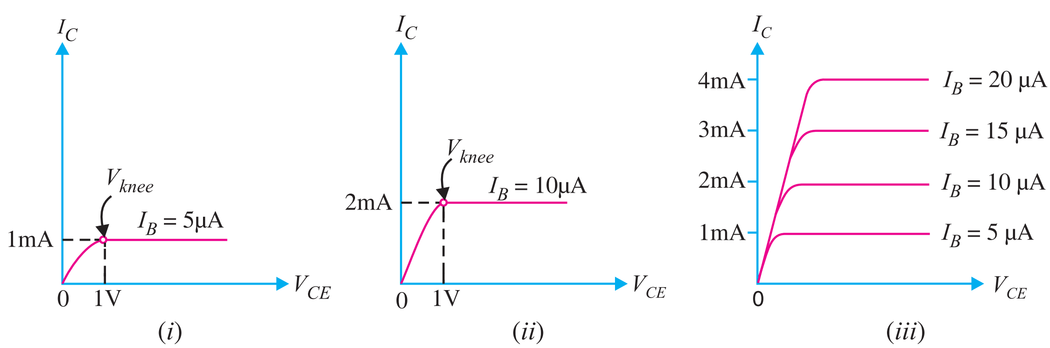


Fig. 8.31

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 1V 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.

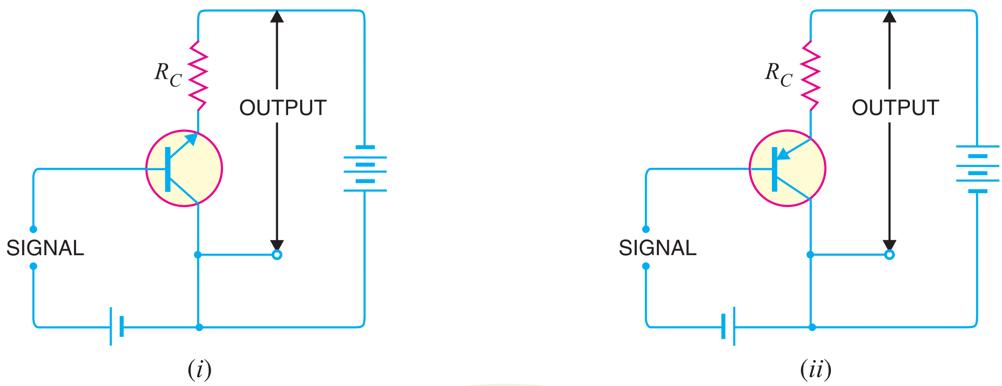


Fig. 8.32

(*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

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

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

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,

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

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

(*ii*) Expression for collector current

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

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

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

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 :

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

(*i*) CB Circuit. The input resistance (r_i) of *CB* circuit is low because I_E is high. The output resistance (r_o) is high because of reverse voltage at the collector. It has no current gain ($\alpha < 1$) but voltage gain can be high. The *CB* circuit is seldom used. The only advantage of *CB* circuit is that it provides good stability against increase in temperature.

(*ii*) CE Circuit. The input resistance (r_i) of a *CE* circuit is high because of small I_B. Therefore, r_i for a *CE* circuit is much higher than that of *CB* circuit. The output resistance (r_o) of *CE* circuit is smaller than that of *CB* circuit. The current gain of *CE* circuit is large because I_C is much larger than I_B. The voltage gain of *CE* circuit is larger than that of *CB* circuit. The *CE* circuit is generally used because it has the best combination of voltage gain and current gain. The disadvantage of *CE* circuit is that the leakage current is amplified in the circuit, but bias stabilisation methods can be used.

(*iii*) CC Circuit. The input resistance (r_i) and output resistance (r_o) of *CC* circuit are respectively high and low as compared to other circuits. There is no voltage gain ($A_v < 1$) in a *CC* circuit. This circuit is often used for impedance matching.

8.15 Commonly Used Transistor Connection

Out of the three transistor connections, the common emitter circuit is the most efficient. It is used in about 90 to 95 per cent of all transistor applications. The main reasons for the widespread use of this circuit arrangement are :

(*i*) High current gain. In a common emitter connection, I_C is the output current and I_B is the input current. In this circuit arrangement, collector current is given by :

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

As the value of β is very large, therefore, the output current I_C is much more than the input current I_B. Hence, the current gain in *CE* arrangement is very high. It may range from 20 to 500.

(*ii*) High voltage and power gain. Due to high current gain, the common emitter circuit has the highest voltage and power gain of three transistor connections. This is the major reason for using the transistor in this circuit arrangement.

(*iii*) Moderate output to input impedance ratio. In a common emitter circuit, the ratio of output impedance to input impedance is small (about 50). This makes this circuit arrangement an ideal one for coupling between various transistor stages. However, in other connections, the ratio of output impedance to input impedance is very large and hence coupling becomes highly inefficient due to gross mismatching.

8.16 Transistor as an Amplifier in *CE* Arrangement

Fig. 8.33 shows the common emitter *npn* amplifier circuit. Note that a battery V_{BB} is connected in the input circuit in addition to the signal voltage. This d.c. voltage is known as *bias voltage* and its magnitude is such that it always keeps the emitter-base junction forward *biased regardless of the polarity of the signal source.

Operation. During the positive half-cycle of the **signal, the forward bias across the emitter-base junction is increased. Therefore, more electrons flow from the emitter to the collector *via* the base. This causes an increase in collector current. The increased collector current produces a greater voltage drop across the collector load resistance R_C. However, during the negative half-cycle of the

* If d.c. bias voltage is not provided, then during negative half-cycle of the signal, the emitter-base junction will be reverse biased. This will upset the transistor action.

** Throughout the book, we shall use sine wave signals because these are convenient for testing amplifiers. But it must be realised that signals (*e.g.* speech, music etc.) with which we work are generally complex having little resemblance to a sine wave. However, fourier series analysis tells us that such complex signals may be expressed as a sum of sine waves of various frequencies.

signal, the forward bias across emitter-base junction is decreased. Therefore, collector current decreases. This results in the decreased output voltage (in the opposite direction). Hence, an amplified output is obtained across the load.

