3.1 INTRODUCTION

The transistor was invented in 1948 by John Barden, Walter Brattain and William Shockley at Bell Laboratory in USA. They were awarded the Nobel Prize in 1956 in recognition of their contributions to Physics. It was the first time in last 50 years, that the Nobel Prize was given not for a concept but for an engineering device.

Because of several advantages over the vacuum tubes, the transistors soon started replacing them in different applications. The vacuum tubes dominated the electronics field for over half a century. But now they have become a history. Since the invention of the junction transistor, there has been a rapid expanding effort to utilize and to develop many more semiconductor devices, such as FET, MOSFET, SCR, UJT, etc.

When a third doped element is added to a crystal diode in such a way that two P-N junctions are formed, the device formed so is called as transistor. Basically, there are two types of transistors. They are,

(1) Unipolar Junction Transistor (UJT).

(2) Bipolar Junction Transistor (BJT).

In unipolar junction transistor, its operation depends on the flow of only one charge carrier, hence its name is unipolar. Whereas, in bipolar junction transistor its operation depends on the flow of both the carriers i.e., electrons and holes, hence its name is bipolar.

The meaning of transistor is nothing but transfer of resistors (or) resistance.

3.2 BIPOLAR JUNCTION TRANSISTOR

Bi-polar junction transistor is a current-controlled device. A junction transistor consists of a silicon crystal in which a layer of N-type silicon is sandwiched between two layers of p-type silicon.

Hence, this type of transistor is called P-N-P transistor. Similarly, a silicon crystal in which a layer of P-type silicon is sandwiched between two layers of N-type silicon.

Hence, this type of transistor is called N-P-N transistor.

Fig. 3.2.1(i) and 3.2.1(ii) shows the basic structure and symbols of NPN and PNP transistor.

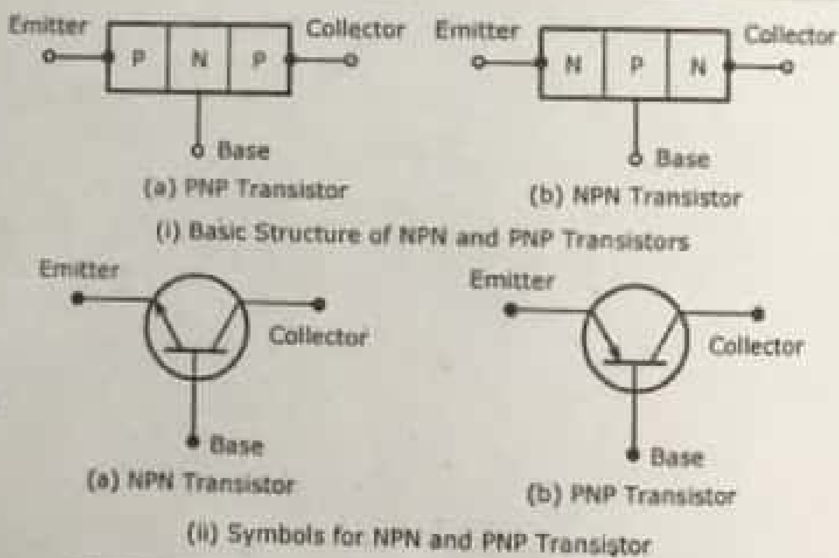


Fig. 3.2.1 Basic Structure and Symbol of NPN and PNP Transistor

In the above symbols, an arrow indicates current flows in which direction.

The transistor having three terminals. They are explained below,

Emitter : It is more heavily doped than any of the other region because its main function is to supply majority charge carriers to the base. The emitter gets its name because it emits or injects its majority carriers into the base region, where they become the minority carriers.

Base : The base region is very thin and lightly doped among all terminals, which allows most of the charge carriers from emitter region to the collector region.

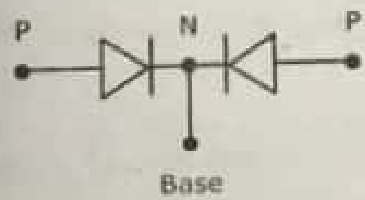
Collector : The collector region is moderately doped and it forms the right hand side section of the transistor as shown in the Fig. 3.2.1 and its main function is to collect the majority charge carriers coming from the emitter and pass them through the base. The collector gets its name because it collects the carriers from the base.

WHY COLLECTOR REGION IS LARGER THAN EMITTER AND BASE?

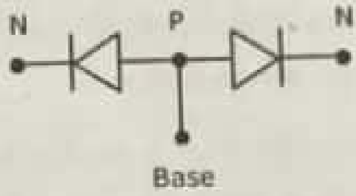
As we know that the main function of collector is to collect the charge carriers in the collector region. ~~Because~~ due to the interaction of the charge carriers the collector region becomes heat up, as all the heat dissipated through this region and the transistor may burn out. So, in order to save the transistor from burning, the collector is always larger than that of the emitter and base region.

DIODE EQUIVALENT STRUCTURE OF TRANSISTOR

A transistor can be considered as two p-n junction diodes connected in series back to back as shown in Fig. 3.2.2.



(a) P-N-P Transistor



(b) N-P-N Transistor

Fig. 3.2.2 Two Diode Transistor Analogy

Theoretically it is possible but practically it is not possible to connect back to back diodes.

3.2.1 Unbiased Transistor

If no external battery is connected between the terminals of a transistor, then the transistor is said to be an unbiased transistor.

As transistor is just like a two P-N junction diodes connected back to back hence two depletion regions are created on either sides of two P-N junctions i.e., at emitter-base junction and at collector-base junction as shown in Fig. 3.2.3,

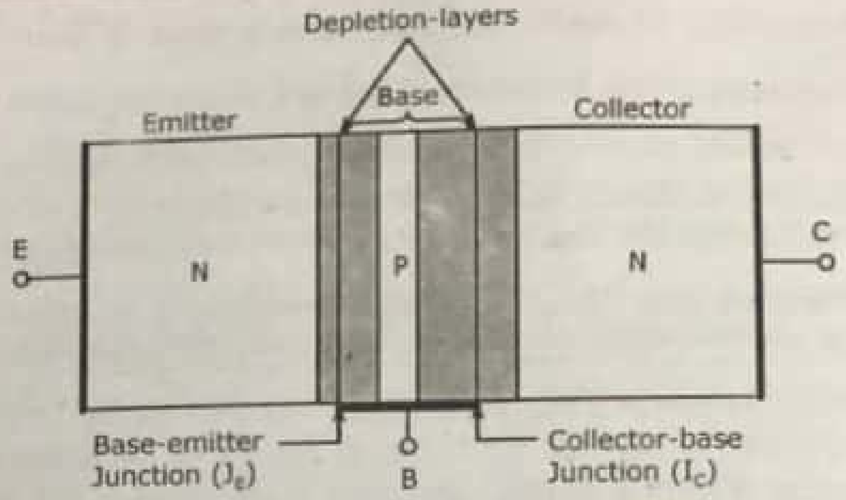


Fig. 3.2.3 Depletion Layers of an Unbiased Transistors

From Fig. 3.2.3, it can be seen that depletion regions penetrate more into base region, because it is lightly doped than collector and emitter regions. Also notice that the emitter being slightly more doped than collector region, therefore, depletion width on emitter region is less on collector region as shown in Fig. 3.2.3.

3.2.2 Biased Transistor

For the proper action of transistor to work as an amplifier, D.C voltages are connected across the different terminals of a transistor, then the transistor is said to be biased transistor.

There are four possible combinations of biasing a transistor. These are known as modes of operation of a transistor.

Table 3.2.1 shows the four possible biasing conditions of a transistor.

Table 3.2.1 Four Possible Biasing Conditions of a Transistor

Emitter-base Junction	Collector-base Junction	Region of Operation	Applications
FB	RB	Active	Amplifiers
FB	FB	Saturation	Switching circuits
RB	RB	Cut-off	
RB	FB	Inverse	Hardly Used

FB - Forward bias, RB - Reverse Bias

3.2.3 Working operation of NPN transistor

For normal operation, the emitter base junction is always forward biased while the collector-base junction is always reverse biased. This is as shown in Fig. 3.2.4.

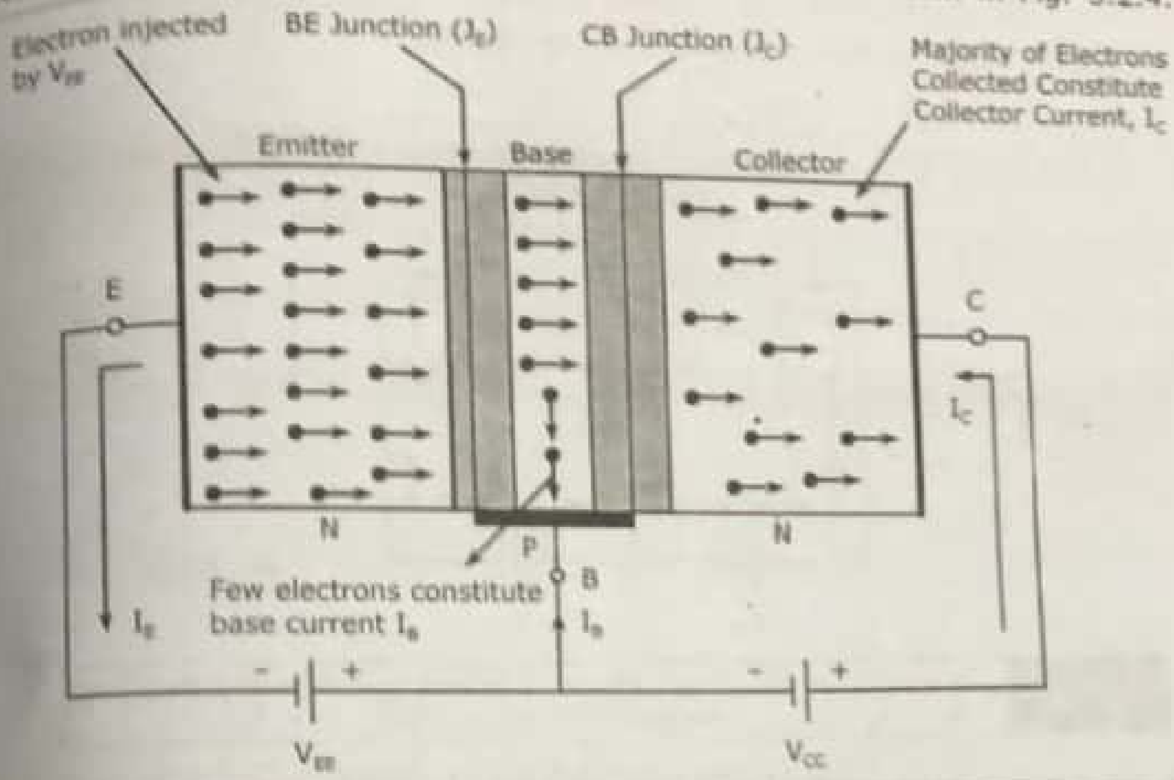


Fig. 3.2.4 An NPN Transistor with Emitter-Base Junction Forward Biased and Collector-Base Junction Reverse Biased

From Fig. 3.2.4, it is clear that the forward bias at the emitter-base junction reduces the barrier potential and narrows the depletion region. Reverse bias at the collector-base region produces a wide depletion region.

As the emitter-base junction is forward biased, a large number of electrons (majority carriers) in the emitter (N-type region) are pushed towards the base. This constitutes the emitter current I_E. When these electrons enter the P-type material (base), they tend to combine with holes. Since the base is lightly doped and very thin, only a few electrons (less than 5%) combine with holes to constitute base current I_B. The remaining electrons (more than 95%) diffuse across thin base region and reach the collector space charge layer.

These electrons then come under the influence of the positively biased N-region and are attracted or collected by the collector. This constitute collector current I_C. Thus, it is seen that almost the entire emitter current flows into the collector circuit. However, to be more precise, the emitter current is the sum of collector current and base current i.e.,

$$I_E = I_C + I_B$$

COMMENT : *As the collected emitter current can be viewed as being controlled by the base-emitter current, therefore, BJT is called as a "current controlled device".*

3.2.4 Working Operation of PNP Transistor

The PNP transistor has its bias voltages VEE and VCC reversed from those in the npn transistor. This is necessary to forward bias the emitter-base junction and reverse bias the collector base junction is shown in Fig. 3.2.5,

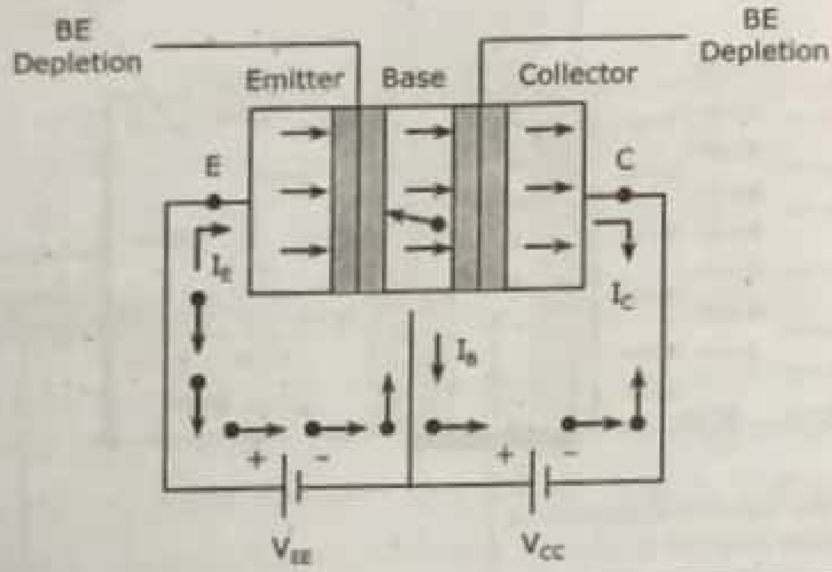


Fig. 3.2.5 Forward Bias the Emitter Base Junction and Reverse Bias the Collector Base Junction

When the emitter-base junction is in forward bias, the positive terminal of the battery repels the emitter holes towards the base, while the negative terminal drives the base electrons towards the emitter. When an emitter hole and a base electron meet, they combine. For each electron that combines with a hole, another electron leaves the emitter and another hole created and enters a positive terminal of a battery. This movement of electrons into base and out of the emitter constitutes base current flow (I_B) and the path of these electrons taken is referred to as the emitter base circuit.

