Transistor:

A junction transistor is obtained by growing a thin layer of one type semiconductor in between two thick layers of other similar type semiconductor. Thus, a junction transistor is a semiconductor device having two junctions and three terminals.

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. 1(a). However, a *p-n-p* transistor is formed by two *p*-sections separated by a thin section of *n*-type as shown in fig. 1(b).

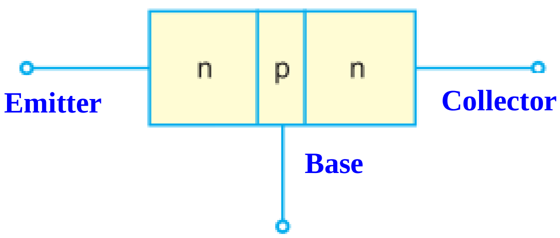


Fig. 1(a)

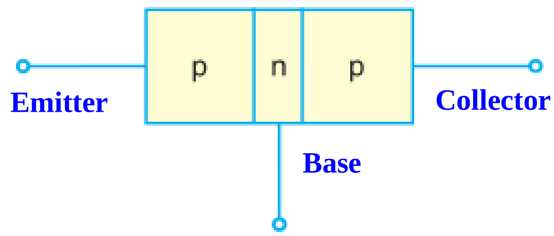


Fig. 1(b)

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

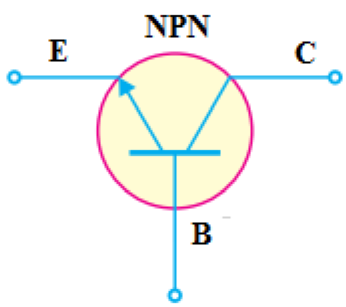
(*i*) These are two *p-n* junctions. Therefore, a transistor may be regarded as a combination of two diodes connected back to back.

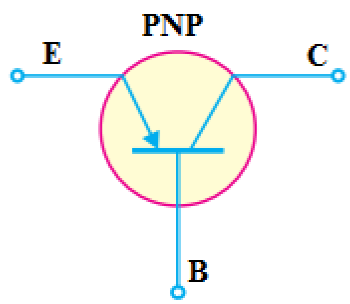
(*ii*) There are three terminals, one taken from each type of semiconductor.

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

Transistor Symbols:

. The symbols used for *n-p-n* and *p-n-p* transistors are shown in figure.





Naming the Transistor Terminals:

A transistor (p-n-p or n-p-n) 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 heavily doped and it is always forward biased w.r.t. base so that it can supply a large number of majority carriers. In fig 2(a), the emitter (p-type) of p-n-p transistor is forward biased and supplies hole charges to its junction with the base. Similarly, in fig. 2(b), the emitter (n-type) of n-p-n 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. In fig 2(a), the collector (p-type) of p-n-p transistor has a reverse bias and receives hole charges that flow in the output circuit. Similarly, in fig 2(b), the collector (n-type) of n-p-n transistor has reverse bias and receives electrons.

(iii) Base. The middle section which forms two p-n-junctions between the emitter and collector is called the base. The base is lightly doped and very thin. 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.

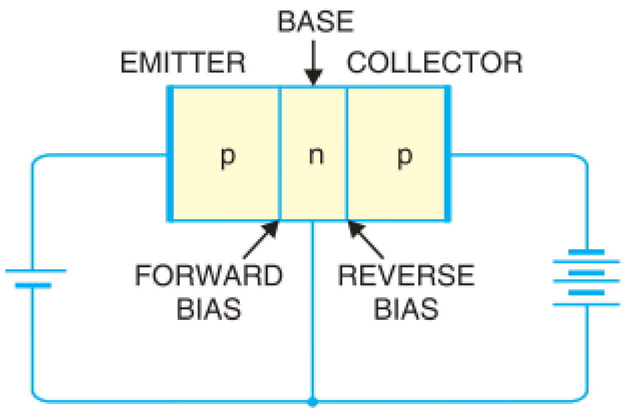


Fig. 2(a)

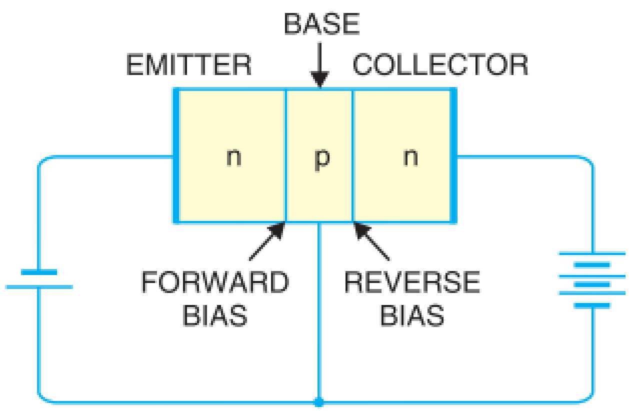


Fig. 2(b)

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.

Transistor Action:

Working of n-p-n transistor:

Fig. 3(a) shows the *n-p-n* 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.*

$$I_E = I_B + I_C$$

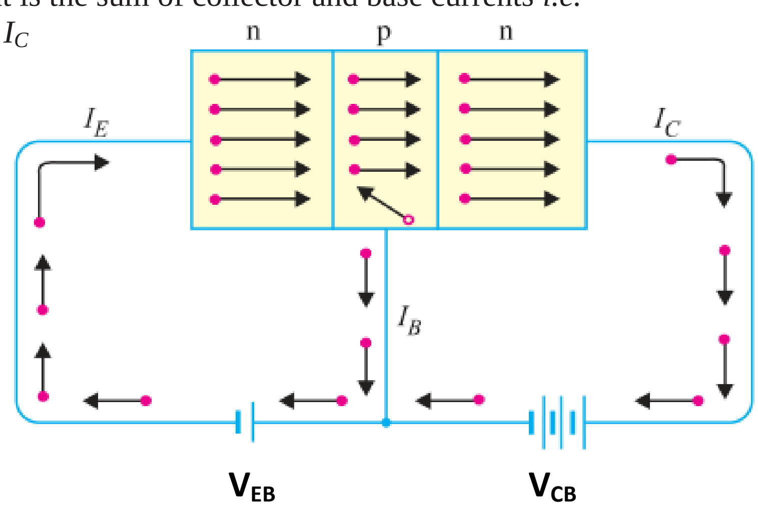


Fig. 3(a)

Working of p-n-p transistor:

Fig. 3(b) shows the basic connection of a *p-n-p* 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 *p-n-p* transistor is by holes. However, in the external connecting wires, the current is still by electrons.

