**2.5.1.1 Steady-state Characteristics.** Out of the three possible circuit configurations for a transistor, common-emitter arrangement is more common in switching applications. So, a common emitter *npn* circuit for obtaining its characteristics is considered as shown in Fig. 2.6 (*a*).

**Input characteristics.** A graph between base current $I_B$ and base-emitter voltage $V_{BE}$ gives input characteristics. As the base-emitter junction of a transistor is like a diode, $I_B$ versus $V_{BE}$ graph resembles a diode curve. When collector-emitter voltage $V_{CE2}$ is more than $V_{CE1}$, base current, for the same $V_{BE}$, decreases as shown in Fig. 2.6 (*b*).

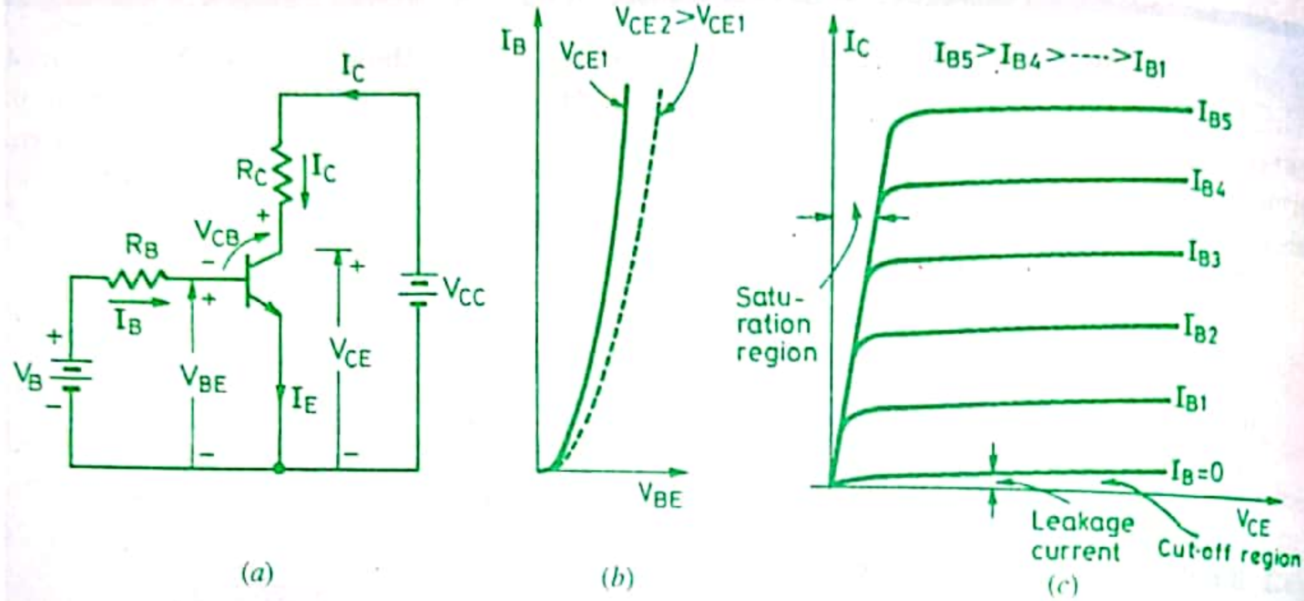


**Fig. 2.6.** (*a*) *npn* transistor circuit characteristics, (*b*) input characteristics and (*c*) output characteristics.

**Output characteristics.** A graph between collector current $I_c$ and collector-emitter voltage $V_{CE}$ gives output characteristics of a transistor. For zero base current, *i.e.* for $I_B = 0$, as $V_{CE}$ is increased, a small leakage (collector) current exists as shown in Fig. 2.6 (*c*). As the base current is increased from $I_B = 0$ to $I_{B1}$, $I_{B2}$ etc., collector current also rises as shown in Fig. 2.6 (*c*).