In the reverse biased junction, the negative voltage on the collector and positive voltage on the base block majority current carriers from crossing the junction. However, this same negative collector voltage acts as a forward bias for the minority current holes in the base, which cross the junction and enters into the collector. The minority current electrons in the collector also sense forward bias. The positive base voltage move into the base. The holes in the collector are filled by electrons that flow from the negative terminal of the battery. At the same time, the electrons leave from the negative terminal of the battery, other electrons in the base break their covalent bonds and enter the positive terminal of the battery. Although, there is only minority current flow in reverse biased junction and it is still very small because of the limited number of minority current carriers.

3.3 TRANSISTOR CURRENT COMPONENTS

To illustrate the various current components of a transistor, let us consider a PNP transistor under normal working operation that is, J_E is forward biased and J_C is reverse biased as shown in Fig. 3.3.1.

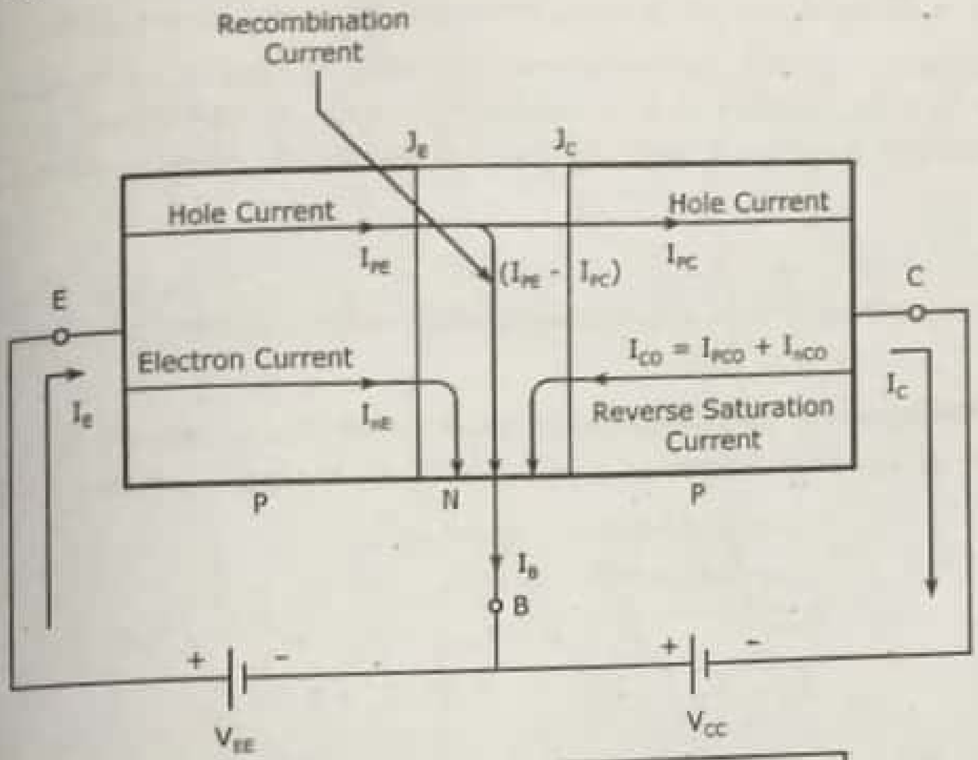


Fig. 3.3.1 PNP Transistor Current Components

Since emitter base junction is forward biased, few electrons (majority carriers) in N-type base terminal cross the junction and constitute the current I_{nE}, similar holes (majority carriers) in P-type emitter terminal repelled by the positive terminal of battery V_{EE}, crosses the junction J_E, thereby, constitute the hole current, I_{pE} as shown in Fig. 3.3.1. Thus emitter current has two current components, i.e., hole current (I_{pE}) and electron current (I_{nE}). The ratio of hole current (I_{pE}) to electron current (I_{nE}) is proportional to ratio of conductivity of P-type to N-type material. That is,

$$\frac{I_{pE}}{I_{nE}} = \frac{\text{Conductivity of P-type material}}{\text{Conductivity of N-type material}}$$

In most of the practical transistors available today, doping in the emitter region is much more than the doping in the base region. Thus conductivity of P-type material is much more than that of N-type and hence I_{pE} is much more than I_{nE}.

Out of all the holes crossing the junction J_E, some of them will recombine with electrons in the base region. Thus the number of holes crossing the junction J_C gets reduced. Let I_{pC} be the hole current as a result of holes crossing the junction J_C. Hence the recombination current is equal to $(I_{pE} - I_{pC})$.

Assume that the emitter-base junction is open-circuited for a moment, while collector-base junction (J_C) is reverse biased. Since J_C is reverse biased, there will be a reverse saturation current (I_{CO}), which has two current components namely,

I_{PCO} → Reverse current due to holes crossing J_C from base to collector.

I_{nCO} → Reverse current due to electrons crossing J_C from collector to base.

Thus collector current under normal working operation of transistor has two components namely, current due to carriers (in case of PNP-holes, in case of NPN-electrons) crossing junction J_e and reverse current due to carriers crossing J_C when I_E = 0.

$$\therefore \quad I_C = I_{CO} - I_{pC} \qquad \text{... (3.3.1)}$$

Let us now define different parameters which relates current components discussed above.

(1) Emitter Efficiency (γ) : The emitter, or injection efficiency denoted by γ is defined as the ratio of current of injected carriers at J_E to the total emitter current, that is,

$$\gamma = \frac{\text{Current of injected carriers at } J_E}{\text{Total emitter current}}$$

$$\therefore \quad \boxed{\gamma = \frac{I_{pE}}{I_{pE} + I_{nE}} \equiv \frac{I_{pE}}{I_E}} \qquad (\because\ I_E = I_{pE} + I_{nE}) \qquad \text{... (3.3.2)}$$

(2) Transport Factor (β) : Transport factor, denoted by β, is defined as the ratio of injected carrier current reaching collector base junction J_C to the injected carrier current at base-emitter junction J_E, that is,

$$\beta = \frac{\text{Injected carrier current reaching } J_C}{\text{Injected carrier current at } J_E} = \frac{I_{pC}}{I_{pE}} \qquad \text{... (3.3.3)}$$

(3) Large Signal Current Gain (α) : Large signal current gain (α) is defined as the ratio of the negative change in the collector current from cut-off ($I_C = I_{CO}$) to the change in emitter-current from cut-off, ($I_E = 0$), that is,

$$\alpha = -\frac{I_C - I_{CO}}{I_E - 0} = -\frac{I_C - I_{CO}}{I_E} \qquad \text{... (3.3.4)}$$

From Eq. (3.2.1), we have,

$$I_C = I_{CO} - I_{pC}$$

$$\therefore \quad \alpha = -\frac{(-I_{pC})}{I_E} = \frac{I_{pC}}{I_E} \qquad \text{... (3.3.5)}$$

Here α represents the number of carriers that have reached collector. The value of α is always positive and its typical values lies in the range of 0.90 to 0.995.

(i) **Relation between α, β* and γ :** Multiplying and dividing Eq. (3.3.5) with I_{pE}, we have,

$$\alpha = \frac{I_{pC}}{I_{pE}} \times \frac{I_{pE}}{I_E} \qquad \text{... (3.3.6)}$$

From Eqs. (3.3.2) and (3.3.3), we have $\frac{I_{pC}}{I_{pE}} = \beta^*$ and $\frac{I_{PE}}{I_E} = \gamma$, using these values, Eq. (3.3.6) reduces as,

$$\therefore \quad \boxed{\alpha = \beta^* \gamma} \qquad \text{... (3.3.7)}$$

(4) **Generalized Expression for Collector Current :** From our discussions about the current components in a transistor, we come to a conclusion that collector current has two components,

(i) The collector current $I_{C(IN)}$ due to the carriers injected by the emitter into the base and

(ii) The collector current I_{CO} due to crossing of thermally generated minority carriers.

$$\boxed{I_C = I_{C[IN]} + I_{CO} = \alpha I_E + I_{CO}} \qquad \text{... (3.3.8)}$$

From Eq. (3.3.8), we conclude that in the active region, collector I_C is independent of voltages and depends entirely on emitter current. Since the collector current is controlled by emitter current, hence transistor is a current controlled device.

Now we shall have a generalized expression of collector I_C, which will be valid not only for reverse-biased collector junction but also for any junction voltage.

The term I_{CO} in Eq. (3.3.8) is the reverse current flowing through the collector-base P-N junction diode. This current is given by volt-ampere relationship of diode,

$$I = I_S(e^{V/\eta V_T} - 1)$$

I_s is replaced with $-I_{CO}$ and V is replaced with V_C, this current would be I_{CO} $(1 - e^{V_c/\eta V_T})$. Hence using this current equation in Eq. (3.3.8). The complete expression for I_C may be written as,

$$\therefore \quad \boxed{I_C = \alpha I_E + I_{CO}\left[I - e^{V_c/\eta V_T}\right]} \qquad \text{... (3.3.9)}$$

Where, V_C represents the voltage drop across junction J_C from the P-side to the N-side.

(5) **D.C Current Gain (α_{DC}) :** If I_{CO} is negligibly small in comparison to I_C, then α is approximately equal to I_C/I_E. This is referred to as the D.C current gain of the common base (CB) transistor and is denoted by α_{DC} and is given by,

$$\boxed{\alpha_{D.C} = \frac{I_C}{I_E}} \quad \text{... (3.3.10)}$$

$\alpha_{D.C}$ is always positive and less than unity.

(6) **Small Signal Current Gain (α_{AC}) :** Small signal current gain, α_{AC}, is defined as the ratio of change in collector current to change in emitter current. It is defined by,

$$\boxed{\alpha_{AC} = \left.\frac{\Delta I_C}{\Delta I_E}\right|_{V_{CB} = \text{Constant}}} \quad \text{... (3.3.11)}$$

α_{AC} has always positive value and it is in the range of 0.95 to 0.995.

3.4 TRANSISTOR AS AN AMPLIFIER

Fig. 3.4.1 shows the basic circuit arrangement of a transistor amplifier.

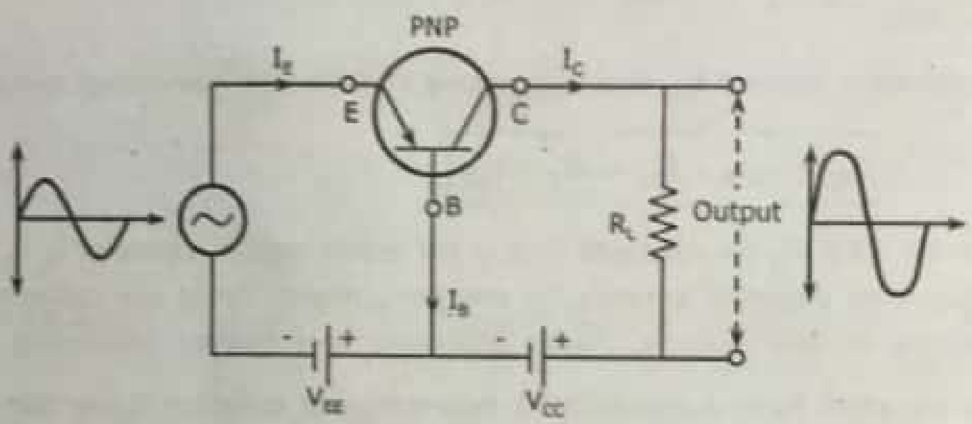


Fig. 3.4.1 Transistor as an Amplifier

Here, the weak signal to be amplified is applied between emitter-base circuit and the output is taken across the load resistor R_L connected in the collector circuit. A D.C voltage V_{EE} is also connected in the input circuit. Now, the question is that why V_{EE} is connected in the circuit?

Let, for the instant, V_{EE} is not connected in the circuit. Now, for the negative peak of the applied signal, the emitter-base junction will be reverse-biased. This is not desirable because to achieve faithful amplification, the input circuit should always remain forward biased. For this purpose, emitter bias battery V_{EE} of such a magnitude's input circuit is always forward-biased regardless of the polarity of the signal is connected.

A small change in signal voltage produces an appreciable change in emitter current because the input circuit has low resistance. Now, due to the transistor action, the change in emitter current causes almost the same change in collector current. When the collector current flows through the load resistance R_L, a large voltage is developed across it.

