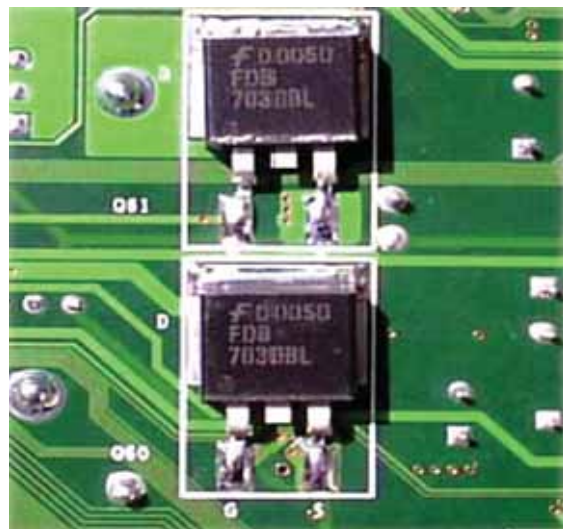


8

Transistors

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INTRODUCTION

When a third doped element is added to a crystal diode in such a way that two pn junctions are formed, the resulting device is known as a *transistor*. The transistor—an entirely new type of electronic device—is capable of achieving amplification of weak signals in a fashion comparable and often superior to that realised by vacuum tubes. Transistors are far smaller than vacuum tubes, have no filament and hence need no heating power and may be operated in any position. They are mechanically strong, have practically unlimited life and can do some jobs better than vacuum tubes.

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Invented in 1948 by J. Bardeen and W.H. Brattain of Bell Telephone Laboratories, U.S.A.; transistor has now become the heart of most electronic applications. Though transistor is only slightly more than 58 years old, yet it is fast replacing vacuum tubes in almost all applications. In this chapter, we shall focus our attention on the various aspects of transistors and their increasing applications in the fast developing electronics industry.

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).

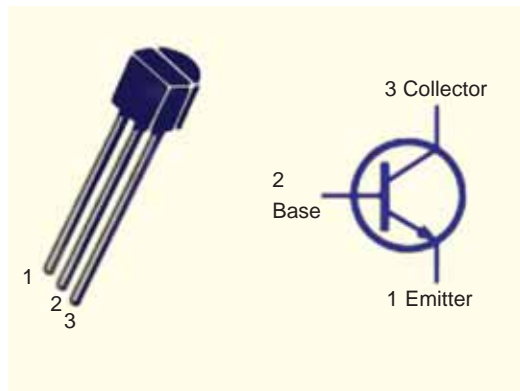


Fig. 8.1

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.

Origin of the name "Transistor". When new devices are invented, scientists often try to devise a name that will appropriately describe the device. A transistor has two pn junctions. As discussed later, one junction is forward biased and the other is reverse biased. The forward biased junction has a low resistance path whereas a reverse biased junction has a high resistance path. The weak signal is introduced in the low resistance circuit and output is taken from the high resistance circuit. Therefore, a transistor **transfers** a signal from a low resistance to high resistance. The prefix 'trans' means the signal transfer property of the device while 'istor' classifies it as a solid element in the same general family with resistors.



* In practice, these three blocks p , n , p are grown out of the same crystal by adding corresponding impurities in turn.

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.

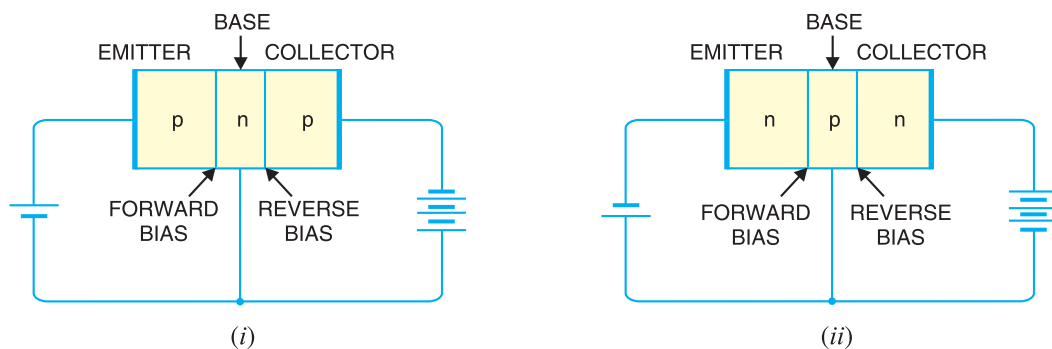


Fig. 8.2

(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.

8.3 Some Facts about the Transistor

Before discussing transistor action, it is important that the reader may keep in mind the following facts about the transistor :

(i) The transistor has three regions, namely ; *emitter*, *base* and *collector*. The base is much thinner than the emitter while **collector is wider than both as shown in Fig. 8.3. However, for the sake of convenience, it is customary to show emitter and collector to be of equal size.

(ii) The emitter is heavily doped so that it can inject a large number of charge carriers (electrons or holes) into the base. The base is lightly doped and very thin ; it passes most of the emitter injected charge carriers to the collector. The collector is moderately doped.

* Holes if emitter is *p*-type and electrons if the emitter is *n*-type.

** During transistor operation, much heat is produced at the collector junction. The collector is made larger to dissipate the heat.



Fig. 8.3

(iii) The transistor has two pn junctions *i.e.* it is like two diodes. The junction between emitter and base may be called *emitter-base diode* or simply the *emitter diode*. The junction between the base and collector may be called *collector-base diode* or simply *collector diode*.

(iv) The emitter diode is always forward biased whereas collector diode is always reverse biased.

(v) The resistance of emitter diode (forward biased) is very small as compared to collector diode (reverse biased). Therefore, forward bias applied to the emitter diode is generally very small whereas reverse bias on the collector diode is much higher.

8.4 Transistor Action

The emitter-base junction of a transistor is forward biased whereas collector-base junction is reverse biased. If for a moment, we ignore the presence of emitter-base junction, then *practically** no current would flow in the collector circuit because of the reverse bias. However, if the emitter-base junction is also present, then forward bias on it causes the emitter current to flow. It is seen that this emitter current almost entirely flows in the collector circuit. Therefore, the current in the collector circuit depends upon the emitter current. If the emitter current is zero, then collector current is nearly zero. However, if the emitter current is 1mA, then collector current is also about 1mA. This is precisely what happens in a transistor. We shall now discuss this transistor action for npn and pnp transistors.

(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.*

$$I_E = I_B + I_C$$

* In actual practice, a very little current (a few μA) would flow in the collector circuit. This is called collector cut off current and is due to minority carriers.

** The electrons which combine with holes become valence electrons. Then as valence electrons, they flow down through holes and into the external base lead. This constitutes base current I_B .

*** The reasons that most of the electrons from emitter continue their journey through the base to collector to form collector current are : (i) The base is lightly doped and very thin. Therefore, there are a few holes which find enough time to combine with electrons. (ii) The reverse bias on collector is quite high and exerts attractive forces on these electrons.

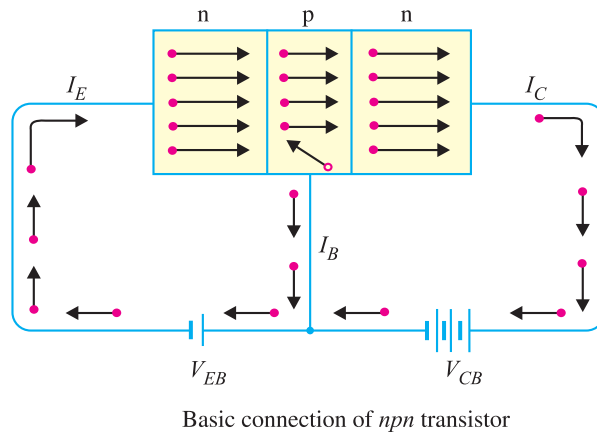


Fig. 8.4

(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

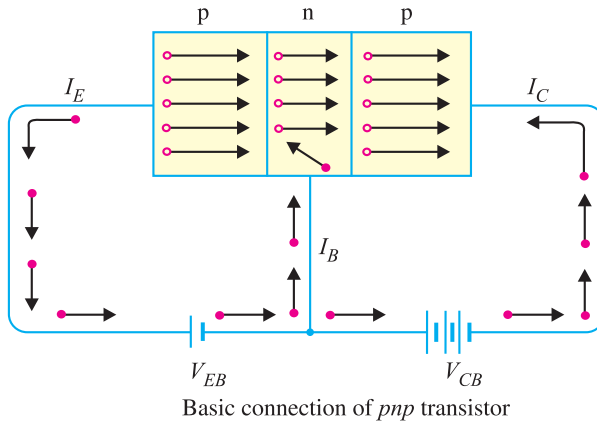
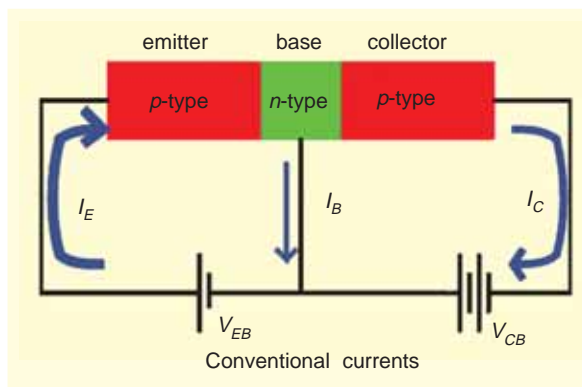


Fig. 8.5

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.

Importance of transistor action. The input circuit (*i.e.* emitter-base junction) has low resistance because of forward bias whereas output circuit (*i.e.* collector-base junction) has high resistance due to reverse bias. As we have seen, the input emitter current almost entirely flows in the collector circuit.



Therefore, a transistor transfers the input signal current from a low-resistance circuit to a high-resistance circuit. This is the key factor responsible for

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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 conduction. 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.

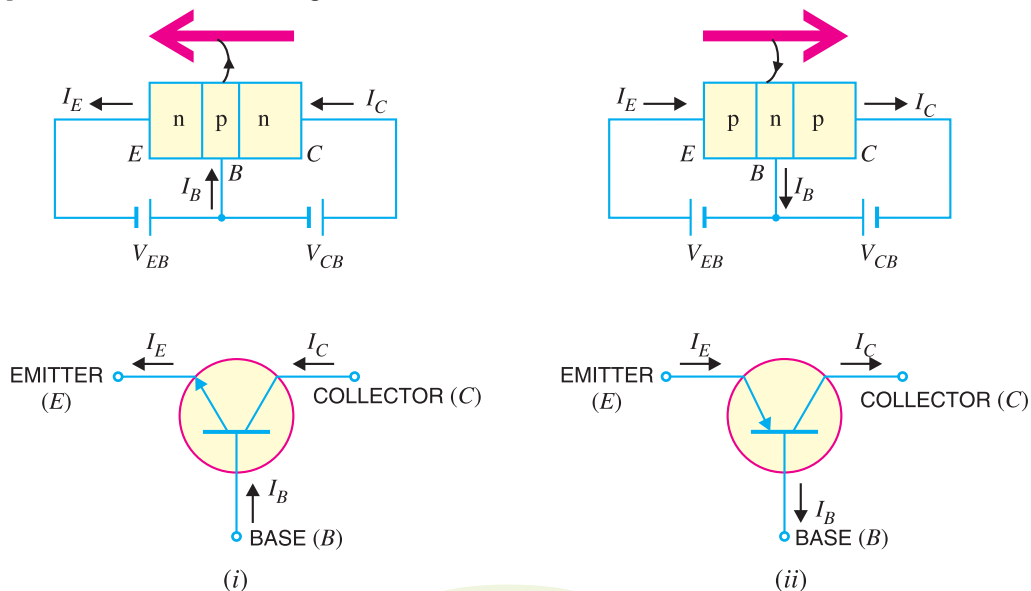


Fig. 8.6

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

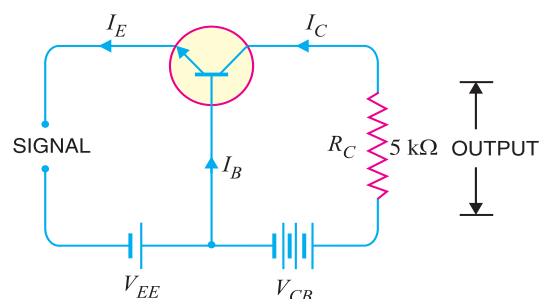


Fig. 8.7

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.

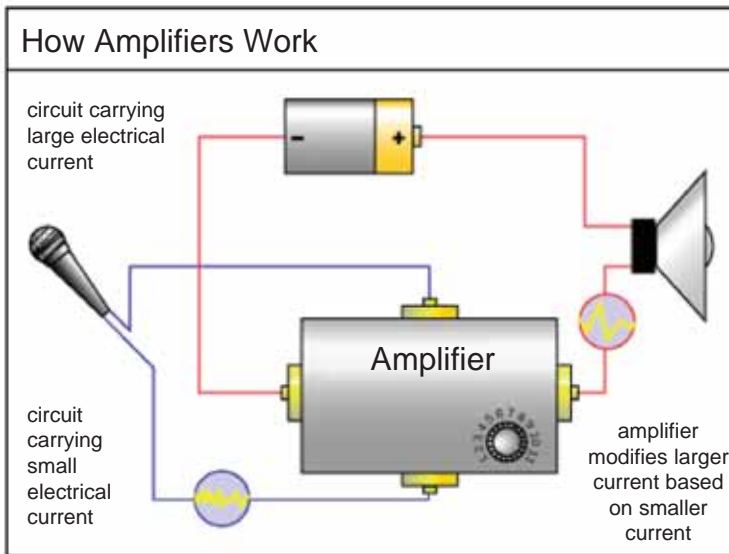


Illustration. The action of a transistor as an amplifier can be made more illustrative if we consider typical circuit values. Suppose collector load resistance $R_C = 5\text{ k}\Omega$. Let us further assume that a change of 0.1 V in signal voltage produces a change of 1 mA in emitter current. Obviously, the change in collector current would also be approximately 1 mA . This collector current flowing through collector load R_C would produce a voltage = $5\text{ k}\Omega \times 1\text{ mA} = 5\text{ V}$. 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 $20\ \Omega$ and output resistance of $100\text{ k}\Omega$. The collector load is $1\text{ k}\Omega$. 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.

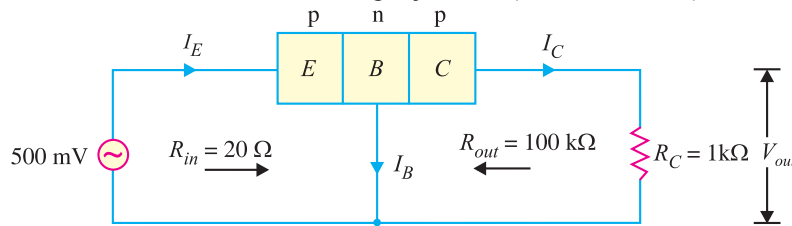


Fig. 8.8

* 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.