Fig. 2.7 (*a*) shows two of the output characteristic curves, 1 for $I_B = 0$ and 2 for $I_B \neq 0$. The initial part of curve 2, characterised by low $V_{CE}$, is called the saturation region. In this region, the transistor acts like a switch. The flat part of curve 2, indicated by increasing $V_{CE}$ and almost constant $I_C$, is the active region. In this region, transistor acts like an amplifier. Almost vertically rising curve is the breakdown region which must be avoided at all costs.

For load resistor $R_C$, Fig. 2.6 (*a*), the collector current $I_C$ is given by

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

This is the equation of load line. It is shown as line *AB* in Fig. 2.7 (*a*). A load line is the locus of all possible operating points. Ideally, when transistor is on, $V_{CE}$ is zero and $I_C = V_{CC}/R_C$. This collector current is shown by point *A* on the vertical axis. When the transistor is off, or in the cut-off region, $V_{CC}$ appears across collector-emitter terminals and there is no collector current. This value is indicated by point *B* on the horizontal axis. For the resistive load, the line joining points *A* and *B* is the load line.

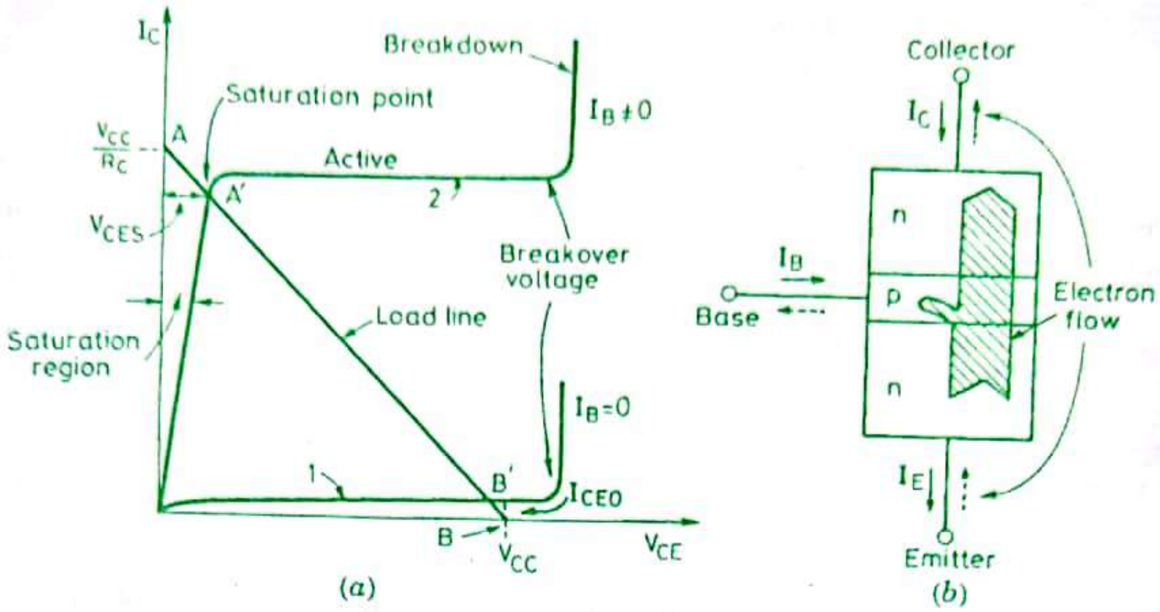


**Fig. 2.7.** (*a*) Output characteristics and load line for *npn* transistor and (*b*) electron flow in an *npn* transistor.

**Relation between $\alpha$ and $\beta$.** Most of the electrons, proportional to $I_E$, given out by emitter, reach the collector as shown in Fig. 2.7 (*b*). In other words, collector current $I_C$, though less than emitter current $I_E$, is almost equal to $I_E$. A symbol $\alpha$ is used to indicate how close in value these two currents are. Here $\alpha$, called *forward current gain*, is defined as

$$\alpha = \frac{I_C}{I_E} \quad ...(2.6)$$

As $I_C < I_E$, value of $\alpha$ varies from 0.95 to 0.99.