In this way, a weak signal applied in the input circuit appears in the amplified form across the output circuit, as shown in Fig. 3.4.1.

Since, current from low resistance input circuit is transferred to high resistance output circuit (across the R_L). Hence, it is a transfer resistor device and it is abbreviated as transistor.

Let a small voltage change be ΔV_i between emitter and base which causes a relatively large emitter-current change ΔI_E. We define by the symbol α that fraction of this current change which is collected and passes through R_L.

Thus, $$\alpha = \frac{\Delta I_C}{\Delta I_E}$$

$$\Rightarrow \quad \Delta I_C = \alpha \cdot \Delta I_E$$

The change in output voltage across the load resistor is given by,

$$\Delta V_o = R_L \times \Delta I_C = R_L \times \alpha \times \Delta I_E$$

Under these circumstances, the voltage amplification, $A = \frac{\Delta V_o}{\Delta V_i}$ will be greater than unity and the transistor acts as an amplifier. If the dynamic resistance of the emitter junction be r_f, then $\Delta V_i = r_f \cdot \Delta I_E$

$$\therefore \quad \boxed{A = \frac{R_L \times \alpha \times \Delta I_E}{r_f \cdot \Delta I_E} = \frac{\alpha R_L}{r_f}} \quad \text{... (3.4.1)}$$

Where α defines the small signal AC current gain usually denoted as α_{AC} and is given by,

$$\alpha_{AC} = \frac{\Delta I_C}{\Delta I_E}$$

EXAMPLE PROBLEM 1

In a certain amplifier circuit, if it has an input resistance of 20 Ω and output resistance of 100 kΩ, If a signal of 400 mV is applied between emitter and base, find voltage amplification. Assume $\alpha_{A.C}$ to be nearly one.

SOLUTION

Given Data : Signal voltage = 400 mV.

Input resistance = 20 Ω.

Output resistance = 100 kΩ.

The small change in emitter current is given by,

$$\Delta I_E = \frac{\text{Signal voltage}}{\text{Input resistance}} = \frac{400 \text{ mV}}{20 \ \Omega} = 20 \text{ mA}$$

We have, small change in collector current as,

$$\Delta I_C = \alpha_{ac} \times \Delta I_E = 1 \times 20 \text{ mA} = 20 \text{ mA}$$

Small change in output voltage,

$$\Delta V_o = \Delta I_C \times R_L = 20 \text{ mA} \times 1 \text{ k}\Omega = 20 \text{ V}$$

∴ Voltage amplification,

$$A = \frac{\text{Output voltage}}{\text{Signal voltage}} = \frac{\Delta V_o}{\Delta V_i}$$

$$= \frac{20 \text{ V}}{400 \text{ mV}}$$

$$= 50$$

3.5 TRANSISTOR CONFIGURATIONS

We have seen in Section 3.4, how a transistor works as an amplifier. For any amplifier, it can be generally said that input is given to the amplifier and the output is taken out from the amplifier. For giving input we need two terminals and for taking output we need two terminals. Thus we need a total of four terminals. But we have seen that a transistor has three leads, namely emitter, base and collector. Therefore, to connect transistor in the circuit, one lead or terminal is made common. The input is fed between common terminal and one of the remaining terminals, whereas, output is connected between the common terminal and other terminal of the transistor. Accordingly, a transistor can be connected in the circuit in the following three ways,

(1) Common Base (CB) configuration.

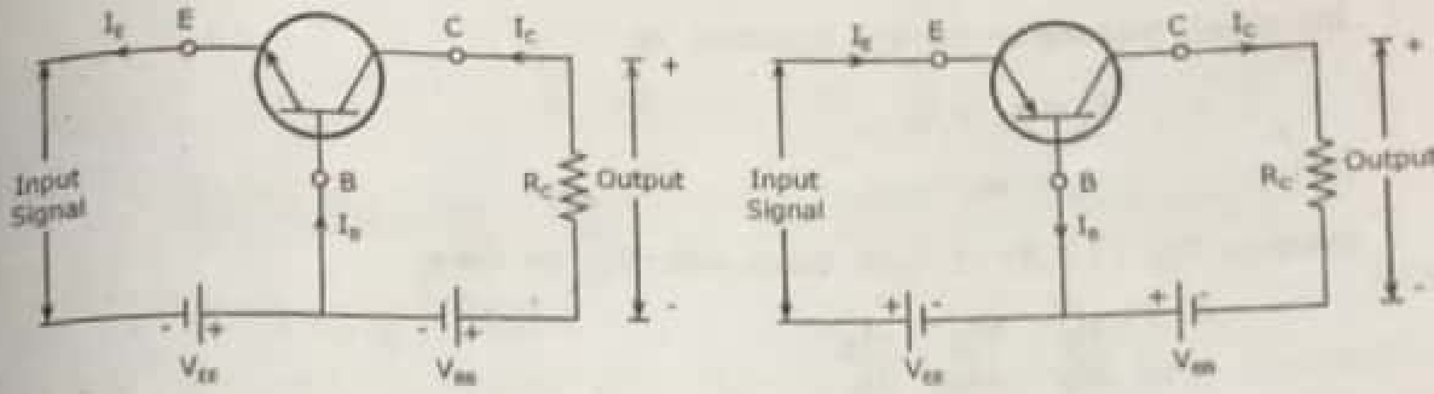
(2) Common Emitter (CE) configuration.

(3) Common Collector (CC) configuration.

COMMENT : ***It is always important to remember here that transistor may be connected in any one of the above three ways, the emitter-base junction is always forward biased and collector-base junction is always reverse biased to operate the transistor in active region.***

3.5.1 Common Base Configuration

Fig. 3.5.1 shows the transistor is in common base configuration.



(a) Common Base Circuit for NPN Transistor (b) Common Base Circuit for PNP Trans

Fig. 3.5.1 CB Configuration

In this arrangement the input is connected between emitter and base and the Ou is taken across collector and base. Since the base and the common to both input output circuits, hence the name is common base configuration.

3.5.1.1 Current Amplification Factor (α)

In general, current amplification is defined as the ratio of output current to the current. Since in a common base configuration, the output current is collector curre whereas the input current is emitter current I_E. Current amplification factor thus, de as the ratio of change in collector current to the change in emitter current at con collector-base voltage V_{CB}. It is generally represented by Greek letter α(alpha).

(1) When a small input signal is applied to the circuit shown in Fig. 3.5.1, then the cu amplification factor is defined as a ratio of change in collector current to char emitter current at constant V_{CB} denoted by α_{AC} and is given by,

$$\boxed{\alpha_{AC} = \left.\frac{\Delta I_C}{\Delta I_E}\right|_{V_{CB} = \text{Constant}}} \quad \text{... (}$$

Where,

ΔI_C = Change in collector current

ΔI_E = Change in emitter current.

(2) When no AC signal is applied to the circuit shown in Fig. 3.5.1 (i.e., only DC V_{BB} and V_{EE} are used) then the current amplification factor is represented as is given by,

$$\boxed{\alpha_{DC} = \frac{I_C}{I_E}} \quad \text{... (3.5.2)}$$

We have, transistor current equation as,

$$I_E = I_C + I_B$$

(or) $$\Delta I_E = \Delta I_C + \Delta I_B \quad \text{... (3.5.3)}$$

Dividing Eq. (3.5.3) on both sides with ΔI_E, we have,

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

$$1 = \alpha + \frac{\Delta I_B}{\Delta I_E}$$

$$\therefore \quad \boxed{\alpha = 1 - \frac{\Delta I_B}{\Delta I_E}} \quad \text{... (3.5.4)}$$

It is clear that the value of current amplification factor is less than unity. The value of α approaches to unity if the value of I_B reduces to zero. This can be achieved by doping the base lightly and making very thin. The practical value of α (α_{AC} or α_{DC}) in commercial transistors varies from 0.95 to 0.99.

3.5.1.2 Expression for Collector Current

In an NPN transistor, because of recombination of very small percentage of electrons with holes in the base region, whole of the emitter current could not reach the collector. On the other hand, the collector current is slightly increased because of the reverse leakage current that flows due to minority carriers as the collector-base junction is reversed biased. Hence, total collector current consists of two current components,

(1) A large percentage of emitter current that reaches the collector terminal i.e., αI_E.

(2) **The Leakage Current (I_{CBO}) :** Under normal working operation of an NPN transistor, the emitter-base junction is forward biased and collector-base junction is reverse biased. If we consider, the emitter-base junction is opened i.e., emitter current (I_E) = 0. Hence, there can be no carriers injected to the base. Then the collector current must be zero. However there are few minority carriers crossing the reverse-biased collector-base junction, so we find here a small collector current. This current is called as leakage current, designated as I_{CBO} as shown in Fig. 3.5.2, Where, CBO means collector to Base current with the Emitter terminal open.

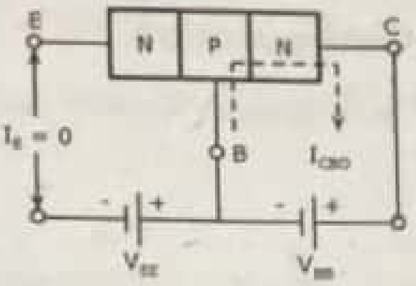


Fig. 3.5.2 Reverse Collector Current (I_{CBO}) When Emitter is Open

$$\therefore \quad \boxed{I_C = \alpha I_E + I_{CBO}} \quad \text{... (3.5.5)}$$

The above expression shows that (when emitter terminal is open circuited i.e., $I_E = 0$), still a small current flows in the collector circuit called *leakage current* ($I_{leakage}$). Since this leakage current, I_{CBO}, is very small when compared to $\alpha.I_E$, hence it can be neglected in transistor circuit calculations.

Collector current can also be expressed as,

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

$$\Rightarrow \quad I_C = \alpha I_C + \alpha IB + I_{CBO}$$

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

$$\therefore \quad \boxed{I_C = \frac{\alpha}{1-\alpha} I_B + \frac{1}{1-\alpha} I_{CBO}} \quad \text{... (3.5.6)}$$

EXAMPLE PROBLEM 1

- **Determine the values of emitter current and collector current of a transistor having $\alpha_{D.C}$ = 0.98 and collector-to-base leakage current, I_{CBO} = 4 μA. The base current is 50 μA.**

SOLUTION

Given Data : $\alpha_{D.C} = 0.98$

I_{CBO} = 4 mA → 0.004

I_B = 50 μA → 0.05

We have collector current as,

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

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

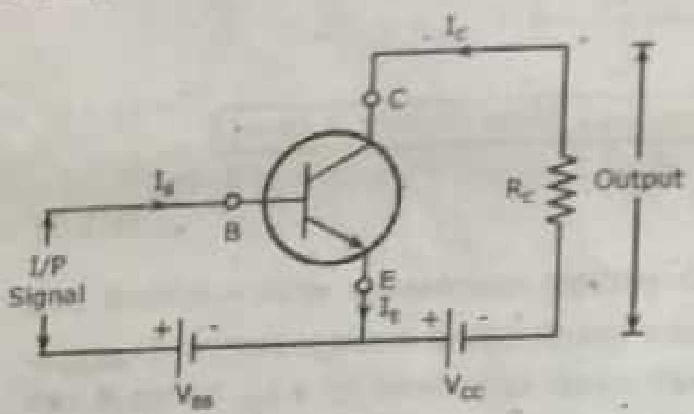
$$\Rightarrow \quad I_C = \frac{\alpha I_B}{1-\alpha} + \frac{I_{CBO}}{1-\alpha} = \frac{0.98 \times 0.05}{1 - 0.98} + \frac{0.004}{1 - 0.98}$$

$$\Rightarrow \quad I_C = 2.45 \text{ mA} + 0.2 \text{ mA} = 2.65\ mA$$

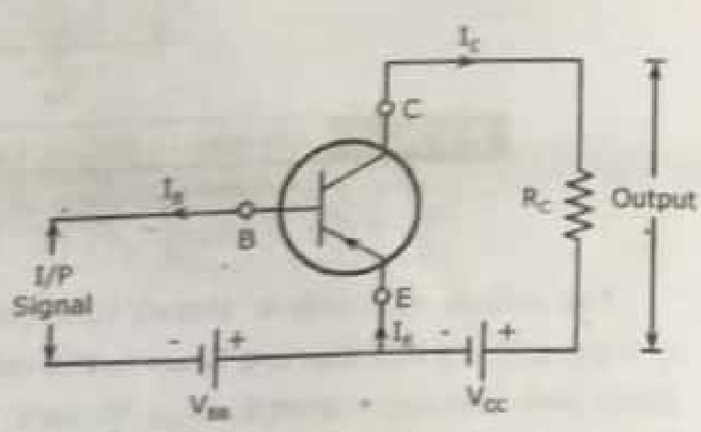
$$\therefore \quad I_E = I_C + I_B = 2.65 + 0.05 = 2.7\ mA$$

3.5.2 Common Emitter Configuration

The common emitter circuit arrangement for NPN and PNP transistor is shown in Fig. 3.5.3(a) and Fig. 3.5.3(b).



(a) CE Circuit of NPN Transistor



(b) CE Circuit of PNP Transistor

Fig. 3.5.3 CE Configuration

In this arrangement, the input is taken across base and emitter, output is collected between emitter and collector. Since the emitter of the transistor is common to both input and output circuits and hence the name is common emitter configuration.