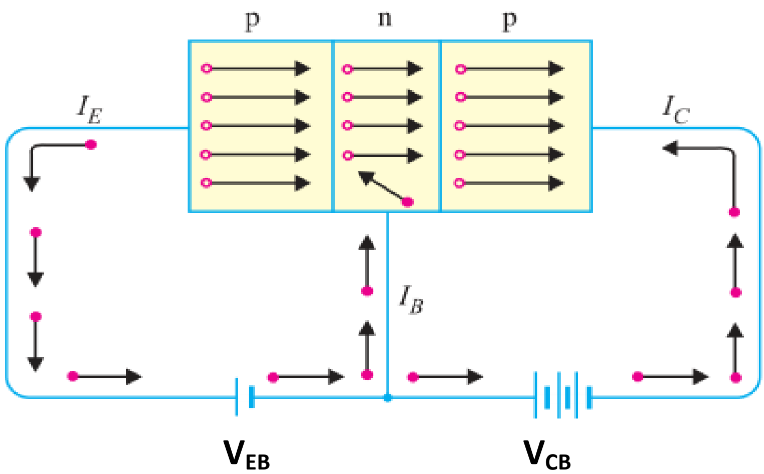


Fig. 3(b)

6.4 OPERATION OF PNP TRANSISTOR

Fig. (4) shows a PNP transistor with emitter-base junction as forward biased and collector-base junction as reverse-biased. The operation of *PNP* transistor is as follows : The holes of *P* region (emitter) are repelled by the positive terminal of battery

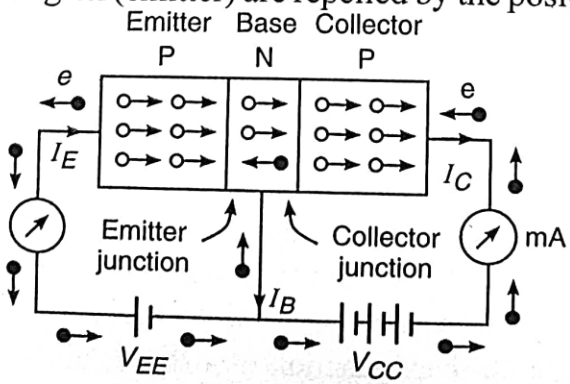


Fig. (4) Operation of *P-N-P* transistor

V_{EE} towards the base. The potential barrier at emitter junction is reduced as it is forward bias and hence the holes cross this junction and penetrate into *N* region. This constitute the emitter current L_E. The width of base region is very thin and it is lightly doped and hence only two to five per cent of the holes recombine with the free electrons of *N* region. This constitute the base current I_B, which, of course, is very small. The remaining holes (95% to 98%) are able to drift across the base and enter the collector region. They are swept up by the negative collector voltage V_{CC}. This constitutes the collector current I_C.

As each hole reaches the collector electrode, an electron is emitted from the negative terminal of battery and neutralizes the hole. Now a covalent bond near the emitter electrode breaks down. The liberated electron enters the positive terminal of battery V_{EE} while the hole immediately moves towards the emitter junction. This process is repeated again and again. Here it should be remembered that :

(i) Current conduction within *PNP* transistor takes place by hole conduction from emitter to collector, *i.e.*, majority charge carriers in a *PNP* transistor are holes. The conduction in the external circuit is carried out by electrons.

(ii) The collector current is slightly less than the emitter current. This is due to the fact that 2 to 5% of the holes are lost in recombination with electrons in base region. Thus, the collector current is slightly less than emitter current.

(iii) The collector current is a function of emitter current, *i.e.,* with the increase or decrease in the emitter current, a corresponding change in collector current is observed.

Beside hole current, there is electron current which flows from base region to emitter region. This current depends upon emitter-base potential. As the width of the base region is very small, the ratio of hole current to electron current is very small. So for all practical purposes, the electron current may be neglected. ***Thus, only the hole current plays the important role in the operation of* P-N-P *transistor.***

By normal convention, the flow of current into transistor is taken as positive while the current flowing out is taken as negative. Therefore, I_E will be positive while I_B and I_C are negative.

6.5 OPERATION OF NPN TRANSISTOR

The schematic energy level diagram of an isolated *N-P-N* transistor is shown in fig. (5) while for a biased *N-P-N* transistor it is shown in fig. (6).

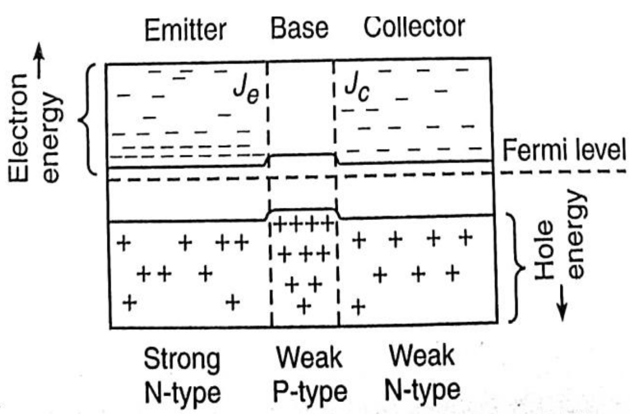


Fig. (5) Schematic energy-level of an isolated *N-P-N* transistor

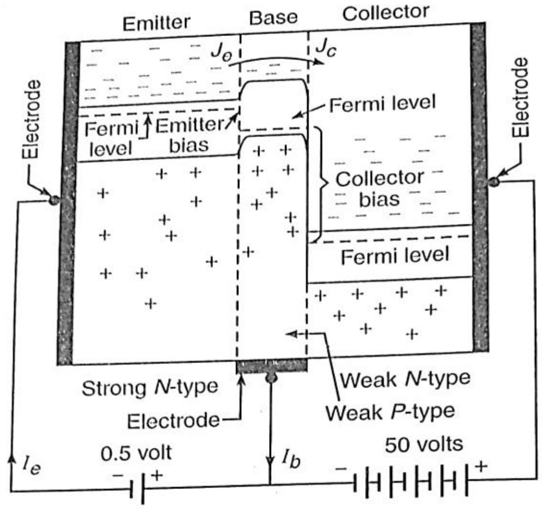


Fig. (6) Schematic energy-level diagram of a biased *N-P-N* transistor (arrows indicate the directions of electron flow).

The biasing of a NPN transistor is shown in fig. (7). The emitter junction is forward-biased because electrons are repelled from the negative emitter battery terminal V_{EE} towards the junction. The collector junction is reverse-biased because electrons are flowing away from the collector junction towards the positive collector battery terminal V_{CC}.

