10

TRANSISTORS

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.

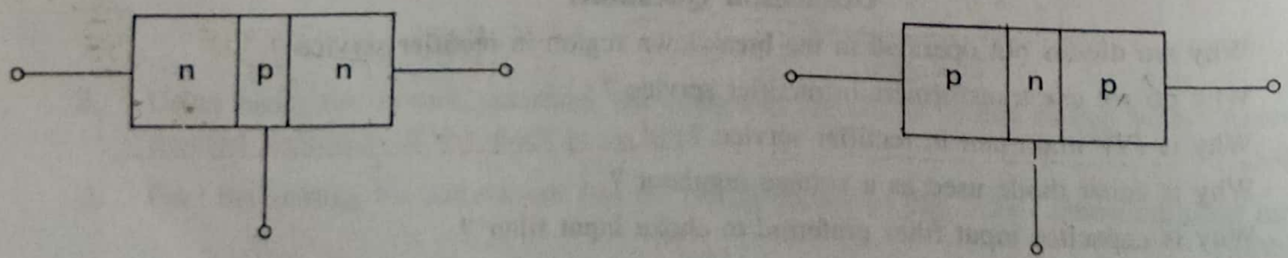
Invented in 1948 by J. Bardeen and W.H. Brattain of Bell Telephone Laboratories, U.S.A.; transistor has now become the heart of most electronic applications. Though transistor is only slightly more than 45 years old, yet it is fast replacing vacuum tubes in almost all applications. In this chapter, we shall focus our attention on the various aspects of transistors and their increasing applications in the fast developing electronics industry.

10.1 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. 10.1 (*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. 10.1 (*ii*).



(*i*) (*ii*)

Fig 10.1

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

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, 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.

10.2 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. 10.2 (*i*), the emitter (*p*-type) of *pnp* transistor is forward biased and supplies hole charges to its junction with the base. Similarly, in Fig. 10.2 (*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. 10.2 (*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. 10.2 (*ii*), the collector (*n*-type) of *npn* transistor has reverse bias and receives electrons.

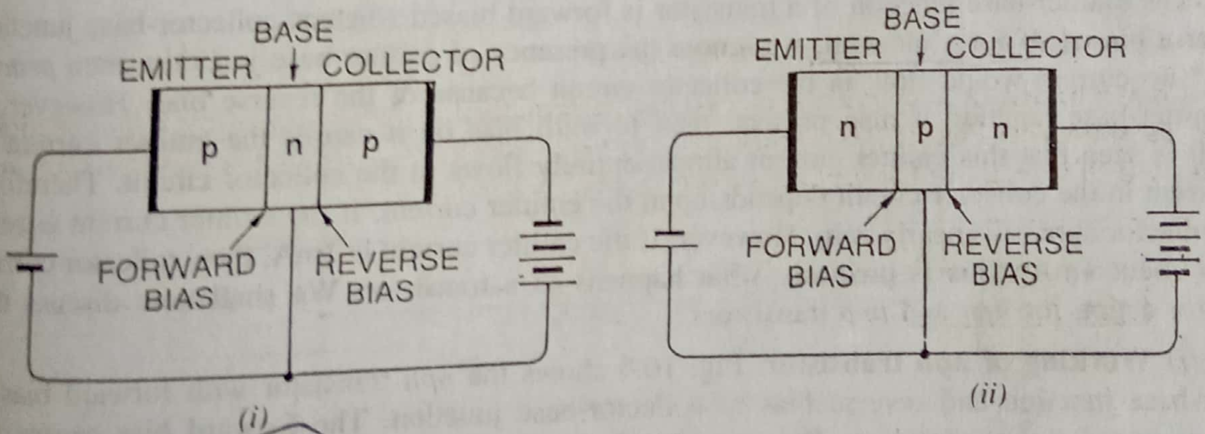


Fig. 10.2

(*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.

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

10.3 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. 10.3. 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.

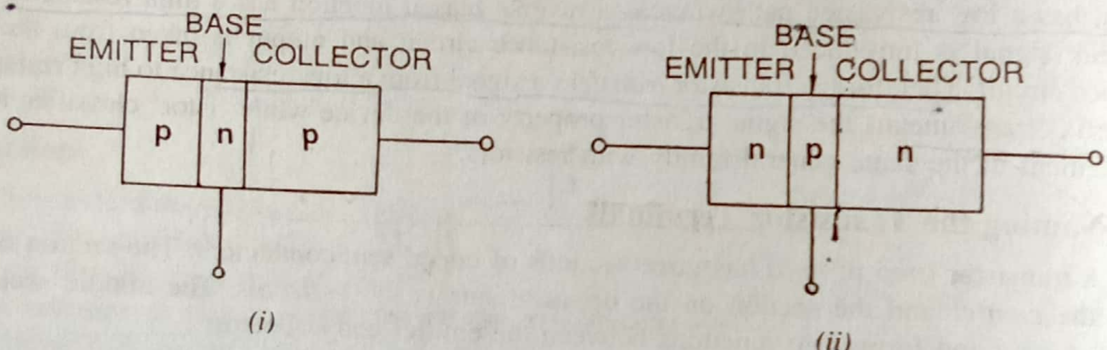


Fig. 10.3

(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.

10.4 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.

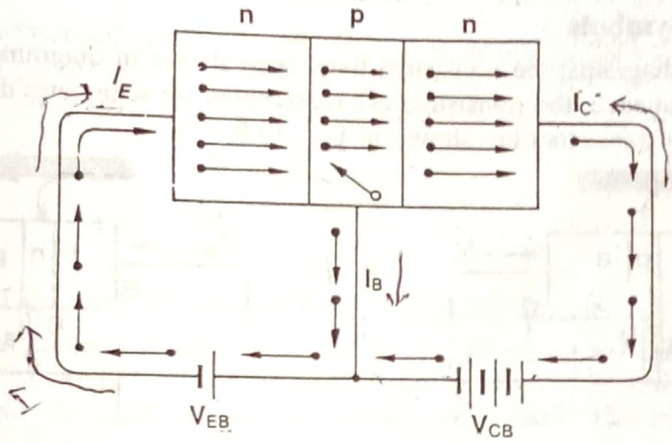
(i) **Working of npn transistor**. Fig. 10.4 shows the *npn* transistor with forward bias to emitter-base junction and reverse bias to collector-base junction. The forward bias causes the electrons in the *n*-type emitter to flow towards the base. This constitutes the emitter current I_E. As these electrons flow through the *p*-type base, they tend to combine with holes. As the base

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

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

is lightly doped and very thin, therefore, only a few electrons (less than 5%) combine with holes to constitute base* current I_B. The remainder (**more than 95%) cross over into the collector region to constitute collector current I_C. In this way, almost the entire emitter current flows in the collector circuit. It is clear that emitter current is the sum of collector and base currents *i.e.*

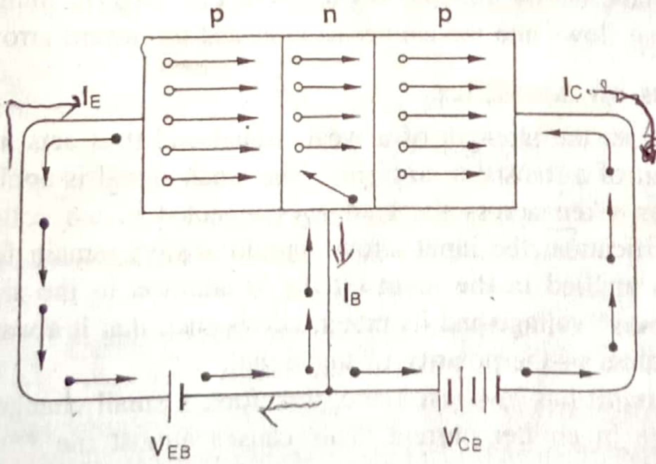
$$I_E = I_B + I_C$$



Basic connection of *npn* transistor

Fig. 10.4

(ii) **Working of pnp transistor.** Fig. 10.5 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 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.