In a transistor, base current is effectively the input current and collector current is the output current. The ratio of collector (output) current $I_C$ to base (input) current $I_B$ is known as the *current gain* $\beta$.

$$\therefore \quad \beta = \frac{I_C}{I_B} \quad ...(2.7)$$

As $I_B$ is much smaller, $\beta$ is much more than unity ; its value varies from 50 to 300. In another system of analysis, called $h$ parameters, $h_{FE}$ is used in place of $\beta$.

$$\therefore \quad \beta = h_{FE} = \frac{I_C}{I_B} \quad ...(2.7)$$

Use of KCL in Fig. 2.6 (*a*) gives

$$I_E = I_C + I_B \quad ...(2.8)$$

Remember that emitter current is the largest of the three currents, collector current is almost equal to, but less than, emitter current. Base current has the least value. Dividing both sides of Eq. (2.8) by $I_C$, we get

$$\frac{I_E}{I_C} = 1 + \frac{I_B}{I_C}$$

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

Medium current diodes have a maximum current rating of 400 mA and reverse voltage of about 200 V.

High-current diodes are also called ***power diodes***. They are rated for high current and high reverse voltage ratings. Metal heat sinks are used for dissipation of heat produced in a diode when it is conducting.

In addition to their use in switching circuits, diodes are used in rectifier circuits for half-wave and full-wave rectification.

## 14.6 ▶ Zener Diode

Like as ordinary diode, zener diode allows current flow in the forward direction and also in the reverse direction at certain reverse voltage, called zener breakdown voltage.

We have known that when a diode is reverse based, only a minutely small current called saturature current flows (ideally no current should flow). If the reverse voltage is increased continuously, the junction breaks down and suddenly a large reverse current flows. This reverse current is controlled or limited by connecting a suitable series resistance so that excessive heat produced due to heavy current flow may not burn the diode. If the reverse breakdown current is limited to the current-carrying capacity of the diode, it can be operated under reverse breakdown condition. The I–V characteristic of the diode under the reverse-biased condition can be made dropping down almost vertically by proper doping of the semiconductor material. A diode with a very sharp breakdown voltage is called a *zener diode*. Diodes designed to operate under the reverse breakdown condition, maintain a fairly constant voltage over a wide range of current levels. When the reverse voltage is reduced below the breakdown voltage, the current level returns to the very low-saturation current level.

There are two ways that breakdown of a zener diode may occur. One is called ***zener breakdown*** and the other is called *avalanche breakdown*. If the depletion layer of a diode is narrow and we apply a reverse voltage, the voltage per unit of width of the depletion layer becomes high. This establishes a strong electric field intensity which causes electrons to break away from their parent atoms. Thus, a depletion layer which was insulating in nature, becomes a conducting path. This kind of breakdown due to the creation of a strong electric field intensity, i.e., V/μm is called zener breakdown.

If the width of the depletion layer is wide for a zener breakdown, a sufficient reverse voltage may provide the free electrons (minority carriers causing saturation current) to gain sufficient energy to knockout electrons from the atoms of the semiconductor in the depletion region. This is called ionization by collision. The breakdown occurring this way is called avalanche breakdown.

Zener breakdown occurs at a voltage less than 5 V and avalanche breakdown voltage is higher than 5 V. The symbol, the circuit, and the I–V characteristic of a zener diode are shown in Fig. 14.12. The forward I–V characteristic of a zener diode is the same as an ordinary diode.

As shown in Fig. 14.12 (b), a zener diode is operating under the reverse-biased condition. A resistance, R is connected to limit the current beyond the normal current-carrying capacity. A constant voltage, $V_R$ will be available across the zener diode, even if the input voltage changes. Manufacturers specify the zener breakdown voltage and the maximum zener current. Type of zener diodes are numbered by manufactures as IN 746, IN 747, IN 755, IN 759, etc.