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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, $I_C = I_E = 25 \text{ mA}$.

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

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

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 + Resistor \longrightarrow 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 *nnp* transistor circuit is shown whereas Fig. 8.9 (ii) shows the common base *pnp* transistor circuit.

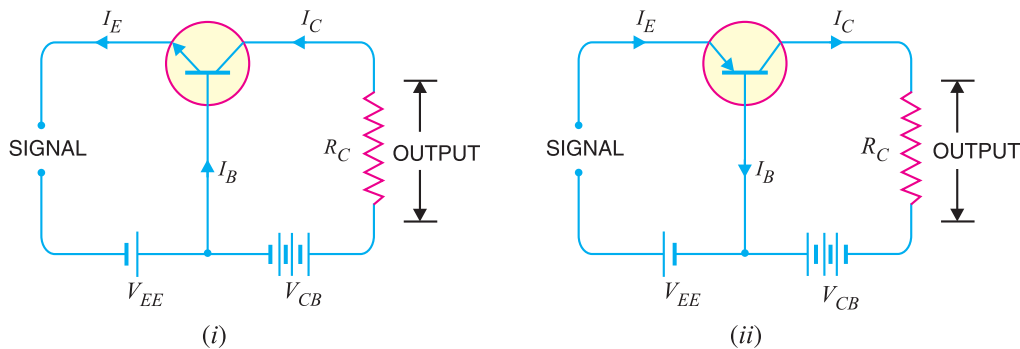


Fig. 8.9

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.

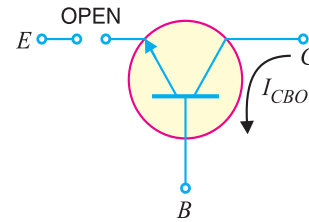


Fig. 8.10

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 .

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

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.

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

Now $I_E = I_C + I_B$

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

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

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

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.

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

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

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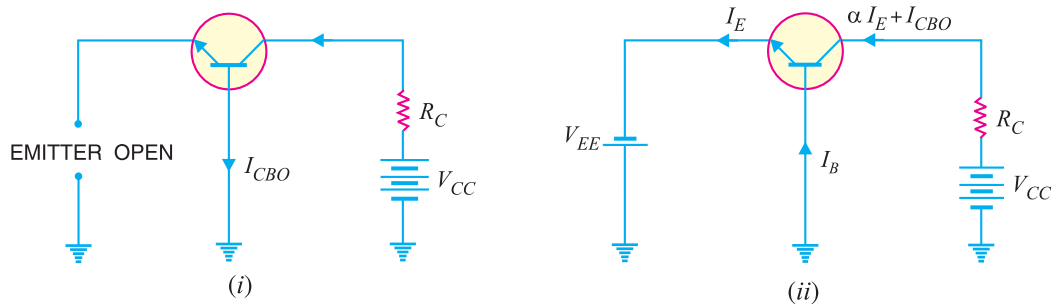


Fig. 8.11

Example 8.2. In a common base connection, $I_E = 1\text{mA}$, $I_C = 0.95\text{mA}$. Calculate the value of I_B .

Solution. Using the relation, $I_E = I_B + I_C$
 or $1 = I_B + 0.95$
 $\therefore I_B = 1 - 0.95 = 0.05\text{ mA}$

Example 8.3. In a common base connection, current amplification factor is 0.9. If the emitter current is 1mA , determine the value of base current.

Solution. Here, $\alpha = 0.9$, $I_E = 1\text{ mA}$
 Now $\alpha = \frac{I_C}{I_E}$
 or $I_C = \alpha I_E = 0.9 \times 1 = 0.9\text{ mA}$
 Also $I_E = I_B + I_C$
 \therefore Base current, $I_B = I_E - I_C = 1 - 0.9 = 0.1\text{ mA}$

Example 8.4. In a common base connection, $I_C = 0.95\text{ mA}$ and $I_B = 0.05\text{ mA}$. Find the value of α .

Solution. We know $I_E = I_B + I_C = 0.05 + 0.95 = 1\text{ mA}$
 \therefore Current amplification factor, $\alpha = \frac{I_C}{I_E} = \frac{0.95}{1} = 0.95$

Example 8.5. In a common base connection, the emitter current is 1mA . If the emitter circuit is open, the collector current is $50\text{ }\mu\text{A}$. Find the total collector current. Given that $\alpha = 0.92$.

Solution. Here, $I_E = 1\text{ mA}$, $\alpha = 0.92$, $I_{CBO} = 50\text{ }\mu\text{A}$
 \therefore Total collector current, $I_C = \alpha I_E + I_{CBO} = 0.92 \times 1 + 50 \times 10^{-3}$
 $= 0.92 + 0.05 = 0.97\text{ mA}$

Example 8.6. In a common base connection, $\alpha = 0.95$. The voltage drop across $2\text{ k}\Omega$ resistance which is connected in the collector is 2V . Find the base current.

Solution. Fig. 8.12 shows the required common base connection. The voltage drop across R_C ($= 2\text{ k}\Omega$) is 2V .

$\therefore I_C = 2\text{ V}/2\text{ k}\Omega = 1\text{ mA}$
 Now $\alpha = I_C/I_E$

$$\therefore I_E = \frac{I_C}{\alpha} = \frac{1}{0.95} = 1.05 \text{ mA}$$

Using the relation, $I_E = I_B + I_C$

$$\therefore I_B = I_E - I_C = 1.05 - 1 = 0.05 \text{ mA}$$

Example 8.7. For the common base circuit shown in Fig. 8.13, determine I_C and V_{CB} . Assume the transistor to be of silicon.

Solution. Since the transistor is of silicon, $V_{BE} = 0.7\text{V}$. Applying Kirchhoff's voltage law to the emitter-side loop, we get,

$$V_{EE} = I_E R_E + V_{BE}$$

or
$$I_E = \frac{V_{EE} - V_{BE}}{R_E}$$

$$= \frac{8\text{V} - 0.7\text{V}}{1.5 \text{ k}\Omega} = 4.87 \text{ mA}$$

$$\therefore I_C \approx I_E = 4.87 \text{ mA}$$

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

$$V_{CC} = I_C R_C + V_{CB}$$

$$\therefore V_{CB} = V_{CC} - I_C R_C$$

$$= 18 \text{ V} - 4.87 \text{ mA} \times 1.2 \text{ k}\Omega = 12.16 \text{ V}$$

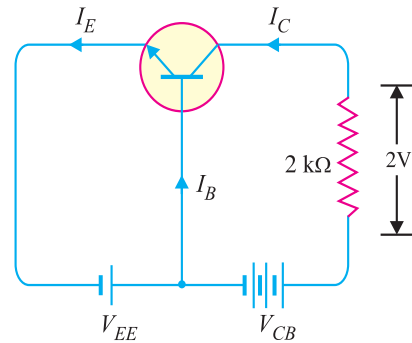


Fig. 8.12

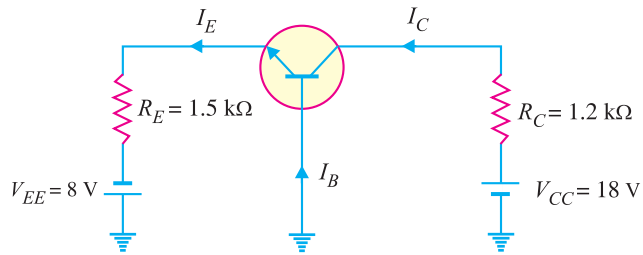


Fig. 8.13

8.9 Characteristics of Common Base Connection

The complete electrical behaviour of a transistor can be described by stating the interrelation of the various currents and voltages. These relationships can be conveniently displayed graphically and the curves thus obtained are known as the characteristics of transistor. The most important characteristics of common base connection are *input characteristics* and *output characteristics*.

1. Input characteristic. It is the curve between emitter current I_E and emitter-base voltage V_{EB} at constant collector-base voltage V_{CB} . The emitter current is generally taken along y-axis and emitter-base voltage along x-axis. Fig. 8.14 shows the input characteristics of a typical transistor in CB arrangement. The following points may be noted from these characteristics :

(i) The emitter current I_E increases rapidly with small increase in emitter-base voltage V_{EB} . It means that input resistance is very small.

(ii) The emitter current is almost independent of collector-base voltage V_{CB} . This leads to the conclusion that emitter current (and hence collector current) is almost independent of collector voltage.

Input resistance. It is the ratio of change in emitter-base voltage (ΔV_{EB}) to the resulting

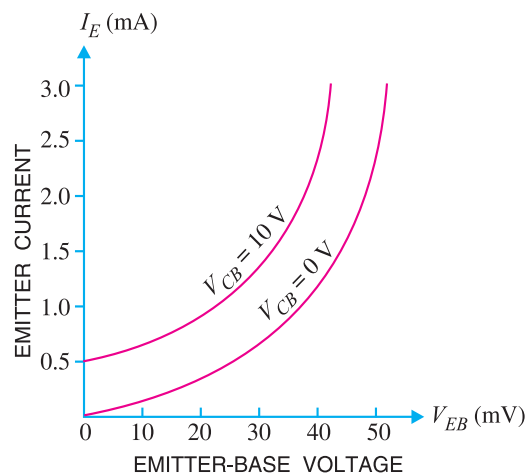


Fig. 8.14

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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 ($< 1\text{V}$). 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.

(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 *nnp* transistor circuit whereas Fig. 8.16 (ii) shows common emitter *pnp* transistor circuit.

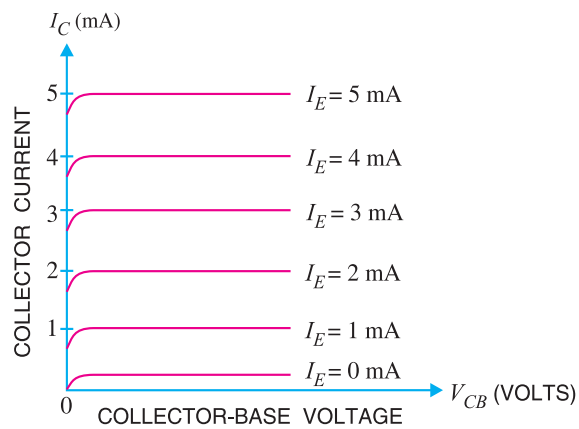


Fig. 8.15

* 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 .

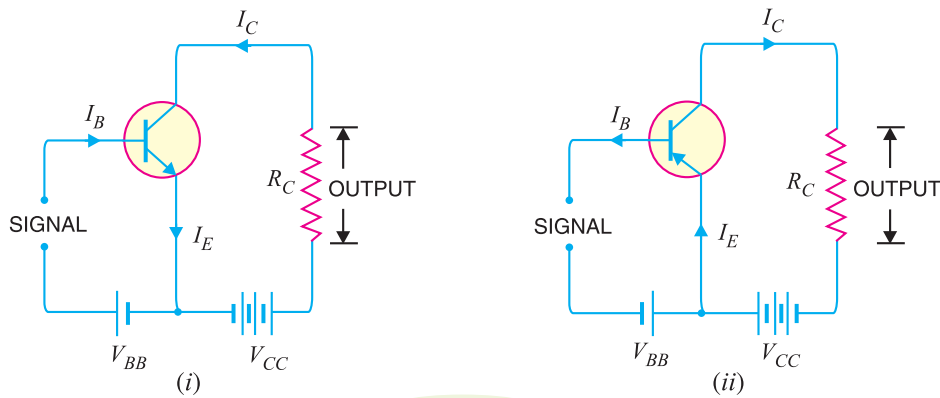


Fig. 8.16

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 :

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

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

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,

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

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

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

\therefore

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

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, $\beta = I_C / I_B$.

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

$$\begin{aligned} \text{We know } I_E &= I_B + I_C && \dots(i) \\ \text{and } I_C &= \alpha I_E + I_{CBO} && \dots(ii) \\ \text{From exp. (ii), we get, } I_C &= \alpha I_E + I_{CBO} = \alpha (I_B + I_C) + I_{CBO} \\ \text{or } I_C (1 - \alpha) &= \alpha I_B + I_{CBO} \\ \text{or } I_C &= \frac{\alpha}{1 - \alpha} I_B + \frac{1}{1 - \alpha} I_{CBO} && \dots(iii) \end{aligned}$$

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.

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

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

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

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

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} .

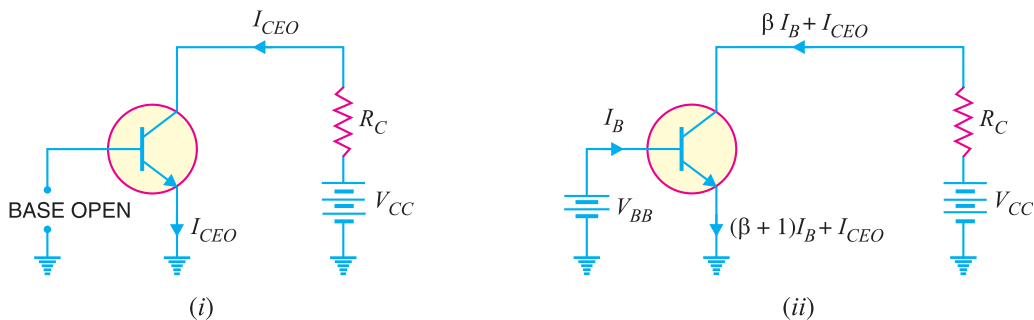


Fig. 8.17

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

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

It may be noted here that :

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

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.

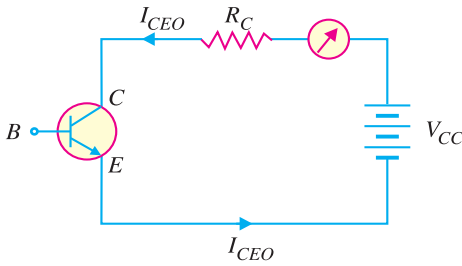


Fig. 8.18

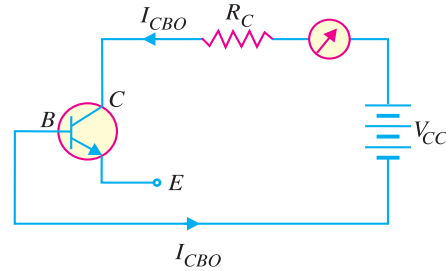


Fig. 8.19

(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) $\alpha = 0.9$ (ii) $\alpha = 0.98$ (iii) $\alpha = 0.99$.

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

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

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

Example 8.9. Calculate I_E in a transistor for which $\beta = 50$ and $I_B = 20 \mu\text{A}$.

Solution. Here $\beta = 50$, $I_B = 20 \mu\text{A} = 0.02 \text{ mA}$

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

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

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

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.