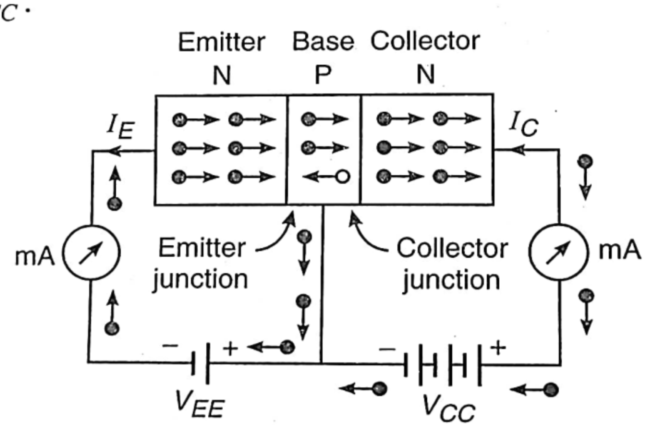


Fig. (7) Operation of *NPN* transistor

The operation of *NPN* transistor is as follows : The electron in the emitter region are repelled from the negative terminal of battery towards the emitter junction. Since the potential barrier at the junction is reduced due to forward bias and base region is very thin and lightly doped, electrons cross the *P*-type base region. A few electrons combine with the holes in *P*-region and are lost as charge carrier. Now the electrons in *N*-region (collector region) are readily swept up by the positive collector voltage V_{CC}. For every electron flowing out of the collector and entering the positive terminal of battery V_{CC}, an electron from the negative emitter battery terminal enters the emitter region. In this way electron conduction takes place continuously so long as the two junctions are properly biased. *So the current conduction in N-P-N transistor is carried out by electrons.*

N-P-N configuration is preferred because in it majority carriers are electrons which have greater mobility and diffusion constant than holes. Current flow when base-emitter junction is forward biased and base-collector junction is reverse biased can be understood as follows :

(i) Under forward bias, electrons in emitter move towards base. Majority of electrons (about 99%) cross over to collector, while very few of them combine with holes in the base.

(ii) As soon as electron combines with a hole in base, an electron leaves the negative pole of the battery V_{EE} and enters through terminal *E*. At the same time positive pole of V_{EE} receives an electron from the base. This creates a hole in the base which compensates for the hole lost by combination. That is how a current flows in the base emitter circuit.

(iii) The electrons entering the collector are favoured by reverse bias and they reach the terminal *C*. For each electron leaving the terminal, *C* and entering the positive pole of the battery V_{CC}, an electron leaves the negative pole of V_{EE} and enters the emitter. That is how the current entering terminal, *C*, called collector current, flows.

6.6 CURRENT COMPONENTS IN A TRANSISTOR

Fig. (8) shows the various current components which flow across the forward-biased emitter junction and reverse-biased collector junction in *PNP* transistor.

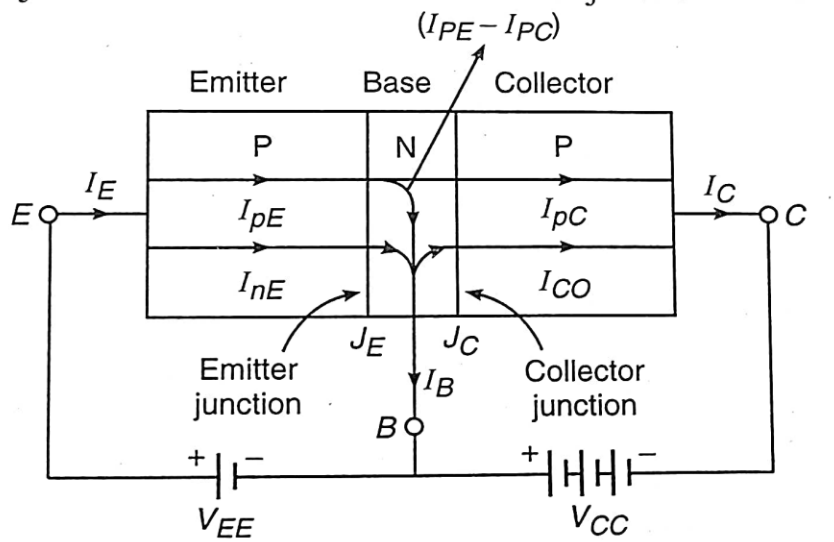


Fig. (8) Current components in a transistor with forward-biased emitter and reverse-biased collector

The emitter current consists of the following two parts :

(i) Hole current I_{pE} constituted by holes (holes crossing from emitter into base),

(ii) Electron current I_{nE} consituted by electrons (electrons crossing from base into the emitter).

$\therefore$ Total emitter current, $I_E = \underset{\text{Majority}}{I_{pE}} + \underset{\text{Minority}}{I_{nE}}$ ...(1)

In commercial transistors the doping of emitter region is made much heavier than base and hence the electron current component I_{nE} is negligibly small in comparison with hole current I_{pE}. Thus, in a commercial *PNP* transistor, *the emitter current consists almost entirely of holes.*

A few of holes crossing the junction J_E combine with the electrons in *N* type base and rest of them cross the collector junction J_C. This reduces the number of holes which ultimately reach the collector. To reduce the number of holes so lost through recombination with electrons in *N*-region, the width of the base region is kept extremely small. Let I_{pC} is the hole current at junction J_C. The difference $(I_{pE} - I_{pC})$ is the recombination current I_B which leaves the base as shown in fig. (8). In fact, electrons enter the base region through the base lead to replenish those electrons which have been lost by recombination with the holes injected into the base across J_E. The holes on reaching the collector junction cross this junction readily and enter the P-region of the collector.

If the emitter were open-circuited, then $I_E = 0$, *i.e.,* I_{pC} would be zero. Under this condition, the base and collector together act as a reversed diode and the collector current I_C equals the reverse saturation current I_{CO}, which consists of the following two parts :

I_{nCO} caused by electrons moving across J_C from *P*-region to *N*-region.

I_{pCO} caused by holes moving across J_C from *N*-region to *P*-region.

$$I_{CO} = I_{nCO} + I_{pCO} \qquad \text{...(2)}$$

In general, $I_C = \underset{\text{Majority}}{I_{pC}} + \underset{\text{Minority}}{I_{CO}}$ ...(3)

Thus, for a PNP transistor, $\boxed{I_E = I_B + I_C}$ ...(4)

In a good transistor, the base current I_B should be very small (about 1% of I_E) and I_E should be almost equal to I_C. However, there is always some base current due to the following reasons :

(i) Some recombination of injected holes with electrons takes place in the base region even when base width is very small. The electrons lost due to recombinations have to be supplied by the base current.

(ii) Some electrons are injected from base to emitter in the forward biased emitter junction even when emitter is heavily doped as compared to base. Base current supplies these electrons.

(iii) Some electrons are swept in the base at the reverse biased collector junction due to thermal generation in the collector. Hence, a small part of the total base-current is compensated by these electrons from the collector.

Note that in case of *NPN* transistor the three current directions are reversed. Electrons flow from emitter to collector and holes must be supplied to the base. The mechanism for operation in the *NPN* transistor is the same as in case of *PNP* transistor. Only the role of electrons and holes are reversed.