Basic connection of *pnp* transistor

Fig. 10.5

* 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.

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

10.5 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. 10.6.

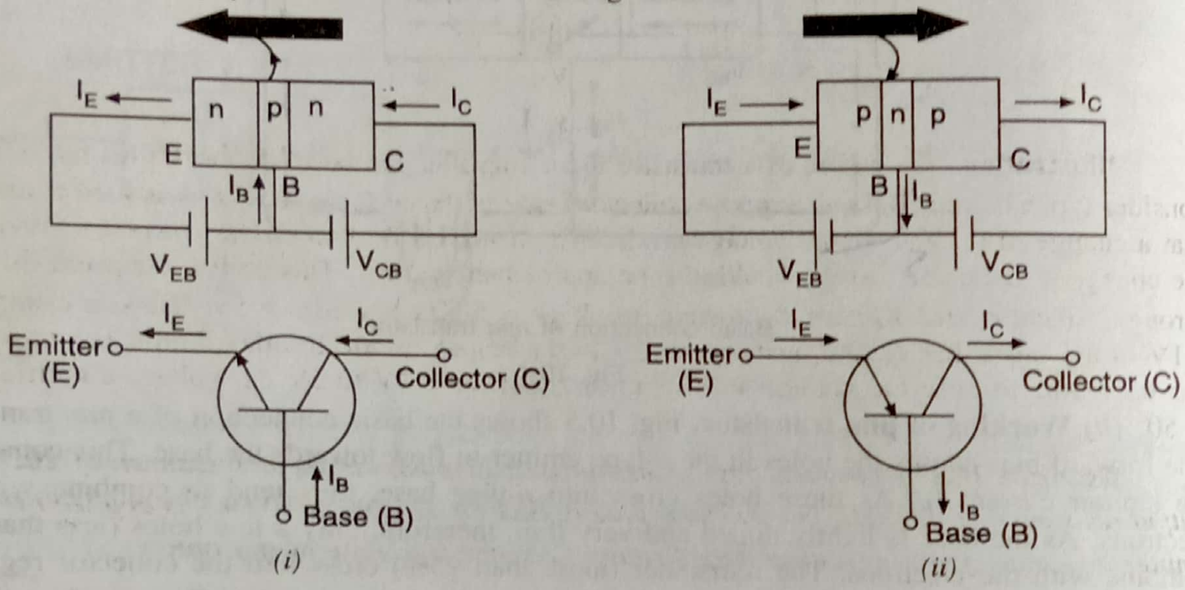


Fig. 10.6

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. 10.6 *(i)*. Similarly, for *pnp* connection, the conventional current flows into the emitter as indicated by inward arrow in Fig. 10.6 *(ii)*.

10.6 Transistor as an Amplifier

A transistor raises the strength of a weak signal and thus acts as an amplifier. Fig. 10.7 shows the basic circuit of a transistor amplifier. The weak signal is applied between emitter-base junction and output is taken across the load R_C connected in the collector circuit. In order to achieve faithful amplification, the input circuit should always remain forward biased. To do so, a d.c. voltage V_{EE} is applied in the input circuit in addition to the signal as shown. This d.c. voltage is known as bias* voltage and its magnitude is such that it always keeps the input circuit forward biased regardless of the polarity of the signal.

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

* It may be recalled that biasing is also necessary in vacuum tube amplifiers for faithful amplification (see Chapter 5). The reader may find the detailed discussion on transistor biasing in Chapter 11.

** 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.

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.

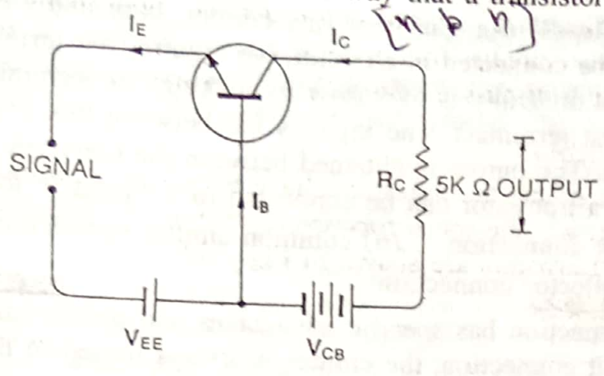


Fig. 10.7

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

Example 10.1 *A common base transistor amplifier has an input resistance of 20Ω and output resistance of 100 kΩ. The collector load is 1kΩ. 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. 10.8 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.

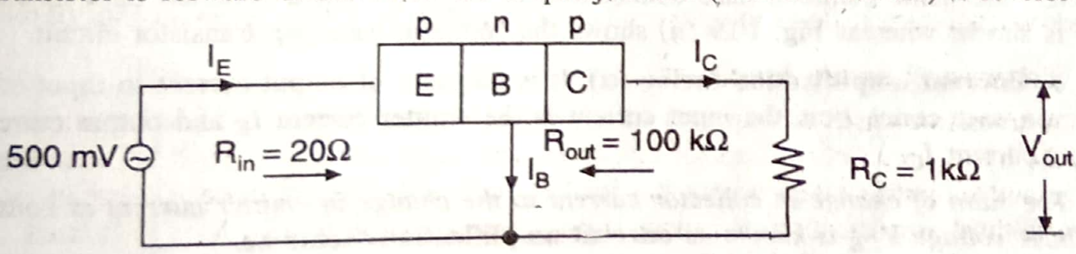


Fig. 10.8

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

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

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

Comments. The reader may note that basic amplifying action is produced by transfering 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 bold letters below :

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

Transfer + Resistor ⟶ Transistor

10.7 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.

10.8 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

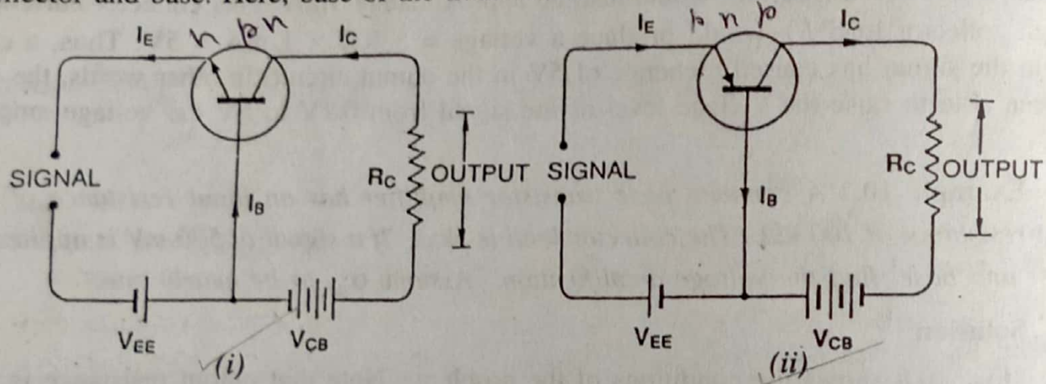


Fig. 10.9

and hence the name common base connection. In Fig. 10.9 (*i*), a common base *npn* transistor circuit is shown whereas Fig. 10.9 (*ii*) shows the common base *pnp* transistor circuit.