3.5.2.1 Current Amplification Factor (β)

Since in CE configuration, the output current is collector current I_C and the input current is base current I_B. Hence the ratio of collector current to base current is known as current amplification factor.

(1) When no AC signal is applied to circuit shown in Fig. 3.5.3 (i.e., only DC source V_{BB}, V_{CC} is applied) then the current amplification factor is denoted by β_{DC} and is given by,

$$\boxed{\beta_{DC} = \frac{I_C}{I_B}} \quad \text{... (3.5.7)}$$

(2) When a small AC signal is applied to the circuit shown in Fig. 3.5.3, then the current amplification factor is defined as ratio of change in collector current to the change in base current and it is denoted as β_{AC} and is given by,

$$\boxed{\beta_{AC} = \frac{\Delta I_C}{\Delta I_B}} \quad \text{... (3.5.8)}$$

Since in almost all transistors, base current is less than 5% of emitter current, hence β is generally greater than 20. Typical values of β ranges from 20 to 500. Because of this high range of amplification factor, CE configuration is more frequently used.

3.5.2.2 Relation between $\alpha_{D.C}$ and $\beta_{D.C}$

β in Terms of α : From Eq. (3.5.7), we have base current gain as,

$$\beta_{D.C} = \frac{I_C}{I_B}$$

From Eq. (3.5.2), we have emitter current gain as,

$$\alpha_{D.C} = \frac{I_C}{I_E}$$

But, we have transistor current equation as,

$$I_E = I_C + I_B$$

$$\Rightarrow \quad I_B = I_E - I_C$$

Substituting I_B in $\beta_{D.C}$ we get,

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

Dividing above equation on both sides with I_E, we get,

$$\beta = \frac{(I_C / I_E)}{(I_E / I_E) - (I_C / I_E)} = \frac{\alpha}{1-\alpha}$$

$$\therefore \quad \boxed{\beta = \frac{\alpha}{1-\alpha}} \qquad \text{... (3.5.9)}$$

The above relation clearly shows that as α approaches to unity, β approaches to infinity. In other words the current gain in common emitter configuration is very high. It is because of this reasons that this circuit arrangement is generally (about 90 to 95%) used in all transistor applications.

α in Terms of β : Adding Both sides of Eq. (3.5.9) with 1 we get,

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

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

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

$$\therefore \quad \boxed{\alpha = \frac{\beta}{\beta+1}} \qquad \text{... (3.5.10)}$$

3.5.2.3 Expression for Collector Current

Even in CE configuration collector current consists of two current components and are as shown in Fig. 3.5.4.

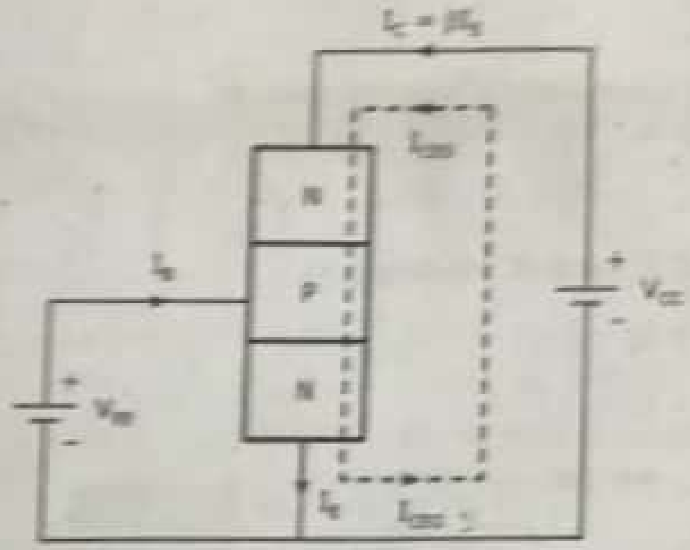


Fig. 3.5.4 Collector Current Components in CE Configuration

From Fig. 3.5.4, it is clear that total collector current is given by,

$$I_C = \beta I_B + I_{CEO} \quad \text{... (3.5.11)}$$

Where,

I_{CEO} = Leakage current from collector to emitter when base terminal is open (I_B = 0).

From Eq. (3.5.6),

We have, $$I_C = \frac{\alpha}{1-\alpha} I_B + \frac{1}{1-\alpha} I_{CBO} \quad \text{... (3.5.12)}$$

From Eq. (3.5.9), we have,

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

Thus, Eq. (3.5.12) becomes,

$$I_C = \beta I_B + \frac{1}{1-\alpha} I_{CBO} \quad \text{... (3.5.13)}$$

Comparing Eq. (3.5.11) and Eq. (3.5.12), we get,

$$\therefore \quad \boxed{I_{CEO} = \frac{1}{1-\alpha} I_{CBO}} \quad \text{... (3.5.14)}$$

We have, $\beta = \frac{\alpha}{1-\alpha}$

Adding the above value with 1 on both sides,

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

$$\Rightarrow \quad 1 + \beta = \frac{1}{1-\alpha} \quad \text{... (3.5.15)}$$

Using Eq. (3.5.15), in Eq. (3.5.13), we get,

$$\boxed{I_C = \beta I_B + (1+\beta) I_{CBO}} \quad \text{... (3.5.16)}$$

EXAMPLE PROBLEM 1

The collector and base current of an NPN transistor are measured as I_C = 5 mA, I = 50 μA and I_{CBO} = 1 μA.

(1) Determine α, β, I_E and I_{CEO}.

(2) Determine the new level of I_B required to produce I_C = 10 mA.

SOLUTION

Given Data : $I_C = 5$ mA

$I_B = 50$ μA

$I_{CBO} = 1$ μA

$I_C = 10$ μA

(1) We have collector current as,

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

$$\Rightarrow \quad \beta = \frac{I_C - I_{CBO}}{I_B + I_{CBO}} = \frac{5 \times 10^{-3} - 1 \times 10^{-6}}{50 \times 10^{-6} + 1 \times 10^{-6}} = 98$$

And $$\alpha = \frac{\beta}{1+\beta} = \frac{98}{99} = 0.99$$

Emitter current,

$$I_E = I_B + I_C = 50 \times 10^{-6} + 5 \times 10^{-3} = 5.05 \text{ mA}$$

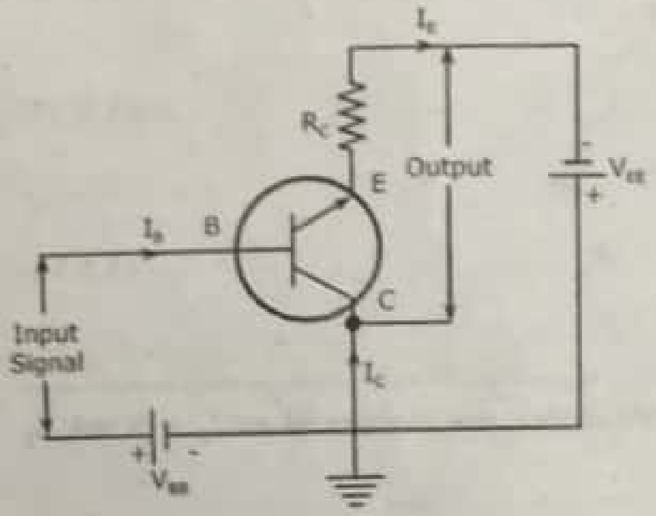
Reverse saturation current,

$$I_{CEO} = \frac{1}{1-\alpha} I_{CBO} = \frac{1}{1-0.99}(1 \times 10^{-6}) = 10^{-4} \text{ A}$$

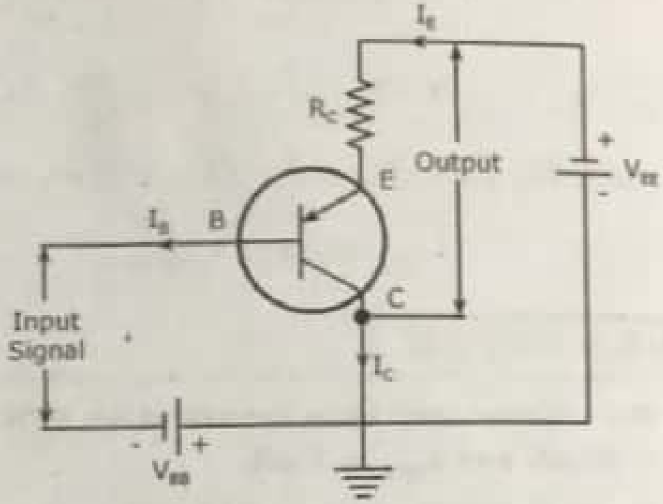
(2) $$I_B = \frac{I_C - (\beta + 1) I_{CBO}}{\beta} = \frac{10 \times 10^{-3} - (98 + 1) \times 1 \times 10^{-6}}{98} = 101 \ \mu A$$

3.5.3 Common Collector Configuration

The common collector circuit arrangement for NPN and PNP transistor is shown in Figs. 3.5.5(a) and 3.5.5(b) respectively.



(a) NPN Transistor in CC Configuration



(b) PNP transistor in CC Configuration

Fig. 3.5.5 Common Collector Configuration

In this arrangement, the input is connected between base and collector while output is taken across the emitter and collector. Since, the collector of the transistor is common to both input and output circuits and hence the name is common collector configuration.

In this arrangement, as output voltage (emitter) closely follows the input signal voltage. Hence this circuit is also called emitter follower.

3.5.3.1 Current Amplification Factor (γ)

In a common collector connection, the ratio of change in emitter current to the change in base current is known as current amplification factor. It is generally represented by Greek letter γ(Gamma).

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

(1) When no signal is applied to the circuit shown in Fig. 3.5.5, then the current amplification is represented as $\gamma_{D.C}$ and is given by,

$$\boxed{\gamma_{D.C} = \frac{I_E}{I_B}}$$

When a small AC input signal is applied to the circuit shown in Fig. 3.5.5, then the current amplification factor is given by,

$$\boxed{\gamma_{AC} = \frac{\Delta I_E}{\Delta I_B}}$$

3.5.12 Relation between α and γ

We have defined γ as,

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

We have defined α as,

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

We have, transistor current equation as,

$$I_E = I_B + I_C$$

$$\Rightarrow \quad I_B = I_E - I_C$$

Using the value I_B in equation of γ, we get,

$$\gamma = \frac{I_E}{I_E - I_C} = \frac{1}{1 - (I_C / I_E)}$$

Since $\alpha = I_C/I_E$. Thus,

$$\boxed{\gamma = \frac{1}{(1-\alpha)}} \qquad \text{... (3.5.17)}$$

This circuit arrangement is seldom used for amplification because in this arrangement input resistance is high (about 750 kΩ) and output resistance is very low (about 25 Ω). Due to this reason, the voltage gain is very low (less than 1). This circuit arrangement is primarily used for *impedance matching*.

3.5.13 Relation between β and γ

From Eq. (3.5.9), we have,

$$\beta = \frac{\alpha}{1-\alpha} \qquad \text{... (3.5.18)}$$

Adding on both sides of β with '1',

We get, $\quad 1 + \beta = \dfrac{\alpha}{1-\alpha} + 1 = \dfrac{\alpha + 1 - \alpha}{1-\alpha}$

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

Substituting this value in Eq. (3.2.30), we have,

$$\therefore \quad \boxed{\gamma = (1+\beta)} \quad \left(\because \frac{1}{1-\alpha} = \gamma\right) \quad \text{... (3.5.19)}$$

3.5.3.4 Expression for Total Emitter Current

From Eq. (3.5.15), we have, collector current as,

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

We have, transistor current equation as,

$$I_E = I_B + I_C$$

Substitute I_C value in the above Equation, we get,

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

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

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

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

$$I_E = (1+\beta)I_B + (1+\beta)I_{CBO} \quad \text{... (3.5.20)}$$

Collector Current (I_C) : We have, common emitter current gain as,

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

$$\Rightarrow \quad I_C = \beta . I_B \quad \text{... (3.5.21)}$$

We have common base current gain as,

$$\boxed{\alpha = \frac{I_C}{I_E}}$$

$$I_C = \alpha I_E \quad \text{... (3.5.22)}$$

$\because$ From Eq. (3.5.21) and Eq. (3.5.22),

We get, $$I_C = \beta I_B = \alpha I_E = \frac{\beta}{\beta+1} I_E \quad \left[\because \alpha = \frac{\beta}{\beta+1}\right]$$

$$\therefore \quad \boxed{I_C = \frac{\beta}{\beta+1} I_E}$$

3.6 BIPOLAR TRANSISTORS WITH THEIR H-PARAMETER EQUIVALENT CIRCUITS

Many efforts have been made to find a suitable A.C equivalent circuit model of an amplifying devices. Usually an amplifying device has only three independent terminals as in case of vacuum tubes, BJT and FET. For incremental small signals the device can be characterized as linear two-port network whose terminal behaviour is specified by two voltages and two currents.

Fig. 3.6.1 represents such a two-port network or usually termed as black-box.

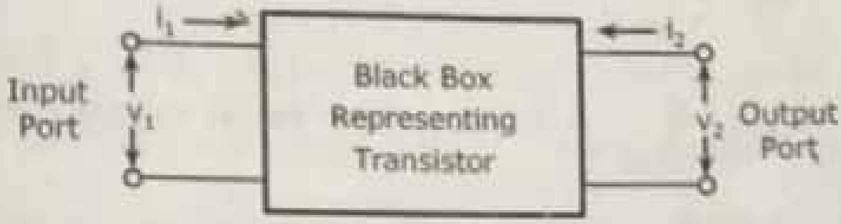


Fig. 3.6.1 A Two-port Network

The terminal-pair voltages (v_1, v_2) and currents (i_1, i_2) are related by two linear equations. We may select two of the four quantities as the independent variables and express the remaining two in terms of the chosen independent variables. This leads to various two-port parameters out of which the following three are generally used,

(1) Open-circuit impedance parameters or z-parameters.