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

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

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

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

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

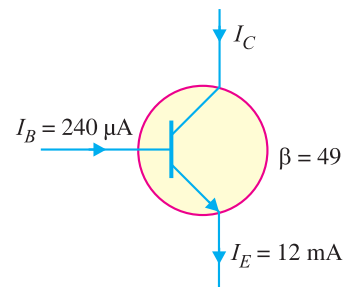


Fig. 8.20

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Example 8.11. For a transistor, $\beta = 45$ and voltage drop across $1\text{k}\Omega$ 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 $R_C (= 1\text{k}\Omega)$ is 1 volt.

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

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

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

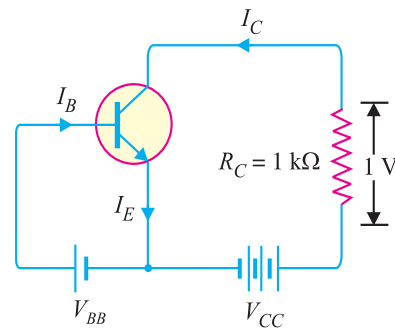


Fig. 8.21

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 $R_C = 800\ \Omega$. If $\alpha = 0.96$, determine :

- (i) collector-emitter voltage
- (ii) base current

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

- (i) Collector-emitter voltage,

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

- (ii) The voltage drop across $R_C (= 800\ \Omega)$ is 0.5 V.

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

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

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

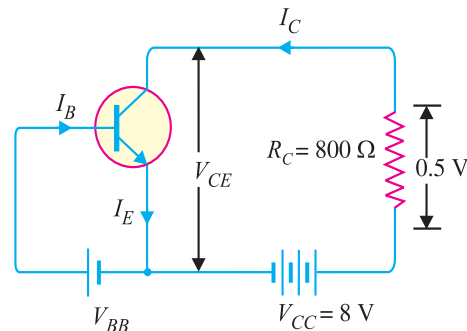


Fig. 8.22

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 $0.2\ \mu\text{A}$ flows. When the base is disconnected and the same voltage is applied between collector and emitter, the current is found to be $20\ \mu\text{A}$. Find α , I_E and I_B when collector current is 1mA.

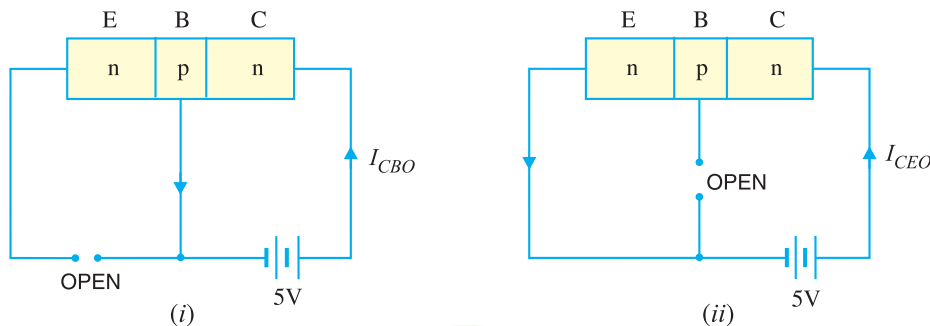


Fig. 8.23

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.

$$\therefore I_{CBO} = 0.2 \mu\text{A} \quad \dots \text{given}$$

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

$$\therefore I_{CEO} = 20 \mu\text{A} \quad \dots \text{given}$$

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

or
$$20 = \frac{0.2}{1 - \alpha}$$

$$\therefore \alpha = 0.99$$

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

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

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

or
$$I_E = \frac{1000 - 0.2}{0.99} = 1010 \mu\text{A}$$

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

Example 8.14. The collector leakage current in a transistor is $300 \mu\text{A}$ in CE arrangement. If now the transistor is connected in CB arrangement, what will be the leakage current? Given that $\beta = 120$.

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

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

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

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

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, $I_B = 20 \mu\text{A}$; $I_C = 2 \text{mA}$ and $\beta = 80$. Calculate I_{CBO} .

Solution.

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

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

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

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

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

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 in 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.

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

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

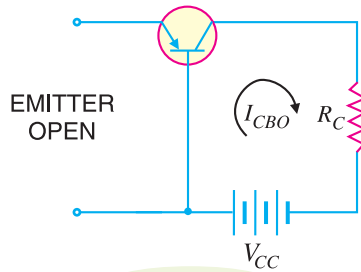


Fig. 8.24

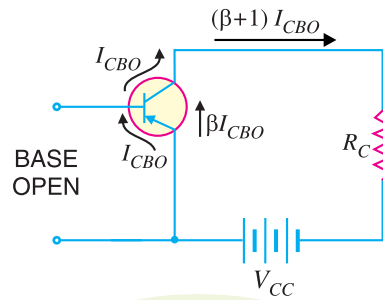


Fig. 8.25

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

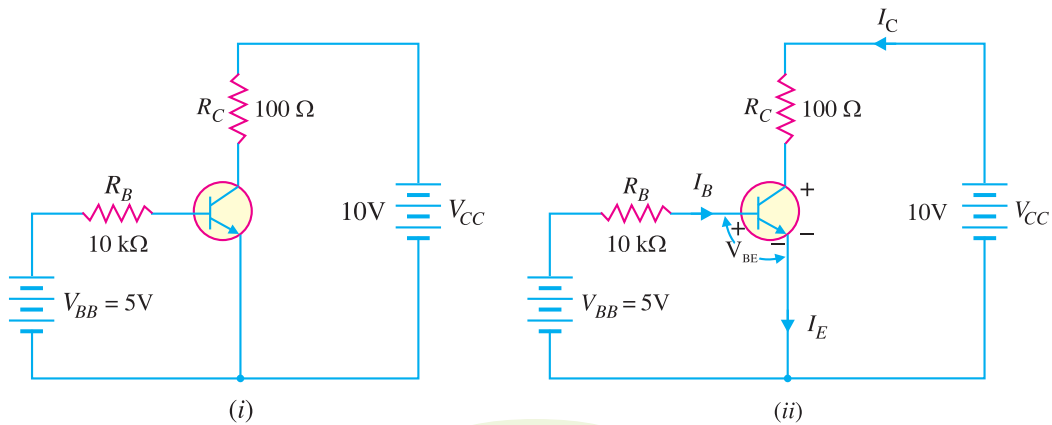


Fig. 8.26

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

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

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

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

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

Now
$$V_{CE} = V_{CC} - I_C R_C = 10V - (64.5\ \text{mA})(100\Omega) = 10V - 6.45V = 3.55V$$

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

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

Example 8.18. In a transistor, $I_B = 68\ \mu\text{A}$, $I_E = 30\ \text{mA}$ and $\beta = 440$. 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 ($= \beta I_B$). If R_B is increased, the base current (I_B) decreases and hence collector current (I_C) will decrease and vice-versa.

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

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

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

Solution.

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

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 ?

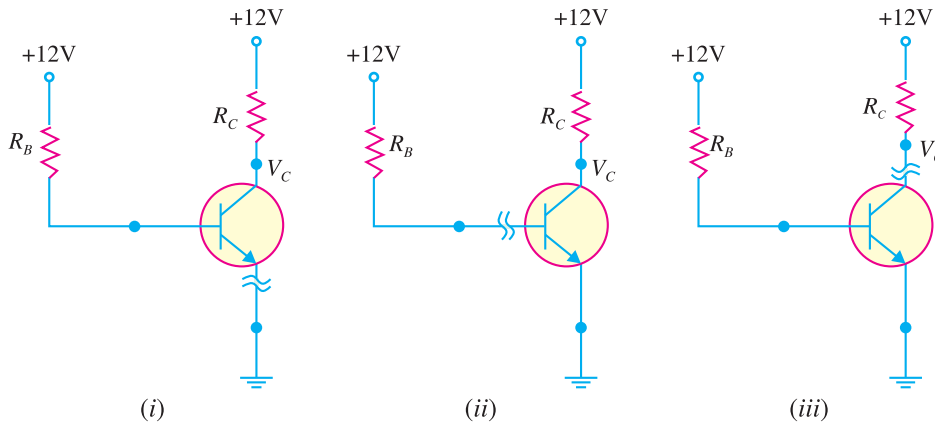


Fig. 8.27

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 ?

* 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.

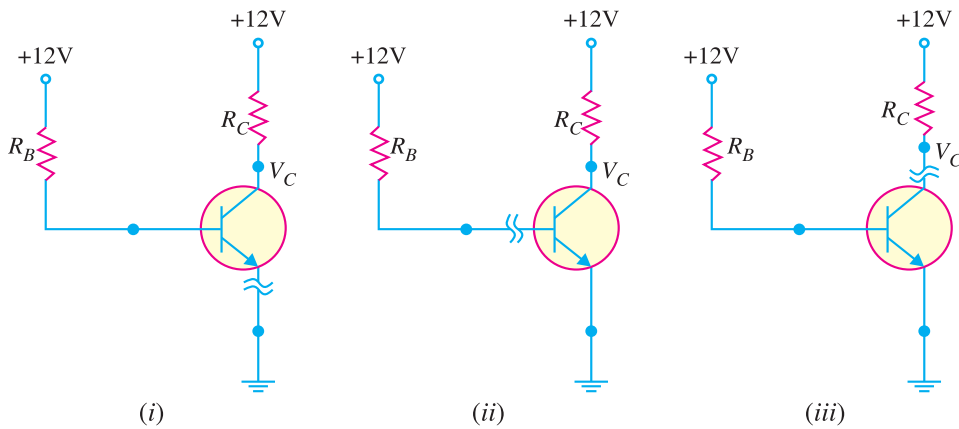


Fig. 8.28

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*.

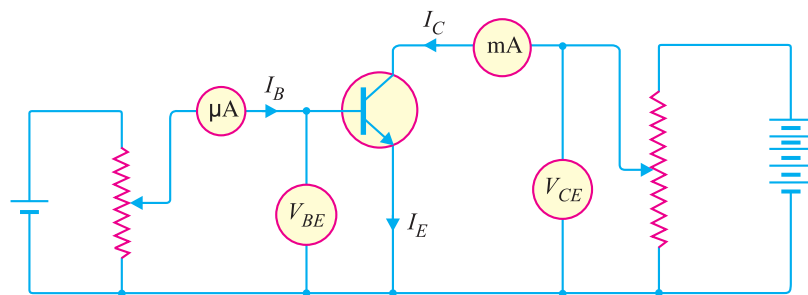


Fig. 8.29

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 :

(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.

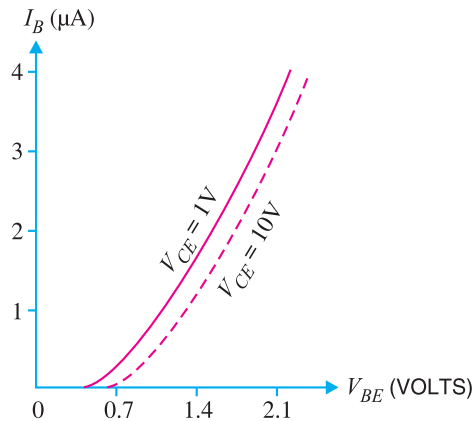


Fig. 8.30

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.

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

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, $5 \mu A$, 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 $I_B = 5 \mu A$ as shown in Fig. 8.31 (i). The test can be repeated for $I_B = 10 \mu A$ 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).

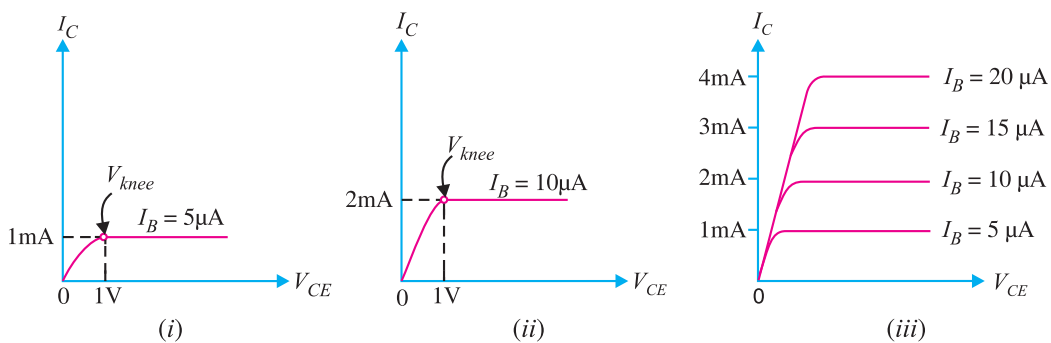


Fig. 8.31

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

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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 k Ω .

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.

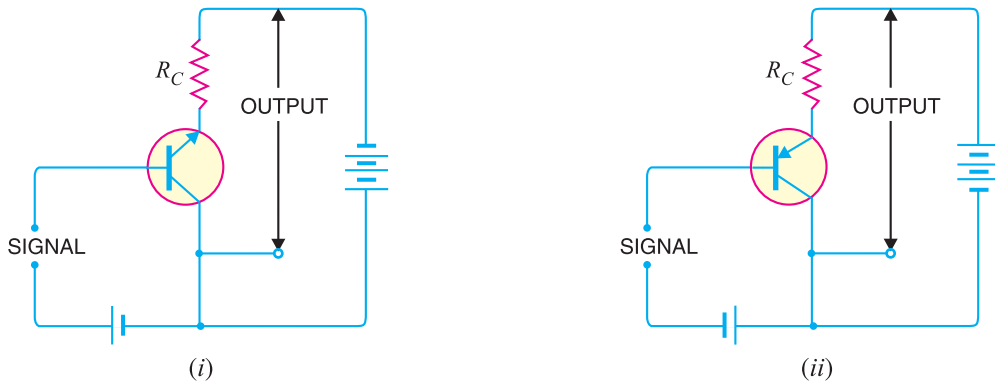


Fig. 8.32

(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 $\Delta I_E \approx \Delta I_C$. However, its voltage gain is always less than 1.

Relation between γ and α

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

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

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,

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

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

(ii) Expression for collector current

We know $I_C = \alpha I_E + I_{CBO}$ (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 $I_C ; I_E = *(\beta + 1) I_B + (\beta + 1) I_{CBO}$

(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 :

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

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(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.

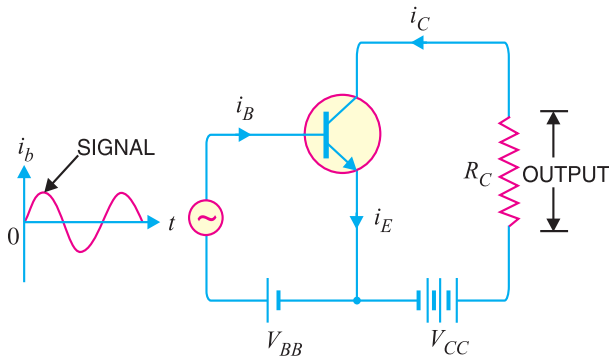


Fig. 8.33

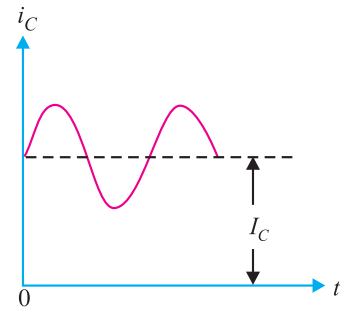


Fig. 8.34

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.