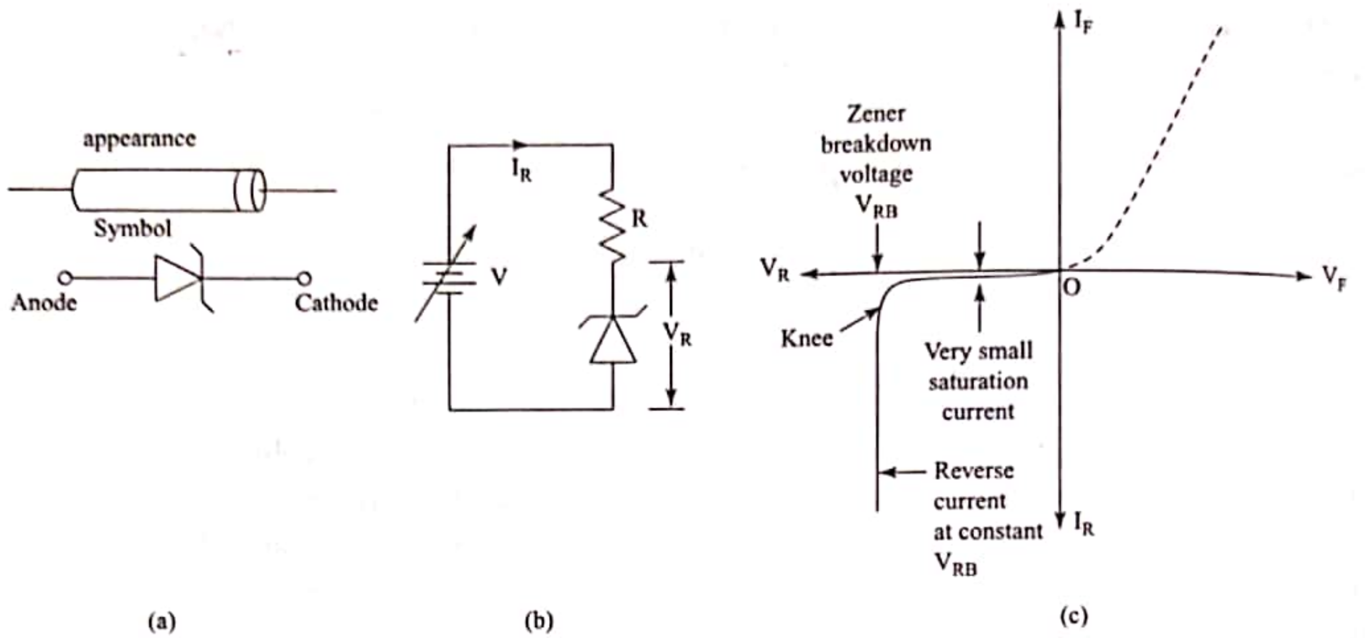


**FIGURE 14.12**

(a) Appearance and (b) Symbol of a zener diode; (b) zener diode circuit; (c) I–V characteristic

### *Zener resistance*

It is the dynamic resistance of the zener diode somewhat below the knee point on the reverse V–I characteristic. It is similar to the dynamic resistance of a forward-biased diode. Zener resistance, $R_Z$ is given by

$$R_z = \frac{\Delta V_z}{\Delta I_z}$$

The value of RZ is to be small so that it will indicate a steep curve where due to a small change in voltage, DVZ a large change in current, DIZ takes place. The value of zener resistance varies with the current. It decreases with increase in current.

An application of zener diode as a voltage regulator or stabilizer, and often used as reference voltage in electronic circuits has been shown in Fig. 14.13. How the zener diode helps in maintaining a constant voltage when the load current changes and when the input voltage changes can be understood from the following two applications.