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.

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

* 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.

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.* $*\alpha I_E$.

(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.

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

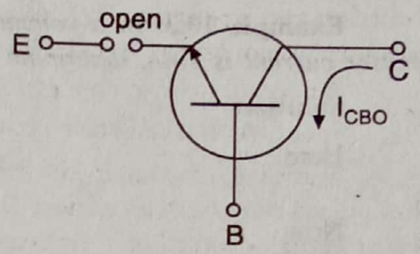


Fig. 10.10

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. 10.10.

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

Now $\quad I_E = I_C + I_B$

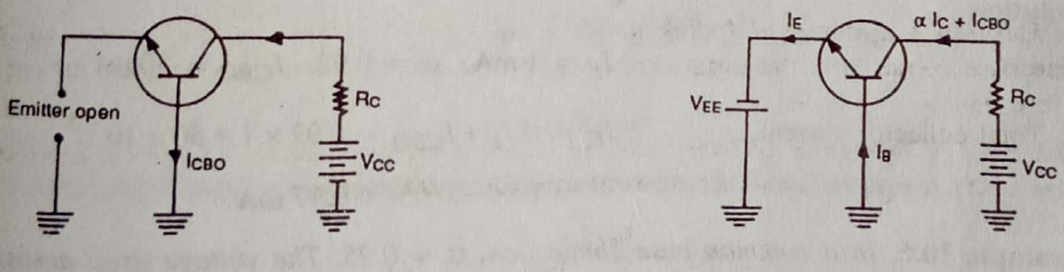
$$\therefore \quad I_C = \alpha (I_C + I_B) + I_{CBO}$$

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

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

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. 10.11 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. 10.11 *(ii)*.



(i) *(ii)*

Fig. 10.11

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.

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* $\alpha = \dfrac{I_C}{I_E} \qquad \therefore \; I_C = \alpha I_E$

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

Using the relation, $I_E = I_B + I_C$

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

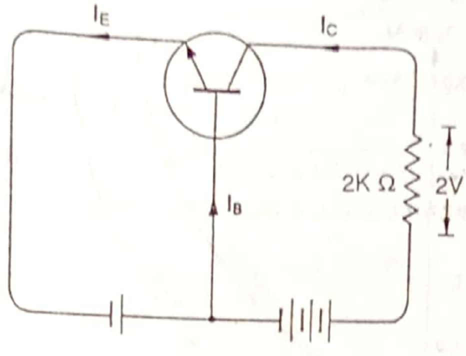


Fig. 10.12

Example 10.7. *For the common base circuit shown in Fig. 10.13, determine I_C and V_{CB}. Assume the transistor to be of silicon.*

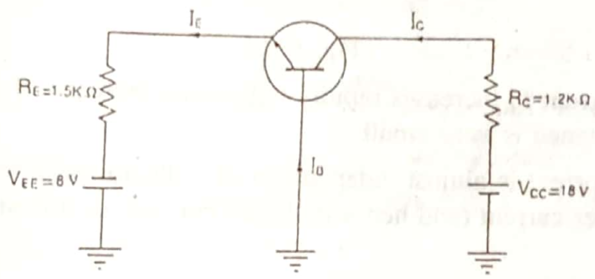


Fig. 10.13

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

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

or $$I_E = \frac{V_{EE} - V_{BE}}{R_E} = \frac{8\text{ V} - 0.7\text{ V}}{1.5\text{ K}\Omega} = 4.87\text{ mA}$$

$\therefore$ $$I_C \simeq I_E = \mathbf{4.87\ mA}$$

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

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

$\therefore$ $$V_{CB} = V_{CC} - I_C R_C = 18\text{ V} - 4.87\text{ mA} \times 1.2\text{ K}\Omega = \mathbf{12.16\ V}$$

10.9 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. 10.14 shows the input characteristics of a typical transistor in CB arrangement. The following points may be noted from these characteristics:

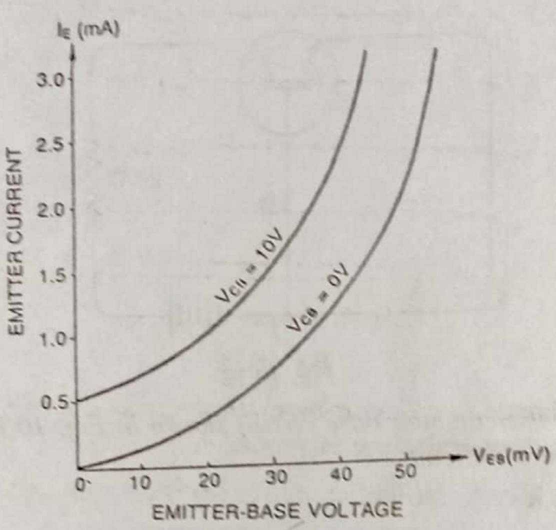


Fig. 10.14

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

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

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 characteristics. 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. 10.15 shows the output characteristics of a typical transistor in CB arrangement.

The following points may be noted from the characteristics :

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

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

* 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.

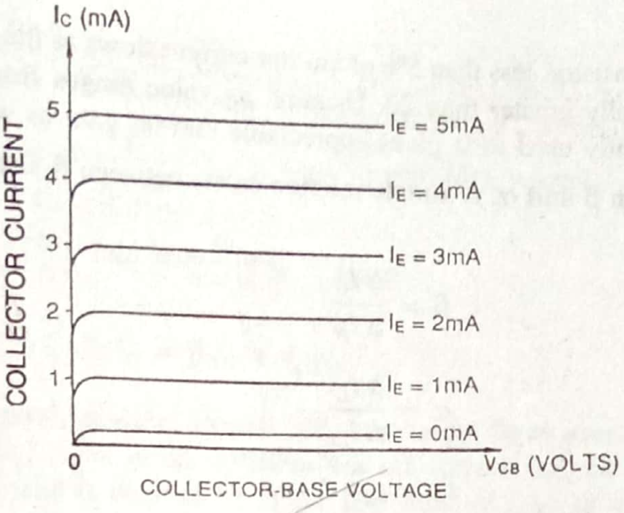


Fig. 10.15

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

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

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

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

10.10 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. 10.16 (*i*) shows common emitter *npn* transistor circuit whereas Fig. 10.16 (*ii*) shows common emitter *pnp* transistor circuit.