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

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.

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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 ;

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

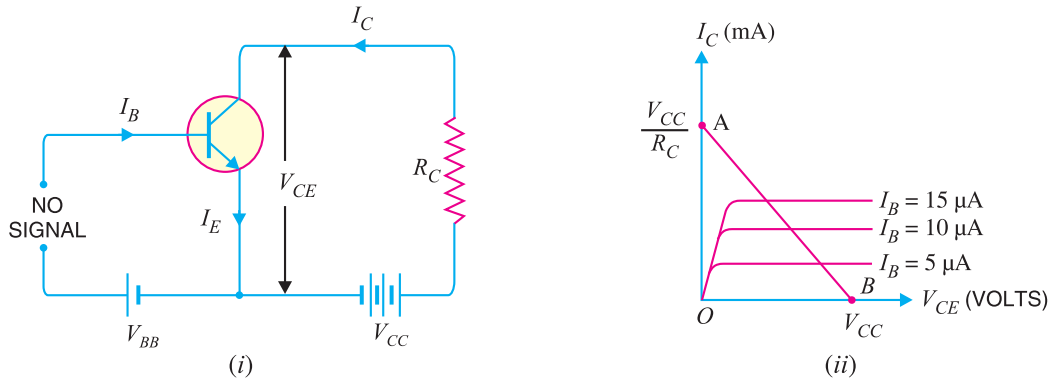


Fig. 8.35

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.

$$\begin{aligned} \text{Max. } V_{CE} &= V_{CC} - I_C R_C \\ &= V_{CC} \quad (\because I_C = 0) \end{aligned}$$

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.

$$\begin{aligned} V_{CE} &= V_{CC} - I_C R_C \\ \text{or} \quad 0 &= V_{CC} - I_C R_C \\ \therefore \quad \text{Max. } I_C &= V_{CC}/R_C \end{aligned}$$

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.

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

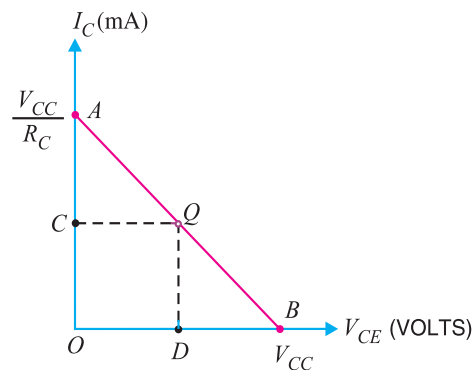


Fig. 8.36

* **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.

Suppose in the absence of signal, the base current is $5 \mu\text{A}$. Then I_C and V_{CE} conditions in the circuit must be represented by some point on $I_B = 5 \mu\text{A}$ 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 $I_B = 5 \mu\text{A}$, the zero signal values are :

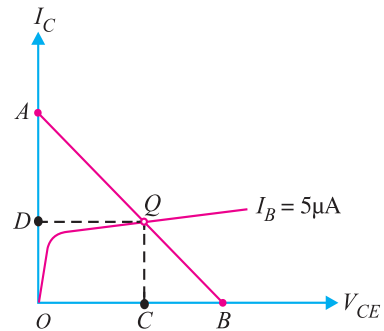


Fig. 8.37

$$\begin{aligned} V_{CE} &= OC \text{ volts} \\ I_C &= OD \text{ mA} \end{aligned}$$

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 ;

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

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.

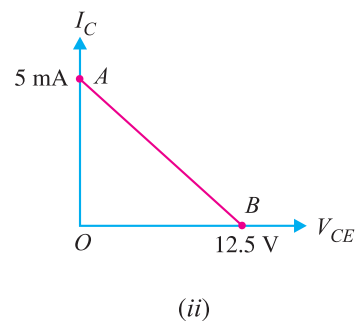
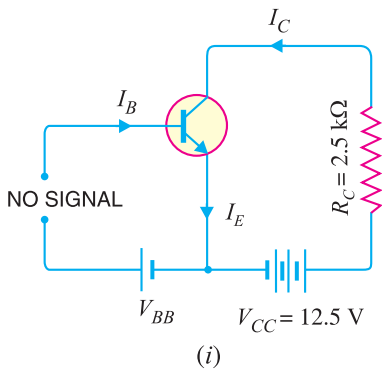


Fig. 8.38

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

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 $V_{CC} = 12\text{V}$ and $R_C = 6\text{ k}\Omega$, draw the d.c. load line. What will be the Q point if zero signal base current is $20\mu\text{A}$ and $\beta = 50$?

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

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

When $I_C = 0$, $V_{CE} = V_{CC} = 12\text{ V}$. This locates the point B of the load line. When $V_{CE} = 0$, $I_C = V_{CC}/R_C = 12\text{ V}/6\text{ k}\Omega = 2\text{ mA}$. 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, $I_B = 20\text{ }\mu\text{A} = 0.02\text{ mA}$

Current amplification factor, $\beta = 50$

\therefore Zero signal collector current, $I_C = \beta I_B = 50 \times 0.02 = 1\text{ mA}$

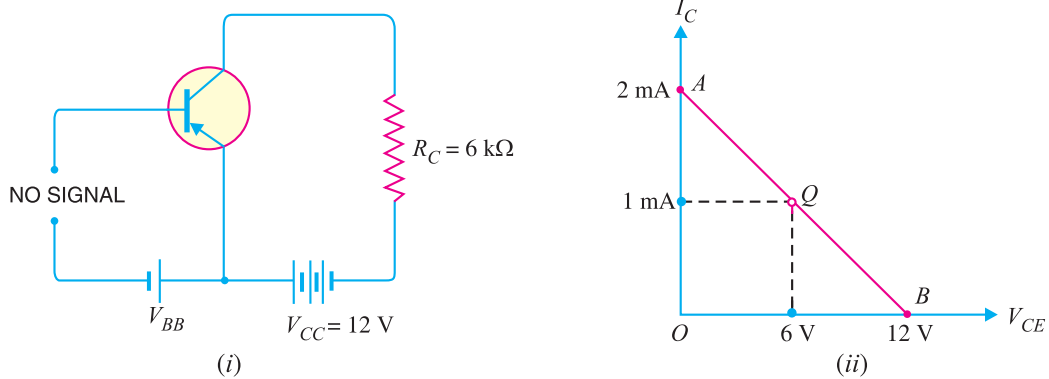


Fig. 8.39

Zero signal collector-emitter voltage is

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

\therefore Operating point is **6 V, 1 mA**.

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

Example 8.24. In a transistor circuit, collector load is $4\text{ k}\Omega$ whereas quiescent current (zero signal collector current) is 1 mA .

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

(ii) What will be the operating point if $R_C = 5\text{ k}\Omega$?

Solution.

$$V_{CC} = 10\text{ V}, I_C = 1\text{ mA}$$

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

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

\therefore Operating point is **6 V, 1 mA**.

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

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

\therefore 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 $\beta = 200$ and $V_{BE} = 0.7\text{ V}$.

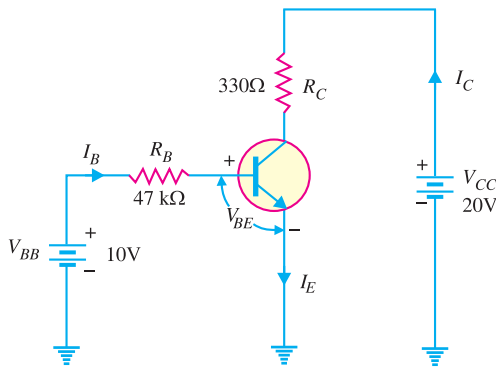


Fig 8.40

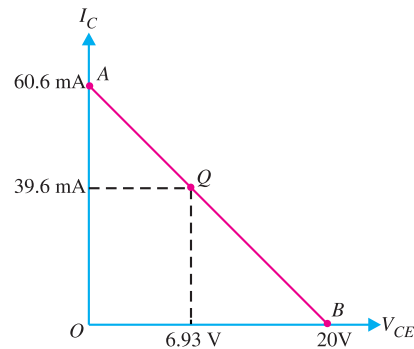


Fig. 8.41

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,

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

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

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

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

Therefore, the Q-point is $I_C = 39.6 \text{ mA}$ 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 $V_{CE} = 0$, $I_C = V_{CC}/R_C = 20V/330\Omega = 60.6 \text{ mA}$. 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 $V_{BE} = 0.7V$.

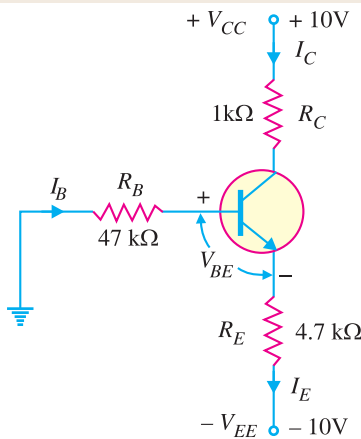


Fig. 8.42

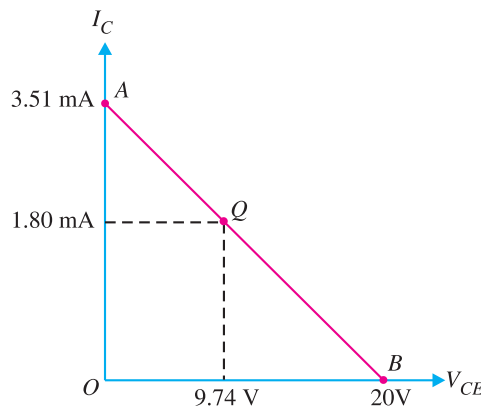


Fig. 8.43

* The presence of two power supplies has an effect on the basic 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 $V_{EE} = -10V$ (d.c.).

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

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
$$V_{CE} = V_{CC} + V_{EE} - I_C (R_C + R_E) \quad (\text{Q } I_E \approx I_C)$$

$$= 10\text{V} + 10\text{V} - 1.8\text{ mA} (1\text{ k}\Omega + 4.7\text{ k}\Omega) = 9.74\text{V}$$

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

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 ($OB = 20\text{V}$) of the load line on the collector-emitter voltage axis. When $V_{CE} = 0$,

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

This locates the second point A ($OA = 3.51\text{ mA}$) 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.

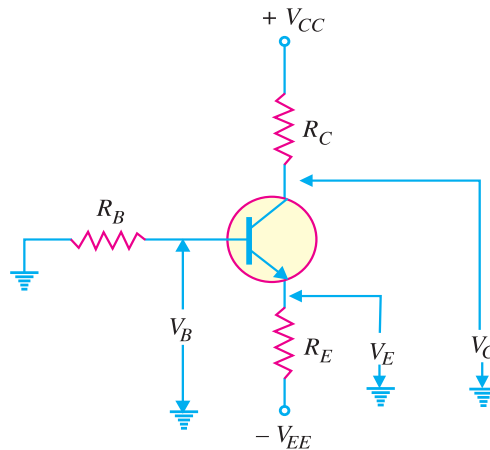


Fig. 8.44

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

Solution. Refer to Fig. 8.44.

(i) The emitter voltage w.r.t. ground is

$$V_E = -V_{EE} + I_E R_E = -10\text{V} + 1.8\text{ mA} \times 4.7\text{ k}\Omega = -1.54\text{V}$$

(ii) The base voltage w.r.t. ground is

$$V_B = V_E + V_{BE} = 10\text{V} + 0.7\text{V} = 10.7\text{V}$$

(iii) The collector voltage w.r.t. ground is

$$V_C = V_{CC} - I_C R_C = 10\text{V} - 1.8\text{ mA} \times 1\text{ k}\Omega = 8.2\text{V}$$

8.19 Practical Way of Drawing CE Circuit

The common emitter circuits drawn so far can be shown in another convenient way. Fig. 8.45 shows the practical way of drawing CE circuit. In Fig. 8.45 (i), the practical way of drawing common emitter npn circuit is shown. Similarly, Fig. 8.45 (ii) shows the practical way of drawing common emitter pnp circuit. In our further discussion, we shall often use this scheme of presentation.

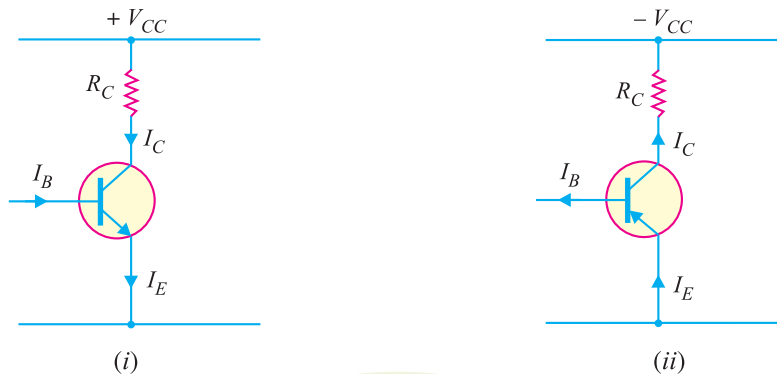


Fig. 8.45

8.20 Output from Transistor Amplifier

A transistor raises the strength of a weak signal and thus acts as an amplifier. Fig. 8.46 shows the common emitter amplifier. There are two ways of taking output from this transistor connection. The output can be taken either across R_C or across terminals 1 and 2. In either case, the magnitude of output is the same. This is clear from the following discussion :

(i) **First method.** We can take the output directly by putting a load resistance R_C in the collector circuit *i.e.*

$$\text{Output} = \text{voltage across } R_C = i_c R_C \quad \dots(i)$$

This method of taking output from collector load is used only in single stage of amplification.

(ii) **Second method.** The output can also be taken across terminals 1 and 2 *i.e.* from collector and emitter end of supply.

$$\begin{aligned} \text{Output} &= \text{Voltage across terminals 1 and 2} \\ &= V_{CC} - i_c R_C \end{aligned}$$

As V_{CC} is a direct voltage and cannot pass through capacitor C_C , therefore, only varying voltage $i_c R_C$ will appear across terminals 1 and 2.

$$\therefore \text{Output} = -i_c R_C \quad \dots(ii)$$

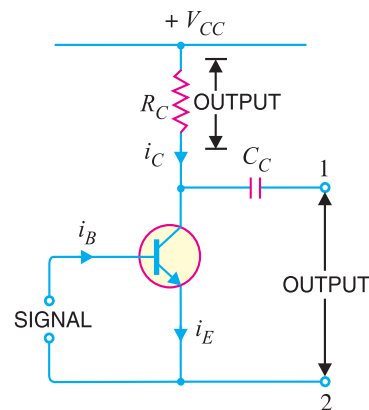


Fig. 8.46

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From exps. (i) and (ii), it is clear that magnitude of output is the same whether we take output across collector load or terminals 1 and 2. The minus sign in exp. (ii) simply indicates the phase reversal. The second method of taking output is used in multistages of amplification.