(2) Short-circuit admittance parameters or y-parameters.

(3) Hybrid parameters or h-parameters.

In the beginning era of transistors, some people used impedance-paramete equivalent and some used admittance-parameter equivalent. But the analysis using bot of them was quite tedious. In the 1970s, people started using hybrid-parameter mode for a BJT. This made the analysis much simpler.

3.6.1 Hybrid Parameter Model

In h-parameter model, i_1, v_2 are taken as the independent variables and i_2, v_1 a taken as the dependent variables. We can now express v_1 and i_2 in terms of i_1 and as follows,

$$v_1 = f_1(i_1, v_2) \qquad \text{... (3.6.}$$

$$i_2 = f_2(i_1, v_2) \qquad \text{... (3.6.}$$

As small signal low-frequency circuit operates in the linear region. Thus, Eqs. (3.6. and (3.6.2) can be represented by linear relationships i.e., v_1 and i_2 can be represent as a linear combinations of i_1 and v_2.

$$v_1 = h_{11}i_1 + h_{12}v_2 \quad \text{... (3.6.3)}$$

And
$$i_2 = h_{21}i_1 + h_{22}v_2 \quad \text{... (3.6.4)}$$

The quantities h_{11}, h_{12}, h_{21} and h_{22} are called the 'h' or hybrid parameters because ey are not all alike dimensionally. Assume that there are no reactive elements present the two-port network. Then, from Eqs. (3.6.3) and (3.6.4) h-parameters are defined : follows,

$$h_{11} = \left.\frac{v_1}{i_1}\right|_{v_2=0} \rightarrow \text{Input impedance with output shorted (ohm } \Omega)$$

$$h_{12} = \left.\frac{v_1}{v_2}\right|_{i_1=0} \rightarrow \text{Reverse open-circuit voltage gain (dimensionless)}$$

$$h_{21} = \left.\frac{i_2}{i_1}\right|_{v_2=0} \rightarrow \text{Short-circuit forward current gain (dimensionless)}$$

$$h_{22} = \left.\frac{i_2}{v_2}\right|_{i_1=0} \rightarrow \text{Output admittance with input open (siemens } \mho)$$

The four parameters h_{11}, h_{12}, h_{21} and h_{22} are real numbers and the voltages and current V_1, V_2 and I_1, I_2 are functions of time. The double subscripts parameter notation (h_{11}, h_{12}, h_{21} and h_{22}) can further be reduced to a single subscript notation as follows,

Let,

i represent 11 denoting input impedance

o represent 22 denoting output admittance

f represent 21 denoting forward transfer current gain

r represent 12 denoting reverse transfer voltage gain

Thus Eqs. (3.6.3) and (3.6.4), will now become as,

$$v_1 = h_i i_1 + h_r v_2 \quad \text{... (3.6.5)}$$

$$i_2 = h_f i_1 + h_o v_2 \quad \text{... (3.6.6)}$$

(1) Circuit Model of $v_1 = h_i i_1 + h_r v_2$: Eq. (3.6.5) represents the Kirchhoff's voltage law (KVL) equation. It has two components $h_i i_1$ representing a voltage drop across element h_i and $h_r v_2$ representing a voltage controlled source. The circuit model based on Eq. (3.6.5) is as shown in Fig. 3.6.2.

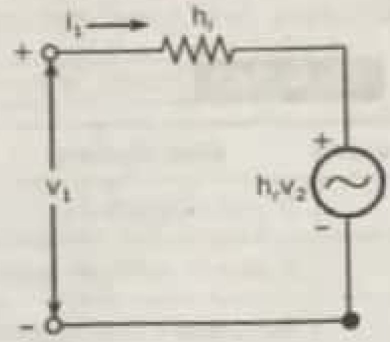


Fig. 3.6.2 Circuit Model of $v_1 = h_i i_1 + h_r v_2$

(2) **Circuit Model of $i_2 = h_f i_1 + h_o v_2$:** Eq. (3.6.6) represents the Kirchoff's current law (KCL) equation. It also has two components $h_f i_1$ representing a current controlled source and $h_o v_2$ representing the current through conductance h_o. The circuit model based on Eq. (3.6.6) is shown in Fig. 3.6.3,

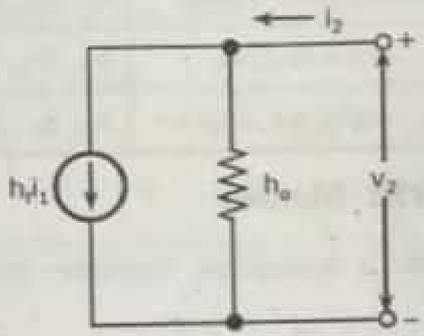


Fig. 3.6.3 Circuit Model of $i_2 = h_f i_1 + h_o v_2$

Combining these two circuit models, we obtain the hybrid model of the two-port network as shown in Fig. 3.6.4,

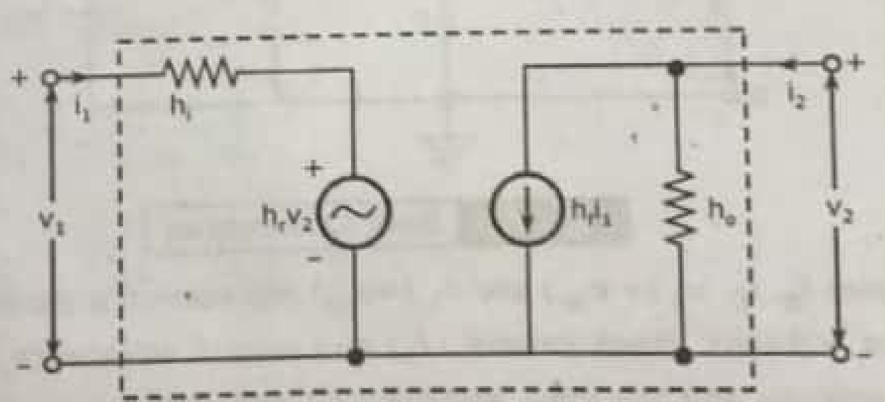


Fig. 3.6.4 Hybrid Model of a Two Port Network

The four basic 'h' parameters and their descriptions are given in Table. 3.6.1,

Table 3.6.1 Basic 'h' Parameters

h Parameter	Description	Condition
h_i	Input impedance	Output shorted
h_r	Reverse voltage gain	Input open
h_f	Forward current gain	Output shorted
h_o	Output admittance	Input open

Notations used in Transistor Circuits : In case of transistors each of the four 'h' parameters carries a second subscript letter (e, b or c) to designate the Common-Emitter(CE), Common-Base(CB) or Common-Collector(CC) amplifier configuration respectively as listed in Table 3.6.2.

Table 3.6.2 Subscripts of h Parameters for the Three Amplifier Configuration

Configuration	h parameters
Common-Emitter	h_{ie}, h_{re}, h_{fe}, h_{oe}
Common-Base	h_{ib}, h_{rb}, h_{fb}, h_{ob}
Common-Collector	h_{ic}, h_{rc}, h_{fc}, h_{oc}

3.6.2 Transistor Hybrid Model

To derive the h-model for a transistor. Consider the basic CE amplifier circuit shown in Fig. 3.6.5.

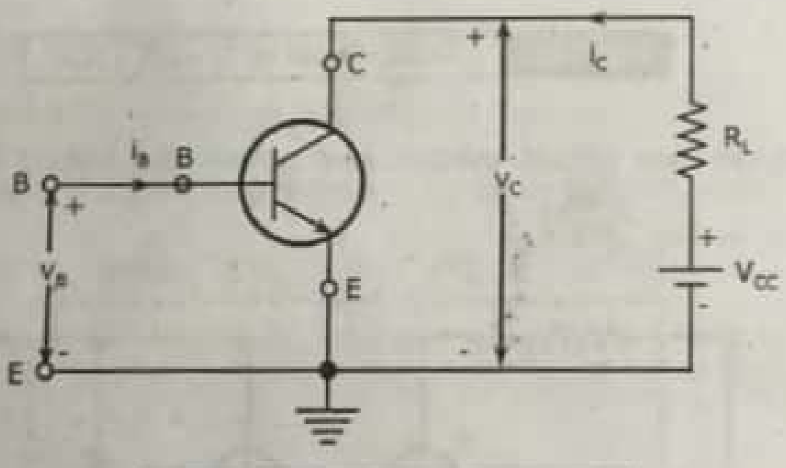


Fig. 3.6.5 Basic CE Amplifier

The variables i_B, i_C, v_B (= v_{BE}) and v_C (=v_{CE}) represent the instantaneous total values of currents and voltages. Input current (i_B) and output voltage (v_C) are chosen as the independent variables and the input voltage (v_B) and output current (i_C) are chosen as functions of i_B and v_C.

Thus, $v_B = f_1(i_B, v_C)$ ... (3.6.7)

$i_C = f_2(i_B, v_C)$ ... (3.6.8)

Using Taylor series expansion of Eq. (3.6.7) and Eq. (3.6.8) about the quiescent operating point $Q(i_B, v_C)$ and neglecting the higher order terms, we get,

$$\Delta v_B = \left.\frac{\partial f_1}{\partial i_B}\right|_{V_c} \cdot \Delta i_B + \left.\frac{\partial f_1}{\partial v_C}\right|_{I_B} \cdot \Delta v_C \qquad \text{... (3.6.9)}$$

$$\Delta i_C = \left.\frac{\partial f_2}{\partial i_B}\right|_{V_c} \cdot \Delta i_B + \left.\frac{\partial f_2}{\partial V_C}\right|_{I_B} \cdot \Delta v_C \qquad \text{... (3.6.10)}$$

In Eqs. (3.6.9) and (3.6.10), partial derivatives $\frac{\partial f_1}{\partial i_B}$ and $\frac{\partial f_2}{\partial i_B}$ are taken by keeping the collector voltage constant as shown by the subscribe V_C attached to the derivative and the partial derivatives $\frac{\partial f_1}{\partial v_C}$ and $\frac{\partial f_2}{\partial v_C}$ are taken by keeping the base current constant as shown by subscript I_B attached to the derivatives.

In Eqs. (3.6.9) and (3.6.10), quantities Δi_B, Δv_B, Δv_C and Δi_C represent small increments in the base, collector voltages and currents. Hence, these four quantities may be represented by symbols i_b, v_b, v_c and i_c respectively. Since for the small AC signals limited to the quasi-linear region the partial derivatives becomes constant. Hence Eqs. (3.6.9) and (3.6.10) becomes,

$$v_b = h_{ie} \cdot i_B + h_{re} \cdot v_c \qquad \text{... (3.6.11)}$$

$$i_c = h_{fe} \cdot i_B + h_{oe} \cdot v_c \qquad \text{... (3.6.12)}$$

Where,

$$h_{ie} = \left.\frac{\partial f_1}{\partial i_B}\right|_{V_C} = \left.\frac{\partial v_B}{\partial i_B}\right|_{V_C} = \left.\frac{\Delta v_B}{\Delta i_b}\right|_{V_c}$$

$$h_{re} = \left.\frac{\partial f_1}{\partial v_C}\right|_{I_B} = \left.\frac{\partial v_B}{\partial v_C}\right|_{I_B} = \left.\frac{\Delta v_B}{\Delta v_C}\right|_{I_B}$$

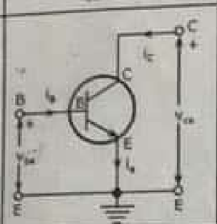
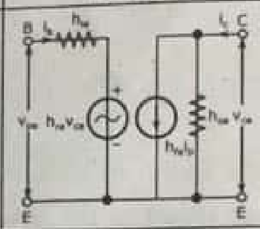
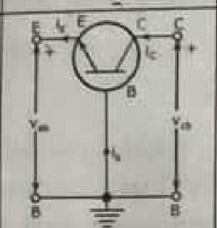
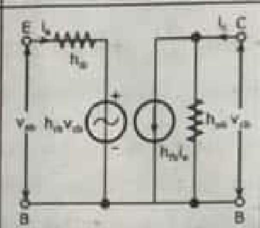
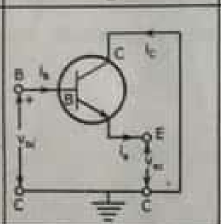
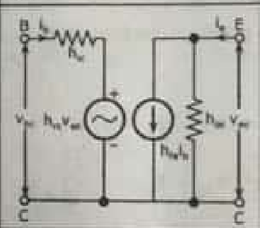
$$h_{fe} = \left.\frac{\partial f_2}{\partial i_B}\right|_{V_C} = \left.\frac{\partial i_C}{\partial i_B}\right|_{V_C} = \left.\frac{\Delta i_C}{\Delta i_B}\right|_{V_c}$$

$$h_{oe} = \left.\frac{\partial f_2}{\partial v_C}\right|_{I_B} = \left.\frac{\partial i_C}{\partial v_C}\right|_{I_B} = \left.\frac{\Delta i_C}{\Delta v_C}\right|_{I_B}$$

The above equations, define the h-parameters of the transistor in CE configuratio

h-parameter models for CE, CB and CC : The h-parameter derived for CE configurations can be extended for CB and CC configurations also. Table 3.5.3 lists the hybrid model and equations for various BJT configurations which are valid for NPN as well as PNP transistors and holds good for all types of loads and methods of biasing.