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.*

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

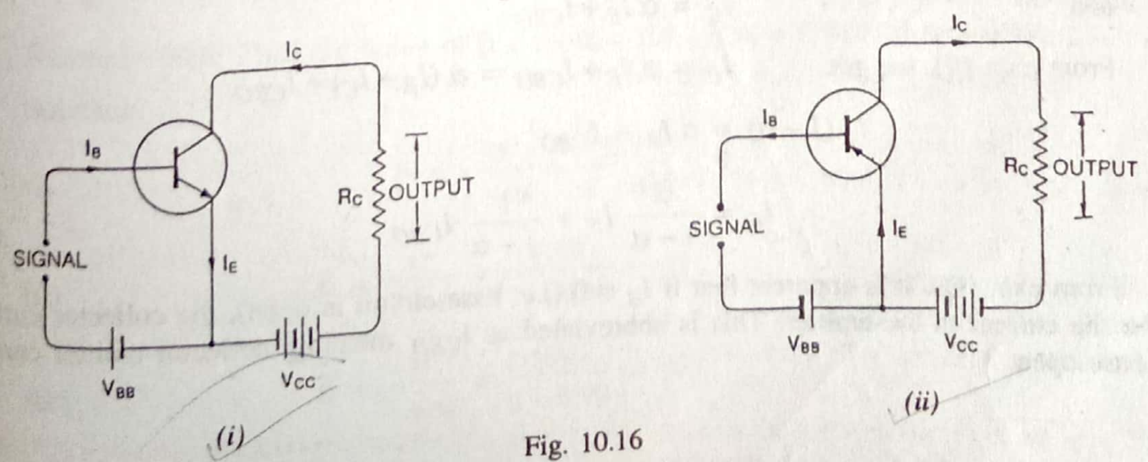


Fig. 10.16

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

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 :

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

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

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,

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

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

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

∴
$$\beta = \frac{\alpha}{1-\alpha}$$

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.

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

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

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

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

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

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

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

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

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

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

or

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

Concept of I_{CEO}. In *CE* configuration, a small collector current flows even when the base current is zero [See Fig. 10.17 *(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}.

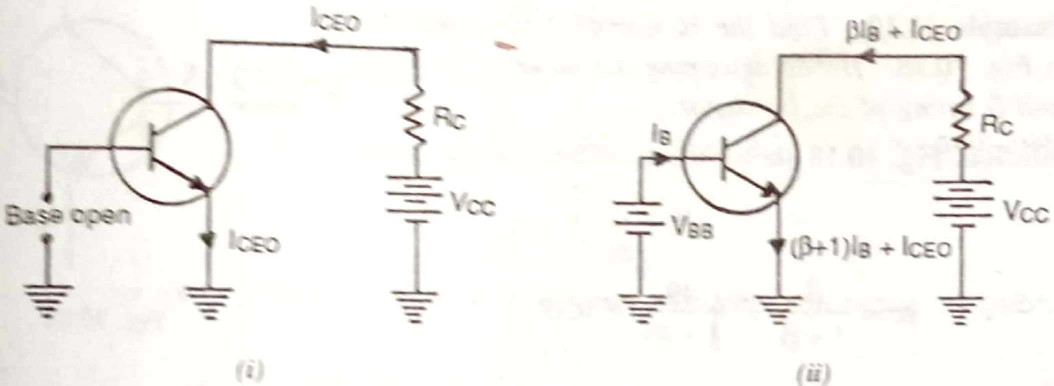


Fig 10.17

When the base voltage is applied as shown in Fig. 10.17 *(ii)*, then the various currents are:

Base current $= I_B$

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

Emitter current = Collector current + Base current

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

It may be noted here that:

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

Example 10.8. *Find the value of β if (i) α = 0.9 (ii) α = 0.98 (iii) α = 0.99.*

Solution

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

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

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

When base is open [See Fig 10.21 (*ii*)], a small leakage current I_{CEO} flows due to minori carriers.

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

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

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

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

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

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

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

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

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

10.11 Characteristics of Common Emitter Connection

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

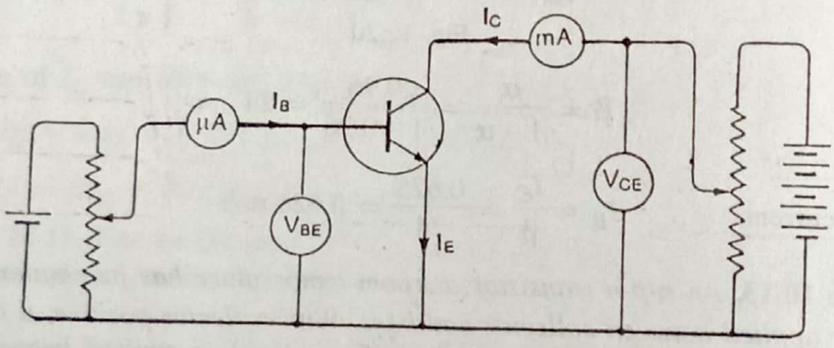


Fig. 10.22

1. Input characteristics. *It is the curve between base current I_B and base-emitter voltag 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. 10.22. Keeping V_{CE} constant (say at 10V), 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. 10.23. 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.

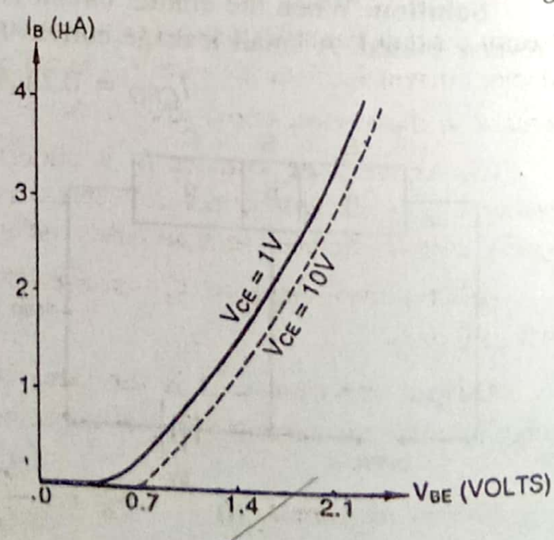


Fig. 10.23

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

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

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

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

2. Output characteristics. *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. 10.22. Keeping the base current I_B fixed at some value say, 5 μA, note the collector current I_C for various values of V_{CE}. Then plot the readings on a graph, taking I_C along *Y*-axis and V_{CE} along *X*-axis. This gives the output characteristic at I_B = 5μA as shown in Fig. 10.24 *(i)*. The test can be repeated for I_B = 10μA to obtain the new output characteristic as shown in Fig. 10.24 *(ii)*. Following similar procedure, a family of output characteristics can be drawn as shown in Fig. 10.24 *(iii)*.