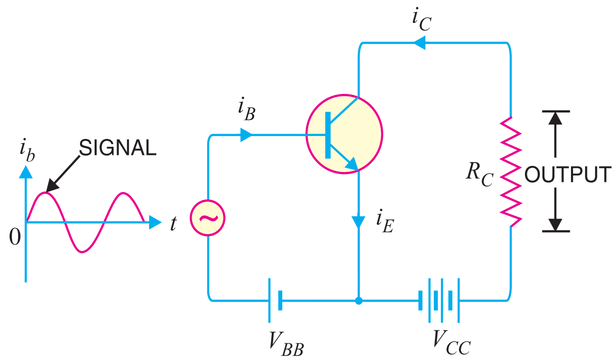


Fig. 8.33

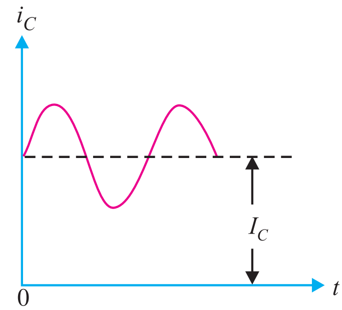


Fig. 8.34

Analysis of collector currents. When no signal is applied, the input circuit is forward biased by the battery V_{BB}. Therefore, a d.c. collector current I_C flows in the collector circuit. This is called *zero signal collector current*. When the signal voltage is applied, the forward bias on the emitter-base junction increases or decreases depending upon whether the signal is positive or negative. During the positive half-cycle of the signal, the forward bias on emitter-base junction is increased, causing total collector current i_C to increase. Reverse will happen for the negative half-cycle of the signal.

Fig. 8.34 shows the graph of total collector current i_C versus time. From the graph, it is clear that total collector current consists of two components, namely ;

(i) The d.c. collector current I_C (zero signal collector current) due to bias battery V_{BB}. This is the current that flows in the collector in the absence of signal.

(ii) The a.c. collector current i_c due to signal.

$\therefore$ Total collector current, $i_C = i_c + I_C$

The useful output is the voltage drop across collector load R_C due to the a.c. component i_c. The purpose of zero signal collector current is to ensure that the emitter-base junction is forward biased at all times. The table below gives the symbols usually employed for currents and voltages in transistor applications.

S. No.	Particular	Instantaneous a.c.	d.c.	Total
1.	Emitter current	i_e	I_E	i_E
2.	Collector current	i_c	I_C	i_C
3.	Base current	i_b	I_B	i_B
4.	Collector-emitter voltage	v_{ce}	V_{CE}	v_{CE}
5.	Emitter-base voltage	v_{eb}	V_{EB}	v_{EB}

8.17 Transistor Load Line Analysis

In the transistor circuit analysis, it is generally required to determine the collector current for various collector-emitter voltages. One of the methods can be used to plot the output characteristics and determine the collector current at any desired collector-emitter voltage. However, a more convenient method, known as *load line method* can be used to solve such problems. As explained later in this section, this method is quite easy and is frequently used in the analysis of transistor applications.

d.c. load line. Consider a common emitter *npn* transistor circuit shown in Fig. 8.35 (*i*) where no signal is applied. Therefore, d.c. conditions prevail in the circuit. The output characteristics of this circuit are shown in Fig. 8.35 (*ii*).

The value of collector-emitter voltage V_{CE} at any time is given by ;

$$V_{CE} = V_{CC} - I_C R_C \qquad ...(i)$$

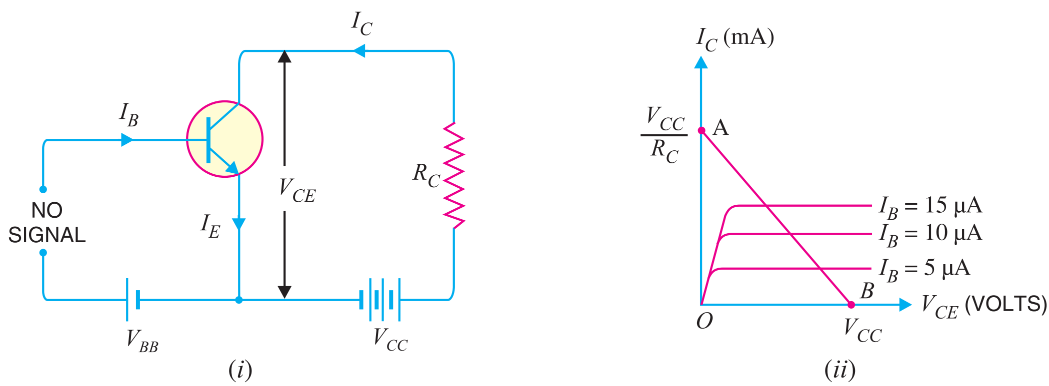


Fig. 8.35

As V_{CC} and R_C are fixed values, therefore, it is a first degree equation and can be represented by a straight line on the output characteristics. This is known as *d.c. load line* and determines the locus of $V_{CE} - I_C$ points for any given value of R_C. To add load line, we need two end points of the straight line. These two points can be located as under :

(*i*) When the collector current $I_C = 0$, then collector-emitter voltage is maximum and is equal to V_{CC} *i.e.*

$$\text{Max. } V_{CE} = V_{CC} - I_C R_C$$
$$= V_{CC} \qquad (\because I_C = 0)$$

This gives the first point B ($OB = V_{CC}$) on the collector-emitter voltage axis as shown in Fig. 8.35 (*ii*).