Transistor Connections:

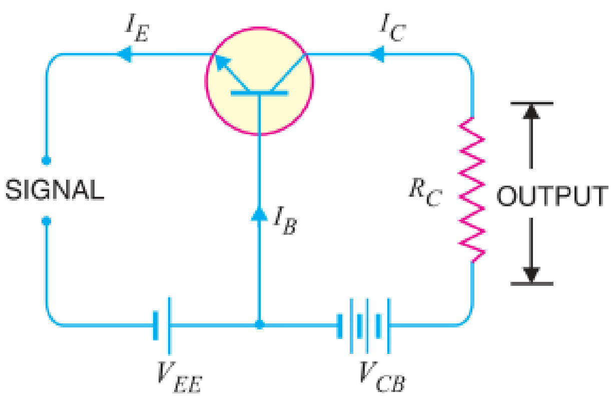
A transistor can be connected in a circuit in the following three ways:

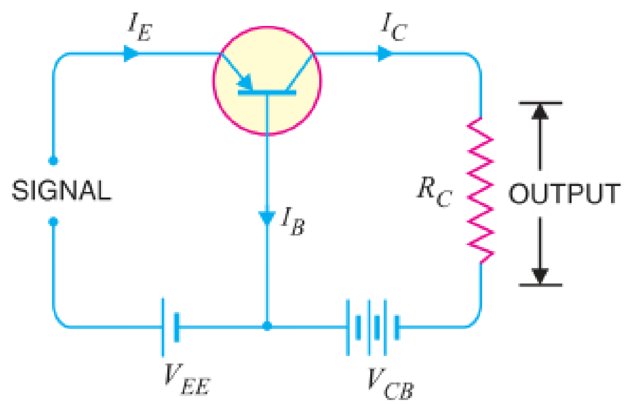
(*i*) Common base connection (*ii*) Common emitter connection

(*iii*) Common collector connection.

(*i*) Common base connection:

In C.B. connection base of the transistor is common to both input and output circuits. In this circuit arrangement, input is applied between emitter and base and output is taken from collector and base. In fig. 4(a), a common base *n-p-n* transistor circuit is shown whereas fig. 4(b), shows the common base *p-n-p* transistor circuit.





Current amplification factor (α):

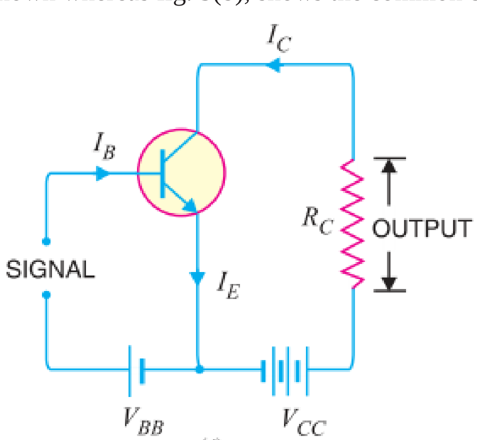
The ratio of change in collector current to the change in emitter current at constant collector base voltage V_{CB} is known as **current amplification factor** i.e.

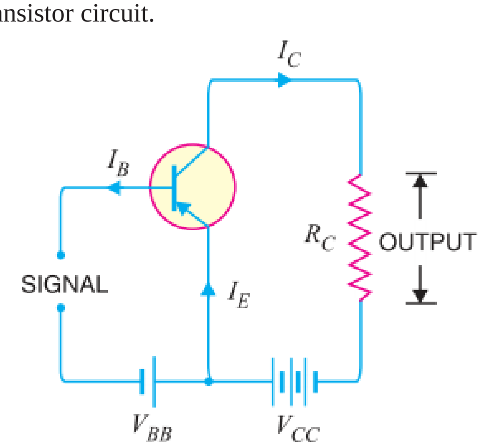
$$\alpha = \frac{\Delta I_C}{\Delta I_E}, \text{ at constant } V_{CB}$$

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. Practical values of α in commercial transistors range from 0.9 to 0.99.

(*ii*) Common emitter connection:

In C.E. connection, emitter of the transistor is common to both input and output circuits. In this circuit arrangement, input is applied between emitter and base and output is taken from collector and emitter. In fig. 5(a), a common base *n-p-n* transistor circuit is shown whereas fig. 5(b), shows the common base *p-n-p* transistor circuit.





Base current amplification factor (β):

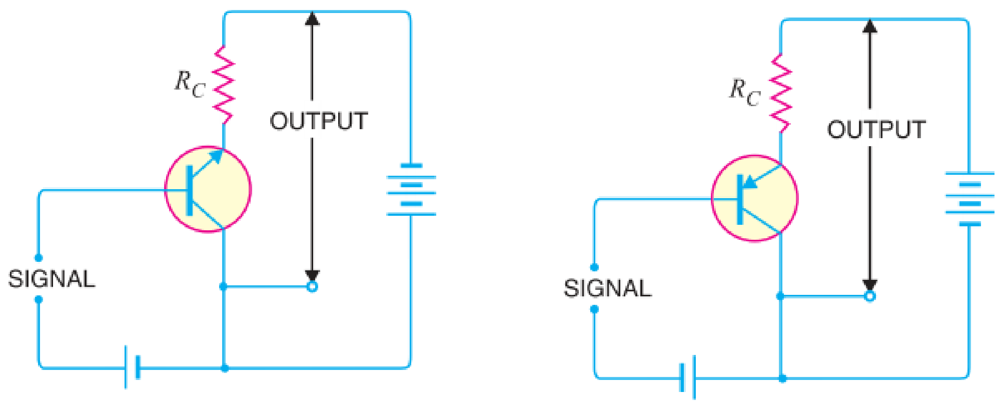
The ratio of change in collector current (ΔI_C) to the change in base current (ΔI_B) is known as **base current amplification factor** i.e.

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

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.

(*iii*) Common collector connection:

In C.C. connection, collector of the transistor is common to both input and output circuits. In this circuit arrangement, input is applied between base and collector while output is taken between the emitter and collector. In fig. 6(a), a common base *n-p-n* transistor circuit is shown whereas fig.65(b), shows the common base *p-n-p* transistor circuit.



Current amplification factor (γ):

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.