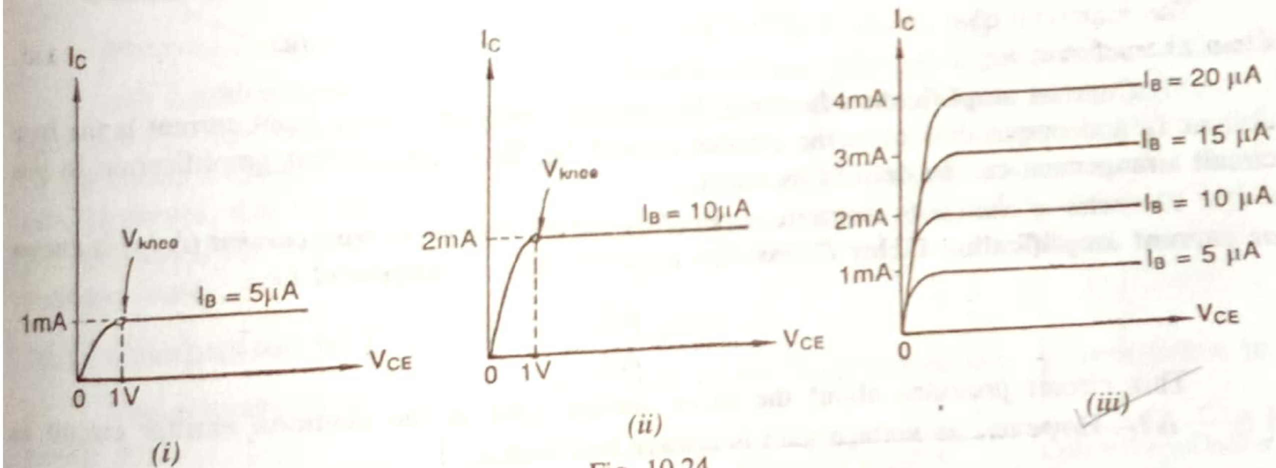


Fig. 10.24

The following points may be noted from the characteristics:–

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

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

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

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

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

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 50KΩ.

10.12 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. 10.25 *(i)* shows common collector *npn* transistor circuit whereas Fig. 10.25 *(ii)* shows common emitter *pnp* circuit.

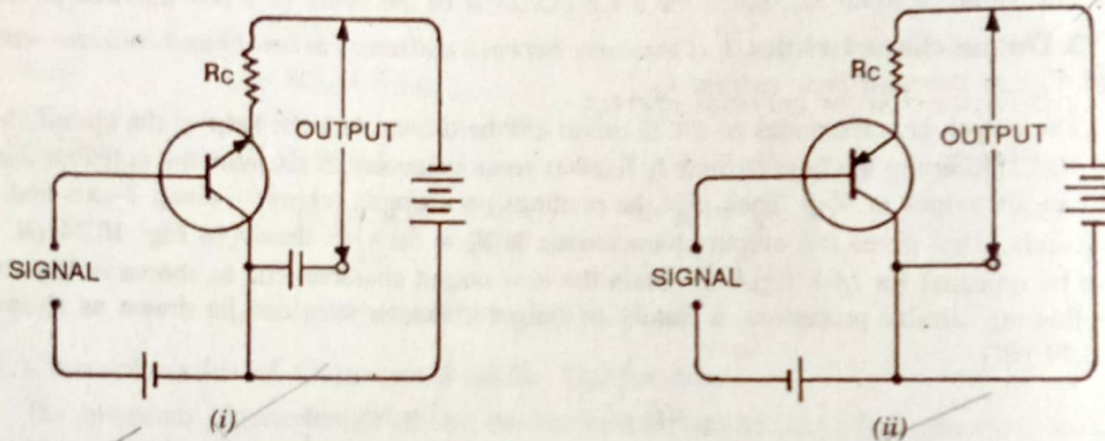


Fig. 10.25

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

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

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

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

Relation between γ and α

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

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

Now, $$I_E = I_B + I_C$$

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

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

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

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

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

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

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

(ii) **Expression for collector current**

We know $\qquad I_C = \alpha I_E + I_{CBO}$ (see Art. 10.8)

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

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

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

or $\qquad I_E = *(\beta+1) I_B + (\beta+1) I_{CBO}$

(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.

10.13 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

10.14 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 ;

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

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

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.

10.15 Transistor as an Amplifier in CE Arrangement

Fig. 10.26 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.

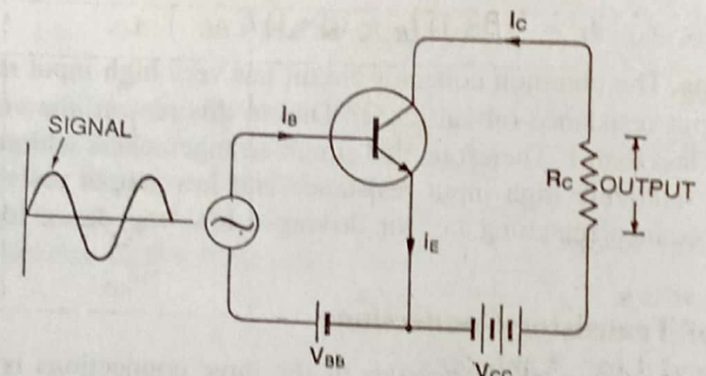


Fig. 10.26

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 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.

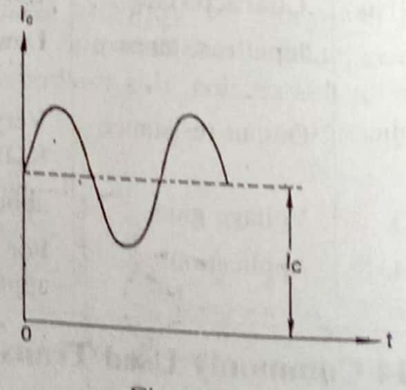


Fig. 10.27

* 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.