(*ii*) When collector-emitter voltage $V_{CE} = 0$, the collector current is maximum and is equal to V_{CC}/R_C *i.e.*

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

or $$0 = V_{CC} - I_C R_C$$

$\therefore$ $$\text{Max. } I_C = V_{CC}/R_C$$

This gives the second point A ($OA = V_{CC}/R_C$) on the collector current axis as shown in Fig. 8.35 (*ii*). By joining these two points, d.c. *load line AB is constructed.

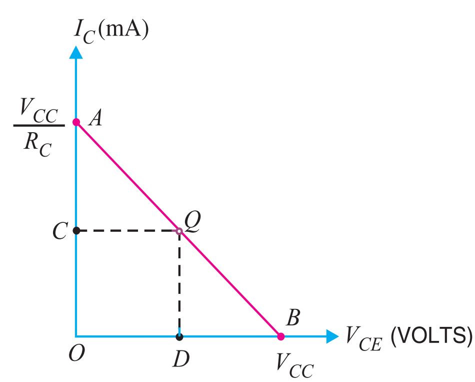


Fig. 8.36

Importance. The current (I_C) and voltage (V_{CE}) conditions in the transistor circuit are represented by some point on the output characteristics. The same information can be obtained from the load line. Thus when I_C is maximum (= V_{CC}/R_C), then $V_{CE} = 0$ as shown in Fig. 8.36. If $I_C = 0$, then V_{CE} is maximum

* **Why load line ?** The resistance R_C connected to the device is called load or load resistance for the circuit and, therefore, the line we have just constructed is called the load line.

and is equal to V_{CC}. For any other value of collector current say OC, the collector-emitter voltage V_{CE} = OD. It follows, therefore, that load line gives a far more convenient and direct solution to the problem.

Note. If we plot the load line on the output characteristic of the transistor, we can investigate the behaviour of the transistor amplifier. It is because we have the transistor output current and voltage specified in the form of load line equation and the transistor behaviour itself specified implicitly by the output characteristics.

8.18 Operating Point

The zero signal values of I_C and V_{CE} are known as the **operating point**.

It is called operating point because the variations of I_C and V_{CE} take place about this point when signal is applied. It is also called quiescent (silent) point or *Q-point* because it is the point on $I_C - V_{CE}$ characteristic when the transistor is silent *i.e.* in the absence of the signal.

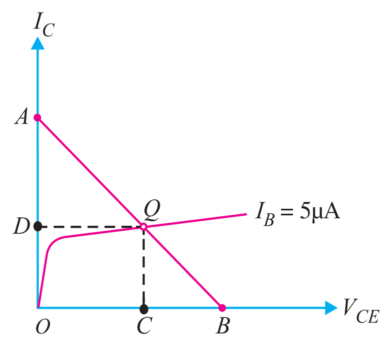


Fig. 8.37

Suppose in the absence of signal, the base current is 5 μA. Then I_C and V_{CE} conditions in the circuit must be represented by some point on I_B = 5 μA characteristic. But I_C and V_{CE} conditions in the circuit should also be represented by some point on the d.c. load line AB. The point Q where the load line and the characteristic intersect is the only point which satisfies both these conditions. Therefore, the point Q describes the actual state of affairs in the circuit in the zero signal conditions and is called the operating point. Referring to Fig. 8.37, for I_B = 5 μA, the zero signal values are :

$$V_{CE} = OC \text{ volts}$$
$$I_C = OD \text{ mA}$$

It follows, therefore, that the zero signal values of I_C and V_{CE} (*i.e.* operating point) are determined by the point where d.c. load line intersects the proper base current curve.

Example 8.22. *For the circuit shown in Fig. 8.38 (i), draw the d.c. load line.*

Solution. The collector-emitter voltage V_{CE} is given by ;

$$V_{CE} = V_{CC} - I_C R_C \quad \text{...(}i\text{)}$$

When $I_C = 0$, then,

$$V_{CE} = V_{CC} = 12.5 \text{ V}$$

This locates the point B of the load line on the collector-emitter voltage axis.

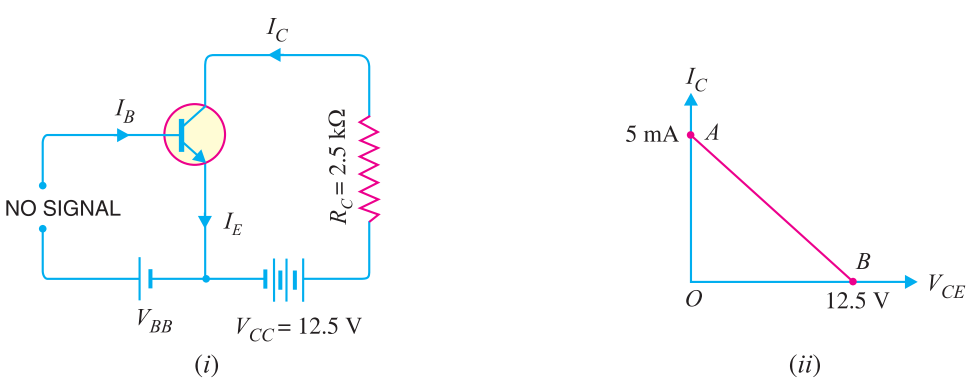


Fig. 8.38

$$\text{When} \quad V_{CE} = 0, \text{ then,}$$
$$I_C = V_{CC}/R_C = 12.5 \text{ V}/2.5 \text{ k}\Omega = 5 \text{ mA}$$

This locates the point *A* of the load line on the collector current axis. By joining these two points, we get the d.c. load line *AB* as shown in Fig. 8.38 (*ii*).