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

Relation between α and β:

If ΔI_E, ΔI_B, and ΔI_C are the change of emitter current, base current and collector current then

$$\alpha = \frac{\Delta I_C}{\Delta I_E} \qquad \text{---- (1)}$$

and

$$\beta = \frac{\Delta I_C}{\Delta I_B} \qquad \text{---- (2)}$$

Again for a transistor,

$$I_E = I_B + I_C$$

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

$$\Rightarrow \Delta I_B = \Delta I_E - \Delta I_C \qquad \text{----(3)}$$

Substituting the value of ΔI_B in equation (2), we get

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

$$\Rightarrow \beta = \frac{\frac{\Delta I_C}{\Delta I_E}}{\frac{\Delta I_E}{\Delta I_E} - \frac{\Delta I_C}{\Delta I_E}}$$

$$\therefore \quad \beta = \frac{\alpha}{1-\alpha} \qquad OR \quad \beta(1-\alpha) = \alpha \Rightarrow \beta - \beta\alpha = \alpha \Rightarrow \alpha(1+\beta) = \beta \Rightarrow \alpha = \frac{\beta}{(1+\beta)}$$

Relation between α and γ:

If ΔI_E , ΔI_B , and ΔI_C are the change of emitter current, base current and collector current then

$$\alpha = \frac{\Delta I_C}{\Delta I_E} \qquad \text{---- (1)}$$

And
$$\gamma = \frac{\Delta I_E}{\Delta I_B} \qquad \text{---- (2)}$$

Again for a transistor,

$$I_E = I_B + I_C$$
$$\Rightarrow \Delta I_E = \Delta I_B + \Delta I_C$$
$$\Rightarrow \Delta I_B = \Delta I_E - \Delta I_C \qquad \text{---- (3)}$$

Substituting the value of ΔI_B in equation (2), we get

$$\gamma = \frac{\Delta I_E}{\Delta I_E - \Delta I_C}$$
$$\Rightarrow \gamma = \frac{\frac{\Delta I_E}{\Delta I_E}}{\frac{\Delta I_E}{\Delta I_E} - \frac{\Delta I_C}{\Delta I_E}}$$
$$\therefore \quad \gamma = \frac{1}{1-\alpha}$$

6.7-1 COMMON-BASE (CB) CONFIGURATION

In this configuration, the input signal is applied between emitter and base while the output is taken from collector and base. As base is common to input and output circuits, hence the name common-base configuration. Fig. (10) shows the common-base *PNP* transistor circuit. This configuration is usually used in amplifier applications.

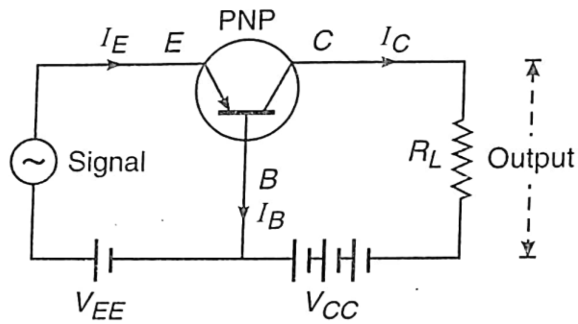


Fig. (10) Common-base PNP transistor amplifier

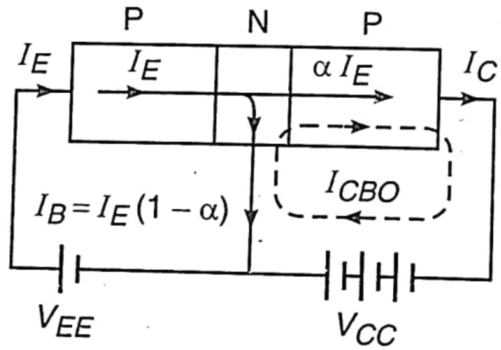


Fig. (11) Showing leakage current

Total collector current : The total collector current consists of the following two parts :

(i) The current produced by normal transistor action, *i.e.,* component controlled by emitter current. This is due to the majority carrier and its value is αI_E.

(ii) The leakage current I_{leakage}. This current is due to the motion of minority carriers across base-collector junction on account of it being reverse-biased. This is much smaller than αI_E. The leakage current is abreviated as I_{CBO}, *i.e.,* collector-base current with emitter open. This is shown in fig. (11).

∴ Total collector current

$$I_C = \underbrace{\alpha I_E}_{\text{Majority}} + \underbrace{I_{CBO}}_{\text{Minority}} \quad \ldots(1)$$

It is clear from eq. (1) that if $I_E = 0$ (emitter circuit is open), even there will be small leakage current in the collector circuit. The current I_{CBO} is usually small and may be neglected in transistor circuit calculations.

(iii) The collector current can also be expressed as

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

or

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

$$I_C = \left(\frac{\alpha}{1-\alpha}\right) I_B + \left(\frac{1}{1-\alpha}\right) I_{CBO}$$

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

$\& \; \alpha = \frac{\beta}{(1+\beta)}$

The relation between α and β is given by

$$\alpha = \frac{\beta}{1+\beta} \quad \text{or} \quad 1-\alpha = \frac{1}{1+\beta}$$

$\because \; \beta = \frac{\alpha}{1-\alpha} \Rightarrow 1-\alpha = \frac{\alpha}{\beta} \Rightarrow 1-\alpha = \frac{1}{\beta}\frac{\beta}{(1+\beta)}$

$\Rightarrow (1-\alpha) = \frac{1}{\ldots}$

$I_C = \beta I_B + (1+\beta)I \ldots$

6.7-2 COMMON-EMITTER (CE) CONFIGURATION

In this configuration, the input signal is applied between base and emitter and the output is taken from collector and emitter. As emitter is common to input and output circuits, hence the name common emitter configuration. Fig. (12) shows the common-emitter *PNP* transistor circuit.

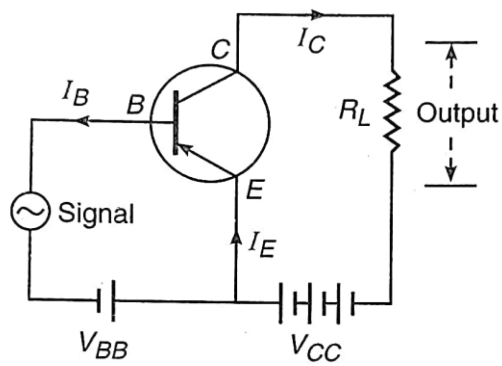


Fig. (12) Common-emitter PNP transistor amplifier

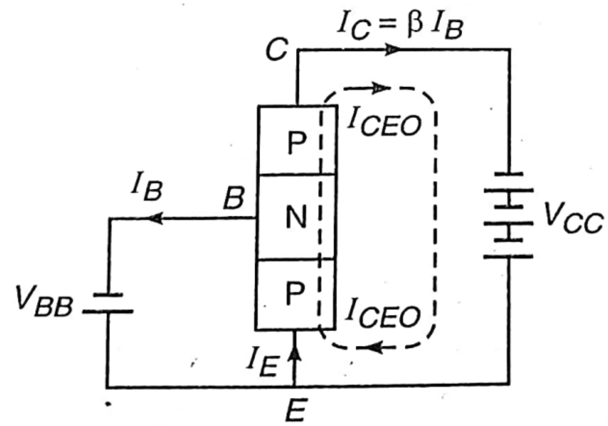


Fig. (13) Showing leakage current

This configuration is frequently used when appreciable current gain as well as voltage gain is required. This configuration is commonly used as a switch or pulse transistor amplifier. This is because the transistor is *open* in the cut-off mode and *closed* in the saturation mode.