8.21 Performance of Transistor Amplifier

The performance of a transistor amplifier depends upon input resistance, output resistance, effective collector load, current gain, voltage gain and power gain. As *common emitter connection* is universally adopted, therefore, we shall explain these terms with reference to this mode of connection.

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

$$\text{Input resistance, } R_i = \frac{\Delta V_{BE}}{\Delta I_B}$$

The value of input resistance is quite small because the input circuit is always forward biased. It ranges from 500Ω for small low powered transistors to as low as 5Ω for high powered transistors. In fact, input resistance is the opposition offered by the base-emitter junction to the signal flow. Fig. 8.47 shows the general form of an amplifier. The input voltage V_{BE} causes an input current I_B .

$$\therefore \text{Input resistance, } R_i = \frac{\Delta V_{BE}}{\Delta I_B} = \frac{V_{BE}}{I_B}$$

Thus if the input resistance of an amplifier is 500Ω and the signal voltage at any instant is 1 V, then,

$$\text{Base current, } i_b = \frac{1V}{500 \Omega} = 2 \text{ mA}$$

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

$$\text{Output resistance, } R_o = \frac{\Delta V_{CE}}{\Delta I_C}$$

The output characteristics reveal that collector current changes very slightly with the change in collector-emitter voltage. Therefore, output resistance of a transistor amplifier is very high—of the order of several hundred kilo-ohms. The physical explanation of high output resistance is that collector-base junction is reverse biased.

(iii) Effective collector load. It is the total load as seen by the a.c. collector current.

In case of single stage amplifiers, the effective collector load is a parallel combination of R_C and R_o as shown in Fig. 8.48 (i).

$$\begin{aligned} \text{Effective collector load, } R_{AC} &= R_C \parallel R_o \\ &= \frac{R_C \times R_o}{R_C + R_o} = *R_C \end{aligned}$$

It follows, therefore, that for a single stage amplifier, effective load is equal to collector load R_C .

However, in a multistage amplifier (i.e. having more than one amplification stage), the input resistance R_i of the next stage also comes into picture as shown in Fig. 8.48 (ii). Therefore, effective collector load becomes parallel combination of R_C , R_o and R_i i.e.

$$\text{Effective collector load, } R_{AC} = R_C \parallel R_o \parallel R_i$$

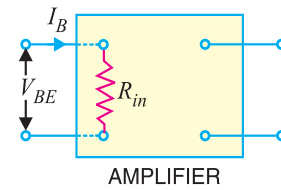


Fig. 8.47

* As output resistance R_o is several times R_C , therefore, R_C can be neglected as compared to R_o .

$$R_{AC} = \frac{R_C \times R_o}{R_o} = R_C$$

$$= *R_C \parallel R_i = \frac{R_C R_i}{R_C + R_i}$$

As input resistance R_i is quite small (25 Ω to 500 Ω), therefore, effective load is reduced.

(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.

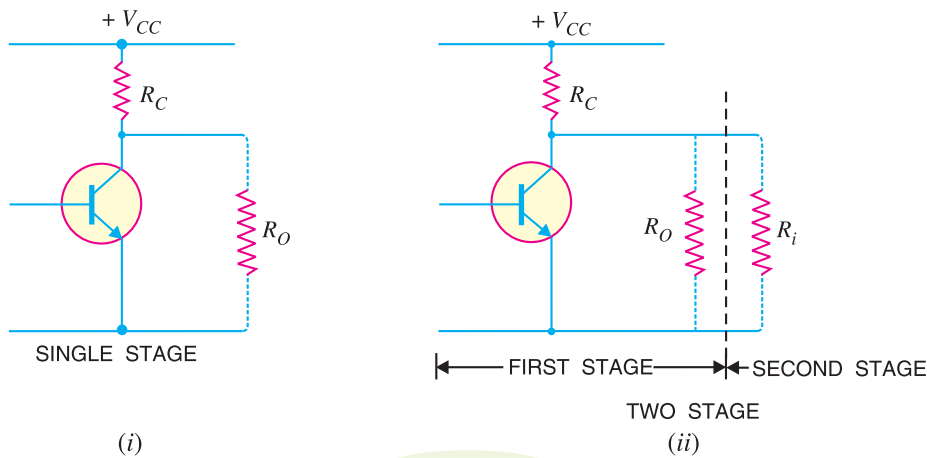


Fig. 8.48

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

$$\begin{aligned} \text{Voltage gain, } A_v &= \frac{\Delta V_{CE}}{\Delta V_{BE}} \\ &= \frac{\text{Change in output current} \times \text{effective load}}{\text{Change in input current} \times \text{input resistance}} \\ &= \frac{\Delta I_C \times R_{AC}}{\Delta I_B \times R_i} = \frac{\Delta I_C}{\Delta I_B} \times \frac{R_{AC}}{R_i} = \beta \times \frac{R_{AC}}{R_i} \end{aligned}$$

For single stage, $R_{AC} = R_C$. However, for multistage, $R_{AC} = \frac{R_C \times R_i}{R_C + R_i}$ 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.

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

Example 8.28. A change of 200 mV in base-emitter voltage causes a change of 100 μA in the base current. Find the input resistance of the transistor.

Solution. Change in base-emitter voltage is

* $R_C \parallel R_O = R_C$ as already explained.

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$$\begin{aligned} \Delta V_{BE} &= 200 \text{ mV} \\ \text{Change in base current, } \Delta I_B &= 100 \text{ } \mu\text{A} \\ \therefore \text{ Input resistance, } R_i &= \frac{\Delta V_{BE}}{\Delta I_B} = \frac{200 \text{ mV}}{100 \text{ } \mu\text{A}} = \mathbf{2 \text{ k}\Omega} \end{aligned}$$

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

Solution. Change in collector-emitter voltage is

$$\begin{aligned} \Delta V_{CE} &= 10 - 2 = 8 \text{ V} \\ \text{Change in collector current is } \Delta I_C &= 3 - 2 = 1 \text{ mA} \\ \therefore \text{ Output resistance, } R_o &= \frac{\Delta V_{CE}}{\Delta I_C} = \frac{8 \text{ V}}{1 \text{ mA}} = \mathbf{8 \text{ k}\Omega} \end{aligned}$$

Example 8.30. For a single stage transistor amplifier, the collector load is $R_C = 2 \text{ k}\Omega$ and the input resistance $R_i = 1 \text{ k}\Omega$. 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, $\beta = 50$

$$\begin{aligned} \therefore \text{ Voltage gain, } A_v &= \beta \times \frac{R_{AC}}{R_i} = \beta \times \frac{R_C}{R_i} \quad [\because \text{ For single stage, } R_{AC} = R_C] \\ &= 50 \times (2/1) = \mathbf{100} \end{aligned}$$

8.22 Cut off and Saturation Points

Fig. 8.49 (i) shows CE transistor circuit while Fig. 8.49 (ii) shows the output characteristics 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_{CE0}) 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.

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

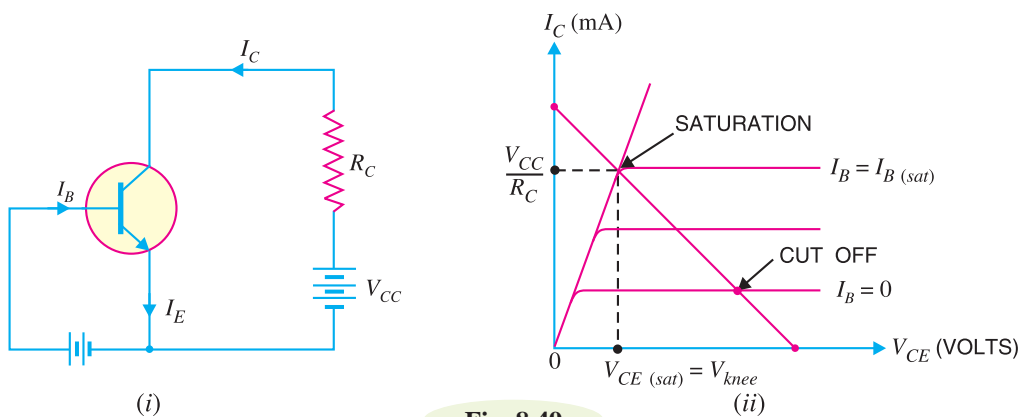


Fig. 8.49

(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.

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

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**.

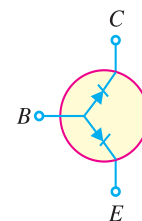


Fig. 8.50

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)].

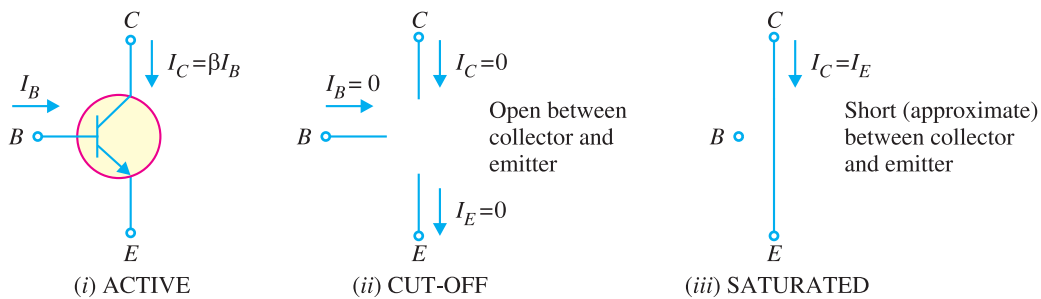


Fig. 8.51

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.

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

* 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).

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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} .

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

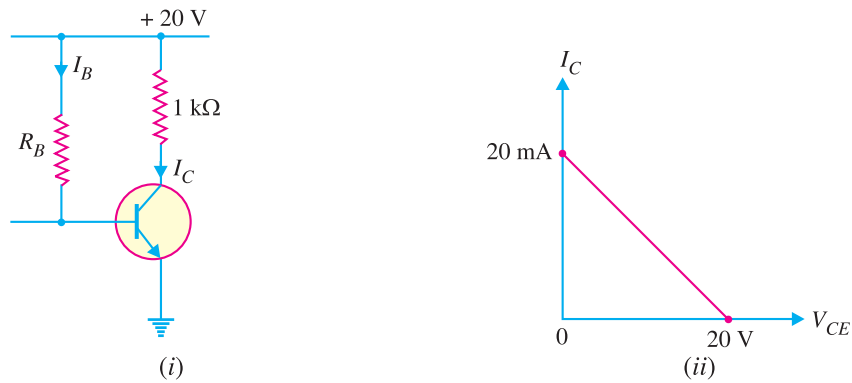


Fig. 8.52

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 $V_{CE(\text{cut-off})} = V_{CC} - I_{CEO} R_C$. 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 $V_{CE(\text{off})}$ and $I_{C(\text{sat})}$ for the circuit shown in Fig. 8.53.

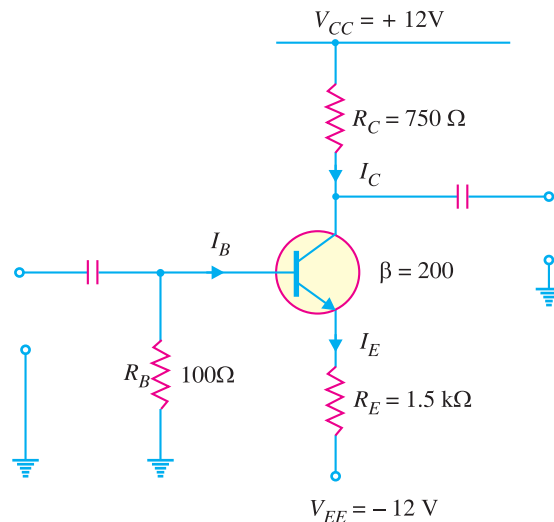


Fig. 8.53

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

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

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

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

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

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

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

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

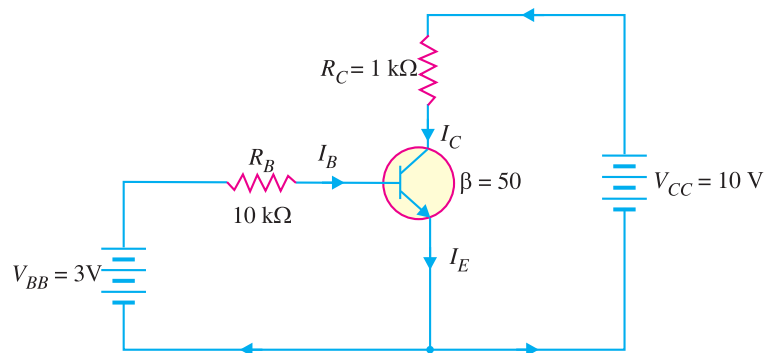


Fig. 8.54

Solution.

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

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

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

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

This shows that with specified β , this base current ($= 0.23\text{ mA}$) 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 ($= 9.8\text{ mA}$).

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

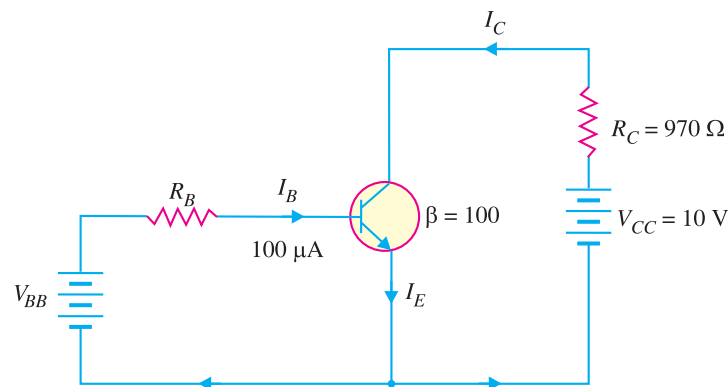


Fig. 8.55

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Solution.

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

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

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

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 $V_{CE} = 0.3\text{V}$. 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**.

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 approximately by closing the imaginary switch between the collector and the emitter in the collector circuit.

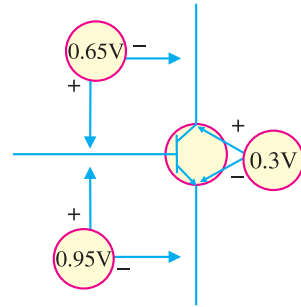


Fig. 8.56

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 $\beta = 200$.

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.

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

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

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

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

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

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

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

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

Therefore, for $V_{BB} \geq 1.95$, 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) $R_C = 2 \text{ k}\Omega$ (ii) $R_C = 4 \text{ k}\Omega$ (iii) $R_C = 8 \text{ k}\Omega$

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.