Table 3.6.3 Hybrid Models and Equations of a BJT Transistor

Configuration	Circuit	Hybrid Model	V-I Equations	h-Parameters
Common Emitter			$v_{be} = h_{ie} \cdot i_b + h_{re} \cdot v_{ce}$ $i_c = h_{fe} \cdot i_b + h_{oe} \cdot v_{ce}$	$h_{ie} = \left.\frac{\partial V_{BE}}{\partial I_B}\right\|_{V_{CE}}$ $h_{fe} = \left.\frac{\partial I_C}{\partial I_B}\right\|_{V_{CE}}$ $h_{re} = \left.\frac{\partial V_{BE}}{\partial V_{CE}}\right\|_{I_B}$ $h_{oe} = \left.\frac{\partial I_C}{\partial V_{CE}}\right\|_{I_B}$
Common Base			$v_{eb} = h_{ib} \cdot i_e + h_{rb} \cdot v_{cb}$ $i_c = h_{fb} \cdot i_e + h_{ob} \cdot v_{cb}$	$h_{ib} = \left.\frac{\partial V_{EB}}{\partial I_E}\right\|_{V_{CB}}$ $h_{fb} = \left.\frac{\partial I_C}{\partial I_E}\right\|_{V_{CB}}$ $h_{rb} = \left.\frac{\partial V_{EB}}{\partial V_{CB}}\right\|_{I_E}$ $h_{ob} = \left.\frac{\partial I_C}{\partial V_{CB}}\right\|_{I_E}$
Common Collector			$v_{bc} = h_{ic} \cdot i_b + h_{rc} \cdot v_{ec}$ $i_e = h_{fc} \cdot i_b + h_{oc} \cdot v_{ec}$	$h_{ic} = \left.\frac{\partial V_{BC}}{\partial I_B}\right\|_{V_{EC}}$ $h_{fc} = \left.\frac{\partial I_E}{\partial I_B}\right\|_{V_{EC}}$ $h_{rc} = \left.\frac{\partial V_{BC}}{\partial V_{EC}}\right\|_{I_B}$ $h_{oc} = \left.\frac{\partial I_E}{\partial V_{EC}}\right\|_{I_B}$

ADVANTAGES OF H-PARAMETERS

Use of h-parameters to describe a transistor have the following advantages,

(1) h-parameters are real numbers up to radio frequencies.

(2) They are easy to measure.

(3) They can be determined from the static transistor characteristic curve.

(4) They are convenient to use in circuit analysis and design.

(5) They are easily convertable from one configuration to other.

(6) There are readily supplied by manufacturers.

DISADVANTAGES OF H-PARAMETERS

Use of h-parameters to describe a transistor have the following disadvanttages,

(1) The exact values of h-parameters for a particular transistor are very difficult to obtain. This is because these parameters are subjected to considerable variations such as variation due to change in temperature, variation due to change in Q-point and varies due to ageing.

(2) Only for small A.C. signals, the h-parameter approach gives correct answer. This is because only for small signals, a transistor behaves as a linear device.

3.7 CHARACTERISTICS OF TRANSISTOR CONFIGURATIONS

In Section 3.5, we determined the amplification factor in transistor configurations. But only amplification factor of transistor does not describe its behaviour. The complete electrical behaviour of transistor can be described by studying various relation between currents and voltages. These relations can be displayed on graph and thus curves obtained are called characteristics of transistor.

Mainly, we consider two sets of characteristics curves for a transistor i.e.,

(1) Input characteristic curves.

(2) Output characteristic curves.

3.7.1 Common Base Characteristics

3.7.1.1 Input Characteristics

In CB configuration, the curve between an input voltage VEB (Emitter-Base Voltage) and input current IE (emitter current) at constant collector-base voltage VCB. The emitter-current is taken along y-axis and emitter base voltage along x-axis.

Fig. 3.7.1 shows input characteristics of common base configuration.

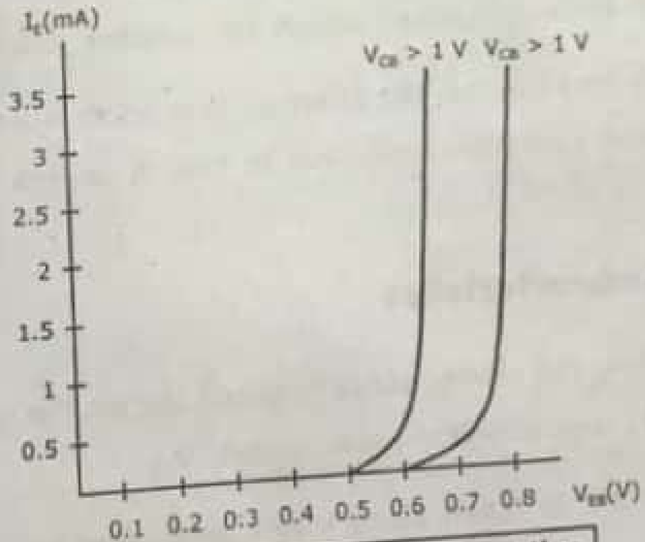


Fig. 3.7.1 CB Input Characteristics

When VCB is equal to zero and the emitter-base junction is forward biased as shown in the characteristics, the junction behaves as a forward biased diode so that the emitter current I_E increases rapidly with small increase in emitter-base voltage V_{EB}. When V_{EB} put constant and V_{CB} is increased, the width of the base region will decrease. The effect of this results, the emitter current IE increases. Therefore, the curves shift towards the left as V_{CB} is increased.

The input resistance 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 (ΔV_{CB}).

It is given by,

$$r_i = \frac{\Delta V_{EB}}{\Delta I_E} \Big/ V_{CB} = \text{Constant.}$$

EARLY EFFECT

When reverse bias voltage VCB increases, the width of depletion region also increases, the width of depletion region also increases, which reduces the electrical base width. This effect is called as early effect (or) base width modulation.

This decrease in base width has three consequences,

(1) There is less chance for recombination within the base region. Hence, no. of majority carriers from emitter reaching the collector region increases i.e., α increases.

(2) The charge gradient of minority carriers in base region increases as a result the minority carrier current injected across the emitter junction is increases.

(3) For extremely large voltages, the effective base width becomes reduced to zero. This condition is called punch-through. Due to this, it causes voltage breakdown in the transistor.

3.7.1.2 Output Characteristics

In CB configuration, the plotted curve between the emitter current IE is kept constant at collector current I_C and collector-base voltage V_{CB}.

The collector current is taken along y-axis and collector base voltage magnitude is taken along x-axis.

Fig. 3.7.2 shows output characteristics for PNP transistor in CB configuration.

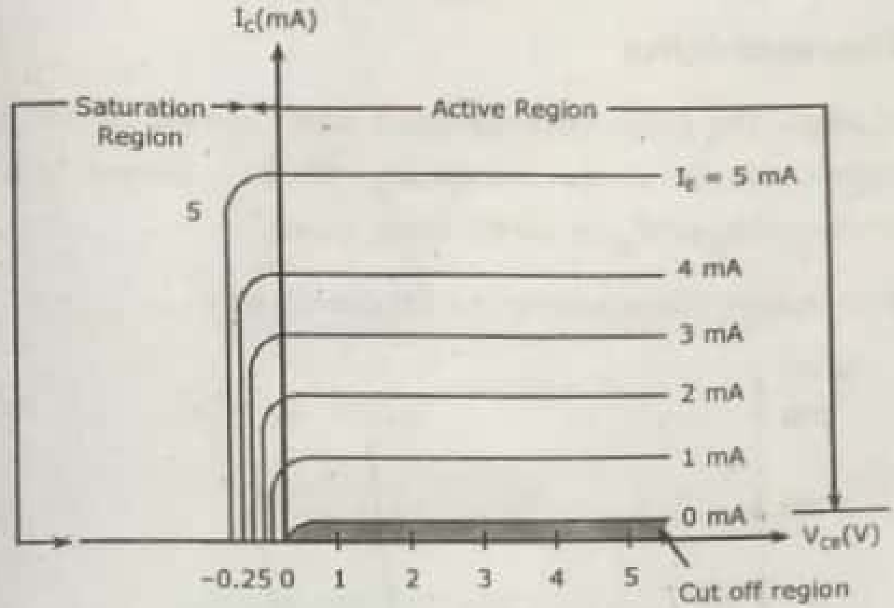


Fig. 3.7.2 CB Output Characteristics

There are three regions inn B output characteristics. They are explained below as follows,

ACTIVE REGION

In active region, the collector junction is reverse biased and the emitter junction in forward direction. In CB configuration, the collector current is given by, $I_C = \alpha I_E + I_{CBO}$, hence in this region collector current is essentially independent of collector voltage and depends only upon the emitter current. Because α is less than, but almost equal to unity, the magnitude of collector current is slightly less than that of the emitter current. However, due to early effect there is nearly 0.5% increase in I_C with increase in reverse bias voltage V_{CB}.

CUT-OFF REGION

The region below the curve $I_E = 0$ is known as cut-off region where the collector current is nearly zero and the collector-base and emitter base junctions of a transistor are reverse-biased.

SATURATION REGION

In this region, the emitter-base junction and collector base junction both are forward biased. Hence, the IC is independent of I_C. I_C decreases rapidly as V_{CB} becomes more negative.

The output resistance,

$$r_0 = \left.\frac{\Delta V_{CB}}{\Delta I_C}\right|_{I_E = \text{Constant.}}$$

3.7.2 Common Emitter Characteristics

3.7.2.1 Input Characteristics

In CE configuration, the curve between input base current IB and base-emitter voltage VBE at constant collector-emitter voltage V_{CE}. The base current IB is taken along y-axis and base-emitter voltage V_{BE} is taken along x-axis.

Fig. 3.7.3 shows output characteristics of CE configuration,

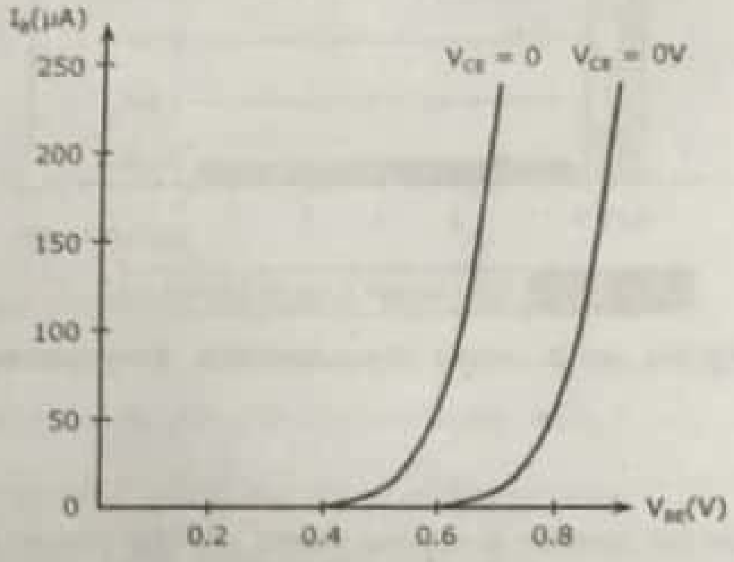


Fig. 3.7.3 CE Input Characteristics

When $V_{CE} = 0$, the base-emitter voltage is forward biased and the junction behaves as a forward biased diode. When V_{CE} is increased, the width of the depletion region at the reverse biased collector base junction will increase. Hence, the effective width of base will decrease. This effect causes a decrease in the base current I_B. Hence, to get the same value of IB as that for $V_{CE} = 0$, V_{BE} should be increased. Therefore, the curve shifts to the right as V_{CE} increases.

Input resistance,

$$r_i = \left.\frac{\Delta V_{BE}}{\Delta I_B}\right|_{\text{at constant } V_{CE}}$$

3.7.2.2 Output Characteristics

In CE configuration, the curve plotted between collector current I_C and collector emitter voltage V_{CE} at constant base current IB.

Fig. 3.7.4 shows output characteristic for NPN transistor in CE configuration.

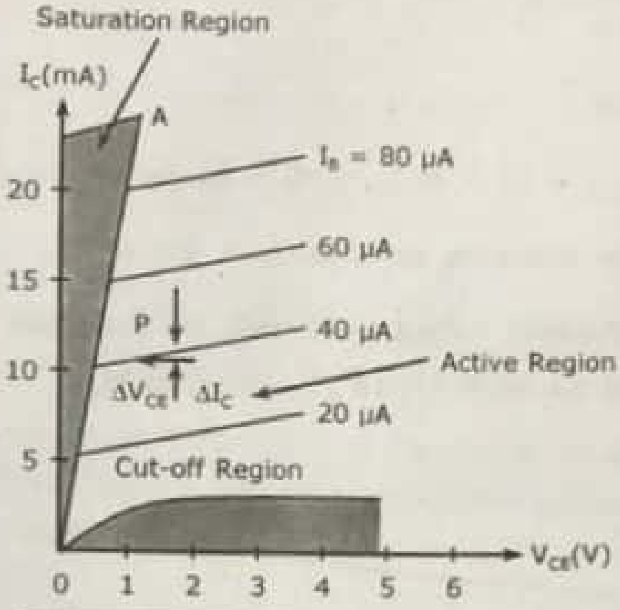


Fig. 3.7.4 CE Output Characteristics

Active Region : For the operation of active region, the base-emitter junction is forward biased and collector emitter junction is reverse biased. The collector current rise more sharply with increasing V_{CE} in the linear region of output characteristics of C_E transistor.