Total collector current : The leakage current for this configuration is shown in fig. (13).

∴ Total collector current

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

where I_{CEO} is the leakage current. It is obvious from eq. (3) that despite $I_B = 0$, there is a leakage current from collector to emitter. It is called I_{CEO}, the subscript CEO stands for collector to emitter with base open.

We know that $I_E = I_B + I_C$

and $I_C = \alpha \, I_E + I_{CBO}$

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

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

or

$$I_C = \frac{\alpha}{1-\alpha} I_B + \frac{1}{1-\alpha} I_{CBO} \qquad \ldots(2)$$

Comparing Eqs. (1) and (2), we get

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

and

$$I_{CEO} = \frac{1}{(1-\alpha)} I_{CBO} \qquad \ldots(3)$$

6.7-3 COMMON-COLLECTOR (CC) CONFIGURATION

In this configuration, the input signal is applied between base and collector and the output is taken from the emitter. As collector is common to input and output circuits, hence the name common collector configuration. Fig. (14) shows the common collector *PNP* transistor circuit. When the transistor is cut-off, no current flows in the emitter terminal at the load. When the transistor is operating in a saturation mode, the load current reaches its maximum. Therefore; the transistor in *CC* configuration can also be used as a switch or pulse-amplifier. However, in *CC* amplifiers there is no voltage gain.

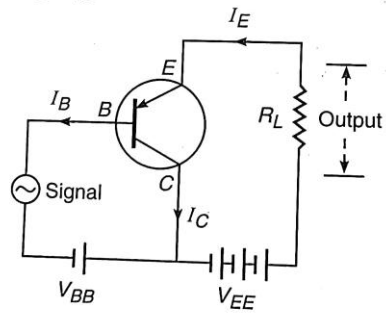


Fig. (14) Common collector *PNP* transistor amplifier

Total emitter current : We know that $I_E = I_B + I_C$

Also

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

$\therefore$

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

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

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

or

$$I_E = (1+\beta)\, I_B + (1+\beta)\, I_{CBO} \qquad \ldots(1)$$

$\because$

$$\frac{1}{(1-\alpha)} = (1+\beta)$$

Application : This configuration has very high input resistance ($\approx 750\ \text{k}\Omega$) and very low output resistance ($\approx 25\ \Omega$) so the voltage gain is always less than one. Hence, this configuration is seldom used for amplification. The most important use is for impedance matching, *i.e.*, for driving a low impedance load from a high impedance source.

The comparison of different characteristic in different configuration is shown below in the tabular form

S. No.	Characteristic	Common base	Common emitter	Common collector
(1)	Input resistance	low (about 100 Ω)	low (about 700 Ω)	very high
(2)	Output resistance	very high (about 400 kΩ)	high (about 50 kΩ)	low (about 50 Ω)
(3)	Voltage gain	about 150	about 500	less than 1
(4)	Applications	At high frequencies	At audio	impedance

Characteristics of Transistors:

1. Characteristics of Common Base Connection:

The fig.15 shows the circuit arrangement to draw the characteristics of a PNP transistor connected in common bas configuration.

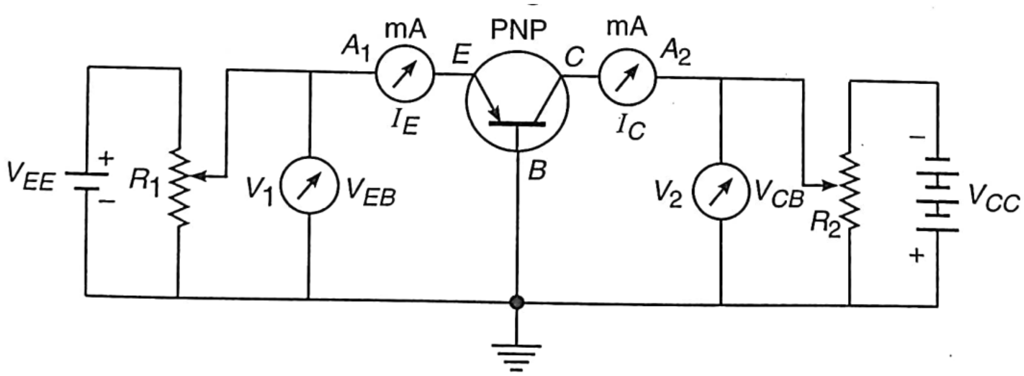
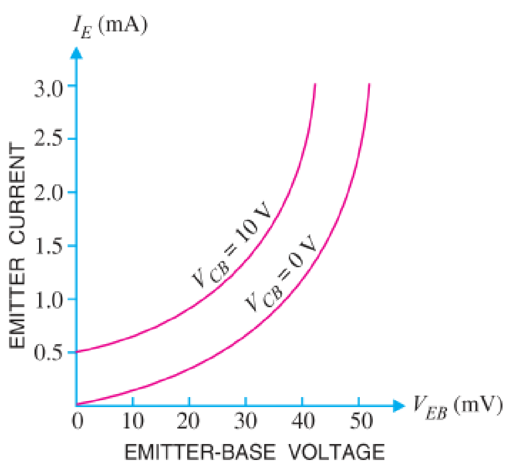


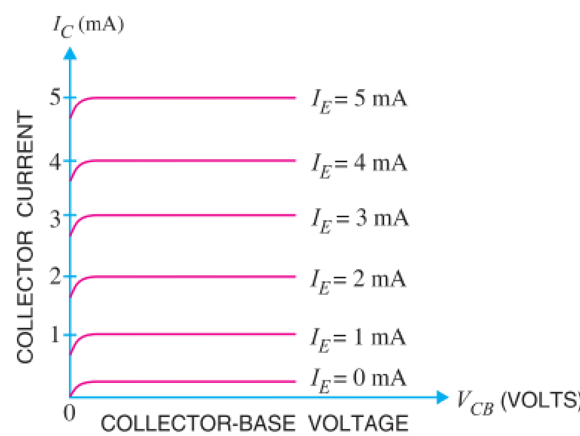
Fig. (15) *PNP* **transistor connected in common base configuration**

The most important characteristics of common base connection are input characteristics and output characteristics.

(a) 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. 1 shows the input characteristics of a typical transistor in *CB* arrangement.





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.*

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

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.

(b) 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. 2 shows the output characteristics of a typical transistor in *CB* arrangement.