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

$$= 2.7\text{V} - 0.7 \text{ V} = 2\text{V}$$

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

(i) **When $R_C = 2 \text{ k}\Omega$.** Suppose the transistor is active.

$$\therefore I_C = I_E = 2 \text{ mA}$$

$$\therefore I_B = I_C / \beta = 2 \text{ mA} / 100 = 0.02 \text{ mA}$$

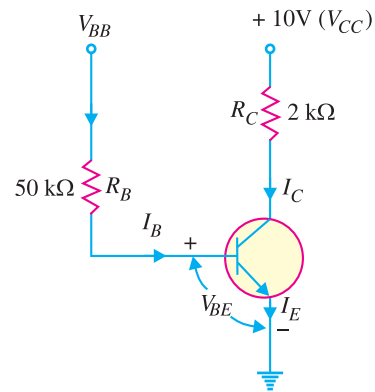


Fig. 8.57

$$\begin{aligned} \text{Collector voltage, } V_C &= V_{CC} - I_C R_C \\ &= 10\text{V} - 2\text{ mA} \times 2\text{ k}\Omega = 10\text{V} - 4\text{V} = 6\text{V} \end{aligned}$$

Since $V_C (= 6\text{V})$ is greater than $V_E (= 2\text{V})$, the transistor is **active**. Therefore, our assumption that transistor is active is correct.

(ii) When $R_C = 4\text{ k}\Omega$. Suppose the transistor is active.

$$\begin{aligned} \therefore I_C &= 2\text{ mA} \text{ and } I_B = 0.02\text{ mA} \dots \text{ as found above} \\ \text{Collector voltage, } V_C &= V_{CC} - I_C R_C \\ &= 10\text{V} - 2\text{ mA} \times 4\text{ k}\Omega = 10\text{V} - 8\text{V} = 2\text{V} \end{aligned}$$

Since $V_C = V_E$, the transistor is just at the edge of **saturation**. We know that at the edge of saturation, the relation between the transistor currents is the same as in the **active state**. Both answers are correct.

(iii) When $R_C = 8\text{ k}\Omega$. Suppose the transistor is active.

$$\therefore I_C = 2\text{ mA} ; I_B = 0.02\text{ mA} \dots \text{ as found earlier.}$$

$$\begin{aligned} \text{Collector voltage, } V_C &= V_{CC} - I_C R_C \\ &= 10\text{V} - 2\text{ mA} \times 8\text{ k}\Omega = 10\text{V} - 16\text{V} = -6\text{V} \end{aligned}$$

Since $V_C < V_E$, the transistor is **saturated** and our assumption is not correct.

Example 8.37. In the circuit shown in Fig. 8.59, V_{BB} is set equal to the following values :

(i) $V_{BB} = 0.5\text{V}$ (ii) $V_{BB} = 1.5\text{V}$ (iii) $V_{BB} = 3\text{V}$

Determine the state of the transistor for each value of the base supply voltage V_{BB} .

Solution. The state of the transistor also depends on the base supply voltage V_{BB} .

(i) For $V_{BB} = 0.5\text{V}$

Because the base voltage $V_B (= V_{BB} = 0.5\text{V})$ is less than 0.7V , the transistor is **cut-off**.

(ii) For $V_{BB} = 1.5\text{V}$

The base voltage V_B controls the emitter voltage V_E which controls the emitter current I_E .

$$\text{Now } V_E = V_B - 0.7\text{V} = 1.5\text{V} - 0.7\text{V} = 0.8\text{V}$$

$$\therefore I_E = \frac{V_E}{R_E} = \frac{0.8\text{V}}{1\text{ k}\Omega} = 0.8\text{ mA}$$

If the transistor is active, we have,

$$I_C = I_E = 0.8\text{ mA} \text{ and } I_B = I_C / \beta = 0.8 / 100 = 0.008\text{ mA}$$

$$\begin{aligned} \therefore \text{Collector voltage, } V_C &= V_{CC} - I_C R_C \\ &= 15\text{V} - 0.8\text{ mA} \times 10\text{ k}\Omega = 15\text{V} - 8\text{V} = 7\text{V} \end{aligned}$$

Since $V_C > V_E$, the transistor is **active** and our assumption is correct.

(iii) For $V_{BB} = 3\text{V}$

$$V_E = V_B - 0.7\text{V} = 3\text{V} - 0.7\text{V} = 2.3\text{V}$$

$$\therefore I_E = \frac{V_E}{R_E} = \frac{2.3\text{V}}{1\text{ k}\Omega} = 2.3\text{ mA}$$

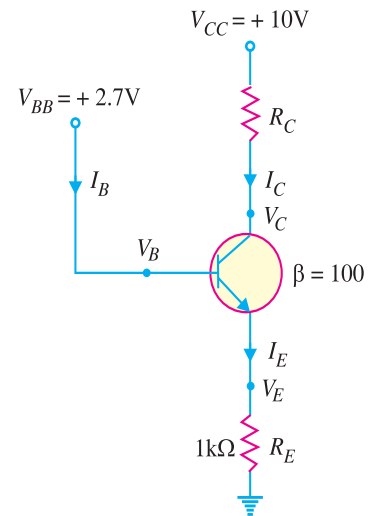


Fig. 8.58

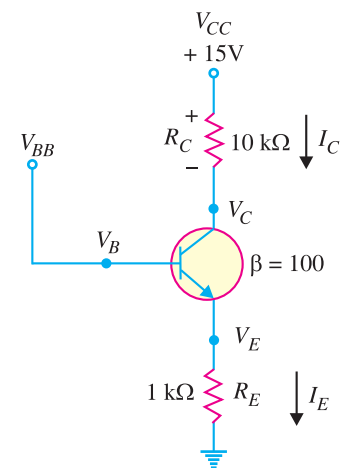


Fig. 8.59

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Assuming the transistor is active, we have,

$$I_C = I_E = 2.3 \text{ mA} \quad ; \quad I_B = I_C / \beta = 2.3 / 100 = 0.023 \text{ mA}$$

$$\begin{aligned} \text{Collector voltage, } V_C &= V_{CC} - I_C R_C \\ &= 15\text{V} - 2.3 \text{ mA} \times 10 \text{ k}\Omega = 15\text{V} - 23\text{V} = -8\text{V} \end{aligned}$$

Since $V_C < V_E$, the transistor is **saturated** and our assumption is not correct.

8.23 Power Rating of Transistor

The maximum power that a transistor can handle without destruction is known as **power rating** of the transistor.

When a transistor is in operation, almost all the power is dissipated at the reverse biased *collector-base junction. The power rating (or maximum power dissipation) is given by :

$$\begin{aligned} P_{D(max)} &= \text{Collector current} \times \text{Collector-base voltage} \\ &= I_C \times V_{CB} \\ \therefore P_{D(max)} &= I_C \times V_{CE} \\ [\because V_{CE} &= V_{CB} + V_{BE}. \text{ Since } V_{BE} \text{ is very small, } V_{CB} \approx V_{CE}] \end{aligned}$$

While connecting transistor in a circuit, it should be ensured that its power rating is not exceeded otherwise the transistor may be destroyed due to excessive heat. For example, suppose the power rating (or maximum power dissipation) of a transistor is 300 mW. If the collector current is 30 mA, then maximum V_{CE} allowed is given by ;

$$\begin{aligned} P_{D(max)} &= I_C \times V_{CE(max)} \\ \text{or } 300 \text{ mW} &= 30 \text{ mA} \times V_{CE(max)} \\ \text{or } V_{CE(max)} &= \frac{300 \text{ mW}}{30 \text{ mA}} = 10\text{V} \end{aligned}$$

This means that for $I_C = 30 \text{ mA}$, the maximum V_{CE} allowed is 10V. If V_{CE} exceeds this value, the transistor will be destroyed due to excessive heat.

Maximum power dissipation curve. For **power transistors, it is sometimes necessary to draw maximum power dissipation curve on the output characteristics. To draw this curve, we should know the power rating (*i.e.* maximum power dissipation) of the transistor. Suppose the power rating of a transistor is 30 mW.

$$\begin{aligned} P_{D(max)} &= V_{CE} \times I_C \\ \text{or } 30 \text{ mW} &= V_{CE} \times I_C \end{aligned}$$

Using convenient V_{CE} values, the corresponding collector currents are calculated for the maximum power dissipation. For example, for $V_{CE} = 10\text{V}$,

$$I_C(max) = \frac{P_{D(max)}}{V_{CE}} = \frac{30 \text{ mW}}{10 \text{ V}} = 3\text{mA}$$

This locates the point A (10V, 3 mA) on the output characteristics. Similarly, many points such as B, C, D etc. can be located on the output characteristics. Now draw a curve through the above points to obtain the maximum power dissipation curve as shown in Fig. 8.60.

In order that transistor may not be destroyed, the transistor voltage and current (*i.e.* V_{CE} and I_C) conditions must at all times be maintained in the portion of the characteristics below the maximum power dissipation curve.

* The base-emitter junction conducts about the same current as the collector-base junction (*i.e.* $I_E \approx I_C$). However, V_{BE} is very small (0.3 V for Ge transistor and 0.7 V for Si transistor). For this reason, power dissipated at the base-emitter junction is negligible.

** A transistor that is suitable for large power amplification is called a **power transistor**. It differs from other transistors mostly in size ; it is considerably larger to provide for handling the great amount of power.

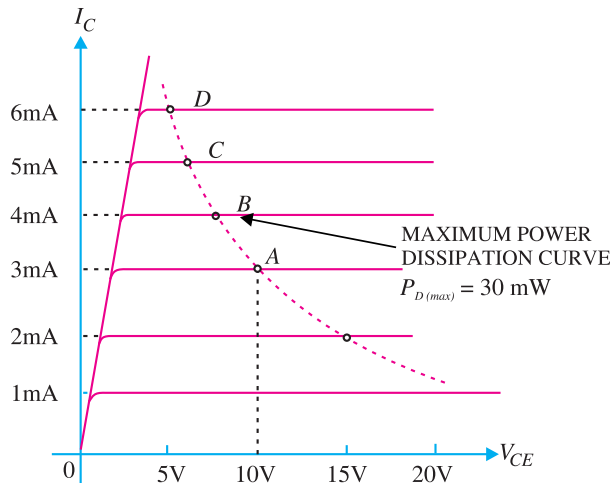


Fig. 8.60

Example 8.38. The maximum power dissipation of a transistor is 100mW. If $V_{CE} = 20V$, what is the maximum collector current that can be allowed without destruction of the transistor?

Solution.

$$P_{D(max)} = V_{CE} \times I_{C(max)}$$

or

$$100 \text{ mW} = 20 \text{ V} \times I_{C(max)}$$

$$\therefore I_{C(max)} = \frac{100 \text{ mW}}{20 \text{ V}} = 5 \text{ mA}$$

Thus for $V_{CE} = 20V$, the maximum collector current allowed is 5 mA. If collector current exceeds this value, the transistor may be burnt due to excessive heat.

Note. Suppose the collector current becomes 7mA. The power produced will be $20 \text{ V} \times 7 \text{ mA} = 140 \text{ mW}$. The transistor can only dissipate 100 mW. The remaining 40 mW will raise the temperature of the transistor and eventually it will be burnt due to excessive heat.

Example 8.39. For the circuit shown in Fig. 8.61, find the transistor power dissipation. Assume that $\beta = 200$.

Solution.

$$I_B = \frac{V_{BB} - V_{BE}}{R_B} = \frac{(5 - 0.7) \text{ V}}{1 \text{ k}\Omega} = 4.3 \text{ mA}$$

$$\therefore I_C = \beta I_B = 200 \times 4.3 = 860 \text{ mA}$$

Now $V_{CE} = V_{CC} - I_C R_C = 5 - I_C \times 0 = 5V$

$$\therefore \text{Power dissipation, } P_D = V_{CE} \times I_C = 5V \times 860 \text{ mA} = 4300 \text{ mW} = 4.3W$$

Example 8.40. For the circuit shown in Fig. 8.62, find the power dissipated in the transistor. Assume $\beta = 100$.

Solution. The transistor is usually used with a resistor R_C connected between the collector and its power supply V_{CC} as shown in Fig. 8.62. The collector resistor R_C serves two purposes. Firstly, it allows us to control the voltage V_C at the collector. Secondly, it protects the transistor from excessive collector current I_C and, therefore, from excessive power dissipation.

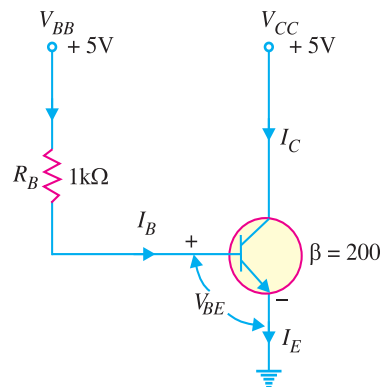


Fig. 8.61

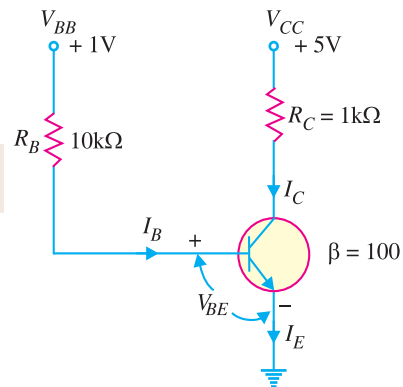


Fig. 8.62

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Referring to Fig. 8.62 and applying Kirchhoff's voltage law to the base side, we have,

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

$$\therefore I_B = \frac{V_{BB} - V_{BE}}{R_B} = \frac{1\text{V} - 0.7\text{V}}{10\text{ k}\Omega} = \frac{0.3\text{V}}{10\text{ k}\Omega} = 0.03\text{ mA}$$

Now $I_C = \beta I_B = 100 \times 0.03 = 3\text{ mA}$

$$\therefore V_{CE} = V_{CC} - I_C R_C = 5\text{V} - 3\text{ mA} \times 1\text{ k}\Omega = 5\text{V} - 3\text{V} = 2\text{V}$$

\therefore Power dissipated in the transistor is

$$P_D = V_{CE} \times I_C = 2\text{V} \times 3\text{ mA} = \mathbf{6\text{ mW}}$$

Example 8.41. The transistor in Fig. 8.63 has the following maximum ratings :

$$P_{D(max)} = 800\text{ mW}; V_{CE(max)} = 15\text{V}; I_{C(max)} = 100\text{ mA}$$

Determine the maximum value to which V_{CC} can be adjusted without exceeding any rating. Which rating would be exceeded first ?