Example 8.23. *In the circuit diagram shown in Fig. 8.39 (i), if V_{CC} = 12V and R_C = 6 kΩ, draw the d.c. load line. What will be the Q point if zero signal base current is 20μA and β = 50 ?*

Solution. The collector-emitter voltage V_{CE} is given by :

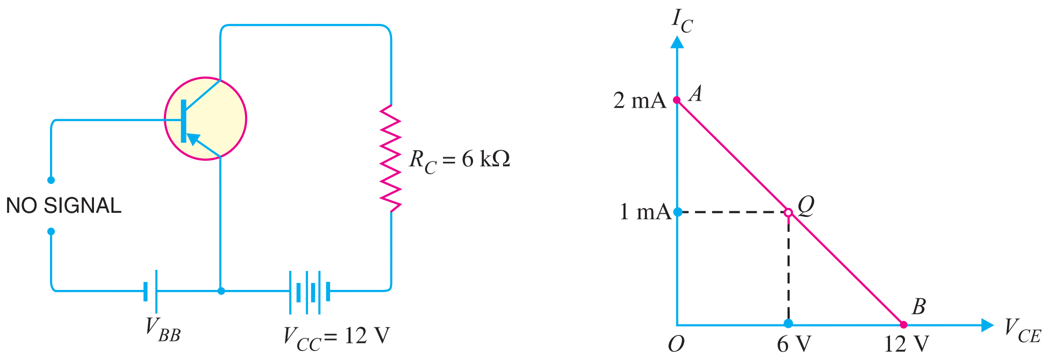
$$V_{CE} = V_{CC} - I_C R_C$$

When $I_C = 0$, $V_{CE} = V_{CC} = 12$ V. This locates the point *B* of the load line. When $V_{CE} = 0$, $I_C = V_{CC}/R_C = 12 \text{ V}/6 \text{ k}\Omega = 2$ mA. This locates the point *A* of the load line. By joining these two points, load line *AB* is constructed as shown in Fig. 8.39 (*ii*).

Zero signal base current, $I_B = 20\ \mu\text{A} = 0.02$ mA

Current amplification factor, $\beta = 50$

∴ Zero signal collector current, $I_C = \beta I_B = 50 \times 0.02 = 1$ mA



(*i*) (*ii*)

Fig. 8.39

Zero signal collector-emitter voltage is

$$V_{CE} = V_{CC} - I_C R_C = 12 - 1 \text{ mA} \times 6 \text{ k}\Omega = 6 \text{ V}$$

∴ Operating point is **6 V, 1 mA**.

Fig. 8.39 (*ii*) shows the *Q* point. Its co-ordinates are $I_C = 1$ mA and $V_{CE} = 6$ V.

Example 8.24. *In a transistor circuit, collector load is 4 kΩ whereas quiescent current (zero signal collector current) is 1mA.*

(i) What is the operating point if V_{CC} = 10 V ?

(ii) What will be the operating point if R_C = 5 kΩ ?

Solution. $V_{CC} = 10$ V, $I_C = 1$ mA

(*i*) When collector load $R_C = 4 \text{ k}\Omega$, then,

$$V_{CE} = V_{CC} - I_C R_C = 10 - 1 \text{ mA} \times 4 \text{ k}\Omega = 10 - 4 = 6 \text{ V}$$

∴ Operating point is **6 V, 1 mA.**

(*ii*) When collector load $R_C = 5 \text{ k}\Omega$, then,

$$V_{CE} = V_{CC} - I_C R_C = 10 - 1 \text{ mA} \times 5 \text{ k}\Omega = 10 - 5 = 5 \text{ V}$$

∴ Operating point is **5 V, 1 mA.**

Example 8.25. *Determine the Q point of the transistor circuit shown in Fig. 8.40. Also draw the d.c. load line. Given β = 200 and V_{BE} = 0.7V.*

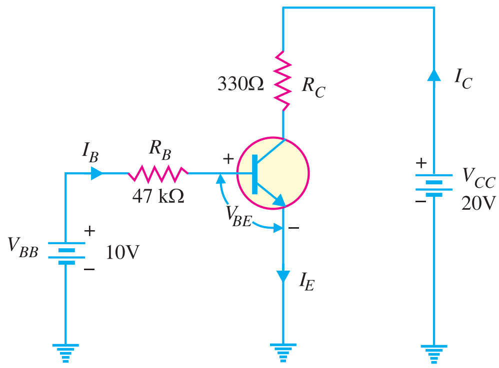


Fig 8.40

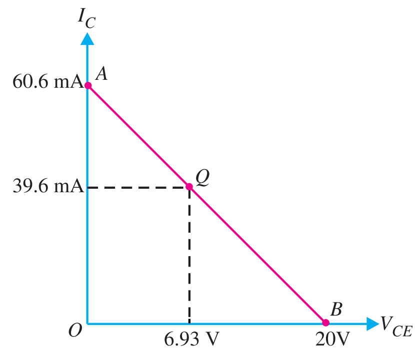


Fig. 8.41

Solution. The presence of resistor R_B in the base circuit should not disturb you because we can apply Kirchhoff's voltage law to find the value of I_B and hence I_C $(= \beta I_B)$. Referring to Fig. 8.40 and applying Kirchhoff's voltage law to base-emitter loop, we have,

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

$$\therefore \qquad I_B = \frac{V_{BB} - V_{BE}}{R_B} = \frac{10V - 0.7V}{47\ k\Omega} = 198\ \mu A$$

$$\text{Now} \qquad I_C = \beta I_B = (200)(198\ \mu A) = 39.6\ mA$$

$$\text{Also} \qquad V_{CE} = V_{CC} - I_C R_C = 20V - (39.6mA)\ (330\ \Omega) = 20V - 13.07V = 6.93V$$

Therefore, the Q-point is I_C = **39.6 mA** and V_{CE} = **6.93V.**

D.C. load line. In order to draw the d.c. load line, we need two end points.

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

When $I_C = 0$, $V_{CE} = V_{CC} = 20V$. This locates the point B of the load line on the collector-emitter voltage axis as shown in Fig. 8.41. When $V_{CE} = 0$, $I_C = V_{CC}/R_C = 20V/330\Omega = 60.6$ mA. This locates the point A of the load line on the collector current axis. By joining these two points, d.c. load line AB is constructed as shown in Fig. 8.41.