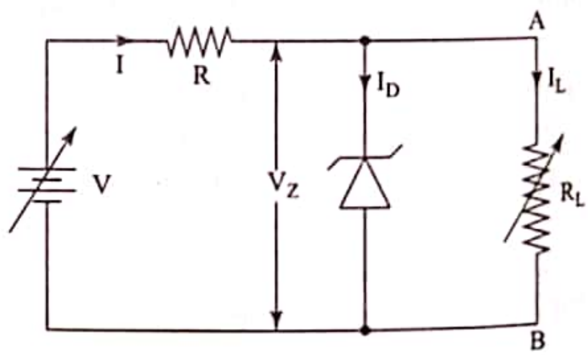


**FIGURE 14.13**

Zener diode voltage regulator circuit

## 14.6.1 Zener Diode As Voltage Regulator

A voltage regulator maintains nearly constant voltage output across the load over a wide range of variation of load current. A zener diode voltage regulator circuit has been shown in Fig. 14.13. The zener diode has been reverse biased.

The task of a voltage regulator is to maintain a nearly constant output voltage as the load current varies over a wide range. The zener diode used in the circuit is shown in Fig. 14.13 maintains a constant voltage across the load terminals A and B. The function of the zener diode is to maintain the output voltage more or less constant even if the load current changes. This is accomplished by operating the zener diode in the breakdown region when voltage across it changes only very slightly over a wide variation of zener current. The zener breakdown voltage has to be lower than the applied voltage, V.

### 14.6.2 Zener Diode As a Reference Voltage

In many applications it becomes desirable that a constant voltage is maintained between two points in a circuit and use this voltage as a reference voltage to which voltage of another point or circuit is to be compared. The difference between reference voltage and compared voltage is first amplified and then used to perform some control operations. A zener diode will maintain a constant voltage across its terminals even if there is a change in the supply voltage, V in the circuit as shown in Fig. 14.13.

## 14.7 ▶ BIPOLAR JUNCTION TRANSISTORS

Transistors are used in almost all electronic circuits. The ability to amplify or switch electrical signals accounts for their wide use. The word transistor is the short form of the word "transfer resistor". The signal amplification in a transistor is achieved by transfering the signal from a region of low resistance to a region of high resistance. The concept of transfer of resistance, when viewed this way, has given the name transistor.

A bipolar junction transistor has three layers of semiconductor material. These layers are arranged either in an n–p–n sequence or in a p–n–p sequence. In an n–p–n transistor, a p-type semiconductor material is sandwiched between two n-type materials. In a p–n–p transistor, an n-type semiconductor material is sandwiched between two p-type materials.

A transistor, in general, has two p–n junctions connected back to back as shown in Fig. 14.14. As shown in the figure, the central layer is called the ***base***, one of the outer layers is called the ***emitter***, and the other is called the ***collector***.

The basic principle of transistor operation is that a small current in the base region can control a much larger current flow through the transistor, i.e., from the emitter to the collector. A transistor can be used as current amplification or a voltage amplification device. Since a transistor combines two junction diodes, it works on the basis of p–n junction theory as has already been explained.

The symbolic representation of a transistor has also been shown. The symbol for an n–p–n or a p–n–p transistor is the same except for the direction of the arrow head. The arrow head has to be shown from p terminal to n terminal between the emitter and the base. The emitter of a transistor is heavily doped. The base is lightly doped while the collector is less heavily doped than the emitter.

The common-collector (CC) circuit has very high input impedance and very low-output impedance. So the voltage gain will be low. Therefore CC circuit is rarely used for voltage amplification.

This circuit, however, is used for impedance matching because of its high-input impedance and low-output impedance.