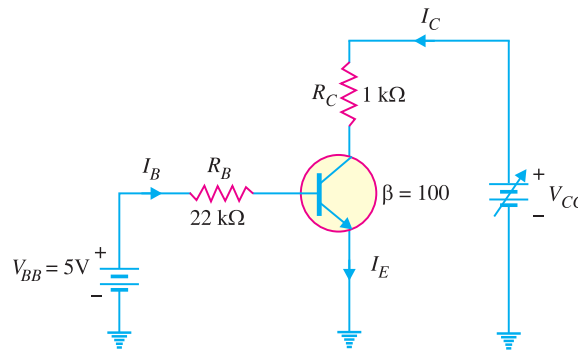


Fig. 8.63

Solution.

$$I_B = \frac{V_{BB} - V_{BE}}{R_B} = \frac{5\text{V} - 0.7\text{V}}{22\text{ k}\Omega} = \frac{4.3\text{V}}{22\text{ k}\Omega} = 195\text{ }\mu\text{A}$$

$$\therefore I_C = \beta I_B = 100 \times 195\text{ }\mu\text{A} = 19.5\text{ mA}$$

Note that I_C is much less than $I_{C(max)}$ and will not change with V_{CC} . It is determined only by I_B and β . Therefore, **current rating is not exceeded.**

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

We can find the value of V_{CC} when $V_{CE(max)} = 15\text{V}$.

$$\therefore V_{CC(max)} = V_{CE(max)} + I_C R_C$$

$$= 15\text{V} + 19.5\text{ mA} \times 1\text{ k}\Omega = 15\text{V} + 19.5\text{ V} = 34.5\text{V}$$

Therefore, we can increase V_{CC} to **34.5V** before $V_{CE(max)}$ is reached.

$$P_D = V_{CE(max)} I_C = (15\text{V})(19.5\text{ mA}) = 293\text{ mW}$$

Since $P_{D(max)} = 800\text{ mW}$, **it is not exceeded** when $V_{CC} = 34.5\text{V}$.

If base current is removed causing the transistor to turn off, $V_{CE(max)}$ **will be exceeded** because the entire supply voltage V_{CC} will be dropped across the transistor.

8.24. Determination of Transistor Configuration

In practical circuits, you must be able to tell whether a given transistor is connected as a common emitter, common base or common collector. There is an easy way to ascertain it. Just locate the terminals where the input a.c. signal is applied to the transistor and where the a.c. output is taken from the transistor. The remaining third terminal is the common terminal. For instance, if the a.c. input is

applied to the base and the a.c output is taken from the collector, then common terminal is the emitter. Hence the transistor is connected in **common emitter configuration**. If the a.c. input is applied to the base and a.c output is taken from the emitter, then common terminal is the collector. Therefore, the transistor is connected in **common collector configuration**.

8.25 Semiconductor Devices Numbering System

From the time semiconductor engineering came to existence, several numbering systems were adopted by different countries. However, the accepted numbering system is that announced by Proelectron Standardisation Authority in Belgium. According to this system of numbering semiconductor devices :

(i) Every semiconductor device is numbered by five alpha-numeric symbols, comprising either two letters and three numbers (e.g. BF194) or three letters and two numbers (e.g. BFX63). When two numbers are included in the symbol (e.g. BFX63), the device is intended for industrial and professional equipment. When the symbol contains three numbers (e.g. BF194), the device is intended for entertainment or consumer equipment.

(ii) The first letter indicates the nature of semiconductor material. For example :
 A = germanium, B = silicon, C = gallium arsenide, R = compound material (e.g. cadmium sulphide)
 Thus AC125 is a germanium transistor whereas BC149 is a silicon transistor.

(iii) The second letter indicates the device and circuit function.

- | | |
|------------------------------------|--------------------------------|
| A = diode | B = Variable capacitance diode |
| C = A.F. low powered transistor | D = A.F. power transistor |
| E = Tunnel diode | F = H.F. low power transistor |
| G = Multiple device | H = Magnetic sensitive diode |
| K = Hall-effect device | L = H.F. power transistor |
| M = Hall-effect modulator | P = Radiation sensitive diode |
| Q = Radiation generating diode | R = Thyristor (SCR or triac) |
| S = Low power switching transistor | T = Thyristor (power) |
| U = Power switching transistor | X = diode, multiplier |
| Y = Power device | Z = Zener diode |

8.26 Transistor Lead Identification

There are three leads in a transistor viz. collector, emitter and base. When a transistor is to be connected in a circuit, it is necessary to know which terminal is which. The identification of the leads of transistor varies with manufacturer. However, there are three systems in general use as shown in Fig. 8.64.

(i) When the leads of a transistor are in the same plane and unevenly spaced [See Fig. 8.64 (i)], they are identified by the positions and spacings of leads. The central lead is the base lead. The collector lead is identified by the larger spacing existing between it and the base lead. The remaining lead is the emitter.

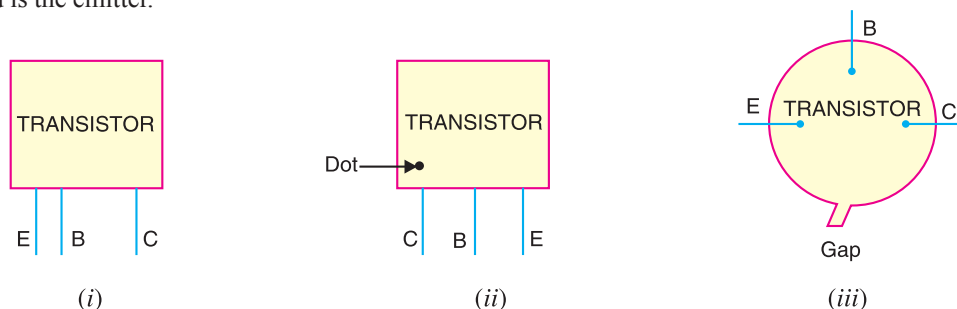


Fig. 8.64

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(ii) When the leads of a transistor are in the same plane but evenly spaced [See Fig. 8.64 (ii)], the central lead is the base, the lead identified by dot is the collector and the remaining lead is the emitter.

(iii) When the leads of a transistor are spaced around the circumference of a circle [See Fig. 8.64 (iii)], the three leads are generally in E-B-C order clockwise from a gap.

8.27 Transistor Testing

An ohmmeter can be used to check the state of a transistor *i.e.*, whether the transistor is good or not. We know that base-emitter junction of a transistor is forward biased while collector-base junction is reverse biased. Therefore, forward biased base-emitter junction should have low resistance and reverse biased collector-base junction should register a much higher resistance. Fig. 8.65 shows the process of testing an *npn* transistor with an ohmmeter.

(i) The forward biased base-emitter junction (biased by internal supply) should read a low resistance, typically $100\ \Omega$ to $1\ \text{k}\Omega$ as shown in Fig. 8.65 (i). If that is so, the transistor is good. However, if it fails this check, the transistor is faulty and it must be replaced.

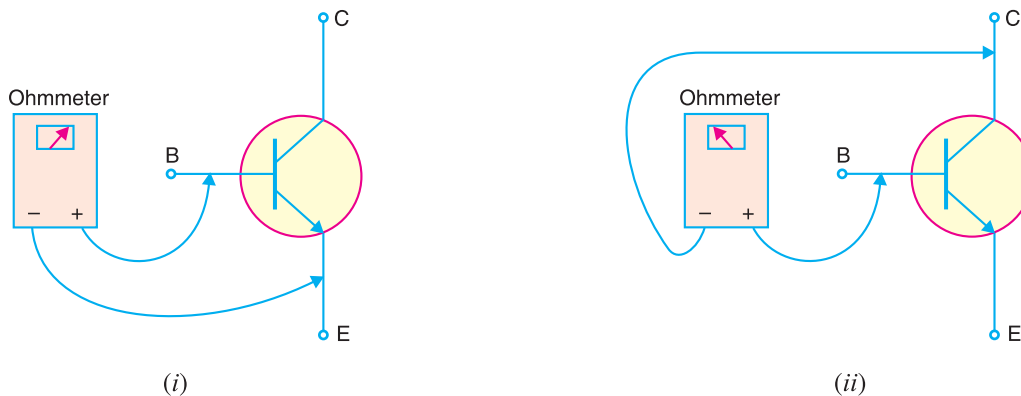


Fig. 8.65

(ii) The reverse biased collector-base junction (again reverse biased by internal supply) should be checked as shown in Fig. 8.65 (ii). If the reading of the ohmmeter is $100\ \text{k}\Omega$ or higher, the transistor is good. If the ohmmeter registers a small resistance, the transistor is faulty and requires replacement.

Note. When testing a *pnp* transistor, the ohmmeter leads must be reversed. The results of the tests, however, will be the same.

8.28 Applications of Common Base Amplifiers

Common base amplifiers are not used as frequently as the *CE* amplifiers. The two important applications of *CB* amplifiers are : (i) to provide voltage gain without current gain and (ii) for impedance matching in high frequency applications. Out of the two, the high frequency applications are far more common.

(i) **To provide voltage gain without current gain.** We know that a *CB* amplifier has a high voltage gain while the current gain is nearly 1 (*i.e.* $A_i \simeq 1$). Therefore, this circuit can be used to provide high voltage gain without increasing the value of circuit current. For instance, consider the case where the output current from an amplifier has sufficient value for the required application but the voltage gain needs to be increased. In that case, *CB* amplifier will serve the purpose because it

would increase the voltage without increasing the current. This is illustrated in Fig. 8.66. The *CB* amplifier will provide voltage gain without any current gain.

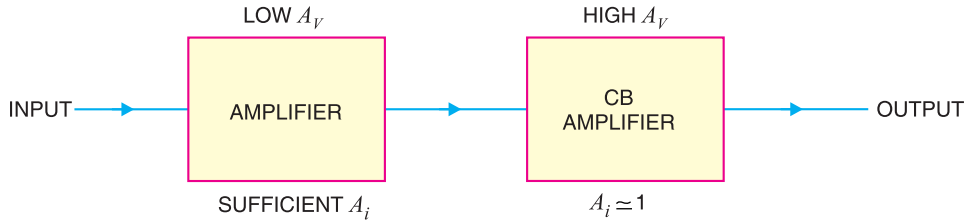


Fig. 8.66

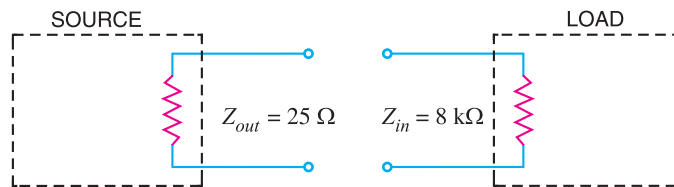


Fig. 8.67

(ii) **For impedance matching in high frequency applications.** Most high-frequency voltage sources have a very *low output impedance*. When such a low-impedance source is to be connected to a high-impedance load, you need a circuit to match the source impedance to the load impedance. Since a common-base amplifier has *low input impedance* and *high output impedance*, the common-base circuit will serve well in this situation. Let us illustrate this point with a numerical example. Suppose a high-frequency source with internal resistance $25\ \Omega$ is to be connected to a load of $8\ \text{k}\Omega$ as shown in Fig. 8.67. If the source is directly connected to the load, small source power will be transferred to the load due to mismatching. However, it is possible to design a *CB* amplifier that has an input impedance of nearly $25\ \Omega$ and output impedance of nearly $8\ \text{k}\Omega$. If such a *CB* circuit is placed between the source and the load, the source will be matched to the load as shown in Fig. 8.68.

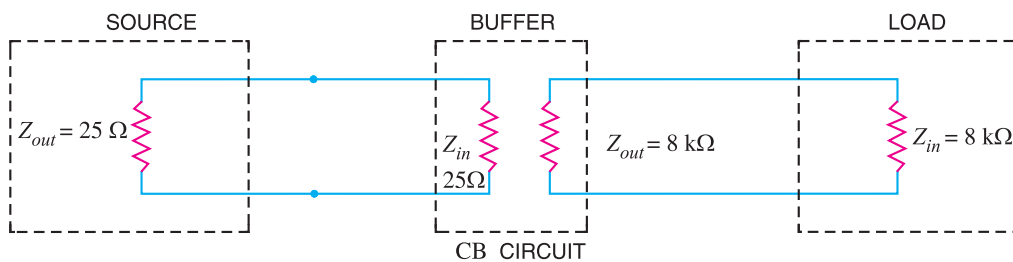


Fig. 8.68

Note that source impedance very closely matches the input impedance of *CB* amplifier. Therefore, there is a maximum power transfer from the source to input of *CB* amplifier. The high output impedance of the amplifier very nearly matches the load resistance. As a result, there is a maximum power transfer from the amplifier to the load. The net result is that maximum power has been transferred from the original source to the original load. A common-base amplifier that is used for this purpose is called a *buffer amplifier*.

8.29 Transistors Versus Vacuum Tubes

Advantages of transistors

A transistor is a solid-state device that performs the same functions as the grid-controlled vacuum tube. However, due to the following advantages, the transistors have upstaged the vacuum tubes in most areas of electronics :

(i) High voltage gain. We can get much more voltage gain with a transistor than with a vacuum tube. Triode amplifiers normally have voltage gain of less than 75. On the other hand, transistor amplifiers can provide a voltage gain of 300 or more. This is a distinct advantage of transistors over the tubes.

(ii) Lower supply voltage. Vacuum tubes require much higher d.c. voltages than transistors. Vacuum tubes generally run at d.c. voltages ranging from 200V to 400V whereas transistors require much smaller d.c. voltages for their operation. The low voltage requirement permits us to build portable, light-weight transistor equipment instead of heavier vacuum-tube equipment.

(iii) No heating. A transistor does not require a heater whereas the vacuum tube can only operate with a heater. The heater requirement in vacuum tubes poses many problems. First, it makes the power supply bulky. Secondly, there is a problem of getting rid of heat. The heater limits the tube's useful life to a few thousand hours. Transistors, on the other hand, last for many years. This is the reason that transistors are permanently soldered into a circuit whereas tubes are plugged into sockets.

(iv) Miscellaneous. Apart from the above salient advantages, the transistors have superior edge over the tubes in the following respects :

- (a)** transistors are much smaller than vacuum tubes. This means that transistor circuits can be more compact and light-weight.
- (b)** transistors are mechanically strong due to solid-state.
- (c)** transistors can be integrated along with resistors and diodes to produce ICs which are extremely small in size.

Disadvantages of transistors

Although transistors are constantly maintaining superiority over the vacuum tubes, yet they suffer from the following drawbacks :

(i) Lower power dissipation. Most power transistors have power dissipation below 300W while vacuum tubes can easily have power dissipation in kW. For this reason, transistors cannot be used in high power applications e.g. transmitters, industrial control systems, microwave systems etc. In such areas, vacuum tubes find wide applications.

(ii) Lower input impedance. A transistors has low input impedance. A vacuum tube, on the other hand, has very high input impedance (of the order of $M\Omega$) because the control grid draws negligible current. There are many electronic applications where we required high input impedance e.g. electronic voltmeter, oscilloscope etc. Such areas of application need vacuum tubes. It may be noted here that field-effect transistor (*FET*) has a very high input impedance and can replace a vacuum tube in almost all applications.

(iii) Temperature dependence. Solid-state devices are very much temperature dependent. A slight change in temperature can cause a significant change in the characteristics of such devices. On the other hand, small variations in temperature hardly affect the performance of tubes. It is a distinct disadvantage of transistors.

(iv) Inherent variation of parameters. The manufacture of solid-state devices is indeed a very difficult process. In spite of best efforts, the parameters of transistors (e.g. β , V_{BE} etc.) are not the same even for the transistors of the same batch. For example, β for BC 148 transistors may vary between 100 and 600.