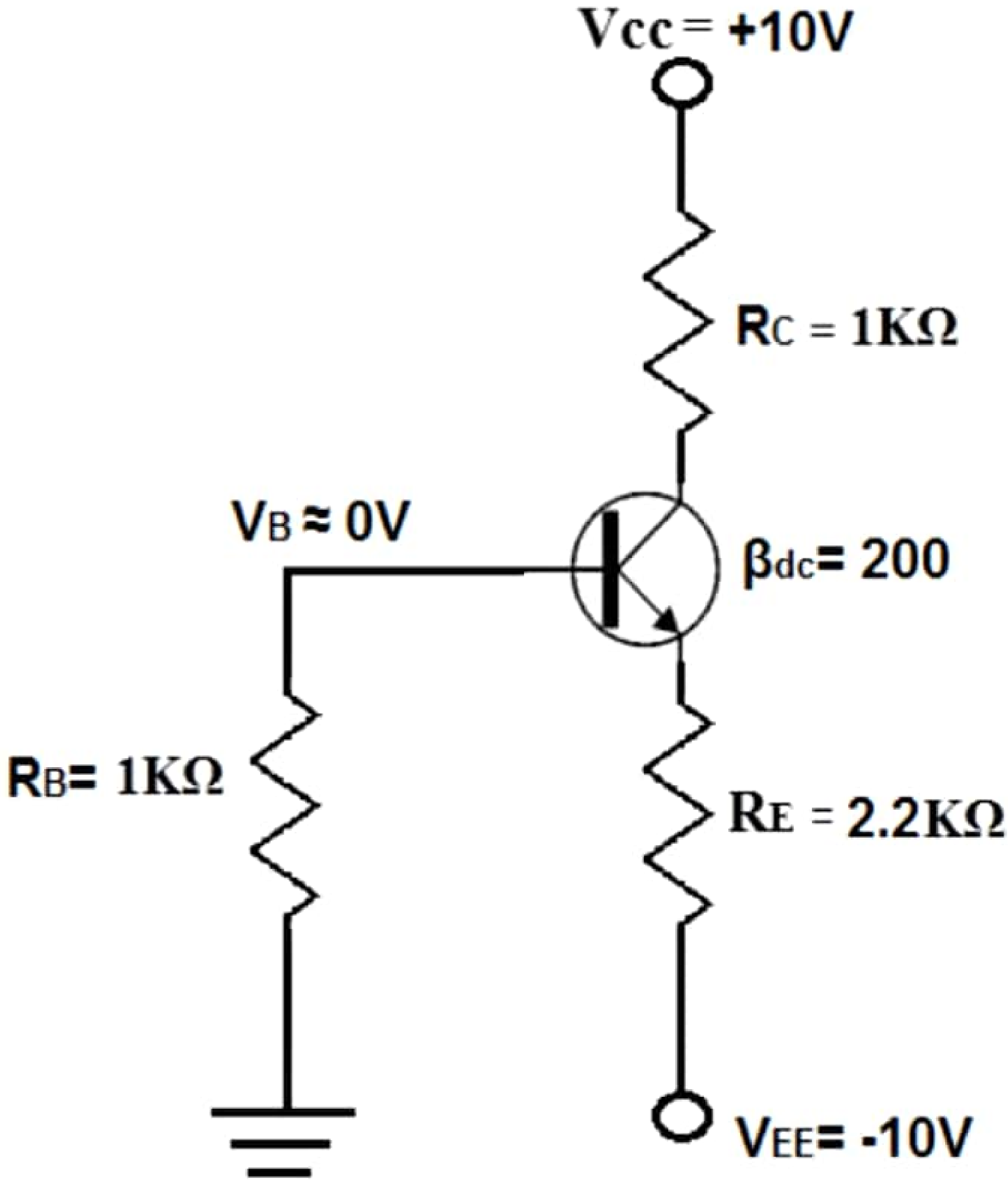
** Throughout the book, we shall use sine wave signals because these are convenient for testing amplifiers. But it must be realised that signals (*e.g.* speech, music *etc.*) with which we work are generally complex having little resemblance to a sine wave. However, fourier series analysis tells us that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

Emitter Bias of a BJT Transistor

One way to bias a BJT transistor is a method called emitter bias.

Emitter bias is a very good and stable way to bias transistors if both positive and negative power supplies are available. Emitter bias fluctuates very little with temperature variation and transistor replacement.

Below is a BJT transistor receiving emitter bias:



You can see how that both positive and negative voltage supplies are necessary to bias a transistor in this way. Positive voltage is fed to the collector of the transistor and negative voltage is fed to the emitter.

Calculations

Assuming this is a silicon transistor, the voltage drop across the base-emitter diode

Calculations

Assuming this is a silicon transistor, the voltage drop across the base-emitter diode is equal to 0.7V.

To calculate the emitter current, I_E, the formula is:

$$I_{EQ} = \frac{V_{EE} - V_{BE}}{\frac{R_B}{(\beta_{dc})} + R_E}$$

$$I_{EQ} = \frac{V_{EE} - V_{BE}}{\frac{R_B}{(\beta_{dc})} + R_E}$$

So in the circuit above, the emitter current calculation is:

$I_E = (10V - 0.7V)/(2.2K\Omega + (1K\Omega/200)) = 4.22mA$

To calculate the collector voltage, V_C, the formula is:

$V_C = V_{CC} - I_C R_C = 10V - (4.23mA \times 1K\Omega) = 5.77V$

Again, emitter bias is an effective way to bias a BJT transistor. However, the voltage divider bias is still the most popular way to do so, while base bias is the least popular way because of the instability it provides if β changes.

(*i*) Base resistor method (*ii*) Biasing with feedback resistor

(*iii*) Voltage-divider bias.

In all these methods, the same basic principle is employed *i.e.* required value of base current (and hence I_C) is obtained from V_{CC} in the zero signal conditions. The value of collector load R_C is selected keeping in view that V_{CE} should not fall below 0.5V for germanium transistors and 1V for silicon transistors.

For example, if $\beta = 100$ and the zero signal collector current I_C is to be set at 1mA, then I_B is made equal to $I_C/\beta = 1/100 = 10\mu A$. Thus, the biasing network should be so designed that a base current of $10\mu A$ flows in the zero signal conditions.

11.8 Base Resistor Method (FIXED BIAS)

In this method, a high resistance R_B (several hundred $K\Omega$) is connected between the base and +ve end of supply for *npn* transistor (see Fig. 11.6) and between base and negative end of supply for *pnp* transistor. Here, the required zero signal base current is provided by V_{CC} and it flows through R_B. It is because now base is positive *w.r.t.* emitter *i.e.* base-emitter junction is forward biased. The required value of zero signal base current I_B (and hence $I_C = \beta I_B$) can be made to flow by selecting the proper value of base resistor R_B.

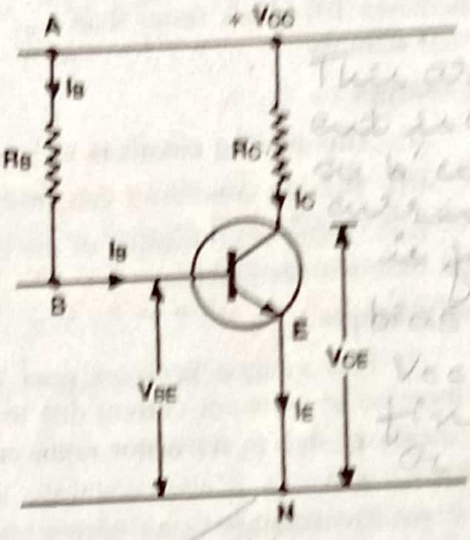


Fig. 11.6

Circuit analysis. It is required to find the value of R_B so that required collector current flows in the zero signal conditions. Let I_C be the required zero signal collector current.

$$\therefore \qquad I_B = \frac{I_C}{\beta}$$

Considering the closed circuit *ABENA* and applying Kirchhoff's voltage law, we get,

$$V_{CC} = I_B R_B + V_{BE}$$

or
$$I_B R_B = V_{CC} - V_{BE}$$

$$\therefore \qquad R_B = \frac{V_{CC} - V_{BE}}{I_B} \qquad \ldots (i)$$

As V_{CC} and I_B are known and V_{BE} can be seen from the transistor manual, therefore, value of R_B can be readily found from exp. (*i*).

Since V_{BE} is generally quite small as compared to V_{CC}, the former can be neglected with little error. It then follows from exp. (*i*) that :

$$R_B = \frac{V_{CC}}{I_B}$$

It may be noted that V_{CC} is a fixed known quantity and I_B is chosen at some suitable value. Hence, R_B can always be found directly, and for this reason, this method is sometimes called *fixed-bias method.*

Stability factor As shown in Art. 11.6, (*i*) Base resistor method (*ii*) Biasing with feedback resistor

(*iii*) Voltage-divider bias.