Saturation Region : In this region, the base-emitter junction and collector-base junction both are forward biased. In this region, I_C does not depend upon the input current I_B. The saturation value of V_{CE}, designated $V_{CE(sat)}$, usually ranges between 0.1 V to 0.3 V.

Cut-off Region : When input IB = 0, the collector current IC is not zero but its value is equal to the reverse leakage current I_{CO} =,

The output resistance,

$$r_0 = \left.\frac{\Delta V_{CE}}{\Delta I_C}\right|_{\text{at constant } I_B}$$

EXAMPLE PROBLEM 1

The output characteristics of an NPN transistor in CE configuration are shown in Fig. 3.7.5. Determine for this transistor,

(a) The dynamic output resistance

(b) The D.C current gain and

(c) The A.C current gain at an operating point,

When V_{CE} = 10 V and I_B = 40 μA.

SOLUTION

Given Data : $V_{CE} = 10$ V

$I_B = 40$ μA

The operating point $V_{CEQ} = 10$ V at $I_B = 40$ A is marked on Fig. 3.7.5.

Collector current at the operating point Q, $I_C = 4.8$ mA.

(a) To determine the dynamic output resistance, let the small change in V_{CE} around the operating point be from 7.5 to 12.5 V. That is,

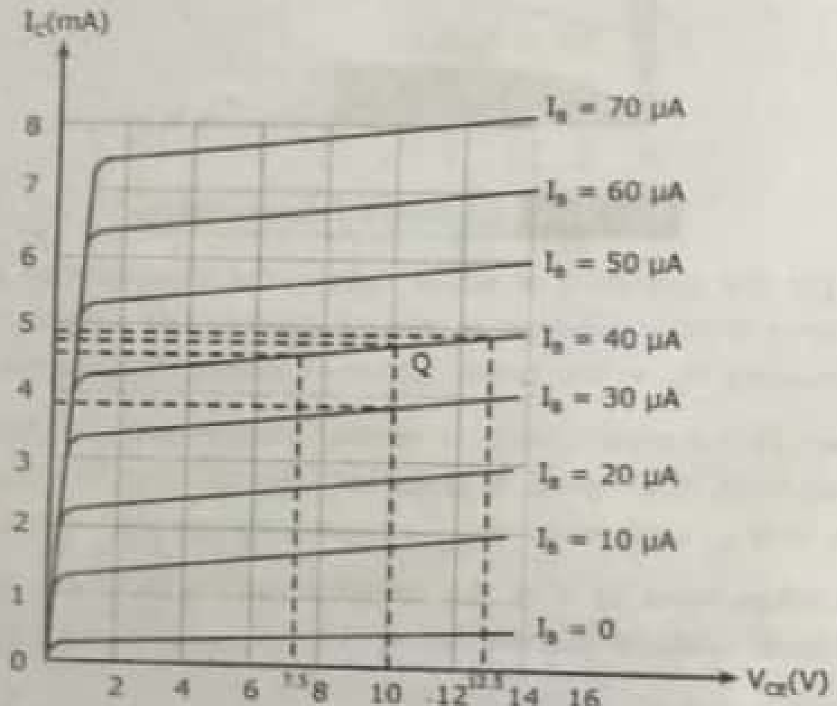


Fig. 3.7.5 Output Characteristics of CE Configuration

$$\Delta V_{CE} = 12.5 - 7.5 = 5V$$

The corresponding change in I_C at constant, $I_B = 40$ μA is,

$$\Delta I_C = 4.9 - 4.7 = 0.2 \text{ mA}$$

Thus, dynamic output resistance,

$$r_o = \left.\frac{\Delta V_{CE}}{\Delta I_C}\right|_{I_B = 40\mu A}$$

$$\Rightarrow \quad r_o = \frac{5 \text{ V}}{0.2 \text{ mA}} = \frac{5}{0.2 \times 10^{-3}} = 25 \text{ k}\Omega$$

(b) To determine β_{DC}, we have to take the value of I_C corresponding to I_B = 40 μA at V_{CE} = 10 V. From graph.

When, I_B = 40 μA, I_C = 4.8 mA at V_{CE} = 10 V

$$\beta_{DC} = \frac{I_C}{I_B} = \frac{4.8 \text{ mA}}{40 \text{ μA}} = 120$$

(c) To determine A.C current gain (β) i.e., $\beta = \frac{\Delta I_C}{\Delta I_B}$

Draw a vertical line corresponding to V_{CE} = 10 V.

From the given characteristics, it is clear that when base current changes from 30 μA to 40 μA, correspondingly the collector current changes from 3.8 mA to 4.8 mA.

$$\beta = \left.\frac{\Delta I_C}{\Delta I_B}\right|_{V_{CE} = 10 V} = \frac{(4.8 - 3.8) \text{ mA}}{(40 - 30) \text{ μA}} = \frac{1.2 \times 10^{-3}}{10 \times 10^{-6}} = 120$$

3.7.3 Common Collector Characteristics

3.7.3.1 Input Characteristics

In CC configuration, the curve between input current I_B and base-collector voltage V_{CB} at constant collector-emitter voltage V_{CE}.

Fig. 3.7.6 shows input characteristics of CC configuration.

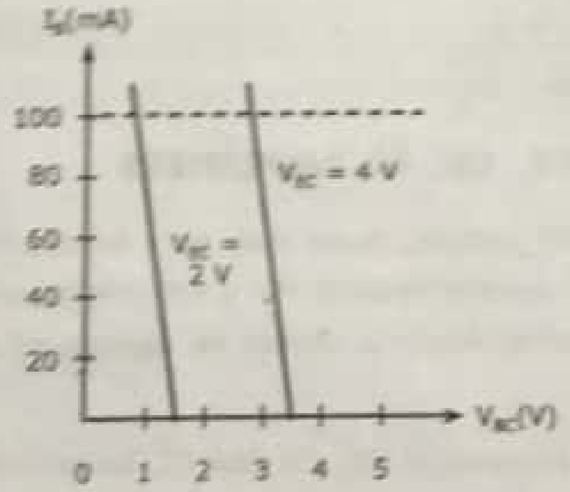


Fig. 3.7.6 CC Input Characteristics

The base-collector voltage V_{BC} increases in equal steps and the corresponding I_B also increases. This is repeated for different fixed values of V_{CE}.

Scanned by CamScanner

3.7.3.2 Output Characteristics

The curve between collector current I_C and emitter-collector voltage V_{EC} at constant current I_B.

Fig. 3.7.7 shows output characteristics of CC configuration.

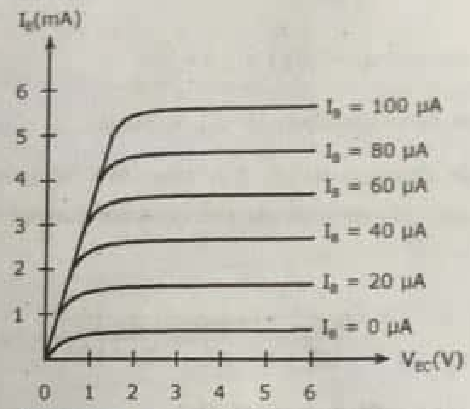


Fig. 3.7.7 CC Output Characteristics

Since, $I_E = I_C$, the output characteristics of CC and CE configuration both are similar characteristics. A family of output characteristic curves are obtained for different value of I_B, i.e., for a particular value of I_B, V_{EC} is varied from 0 to V(volts) and corresponding I_E values are obtained.

Any point in active region curve gives the output resistance,

$$R_0 = \frac{1}{\text{Slope}} = \frac{\Delta V_{EC}}{\Delta I_E}$$

3.8 ANALYSIS OF CE, CB, CC AMPLIFIERS

In most of the transistor circuits, there may be a feedback resistor from collector to base, or it may have an emitter resistor for a CE configuration. In such cases, the equations derived in the earlier sections cannot be applied to determine the amplifier parameters.

Now, we can see the analysis of CE, CB and CC amplifiers.

3.8.1 Analysis of CE Amplifier Using Exact h-model

The circuit arrangement of transistor in a common emitter configuration is shown in Fig. 3.8.1,

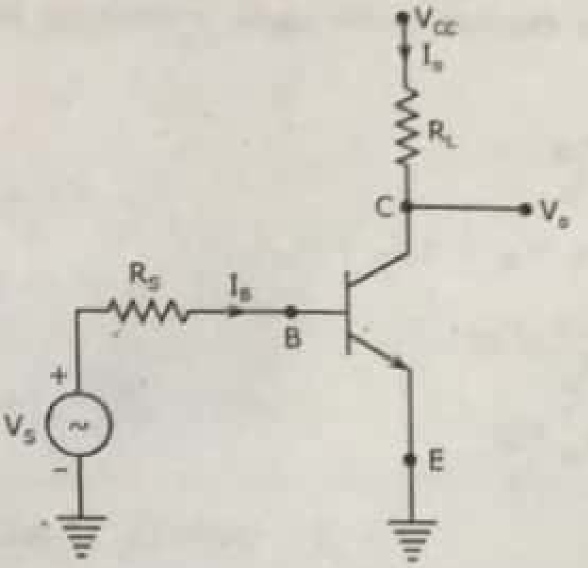


Fig. 3.8.1 Transistor in a Common Emitter Configuration

The h-parameter equivalent circuit of the transistor in common emitter amplifier is shown in Fig. 3.8.2,

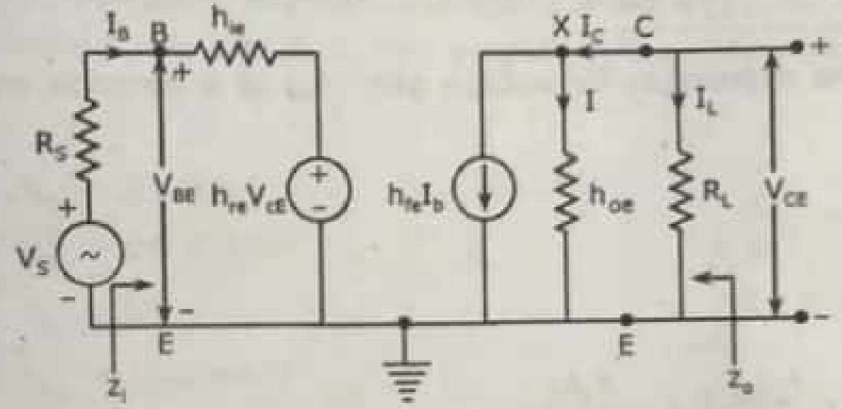


Fig. 3.8.2 Equivalent Circuit of h-parameter

Current Gain (A_I) : Current Gain (A_I) in common emitter configuration is given by,

$$A_I = \frac{I_L}{I_B} = \frac{-I_C}{I_B} \qquad (\because I_L = -I_C) \qquad \text{... (3.8.1)}$$

From Fig. 3.8.2. Applying KCL at node X we have,

$$I_c = h_{fe}I_B + h_{oe}V_{CE}$$

$$\Rightarrow \quad I_c = h_{fe}I_B - I_c h_{oe}R_L \qquad (\because V_{CE} = I_L R_L = -I_C R_L)$$

$$\Rightarrow \quad I_c(1 + h_{oe}R_L) = h_{fe}I_B$$

$$\therefore \quad \boxed{A_I = \frac{-I_c}{I_B} = \frac{-h_{fe}}{1 + h_{oe}R_L}} \qquad \text{... (3.8.2)}$$

Input Impedance (Z_i) : The expression for input impedance (Z_i) of a common emitter amplifier is defined as,

$$Z_i = \frac{V_{BE}}{I_B} \qquad \text{... (3.8.3)}$$

From Fig. 3.8.2, we have, $V_{BE} = h_{ie}I_B + h_{re}V_{CE}$

$$\Rightarrow \qquad Z_i = \frac{h_{ie}I_B + h_{re}V_{CE}}{I_B}$$

$$\Rightarrow \qquad Z_i = h_{ie} + h_{re}\frac{V_{CE}}{I_B}$$

But, $V_{CE} = -I_cR_L = A_II_BR_L$ [$\because$ From Eq. (3.8.2), $-I_C = A_II_B$]

$$\Rightarrow \qquad Z_i = h_{ie} + h_{re}\frac{A_II_BR_L}{I_B} = h_{ie} + h_{re}A_IR_L$$

$$\therefore \qquad \boxed{Z_i = h_{ie} + \frac{h_{re}h_{fe}R_L}{1 + h_{oe}R_L}}$$ [$\because$ Using the value of A_I from Eq. (3.8.2)]

Voltage Gain (A_V) : The expression for voltage gain (A_V) of a common emitter amplifier is given by,

$$A_V = \frac{V_{CE}}{V_{BE}} \qquad \text{... (3.8.4)}$$

But, $V_{CE} = -I_cR_L = A_II_BR_L$.