Example 8.26. *Determine the Q point of the transistor circuit shown in *Fig. 8.42. Also draw the d.c. load line. Given $\beta = 100$ and $V_{BE} = 0.7V$.*

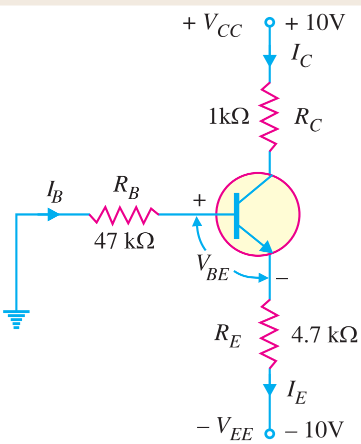


Fig. 8.42

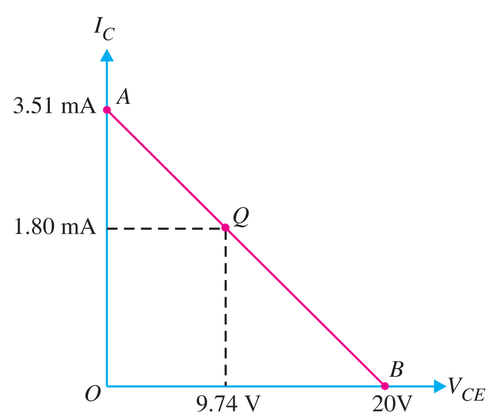


Fig. 8.43

* The presence of two power supplies has an effect on the baisc equations for I_C and V_{CE} used for single power supply (*i.e.* V_{CC}). Normally, the two supply voltages will be equal. For example, if $V_{CC} = +\ 10V$ (d.c.), then $V_{EE} = -\ 10$ V (d.c.).

Solution. The transistor circuit shown in Fig. 8.42 may look complex but we can easily apply Kirchhoff's voltage law to find the various voltages and currents in the * circuit.

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

$$-I_B R_B - V_{BE} - I_E R_E + V_{EE} = 0 \quad \text{or} \quad V_{EE} = I_B R_B + I_E R_E + V_{BE}$$

Now $I_C = \beta I_B$ and $I_C \simeq I_E$. $\therefore$ $I_B = I_E/\beta$. Putting $I_B = I_E/\beta$ in the above equation, we have,

$$V_{EE} = \left(\frac{I_E}{\beta}\right) R_B + I_E R_E + V_{BE}$$

or
$$I_E \left(\frac{R_B}{\beta} + R_E\right) = V_{EE} - V_{BE} \quad \text{or} \quad I_E = \frac{V_{EE} - V_{BE}}{R_E + R_B/\beta}$$

Since $I_C \simeq I_E$,
$$I_C = \frac{V_{EE} - V_{BE}}{R_E + R_B/\beta} = \frac{10\text{V} - 0.7\text{V}}{4.7\text{ k}\Omega + 47\text{ k}\Omega/100} = \frac{9.3\text{ V}}{5.17\text{ k}\Omega} = 1.8\text{ mA}$$

Applying Kirchhoff's voltage law to the collector side, we have,

$$V_{CC} - I_C R_C - V_{CE} - I_E R_E + V_{EE} = 0$$

or
$$V_{CE} = V_{CC} + V_{EE} - I_C (R_C + R_E) \qquad (\because\ I_E \simeq I_C)$$
$$= 10\text{V} + 10\text{V} - 1.8\text{ mA } (1\text{ k}\Omega + 4.7\text{ k}\Omega) = 9.74\text{V}$$

Therefore, the operating point of the circuit is I_C = **1.8 mA** and V_{CE} = **9.74V.**

D.C. load line. The d.c. load line can be constructed as under :

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

When $I_C = 0$; $V_{CE} = V_{CC} + V_{EE} = 10\text{V} + 10\text{V} = 20\text{V}$. This locates the first point B (OB = 20V) of the load line on the collector-emitter voltage axis. When $V_{CE} = 0$,

$$I_C = \frac{V_{CC} + V_{EE}}{R_C + R_E} = \frac{10V + 10V}{1\text{ k}\Omega + 4.7\text{ k}\Omega} = \frac{20V}{5.7\text{ k}\Omega} = 3.51\text{ mA}$$

This locates the second point A (OA = 3.51 mA) of the load line on the collector current axis. By joining points A and B, d.c. load line AB is constructed as shown in Fig. 8.43.

Example 8.27. *In the above example, find (i) emitter voltage w.r.t. ground (ii) base voltage w.r.t. ground (iii) collector voltage w.r.t. ground.*

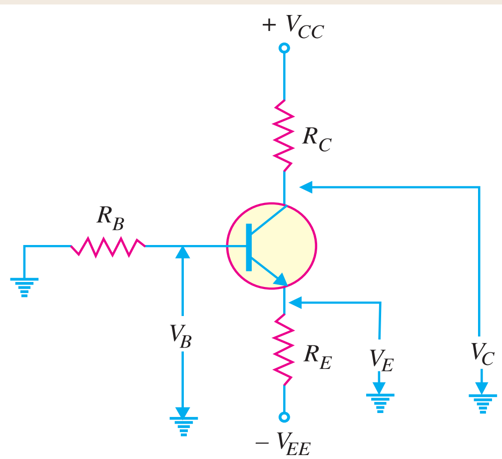


Fig. 8.44

* The emitter resistor R_E provides stabilisation of Q-point (See Art. 9.12).

$$\Delta V_{BE} = 200 \text{ mV}$$

Change in base current, $\Delta I_B = 100 \ \mu\text{A}$

$\therefore$ Input resistance, $R_i = \dfrac{\Delta V_{BE}}{\Delta I_B} = \dfrac{200 \text{ mV}}{100 \ \mu \text{ A}} = \mathbf{2 \ k\Omega}$

Example 8.29. *If the collector current changes from 2 mA to 3mA in a transistor when collector-emitter voltage is increased from 2V to 10V, what is the output resistance ?*