In all these methods, the same basic principle is employed *i.e.* required value of base current (and hence I_C) is obtained from V_{CC} in the zero signal conditions. The value of collector load R_C is selected keeping in view that V_{CE} should not fall below 0.5 V for germanium transistors and 1 V for silicon transistors.

base bias is called fixed bias

For example, if $\beta = 100$ and the zero signal collector current I_C is to be set at 1mA, then I_B is made equal to $I_C/\beta = 1/100 = 10\mu A$. Thus the biasing network should be so designed that a base current of $10\mu A$ flows in the zero signal conditions.

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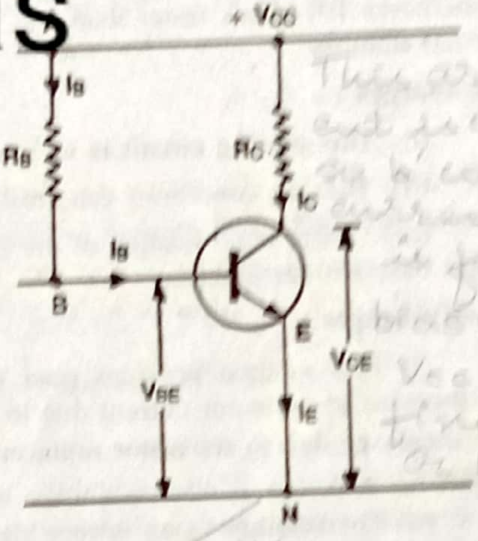

Fig. 11.6

Circuit analysis. It is required to find the value of R_B so that required collector current flows in the zero signal conditions. Let I_C be the required zero signal collector current.

$$\therefore \quad I_B = \frac{I_C}{\beta}$$

Considering the closed circuit *ABENA* and applying Kirchhoff's voltage law, we get,

$$V_{CC} = I_B R_B + V_{BE}$$

$$\text{or} \quad I_B R_B = V_{CC} - V_{BE}$$

$$\therefore \quad R_B = \frac{V_{CC} - V_{BE}}{I_B} \quad \text{... } (i)$$

As V_{CC} and I_B are known and V_{BE} can be seen from the transistor manual, therefore, value of R_B can be readily found from exp. (*i*).

Since V_{BE} is generally quite small as compared to V_{CC}, the former can be neglected with little error. It then follows from exp. (*i*) that :

$$R_B = \frac{V_{CC}}{I_B}$$

It may be noted that V_{CC} is a fixed known quantity and I_B is chosen at some suitable value. Hence, R_B can always be found directly, and for this reason, this method is sometimes called *fixed-bias method.*

Stability factor As shown in Art. 11.6,

$$\text{Stability factor, } S = \frac{\beta+1}{1-\beta\frac{(dI_B)}{(dI_C)}}$$

In fixed-bias method of biasing, I_B is independent of I_C so that $dI_B/dI_C = 0$. Putting the value of $dI_B / dI_C = 0$ in the above expression, we have,

Stability factor, $S = \beta + 1$

Thus the stability factor in a fixed bias is (β + 1). This means that I_C changes (β + 1) times as much as any change in I_{CO}. For instance, if β = 100, then S = 101 which means that I_C increases 101 times faster than I_{CO}. Due to the large value of S in a fixed bias, it has poor thermal stability

Advantages :

(*i*) This biasing circuit is very simple as only one resistance R_B is required.

(*ii*) Biasing conditions can easily be set and the calculations are simple.

(*iii*) There is no loading of the source by the biasing circuit since no resistor is employed across base-emitter junction.

Disadvantages :

(*i*) This method provides poor stabilisation. It is because there is no means to stop a self-increase in collector current due to temperature rise and individual variations. For example, if β increases due to transistor replacement, then I_C also increases by the same factor as I_B is constant.

(*ii*) The stability factor is very high. Therefore, there are strong chances of thermal runway.

Due to these disadvantages, this method of biasing is rarely employed.

Example 11.3. *Fig 11.7 (i) shows biasing with base resistor method. (i) Determine the collector current I_C and collector-emitter voltage V_{CE}. Neglect small base-emitter voltage. Given that β = 50.*

(*ii*) *If R_B in this circuit is changed to 50KΩ, find the new operating point.*

Solution

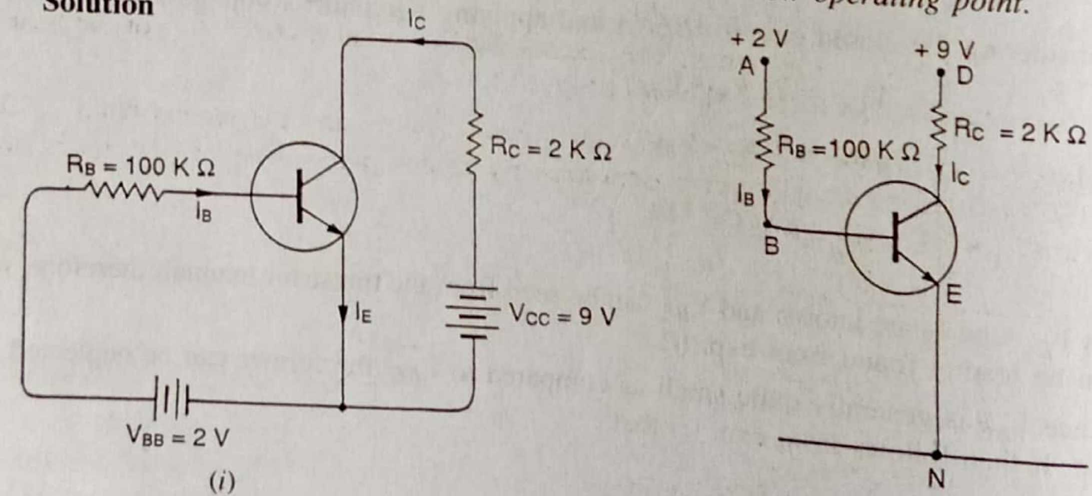

Fig. 11.7

In the circuit shown in Fig. 11.7 (*i*), biasing is provided by a battery V_{BB} (= 2V) in the base circuit which is separate from the battery V_{CC} (= 9V) used in the output circuit. The same circuit is shown in a simplified way in Fig. 11.7 (*ii*). Here, we need show only the supply voltages, +2V and +9V. It may be noted that negative terminals of the power supplies are grounded to get a complete path of current.

Also, $I_B = \frac{I_C}{\beta} = \frac{1\ mA}{100} = 0.01\ mA$

Using the relation,

$$R_B = \frac{V_{CC} - V_{BE} - \beta I_B R_C}{I_B}$$

$$= \frac{12 - 0.3 - 100 \times 0.01 \times 4}{0.01} = \mathbf{770\ K\Omega}$$

(ii) Now $\beta = 50$, and other circuit values remain the same.

$\therefore \quad V_{CC} = V_{BE} + I_B R_B + \beta I_B R_C$

or $\quad 12 = 0.3 + I_B (R_B + \beta R_C)$

or $\quad 11.7 = I_B (770 + 50 \times 4)$

or $\quad I_B = \frac{11.7\ V}{970\ K\Omega} = 0.012\ mA$

$\therefore$ Collector current,

$$I_C = \beta I_B = 50 \times 0.012 = 0.6\ mA$$

$\therefore$ Collector-emitter voltage,

$$V_{CE} = V_{CC} - I_C R_C = 12 - 0.6\ mA \times 4\ K\Omega = \mathbf{9.6\ V}$$

$\therefore$ New operating point is **9.6V, 0.6mA**

Comments. It may be seen that operating point is changed when a new transistor with lesser β is used. Therefore, biasing with feedback resistor does not provide very good stabilisation. It may be noted, however, that change in operating point is less than that of base resistor method.