### 14.8.4 Comparison of Transistor Characteristics of Different Configurations

The basic characteristic parameters for comparison are input impedance, output impedance, current gain, voltage gain, and application areas. These are shown in a tabular from.

| Characteristics | Common base | Common emitter | Common collector |
|---|---|---|---|
| 1. Input Impedence | Low in ohms | Low in ohms | High in Kilo-ohms |
| 2. Output Impedence | Very high in Kilo-ohms | High in Kilo-ohms | Low in ohms |
| 3. Current Gain | Less than unity | High | High |
| 4. Voltage Gain | High | High | Less than unity |
| 5. Applications | For High frequency applications | For Audio frequency application | For impedance matching |

From the above comparison, it is seen that common emitter circuits are most efficient and therefore are used most often. The CE configuration provides high current gain, high voltage and power gain, and moderate output to input impedance ratio.

### 14.8.5 Transistor As an Amplifier

In Fig. 14.24 is shown a simple transistor amplifier circuit using an n–p–n transistor connected in the common-emitter configuration. The ac signal which is to be amplified is connected to the base circuit as shown. The output is taken across a resistance, $R_L$ in the collector circuit. The base circuit dc voltage, $V_{BB}$ is such that the base will always remain positive irrespective of the magnitude of the input ac signal. The voltage, $V_{BE}$ is the summation of dc voltage $V_{BB}$ and the ac input signal, $V_i$. The dc voltage, $V_{BB}$ is the bias voltage. The magnitude of $V_{BB}$ must be higher than the maximum value of the input signal. Then, only the base will always remain positively biased in both half cycles of the input ac signal voltage. When the ac signal is applied, this becomes superimposed on the battery voltage, $V_{BB}$ and the base current $I_B$ will flow, which is the sum of the dc base current $I_{B\alpha}$ and the ac signal current. It can be observed that $I_B$ is always positive.

During the positive half cycle of the input signal, the dc and ac voltages are added up and as such the base current is highly positive. During the negative half cycle, ac voltage is subtracted from the dc voltage. The net voltage is low but positive. The base current now will be positive but low.

Because of the large variation in the base current there will be a large variation in the collector current, which will flow through the load resistance. An amplified output voltage is, thus available across the load. The amplified collector ac current is superimposed on the dc current, $I_{CQ}$ which will flow through the collector when the ac input signal is not applied. It is the current when the base current is $I_{BQ}$.