MULTIPLE-CHOICE QUESTIONS

1. A transistor has
 - (i) one *pn* junction
 - (ii) two *pn* junctions
 - (iii) three *pn* junctions
 - (iv) four *pn* junctions
2. The number of depletion layers in a transistor is
 - (i) four
 - (ii) three
 - (iii) one
 - (iv) two
3. The base of a transistor is doped.
 - (i) heavily
 - (ii) moderately
 - (iii) lightly
 - (iv) none of the above
4. The element that has the biggest size in a transistor is
 - (i) collector
 - (ii) base
 - (iii) emitter
 - (iv) collector-base junction
5. In a *pnp* transistor, the current carriers are
 - (i) acceptor ions
 - (ii) donor ions
 - (iii) free electrons
 - (iv) holes
6. The collector of a transistor is doped.
 - (i) heavily
 - (ii) moderately
 - (iii) lightly
 - (iv) none of the above
7. A transistor is a operated device.
 - (i) current
 - (ii) voltage
 - (iii) both voltage and current
 - (iv) none of the above
8. In an *npn* transistor, are the minority carriers.
 - (i) free electrons
 - (ii) holes
 - (iii) donor ions
 - (iv) acceptor ions
9. The emitter of a transistor is doped.
 - (i) lightly
 - (ii) heavily
 - (iii) moderately
 - (iv) none of the above
10. In a transistor, the base current is about of emitter current.
 - (i) 25%
 - (ii) 20%
 - (iii) 35%
 - (iv) 5%
11. At the base-emitter junction of a transistor, one finds
 - (i) reverse bias
 - (ii) a wide depletion layer
 - (iii) low resistance
 - (iv) none of the above
12. The input impedance of a transistor is
 - (i) high
 - (ii) low
 - (iii) very high
 - (iv) almost zero
13. Most of the majority carriers from the emitter
 - (i) recombine in the base
 - (ii) recombine in the emitter
 - (iii) pass through the base region to the collector
 - (iv) none of the above
14. The current I_B is
 - (i) electron current
 - (ii) hole current
 - (iii) donor ion current
 - (iv) acceptor ion current
15. In a transistor,
 - (i) $I_C = I_E + I_B$
 - (ii) $I_B = I_C + I_E$
 - (iii) $I_E = I_C - I_B$
 - (iv) $I_E = I_C + I_B$
16. The value of α of a transistor is
 - (i) more than 1
 - (ii) less than 1
 - (iii) 1
 - (iv) none of the above
17. $I_C = \alpha I_E + \dots\dots\dots$
 - (i) I_B
 - (ii) I_{CEO}
 - (iii) I_{CBO}
 - (iv) βI_B
18. The output impedance of a transistor is
 - (i) high
 - (ii) zero
 - (iii) low
 - (iv) very low
19. In a transistor, $I_C = 100$ mA and $I_E = 100.5$ mA. The value of β is
 - (i) 100
 - (ii) 50
 - (iii) about 1
 - (iv) 200
20. In a transistor if $\beta = 100$ and collector current is 10 mA, then I_E is
 - (i) 100 mA
 - (ii) 100.1 mA
 - (iii) 110 mA
 - (iv) none of the above
21. The relation between β and α is
 - (i) $\beta = \frac{1}{1 - \alpha}$
 - (ii) $\beta = \frac{1 - \alpha}{\alpha}$
 - (iii) $\beta = \frac{\alpha}{1 - \alpha}$
 - (iv) $\beta = \frac{\alpha}{1 + \alpha}$

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22. The value of β for a transistor is generally
- (i) 1 (ii) less than 1
(iii) between 20 and 500
(iv) above 500
23. The most commonly used transistor arrangement is arrangement.
- (i) common emitter
(ii) common base
(iii) common collector
(iv) none of the above
24. The input impedance of a transistor connected in arrangement is the highest.
- (i) common emitter
(ii) common collector
(iii) common base
(iv) none of the above
25. The output impedance of a transistor connected in arrangement is the highest.
- (i) common emitter
(ii) common collector
(iii) common base
(iv) none of the above
26. The phase difference between the input and output voltages in a common base arrangement is
- (i) 180° (ii) 90°
(iii) 270° (iv) 0°
27. The power gain of a transistor connected in arrangement is the highest.
- (i) common emitter
(ii) common base
(iii) common collector
(iv) none of the above
28. The phase difference between the input and output voltages of a transistor connected in common emitter arrangement is
- (i) 0° (ii) 180°
(iii) 90° (iv) 270°
29. The voltage gain of a transistor connected in arrangement is the highest.
- (i) common base (ii) common collector
(iii) common emitter
(iv) none of the above
30. As the temperature of a transistor goes up, the base-emitter resistance
- (i) decreases (ii) increases
(iii) remains the same
(iv) none of the above
31. The voltage gain of a transistor connected in common collector arrangement is
- (i) equal to 1 (ii) more than 10
(iii) more than 100 (iv) less than 1
32. The phase difference between the input and output voltages of a transistor connected in common collector arrangement is
- (i) 180° (ii) 0°
(iii) 90° (iv) 270°
33. $I_C = \beta I_B + \dots\dots\dots$
- (i) I_{CBO} (ii) I_C
(iii) I_{CEO} (iv) αI_E
34. $I_C = \frac{\alpha}{1-\alpha} I_B + \dots\dots\dots$
- (i) I_{CEO} (ii) I_{CBO}
(iii) I_C (iv) $(1-\alpha) I_B$
35. $I_C = \frac{\alpha}{1-\alpha} I_B + \frac{\dots\dots\dots}{1-\alpha}$
- (i) I_{CBO} (ii) I_{CEO}
(iii) I_C (iv) I_E
36. BC 147 transistor indicates that it is made of
- (i) germanium (ii) silicon
(iii) carbon (iv) none of the above
37. $I_{CEO} = (\dots\dots\dots) I_{CBO}$
- (i) β (ii) $1 + \alpha$
(iii) $1 + \beta$ (iv) none of the above
38. A transistor is connected in *CB* mode. If it is now connected in *CE* mode with same bias voltages, the values of I_E , I_B and I_C will
- (i) remain the same
(ii) increase
(iii) decrease (iv) none of the above
39. If the value of α is 0.9, then value of β is
- (i) 9 (ii) 0.9
(iii) 900 (iv) 90
40. In a transistor, signal is transferred from a circuit.
- (i) high resistance to low resistance
(ii) low resistance to high resistance
(iii) high resistance to high resistance
(iv) low resistance to low resistance
41. The arrow in the symbol of a transistor indicates the direction of
- (i) electron current in the emitter
(ii) electron current in the collector
(iii) hole current in the emitter
(iv) donor ion current
42. The leakage current in *CE* arrangement is

- that in *CB* arrangement.
- (i) more than (ii) less than
 (iii) the same as (iv) none of the above
43. A heat sink is generally used with a transistor to
- (i) increase the forward current
 (ii) decrease the forward current
 (iii) compensate for excessive doping
 (iv) prevent excessive temperature rise
44. The most commonly used semiconductor in the manufacture of a transistor is
- (i) germanium (ii) silicon
 (iii) carbon (iv) none of the above
45. The collector-base junction in a transistor has
- (i) forward bias at all times
 (ii) reverse bias at all times
 (iii) low resistance
 (iv) none of the above

Answers to Multiple-Choice Questions

- | | | | | |
|-----------|-----------|-----------|-----------|-----------|
| 1. (ii) | 2. (iv) | 3. (iii) | 4. (i) | 5. (iv) |
| 6. (ii) | 7. (i) | 8. (ii) | 9. (ii) | 10. (iv) |
| 11. (iii) | 12. (ii) | 13. (iii) | 14. (i) | 15. (iv) |
| 16. (ii) | 17. (iii) | 18. (i) | 19. (iv) | 20. (ii) |
| 21. (iii) | 22. (iii) | 23. (i) | 24. (ii) | 25. (iii) |
| 26. (iv) | 27. (i) | 28. (ii) | 29. (iii) | 30. (i) |
| 31. (iv) | 32. (ii) | 33. (iii) | 34. (i) | 35. (i) |
| 36. (ii) | 37. (iii) | 38. (i) | 39. (iv) | 40. (ii) |
| 41. (iii) | 42. (i) | 43. (iv) | 44. (ii) | 45. (ii) |

Chapter Review Topics

- What is a transistor? Why is it so called?
- Draw the symbol of *npn* and *pnp* transistor and specify the leads.
- Show by means of a diagram how you normally connect external batteries in (i) *pnp* transistor (ii) *npn* transistor.
- Describe the transistor action in detail.
- Explain the operation of transistor as an amplifier.
- Name the three possible transistor connections.
- Define α . Show that it is always less than unity.
- Draw the input and output characteristics of *CB* connection. What do you infer from these characteristics?
- Define β . Show that : $\beta = \frac{\alpha}{1 - \alpha}$.
- How will you determine the input and output characteristics of *CE* connection experimentally?
- Establish the following relations :

(i) $I_C = \alpha I_E + I_{CBO}$	(ii) $I_C = \frac{\alpha}{1 - \alpha} I_B + \frac{1}{1 - \alpha} I_{CBO}$
(iii) $I_C = \beta I_B + I_{CEO}$	(iv) $\gamma = \frac{1}{1 - \alpha}$
(v) $I_E = (\beta + 1) I_B + (\beta + 1) I_{CBO}$	
- How will you draw d.c. load line on the output characteristics of a transistor? What is its importance?
- Explain the following terms : (i) voltage gain (ii) power gain (iii) effective collector load.
- Write short notes on the following : (i) advantages of transistors (ii) operating point (iii) d.c. load line.

Problems

1. In a transistor if $I_C = 4.9\text{mA}$ and $I_E = 5\text{mA}$, what is the value of α ? [0.98]
2. In a transistor circuit, $I_E = 1\text{mA}$ and $I_C = 0.9\text{mA}$. What is the value of I_B ? [0.1 mA]
3. Find the value of β if $\alpha = 0.99$. [100]
4. In a transistor, $\beta = 45$, the voltage across $5\text{k}\Omega$ resistance which is connected in the collector circuit is 5 volts. Find the base current. [0.022 mA]
5. In a transistor, $I_B = 68\ \mu\text{A}$, $I_E = 30\ \text{mA}$ and $\beta = 440$. Find the value of α . Hence determine the value of I_C . [0.99 ; 29.92 mA]
6. The maximum collector current that a transistor can carry is 500 mA. If $\beta = 300$, what is the maximum allowable base current for the device? [1.67 mA]
7. For the circuit shown in Fig. 8.69, draw the d.c. load line.

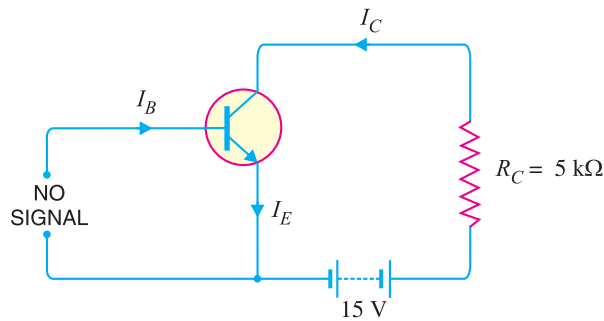


Fig. 8.69

8. Draw the d.c. load line for Fig. 8.70. [The end points of load line are 6.06 mA and 20 V]

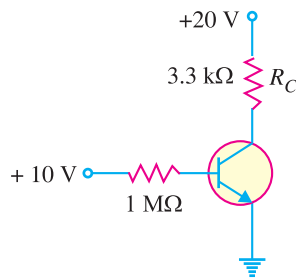


Fig. 8.70

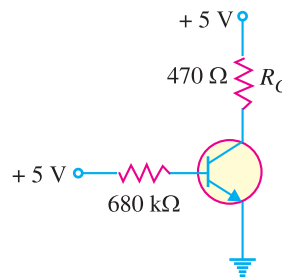


Fig. 8.71

9. If the collector resistance R_C in Fig. 8.70 is reduced to $1\ \text{k}\Omega$, what happens to the d.c. load line? [The end points of d.c. load line are now 20 mA and 20 V]
10. Draw the d.c. load line for Fig. 8.71. [The end points of d.c. load line are 10.6 mA and 5V]
11. If the collector resistance R_C in Fig. 8.71 is increased to $1\ \text{k}\Omega$, what happens to the d.c. load line? [The end points of d.c. load line are now 5 mA and 5 V]

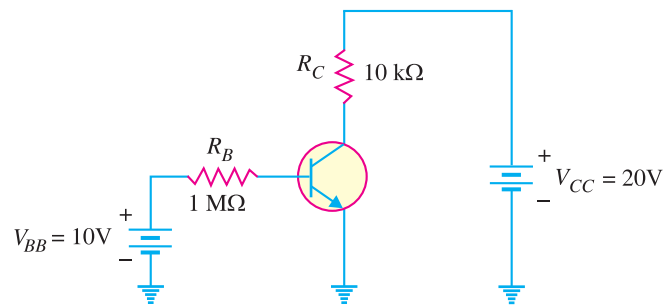


Fig. 8.72

12. Determine the intercept points of the d.c. load line on the vertical and horizontal axes of the collector curves in Fig. 8.72. [2 mA ; 20 V]
13. For the circuit shown in Fig. 8.73, find (i) the state of the transistor and (ii) transistor power. [(i) active (ii) 4.52 mW]

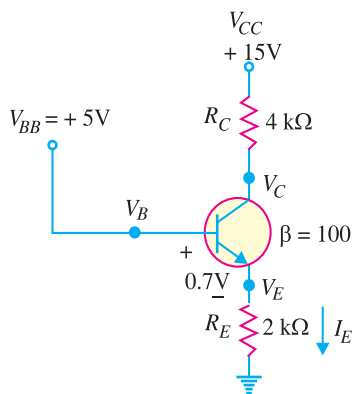


Fig. 8.73

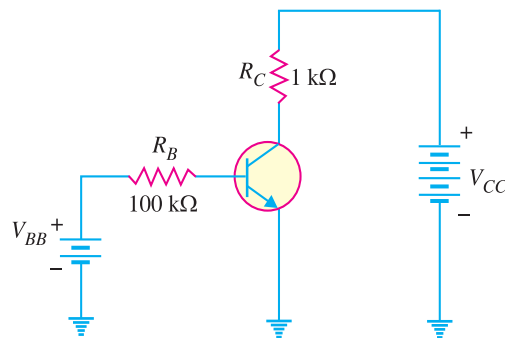


Fig. 8.74

14. A base current of 50 μA is applied to the transistor in Fig. 8.74 and a voltage of 5V is dropped across R_C . Calculate α for the transistor. [0.99]
15. A certain transistor is to be operated at a collector current of 50 mA. How high can V_{CE} go without exceeding $P_{D(max)}$ of 1.2 W ? [24 V]

Discussion Questions

1. Why is a transistor low powered device ?
2. What is the significance of arrow in the transistor symbol ?
3. Why is collector wider than emitter and base ?
4. Why is collector current slightly less than emitter current ?
5. Why is base made thin ?