Solution. Change in collector-emitter voltage is

$$\Delta V_{CE} = 10 - 2 = 8 \text{ V}$$

Change in collector current is $\Delta I_C = 3 - 2 = 1 \text{ mA}$

$\therefore$ Output resistance, $R_O = \dfrac{\Delta V_{CE}}{\Delta I_C} = \dfrac{8 \text{ V}}{1 \text{ mA}} = \mathbf{8 \ k\Omega}$

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, $R_C = 2 \ k\Omega$

Input resistance, $R_i = 1 \ k\Omega$

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, $R_{AC} = R_C$]

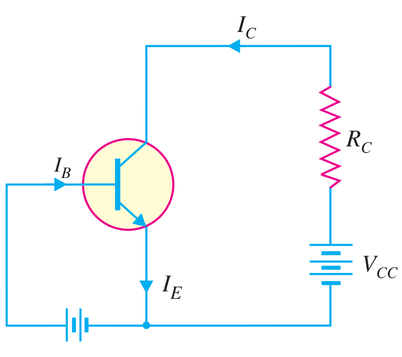
$= 50 \times (2/1) = \mathbf{100}$

8.22 Cut off and Saturation Points

Fig. 8.49 (*i*) shows *CE* transistor circuit while Fig. 8.49 (*ii*) shows the output characteristcs along with the d.c. load line.

(*i*) Cut off. The point where the load line intersects the $I_B = 0$ curve is known as *cut off*. At this point, $I_B = 0$ and only small collector current (*i.e.* collector leakage current I_{CEO}) exists. At cut off, the base-emitter junction no longer remains forward biased and normal transistor action is lost. The collector-emitter voltage is nearly equal to V_{CC} *i.e.*

$$V_{CE\ (cut\ off)} = V_{CC}$$



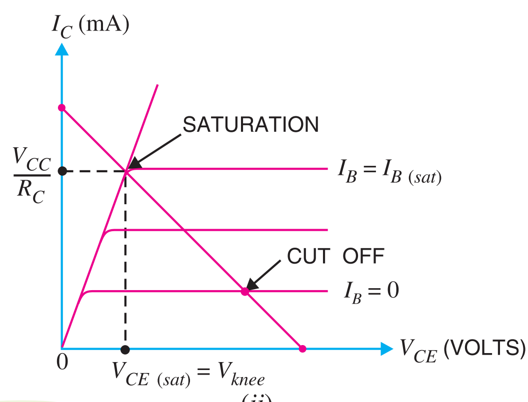


Fig. 8.49

(*ii*) Saturation. The point where the load line intersects the $I_B = I_{B(sat)}$ curve is called *saturation.* At this point, the base current is maximum and so is the collector current. At saturation, collector-base junction no longer remains reverse biased and normal transistor action is lost.

$$I_{C\,(sat)} \simeq \frac{V_{CC}}{R_C}\,;\quad V_{CE} = V_{CE(sat)} = V_{knee}$$

If base current is greater than $I_{B(sat)}$, then collector current cannot increase because collector-base junction is no longer reverse-biased.

(*iii*) Active region. The region between cut off and saturation is known as *active region*. In the active region, collector-base junction remains reverse biased while base-emitter junction remains forward biased. Consequently, the transistor will function normally in this region.

Note. We provide biasing to the transistor to ensure that it operates in the active region. The reader may find the detailed discussion on transistor biasing in the next chapter.

Summary. A transistor has two *pn* junctions *i.e.*, it is like two diodes. The junction between base and emitter may be called *emitter diode*. The junction between base and collector may be called *collector diode*. We have seen above that transistor can act in one of the three states : **cut-off, saturated** and **active**. The state of a transistor is entirely determined by the states of the emitter diode and collector diode [See Fig. 8.50]. The relations between the diode states and the transistor states are :

CUT-OFF : Emitter diode and collector diode are **OFF.**

ACTIVE : Emitter diode is **ON** and collector diode is **OFF.**

SATURATED : Emitter diode and collector diode are **ON.**

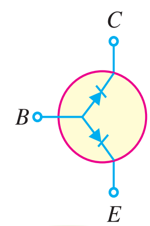


Fig. 8.50

In the **active state**, collector current [See Fig 8.51 (*i*)] is β times the base current (*i.e.* $I_C = \beta I_B$). If the transistor is **cut-off,** there is no base current, so there is no collector or emitter current. That is collector emitter pathway is open [See Fig. 8.51 (*ii*)]. In **saturation,** the collector and emitter are, in effect, shorted together. That is the transistor behaves as though a switch has been closed between the collector and emitter [See Fig. 8.51 (*iii*)].

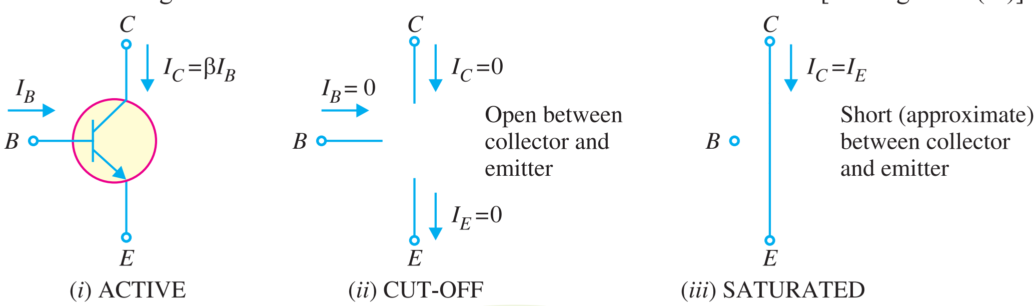


Fig. 8.51

Note. When the transistor is in the active state, $I_C = \beta I_B$. Therefore, a transistor acts as an amplifier when operating in the active state. Amplification means *linear amplification*. In fact, small signal amplifiers are the most common *linear devices*.