Example 11.10. *It is desired to set the operating point at 2V, 1mA by biasing a silicon transistor with feedback resistor R_B. If $\beta = 100$, find the value of R_B.*

Solution

For a silicon transistor,

$V_{BE} = 0.7V$

$I_B = \frac{I_C}{\beta} = 1/100 = 0.01\ mA$

Now, $\quad V_{CE} = V_{BE} + V_{CB}$

or $\quad 2 = 0.7 + V_{CB}$

$\therefore \quad V_{CB} = 2 - 0.7 = 1.3V$

$$R_B = \frac{V_{CB}}{I_B} = \frac{1.3V}{0.01\ mA} = \mathbf{130\ K\Omega}$$

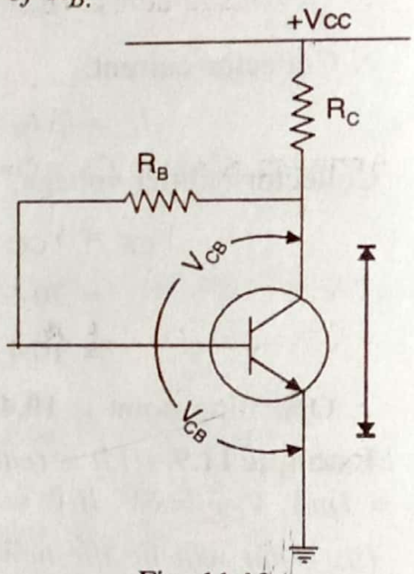

Fig. 11.13

11.10 Voltage Divider Bias Method

This is the most widely used method of providing biasing and stabilisation to a transistor. In this method, tworesistances R_1 and R_2 are connected across the supply voltage V_{CC} (See Fig. 11.14) and provide biasing. The emitter resistance R_E provides stabilisation. The name "voltage divider" comes from the voltage divider formed by R_1 and R_2. The voltage drop across R_2 forward biases the base-emitter junction. This causes the base current and hence collector current flow in the zero signal conditions.

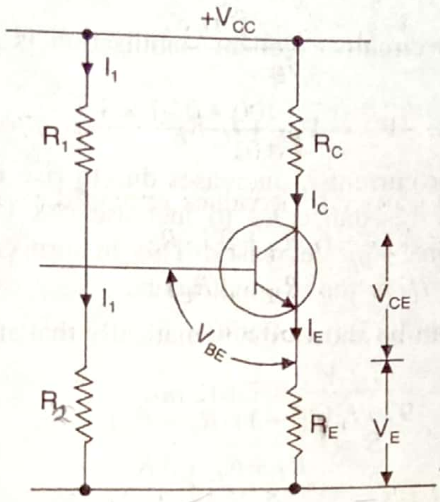

Fig. 11.14

Circuit analysis. Suppose that the current flowing through resistance R_1 is I_1. As base current I_B is very small, therefore, it can be assumed with reasonable accuracy that current flowing through R_2 is also I_1.

(i) Collector current I_C :

$$I_1 = \frac{V_{CC}}{R_1 + R_2}$$

∴ Voltage across resistance R_2,

$$V_2 = \left(\frac{V_{CC}}{R_1 + R_2}\right) R_2$$

Applying Kirchhoff's voltage law to the base circuit of Fig. 11.14,

$$V_2 = V_{BE} + V_E$$

or

$$V_2 = V_{BE} + I_E R_E$$

or

$$I_E = \frac{V_2 - V_{BE}}{R_E}$$

Since

$$I_E \simeq I_C$$

∴

$$I_C = \frac{V_2 - V_{BE}}{R_E} \quad \ldots (i)$$

It is clear from exp. *(i)* above that I_C does not at all depend upon β. Though I_C depends upon V_{BE} but in practice $V_2 >> V_{BE}$ so that I_C is practically independent of V_{BE}. Thus I_C in this circuit is almost independent of transistor parameters and hence good stabilisation is ensured. It is due to this reason that potential divider bias has become universal method for providing transistor biasing.

(ii) Collector-emitter voltage V_{CE}. Applying Kirchhoff's voltage law to the collector side,

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

$$(\because I_E \sim I_C) \quad = I_C R_C + V_{CE} + I_C R_E$$

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

$$\therefore \quad V_{CE} = V_{CC} - I_C (R_C + R_E)$$

Stabilisation. In this circuit, excellent stabilisation is provided by R_E. Consideration of eq. *(i)* reveals this fact.

$$V_2 = V_{BE} + I_C R_E$$

Suppose the collector current I_C increases due to rise in temperature. This will cause the voltage drop across emitter resistance R_E to increase. As voltage drop across R_2 (*i.e.* V_2) is *independent of I_C, therefore, V_{BE} decreases. This in turn causes I_B to decrease. The reduced value of I_B tends to restore I_C to the original value.

Stability factor. It can be shown mathematically that stability factor of the circuit is given by ;

$$\text{Stability factor,} \quad S = \frac{(\beta + 1)(R_T + R_E)}{R_T + R_E + \beta R_E}$$

$$= (\beta + 1) \times \frac{1 + \frac{R_T}{R_E}}{\beta + 1 + \frac{R_T}{R_E}} \quad \text{where } R_T = \frac{R_1 R_2}{R_1 + R_2}$$

If the ratio R_T/R_E is very small, then R_T/R_E can be neglected as compared to 1 and the stability factor becomes :

$$\text{Stability factor} = (\beta + 1) \times \frac{1}{\beta + 1} = 1$$

This is the smallest possible value of S and leads to the maximum possible thermal stability. Due to design **considerations, R_T/R_E has a value that cannot be neglected as compared to 1. In actual practice, the circuit may have stability factor around 10.

Example 11.11. *Fig. 11.15 (i) shows the voltage divider bias method. Draw the d.c. load line and determine the operating point. Assume the transistor to be of silicon.*

Solution

(i) **d.c. load line.** The collector-emitter voltage V_{CE} is given by ;

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

When $I_C = 0$, $V_{CE} = V_{CC} = 15\text{V}$. This locates the first point B ($OB = 15\text{V}$) of the load line on the collector-emitter voltage axis.

$$\text{When } V_{CE} = 0, \quad I_C = \frac{V_{CC}}{R_C + R_E} = \frac{15 \text{ V}}{(1 + 2) \text{ K}\Omega} = 5mA$$

This locates the second point A ($OA = 5mA$) of the load line on the collector current axis. By joining points A and B, the d.c. load line AB is constructed as shown in Fig. 11.15 *(ii)*.

* voltage drop across $R_2 = \left(\frac{V_{CC}}{R_1 + R_2}\right) R_2$

** Low value of R_T can be obtained by making R_2 very small. But with low value of R_2, current drawn from V_{CC} will be large. This puts restrictions on the choice of R_T. Increasing the value of R_E requires greater V_{CC} in order to maintain the same value of zero signal collector current. Therefore, the ratio R_T/R_E cannot be made very small from design point of view.