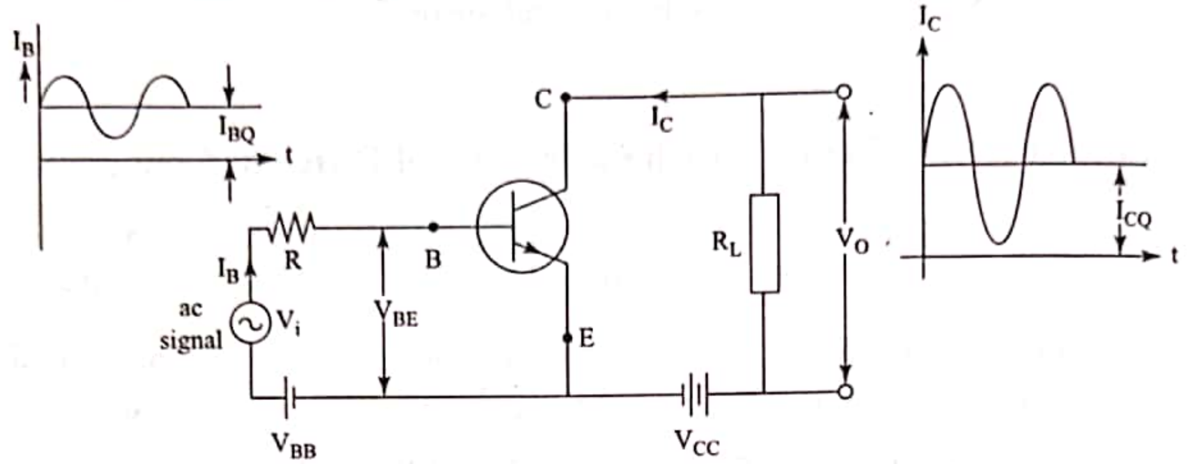


**FIGURE 14.24**

Transistor as an amplifier

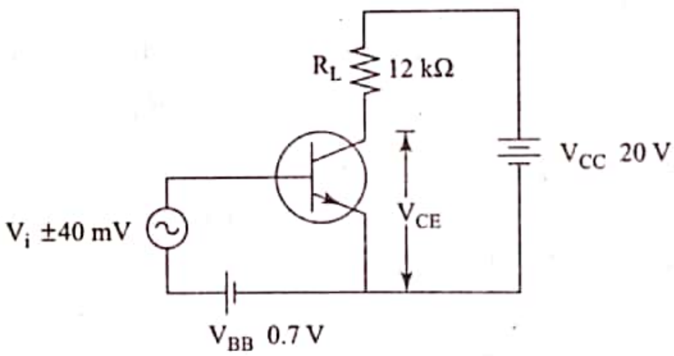


**FIGURE 14.25**

Transistor amplifier circuit

## EXAMPLE 14.3

In an n–p–n transistor in the common emitter configuration, an ac input signal of ±40 mV is applied as shown in Fig. 14.25. The dc current gain, $\beta_{dc}$ and ac current gain $\beta_{ac}$ are given as 80 and 100, respectively. Calculate the voltage amplification, $A_V$ of the amplifier. The $I_B$ versus $V_{BE}$ characteristic is such that for $V_B = 0.7$ V, $I_B = 12$ μA and for $V_i = \pm 40$ mV, $I_b = \pm 4$ μA. Also calculate the dc collector voltage.

### SOLUTION

DC base current, $I_B = 12$ μA for dc voltage, $V_{BB} = 0.7$ V and $\beta_{dc} = 80$

$I_C = \beta_{dc} I_B = 80 \times 12\ \mu A = 0.96$ mA

The collector voltage $V_{CE}$ is calculated as

$$\begin{aligned} V_{CE} &= V_{CC} - I_C R_L \\ &= 20 - 0.96 \times 10^{-3} \times 12 \times 10^3 \\ &= 20 - 11.52 \\ &= 8.48 \text{ V} \end{aligned}$$

AC base current, $I_b = \pm 4\ \mu A$ for $V_i = \pm 40$ mV

$I_C = \beta_{ac} I_b = 100 \times (\pm 4\ \mu A) = \pm 400\ \mu A$

AC output voltage across load resistance, $V_0$ is calculated as

$V_0 = I_C R_L = \pm 400 \times 10^{-6} \times 12 \times 10^3 = \pm 4.8$ V

AC voltage amplification factor, $A_V$ is calculated as

$$A_v = \frac{v_0}{v_i} = \frac{\pm 4.8 \text{ V}}{\pm 40 \text{ mV}} = \frac{\pm 4.8}{\pm 40 \times 10^{-3}} = 60$$

### 14.8.6 Transistor As a Switch

A BJT can be used as an amplifier and also as a switch. A switch either closes a circuit or opens a circuit. There are two states for a switch, i.e., either there is no current flow (cut off) or the switch is closed, i.e., current flows through it with the minimum of resistance offered.

These two conditions can be created by applying a pulse wave input to the base of the BJT. In the case of an amplifier we had applied a bias voltage plus an ac signal that had to be amplified to the base circuit. In the case of switching operation, a pulse voltage of appropriate level has to be applied as shown in Fig. 14.26 (a) and (b).

The base voltage level is either at zero level or at an appropriate positive level. When the input voltage, $V_i$ is at zero level, the base current is zero and there is no collector current, i.e., $I_c = 0$ as shown is Fig. 14.26 (a).

The transistor is cut off and works like an open switch.