Example 8.31. *Find $I_{C(sat)}$ and $V_{CE(cut\ off)}$ for the circuit shown in Fig. 8.52 (i).*

Solution. As we decrease R_B, base current and hence collector current increases. The increased collector current causes a greater voltage drop across R_C; this decreases the collector-emitter voltage. Eventually at some value of R_B, V_{CE} decreases to V_{knee}. At this point, collector-base junction is no longer reverse biased and transistor action is lost. Consequently, further increase in collector current is not possible. The transistor conducts maximum collector current ; we say the transistor is saturated.

$$I_{C(sat)} = \frac{V_{CC} - {}^{*}V_{knee}}{R_C} = \frac{V_{CC}}{R_C} = \frac{20\text{ V}}{1\text{ k}\Omega} = \mathbf{20mA}$$

* V_{knee} is about 0.5 V for Ge transistor and about 1V for Si transistor. Consequently, V_{knee} can be neglected as compared to V_{CC} (= 20 V in this case).

As we increase R_B, base current and hence collector current decreases. This decreases the voltage drop across R_C. This increases the collector-emitter voltage. Eventually, when $I_B = 0$, the emitter-base junction is no longer forward biased and transistor action is lost. Consequently, further increase in V_{CE} is not possible. In fact, V_{CE} now equals to V_{CC}.

$$V_{CE(cut\text{-}off)} = V_{CC} = \mathbf{20\ V}$$

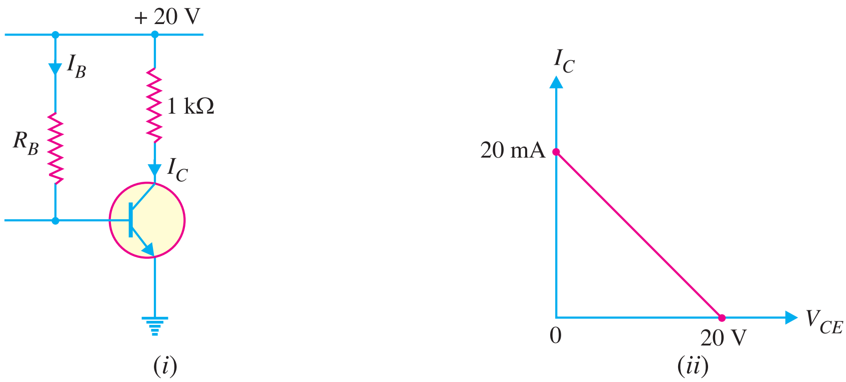


Fig. 8.52

Figure 8.52 (*ii*) shows the saturation and cut off points. Incidentally, they are end points of the d.c. load line.

Note. The exact value of $V_{CE(cut\text{-}off)} = V_{CC} - I_{CEO} R_C$. Since the collector leakage current I_{CEO} is very small, we can neglect $I_{CEO} R_C$ as compared to V_{CC}.

Example 8.32. *Determine the values of $V_{CE\,(off)}$ and $I_{C\,(sat)}$ for the circuit shown in Fig. 8.53.*

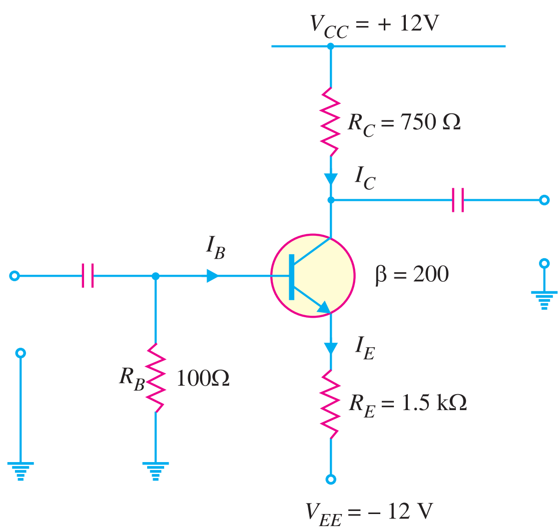


Fig. 8.53

Solution. Applying Kirchhoff's voltage law to the collector side of the circuit in Fig. 8.53, we have,

$$V_{CC} - I_C R_C - V_{CE} - {}^*I_C R_E + V_{EE} = 0$$

or $$V_{CE} = V_{CC} + V_{EE} - I_C (R_C + R_E) \quad \text{... (i)}$$

* Voltage across $R_E = I_E R_E$. Since $I_E \simeq I_C$, voltage across $R_E = I_C R_E$.

We have $V_{CE\ (off)}$ when $I_C = 0$. Therefore, putting $I_C = 0$ in eq. (i), we have,

$$V_{CE\ (off)} = V_{CC} + V_{EE} = 12 + 12 = \mathbf{24V}$$

We have $I_{C\ (sat)}$ when $V_{CE} = 0$.

$$\therefore \quad I_{C\ (sat)} = \frac{V_{CC} + V_{EE}}{R_C + R_E} = \frac{(12+12)\,V}{(750+1500)\,\Omega} = \mathbf{10.67\ mA}$$

Example 8.33. *Determine whether or not the transistor in Fig. 8.54 is in stauration. Assume $V_{knee} = 0.2V$.*

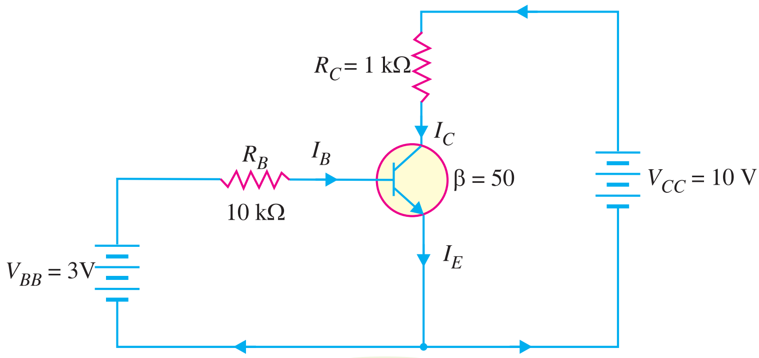


Fig. 8.54

Solution.