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.*

$$\text{Output resistance, } R_0 = \frac{\Delta V_{CB}}{\Delta I_C}, \text{ at constant } I_E$$

The output resistance of *CB* circuit is very high, of the order of several tens of kilo-ohms.

2. Characteristics of Common Emitter Connection:

The fig.18 shows the circuit arrangement to draw the characteristics of a PNP transistor connected in common emitter configuration. The most important characteristics of common emitter connection are input characteristics and output characteristics.

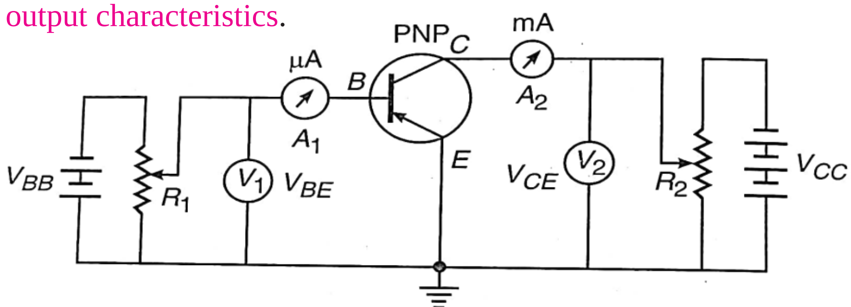


Fig. (18) *PNP* transistor connected in common emitter configuration

(a) Input characteristic:

It is the curve between base current I_B and base-emitter voltage V_{BE} at constant collector-emitter voltage V_{CE}.

By 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. 2. Following a similar procedure, a family of input characteristics can be drawn.

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.*

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

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

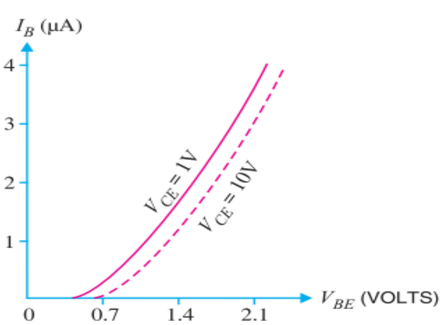


Fig. 2 (Input characteristics)

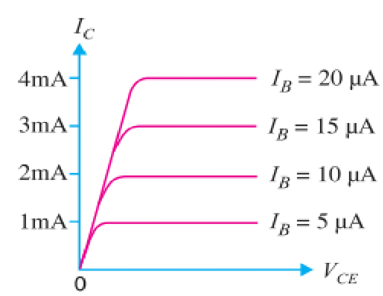


Fig. 3 (Output characteristics)

(b) Output characteristic:

It is the curve between collector current I_C and collector-emitter voltage V_{CE} at constant base current I_B.

Keeping the base current I_B fixed at some value say, 5 μA, note the collector current I_C for various values of V_{CE}. Then plot the readings on a graph, taking I_C along *y*-axis and V_{CE} along *x*-axis. This gives the output characteristic at I_B = 5 μA as shown in fig. 3. Following similar procedure, a family of output characteristics can be drawn as shown in fig. 3.

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.*

Output resistance, $R_0 = \dfrac{\Delta V_{CE}}{\Delta I_C}$, at constant I_B

The output resistance of a *CE* circuit is less than that of *CB* circuit. Its value is of the order of 50 kΩ.

6.10 D.C. LOAD LINE

In a transistor circuit analysis, sometimes it is required to know the collector currents for various collector-emitter voltages. The one way is to draw the output characteristics and then to determine the collector current at any desired collector-emitter voltage. The other way, a more convenient method, is load line method. Here we shall consider a common emitter *PNP* transistor. The output characteristics are shown in fig. (20). For drawing D.C. load line of a transistor, we require only its cutoff and saturation points. Then the line joining these two points is known as D.C. load line. This is discussed below :

The voltage equation of the collector emitter circuit is :

$$V_{CC} = V_{CE} + I_C R_L$$

$$\therefore \quad {}^*I_C = \frac{V_{CC}}{R_L} - \frac{V_{CE}}{R_L}$$

Here V_{CC} and R_L are fixed values and hence it is a first degree equation which can be represented by a straight line. We now consider the cutoff and saturation points.

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

$$V_{CE} = V_{CC} - I_C R_L = V_{CC} \qquad (\because I_C = 0)$$

This gives the cutoff point B as shown in fig. (21).

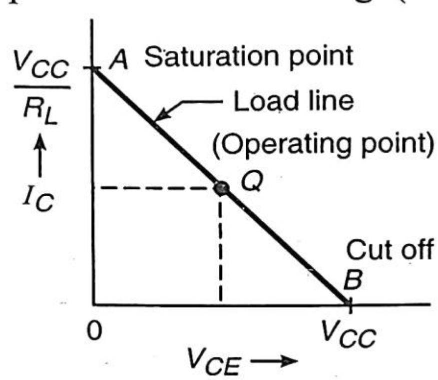


Fig. (21) D.C. load line

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

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

$$0 = V_{CC} - I_C R_L$$

$$\text{or} \quad I_C = V_{CC}/R_L$$

This gives the saturation point A as shown in fig. (21).

6.10-1 OPERATING POINT

This is a point on D.C. load line which represents the values of I_L and V_{CE} that exist in a transistor circuit when no signal is applied. This is also known as operating point or working point.

Suppose in the absence of the signal, the base current is $-10\,\mu A$ (output characteristic is shown in fig. (20)). Then I_C and V_{CE} conditions in the circuit must be represented by some point on this characteristic. But I_C and V_{CE} conditions should also be represented by some point on D.C. load line. The intersection of the output characteristic for $-10\,\mu A$ base current, and D.C. load line represents the actual state of affairs in the circuit and is called the operating point Q. This is shown in fig. (21). The best position for this point is midway between cut off and saturation points. The selection of the operating point is done according to the use to which the device is put. For small signal amplifier, in which power is conserved, operating point should be selected as to give lowest quiescent value of collector current, while for an amplifier required to deliver sufficient amount of power, operating point is chosen so as to give quiescent current about one half of the maximum permissible collector current of the transistor.