From Fig. 14.26 (b),

$V_{CE}$ = Supply voltage – voltage drop across $R_2$

$V_{CE} = V_{CC} - I_C R_2$

When the base-emitter voltage is at zero level, the transistor is not working, and hence, $I_C = 0$. Therefore,

$$V_{CE} = V_{CC}$$

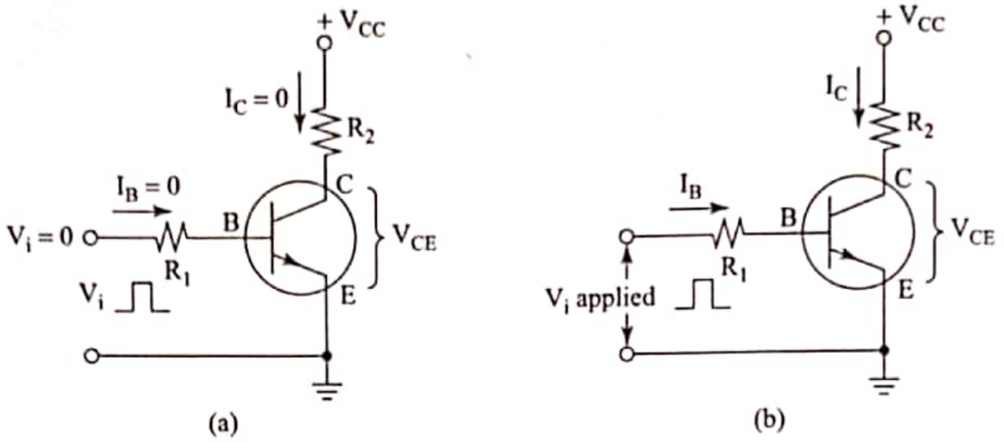


**FIGURE 14.26**

(a) Off state of a BJT; (b) on state of a BJT

When $V_i$ is at positive level, base current, $I_B$ will flow. If the BJT is to be used as a switching device, the level of $I_B$ is made high enough so that the transistor is saturated. At saturated state the level of $I_C$ will be such that $I_CR_2$ will be equal to $V_{CC}$ for which $V_{CE} = 0$. The transistor will operate as a closed switch between the collector and emitter.

## EXAMPLE 14.4

What minimum input voltage level is required to switch a BJT into saturation (on state) when $V_{CC}$ = 10 V, R1 = 16 kW, $R_2$ = 6.2 kW and $\beta_{dc}$ = 20 in an n–p–n CE configuration BJT, as has been shown in Fig. 14.27.

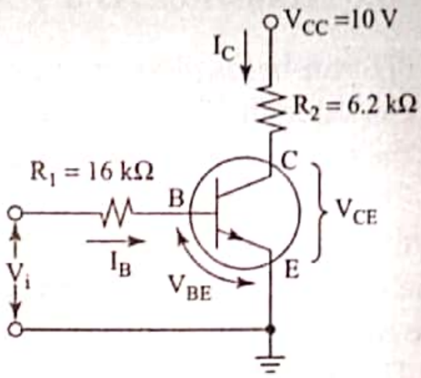


**FIGURE 14.27**

### SOLUTION

$$V_{CC} = I_CR_2 + V_{CE}$$

for $V_{CE} = 0$

$$I_C = \frac{V_{CC}}{R_2} = \frac{10}{6.2\times10^3} = 1.612 \text{ mA}$$

$$= 1612\ \mu\text{A}$$

$$I_C = \beta_{dc} I_B$$

or,

$$I_B = \frac{I_C}{\beta_{dc}} = \frac{1612}{20} = 80.6\ \mu\text{A}$$

Taking $V_{BE} = 0.7$ V,

$$V_i - I_BR_1 = V_{BE}$$

or,

$$V_i = V_{BE} + I_BR_1$$

$$= 0.7\text{V} + 80.6\times10^{-6}\times16\times10^3\text{ V}$$

$$= (0.7+1.29)\text{V} = 1.99\text{ V}$$