$$I_{C\ (sat)} = \frac{V_{CC} - V_{knee}}{R_C} = \frac{10\,V - 0.2\,V}{1\,k\Omega} = \frac{9.8\,V}{1\,k\Omega} = 9.8\text{ mA}$$

Now we shall see if I_B is large enough to produce $I_{C\ (sat)}$.

$$\text{Now} \quad I_B = \frac{V_{BB} - V_{BE}}{R_B} = \frac{3V - 0.7V}{10\,k\Omega} = \frac{2.3\,V}{10\,k\Omega} = 0.23\text{ mA}$$

$$\therefore \quad I_C = \beta I_B = 50 \times 0.23 = 11.5\text{ mA}$$

This shows that with specified β, this base current (= 0.23 mA) is capable of producing I_C greater than $I_{C\ (sat)}$. Therefore, the transistor is **saturated.** In fact, the collector current value of 11. 5 mA is never reached. If the base current value corresponding to $I_{C\ (sat)}$ is increased, the collector current remains at the saturated value (= 9.8 mA).

Example 8.34. *Is the transistor in Fig. 8.55 operating in saturated state ?*

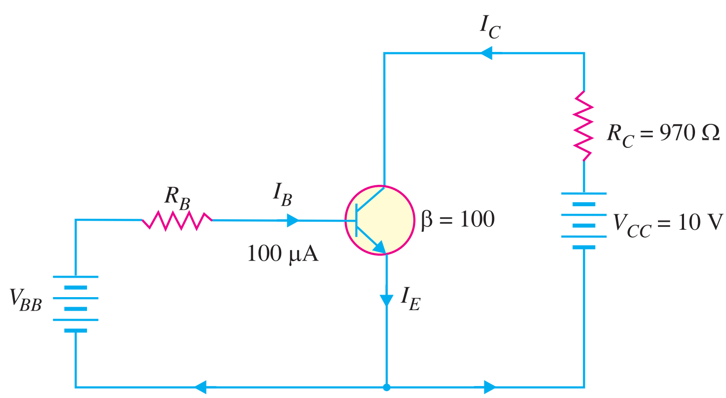


Fig. 8.55

Solution.

$$I_C = \beta I_B = (100)(100\ \mu A) = 10\ mA$$

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

$$= 10V - (10\ mA)(970\Omega) = 0.3V$$

Let us relate the values found to the transistor shown in Fig. 8.56. As you can see, the value of V_{BE} is 0.95V and the value of V_{CE} = 0.3V. This leaves V_{CB} of 0.65V (Note that $V_{CE} = V_{CB} + V_{BE}$). In this case, collector – base junction (*i.e.*, collector diode) is forward biased as is the emitter-base junction (*i.e.*, emitter diode). Therefore, the transistor is operating in the **saturation region.**

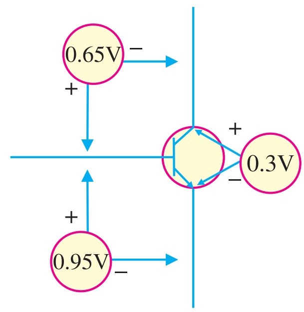


Fig. 8.56

Note. When the transistor is in the saturated state, the base current and collector current are independent of each other. The base current is still (and always is) found only from the base circuit. The collector current is found apporximately by closing the imaginary switch between the collector and the emitter in the collector circuit.

Example 8.35. *For the circuit in Fig. 8.57, find the base supply voltage (V_{BB}) that just puts the transistor into saturation. Assume β = 200.*

Solution. When transistor first goes into saturation, we can assume that the collector shorts to the emitter (*i.e.* V_{CE} = 0) but the collector current is still β times the base current.

$$I_{C(sat)} = \frac{V_{CC} - V_{CE}}{R_C} = \frac{V_{CC} - 0}{R_C}$$

$$= \frac{10\ V - 0}{2\ k\Omega} = 5\ mA$$

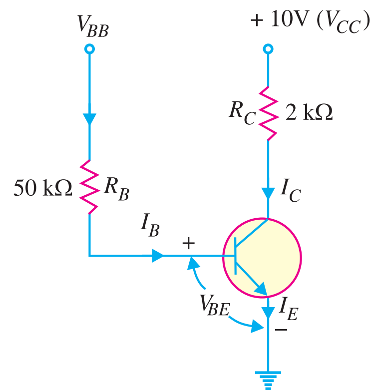


Fig. 8.57

The base current I_B corresponding to $I_{C\,(sat)}$ (=5 mA) is

$$I_B = \frac{I_{C\,(sat)}}{\beta} = \frac{5\ mA}{200} = 0.025\ mA$$

Applying Kirchhoff's voltage law to the base circuit, we have,

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

or $$V_{BB} = V_{BE} + I_B R_B$$

$$= 0.7V + 0.025\ mA \times 50\ k\Omega = 0.7 + 1.25 = 1.95V$$

Therefore, for $\boldsymbol{V_{BB} \geq 1.95}$, the transistor will be in *saturation.*

Example. 8.36. *Determine the state of the transistor in Fig. 8.58 for the following values of collector resistor :*

(i) R_C = 2 kΩ (ii) R_C = 4 kΩ (iii) R_C = 8 kΩ

Solution. Since I_E does not depend on the value of the collector resistor R_C, the emitter current (I_E) is the same for all three parts.

Emitter voltage, $V_E = V_B - V_{BE} = V_{BB} - V_{BE}$

$$= 2.7V - 0.7\ V = 2V$$

Also $$I_E = \frac{V_E}{R_E} = \frac{2V}{1\ k\Omega} = 2\ mA$$

(*i*) When R_C = 2 kΩ. Suppose the transistor is active.

∴ $I_C = I_E = 2\ mA$

∴ $I_B = I_C/\beta = 2\ mA/100 = 0.02\ mA$