EXAMPLE 1 *For the circuit shown in fig. (22a), draw the D.C. load line and locate its quiescent or D.C. working point.*

Solution The load line and quiescent point are shown in fig. (22b). The cut off point

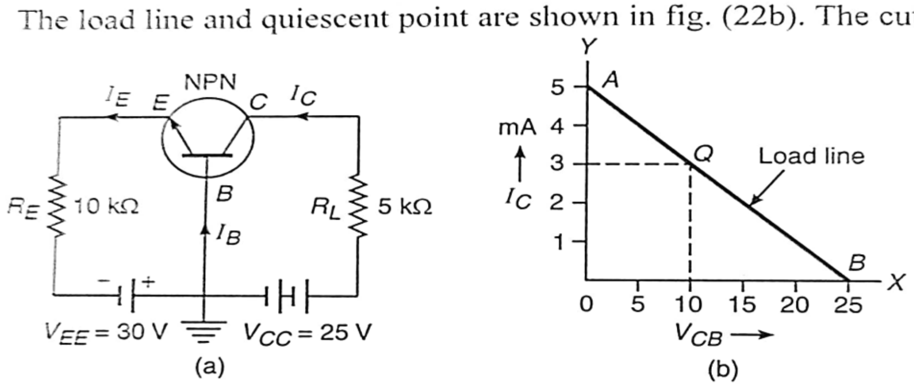


Fig. (22)

lies on X-axis where $V_{CB} = V_{CC} = 25$ V (shown by point B). The saturation point lies on Y-axis where the saturation value of collector current is given by

$$\boxed{(I_C)_{sat} = V_{CC}/R_L} = 25/5\text{ k}\Omega = \frac{25}{5\times 10^3} = 5\times 10^{-3} = 5\text{ mA.}$$

This is shown by a point A.

The line joining the points A and B represents the load line. Now we shall find the working or operating point.

$$\boxed{I_L = V_{EE}/R_E} = \frac{30}{10\text{ k}\Omega} = 3\text{ mA} \quad (\text{neglecting } V_{BE})$$

Now, $I_C = \alpha I_E \simeq I_E \simeq 3$ mA

EXAMPLE 2 *For the circuit shown in fig. (23a), draw the D.C. load line and locate the quiescent or D.C. working point. Assume* $\beta = 50$ *and neglect* V_{BE}.

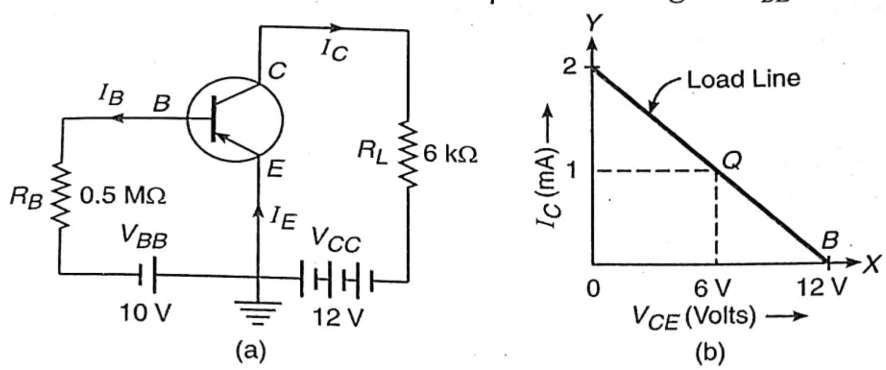


Fig. (23)

Solution The load line and quiescent point are shown in fig. (23b).

The cutoff point B is located where

$$I_C = 0 \quad \text{and} \quad V_{CE} = V_{CC} = 12 \text{ volt}$$

The saturation point A lies, where

$$V_{CE} = 0 \quad \text{and} \quad (I_C)_{sat} = \frac{V_{CC}}{R_L} = \frac{12\text{ V}}{6\text{ k}\Omega} = 2\text{ mA}.$$

The line joining the points A and B is the load line. For locating the quiescent point Q, let us calculate the base current I_B.

$$I_B = \frac{10\text{ V}}{0.5\text{ M}\Omega} = 20\ \mu\text{A}$$

Now,
$$I_C = \beta I_B = 50 \times 20\ \mu\text{A} = 1\text{ mA}$$

Further,
$$V_{CE} = V_{CC} - I_C R_L = 12\text{ volt} - (1\text{ mA})(6\text{ k}\Omega)$$
$$= 12\text{ volt} - 6\text{ volt} = 6\text{ volt}.$$

Hence Q point is **(6 V, 1 mA).**

ADDITIONAL SOLVED EXAMPLES

EXAMPLE 5 *In common base connection* $I_C = 0.96$ mA *and* $I_B = 0.05$ mA. *What is the value of* α?

Solution We know that, $\alpha = I_C / I_E$ and $I_E = I_B + I_C$

$\therefore$
$$\alpha = \frac{I_C}{I_C + I_B}$$

$$= \frac{0.96 \times 10^{-3}}{0.96 \times 10^{-3} + 0.05 \times 10^{-3}} = \frac{0.96}{1.01}$$

$$= \mathbf{0.95}$$

EXAMPLE 6 *In common base connection, the emitter current is* 1 mA. *If the emitter side is open, the collector current is* 60 μA. *Calculate the total current if* $\alpha = 0.93$.

Solution We know that $I_T = \alpha I_E + I_{CO}$

EXAMPLE 7 *The reverse saturation current in NPN transistor in common base configuration is* 15.5 μA. *For an emitter current of* 4 mA, *collector current is* 2.47 mA. *Find the value of current gain and base current.*

Solution We know that $I_C = \alpha I_E + I_{CBO}$

or $\alpha I_E = I_C - I_{CBO}$

$\therefore$ $$\alpha = \frac{I_C - I_{CBO}}{I_E}$$

$$= \frac{2.47\times10^{-3} - 15.5\times10^{-6}}{4\times10^{-3}}$$

$$= \frac{(2.47 - 0.0155)\times10^{-3}}{4\times10^{-3}} = \mathbf{0.11}$$

Now, $I_B = I_E - I_C$

$= 4 - 2.47$

$= \mathbf{1.53\ mA}$

EXAMPLE 8 *The emitter current* I_E *in a transistor is* 4 mA. *If the leakage current* I_{CBO} *is* 6 mA *and* $\alpha = 0.98$, *find the collector and base currents.*

Solution We know that, $I_C = \alpha I_E + I_{CBO}$

$\therefore$ $I_C = 0.98\times(4\times10^{-3}) + 0.006\times10^{-3}$

$= 3.926\times10^{-3}$

$= \mathbf{3.926\ mA}$

Now, $I_B = I_E - I_C = (4\times10^{-3}) - (3.926\times10^{-3})$

$= 0.074\times10^{-3}$

$= \mathbf{0.074\ mA}$

EXAMPLE 9 *In a transistor circuit* $I_E = 5$ mA, $I_C = 4.95$ mA, $I_{CEO} = 200\ \mu$A. *Calculate* β *and leakage current* I_{CBO}.

Solution $$\beta = \frac{I_C}{I_B} = \frac{I_C}{I_E - I_C}$$

$$= \frac{4.95\times10^{-3}}{5\times10^{-3} - 4.95\times10^{-3}} = \frac{4.95}{5 - 4.95}$$

$$= \frac{4.95}{0.05} = \mathbf{99}$$

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

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

$$= \frac{200\ \mu\text{A}}{}$$