$$\text{Thus,} \qquad A_V = \frac{A_II_BR_L}{V_{BE}} = \frac{A_IR_L}{(V_{BE}/I_B)}$$

$$\therefore \qquad A_V = \frac{A_IR_L}{Z_i} \qquad \left[\because \text{ Using } Z_i = \frac{V_{BE}}{I_B} \text{ from Eq. (3.8.3)}\right] \qquad \text{... (3.8.5)}$$

Output Admittance (Y_o) : The expression for output admittance of a common emitter amplifier is given by,

$$Y_o = \left.\frac{I_C}{V_{CE}}\right|_{V_S = 0} \qquad \text{... (3.8.6)}$$

From Fig. 3.8.2. Applying KCL at node X, we have,

$$I_c = h_{fe}I_B + h_{oe}V_{CE} \qquad \text{... (3.8.7)}$$

Using Eq. (3.8.7) in Eq. (3.8.6), we get,

$$\Rightarrow \qquad Y_o = h_{fe}\frac{I_B}{V_{CE}} + h_{oe} \qquad \text{... (3.6.8)}$$

With, $V_S = 0$, by applying KVL in input circuit, we have,

$$R_s I_B + h_{re} V_{CE} + h_{ie} I_B = 0$$

$$\Rightarrow \quad I_B(R_s + h_{ie}) + h_{re} V_{CE} = 0$$

$$\Rightarrow \quad \frac{I_B}{V_{CE}} = \frac{-h_{re}}{R_s + h_{ie}} \qquad \text{... (3.8.9)}$$

Substituting Eq. (3.8.9) in Eq. (3.8.9),

We get, $$Y_o = h_{fe}\left(\frac{-h_{re}}{h_{ie} + R_s}\right) + h_{oe}$$

$$\therefore \quad \boxed{Y_o = h_{oe} - \frac{h_{fe} h_{re}}{h_{ie} + R_s}} \qquad \text{... (3.8.10)}$$

EXAMPLE PROBLEM 1

The h-parameters of a transistor used in a CE circuit are h_{ie} = 1.0 kΩ, h_{re} = 10 × 10^{-4}, h_{fe} = 50, h_{oe} = 100 μA/V. The load resistance for the transistor is 1 kΩ in the collector circuit. Determine Z_i, A_v and A_i in the amplifier stage (Assume R_s = 1000 W)

SOLUTION

[May/June - 08]

Given Data : h_{ie} = 1.9 kΩ

h_{re} = 10 × 10^{-4}

h_{fe} = 50

h_{oe} = 100 mA/V

Load resistance, R_L = 1 kΩ

Current gain,

$$A_I = \frac{-h_{fe}}{1 + h_{oe} R_L}$$

$$= \frac{-50}{1 + 100 \times 10^{-6} \times 10^3}$$

$$= -45.45$$

Input impedance,

$$Z_i = h_{ie} + h_{re} A_I R_L$$

$$= 1 \times 10^3 + 10 \times 10^{-4} \times -45.45 \times 10^3$$

$$= 1000 - 45.45$$

$$= 954.55\ \Omega$$

Voltage gain,

$$A_V = \frac{A_I R_L}{Z_i}$$

$$= \frac{(-45.45)(1 \times 10^3)}{954.55}$$

$$= -47.61$$

Output admittance,

$$Y_o = h_{oe} - \frac{h_{fe} h_{re}}{h_{ie} + R_s}$$

$$= 100 \times 10^{-6} - \frac{50 \times 10 \times 10^{-4}}{10^3 + 10^3}$$

$$= 100 \times 10^{-6} - 25 \times 10^{-6}$$

$$= 75 \times 10^{-6}$$

$$= 75\ \mu A/V \text{ (or) } 75\ \mu℧$$

Output impedance,

$$Z_o = \frac{1}{Y_o}$$

$$= \frac{1}{40}$$

$$= \frac{1}{75 \times 10^{-6}}$$

$$= 13.33\ k\Omega$$

3.8.2 Analysis of CB Amplifier using Exact h-model

The circuit arrangement of transistor in a common base amplifier is shown in Fig. 3.8.3

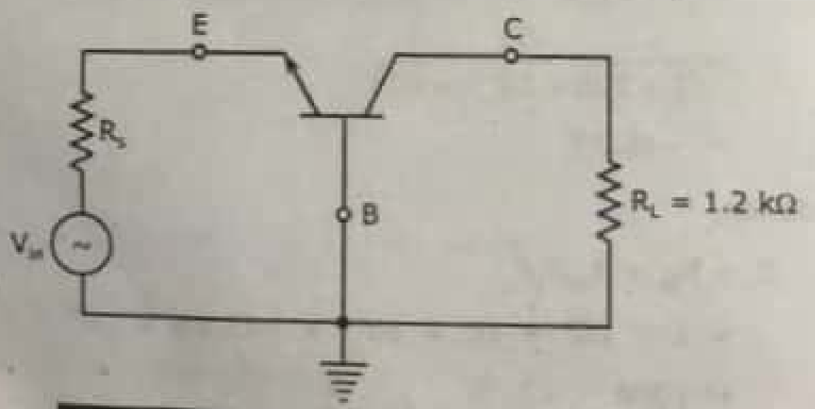


Fig. 3.8.3 Common Base Amplifier Circuit

The h-parameter equivalent circuit of the transistor in the CB configuration is shown in Fig. 3.8.4,

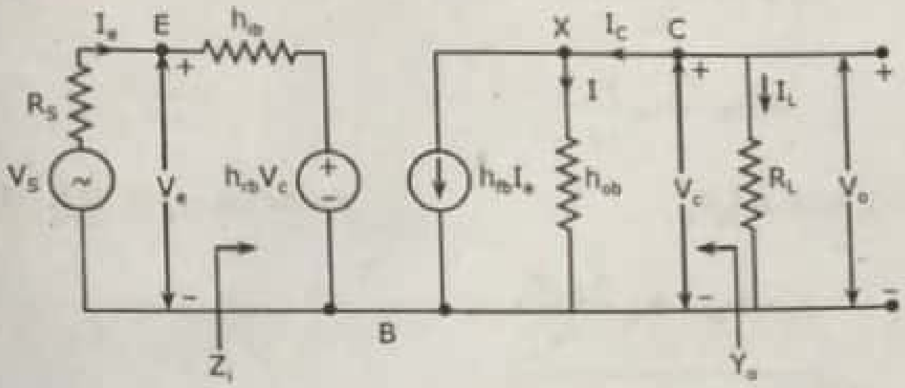


Fig. 3.8.4 Equivalent h-parameter Circuit

Current Gain (A_i) : The expression for current gain in common base configuration is definec as,

$$A_I = \frac{I_L}{I_e} = \frac{-I_c}{I_e} \qquad \text{... (3.8.11}$$

In Fig. 3.8.4, applying KCL at node X, we have,

$$I_c = h_{fb}I_e + h_{ob}V_c$$

But, $V_c = I_LR_L = -I_cR_L$. Thus,

$$I_c = h_{fb}I_e - I_ch_{ob}R_L$$

$$\Rightarrow \quad I_c(1 + h_{ob}R_L) = h_{fb}I_e$$

$$\Rightarrow \quad \frac{I_c}{I_e} = \frac{-h_{fb}}{1 + h_{ob}R_L}$$

But, $A_I = \frac{-I_c}{I_e} = -\left(\frac{-h_{fb}}{1 + h_{ob}R_L}\right)$

$$\therefore \quad \boxed{A_I = \frac{h_{fb}}{1 + h_{ob}R_L}} \qquad \text{... (3.8.}$$

Input Impedance (Z_i) : The expression for input impedance of a common base ampli is defined as,

$$Z_i = \frac{V_e}{I_e} \qquad \text{... (3.8.}$$

From Fig. 3.8.4, we have, $V_e = h_{ib} I_e + h_{rb} V_c$

$$\Rightarrow \quad Z_i = \frac{h_{ib} I_e + h_{rb} V_c}{I_e}$$

$$= h_{ib} + h_{rb} \frac{V_c}{I_e}$$

But, $V_c = -I_c R_L = A_i I_e R_L$ [$\because$ From Eq. (3.8.11), $-I_c = A_i I_e$].

$$\Rightarrow \quad Z_i = h_{ib} + h_{rb} \frac{A_i I_e R_L}{I_e}$$

$$\therefore \quad \boxed{Z_i = h_{ib} + h_{rb} A_i R_L} \quad \text{... (3.8.14)}$$

Voltage Gain (A_v) : The expression for voltage gain of a common base amplifier is defined as,

$$A_V = \frac{V_c}{V_e} \quad \text{... (3.8.15)}$$

But, $V_c = -I_c R_L = A_i I_e R_L$ [$\because$ From Eq. (3.8.11), $-I_c = A_i I_e$]

$$\Rightarrow \quad A_V = \frac{A_i I_e R_L}{V_e}$$

$$= \frac{A_i R_L}{\frac{V_e}{I_e}}$$

Since $Z_i = \frac{V_e}{I_e}$. Thus,

$$\therefore \quad \boxed{A_V = \frac{A_i R_L}{Z_i}} \quad \text{... (3.8.16)}$$

Output Admittance (Y_o) : Output admittance common base amplifier is defined as,

$$Y_o = \left. \frac{I_C}{V_C} \right|_{V_S = 0}$$

Applying KCL at node X in Fig. 3.8.4,

We get, $I_c = h_{fb} I_e + h_{ob} V_c$ ... (3.8.17)

With $V_s = 0$, applying KVL in the input circuit of Fig. 3.8.4, we have,

$$I_e R_S + I_e h_{ib} + h_{rb} V_C = 0$$

$$\Rightarrow \quad I_e(R_S + h_{ib}) = -h_{rb} V_c$$

$$\Rightarrow \quad I_e = \frac{-h_{rb} V_c}{R_s + h_{ib}}$$

Substituting $I_e = \frac{-h_{rb} V_c}{h_{ib} + R_S}$ in Eq. (3.8.17),

We get, $$I_c = h_{fb}\left(\frac{-h_{rb} V_c}{h_{ib} + R_S}\right) + h_{ob} V_c$$

$$\Rightarrow \quad I_c = V_c\left(\frac{-h_{rb} h_{fb}}{h_{ib} + R_S} + h_{ob}\right)$$

$$\Rightarrow \quad \frac{I_c}{V_c} = \frac{-h_{rb} h_{fb}}{h_{ib} + R_s} + h_{ob}$$

$$\therefore \quad \boxed{Y_o = h_{ob} - \frac{h_{rb} h_{fb}}{h_{ib} + R_S}} \quad \text{... (3.8.18)}$$

EXAMPLE PROBLEM 1

A transistor used in a CB amplifier has the following values of h-parameters h_{ib} = 25 Ω, h_{fb} = –0.98, h_{rb} = 5 × 10–4 and h_{ob} = 0.34 × 10^{-6} S. Calculate the values of Z_i, Z_o, A_i and A_v, if the load resistance is 1.2 kΩ. Assume source resistance as zero.

SOLUTION

Given Data : $h_{ib} = 25\ \Omega$

$h_{fb} = -0.98$

$h_{rb} = 5 \times 10^{-4}$

$h_{ob} = 0.34 \times 10^{-6}$s

Load resistance, $R_L = 1.2$ kΩ

Current gain,

$$(A_I) = \frac{-h_{fb}}{1 + h_{ob} R_L}$$

$$= \frac{-(-0.98)}{1 + (0.34 \times 10^{-6})(1.2 \times 10^{3})}$$

$$= 0.98$$

Input impedance,

$$Z_i = h_{ib} + h_{rb}A_iR_L$$

$$= 28 + (5 \times 10^{-4})\ (0.98)\ (1.2 \times (10^3)$$

$$= 28 + 0.588$$

$$= 28.59\ \Omega$$

Voltage gain,

$$(A_v) = \frac{A_iR_L}{Z_i}$$

$$= \frac{(0.98)\ (1.2 \times 10^3)}{28.59}$$

$$= 41.13$$

Output admittance,

$$Y_o = h_{ob} - \frac{h_{fb}h_{rb}}{h_{ib} + R_s}$$

$$\Rightarrow \qquad Y_o = h_{ob} - \frac{h_{fb}h_{rb}}{h_{ib}}$$

$$= 0.34 \times 10^{-6} + \frac{(-0.98)\ (5 \times 10^{-4})}{28}$$

$$= 0.34 \times 10^{-4} - 0.175 \times 10^{-4}$$

$$= 17.84 \times 10^{-6}$$

$$= 17.84\ \mu\mho$$

3.8.3 Analysis of CC Amplifier Using Exact h-model

Common Collector amplifier is also called as an "*emitter follower*" because common collector circuit has unity gain and the output signal at the emitter follows the input.

Fig. 3.8.5 shows basic CC amplifier circuit,

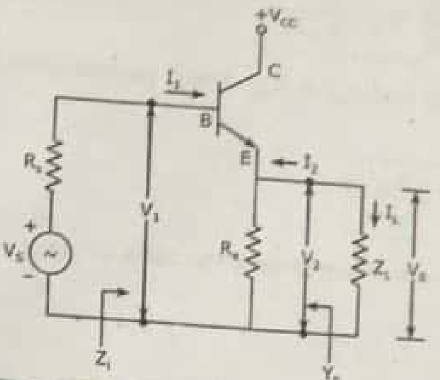


Fig. 3.8.5 Basic CC Amplifier Circuit

Hybrid Model equivalent circuit of CC amplifier is shown in Fig. 3.8.6,

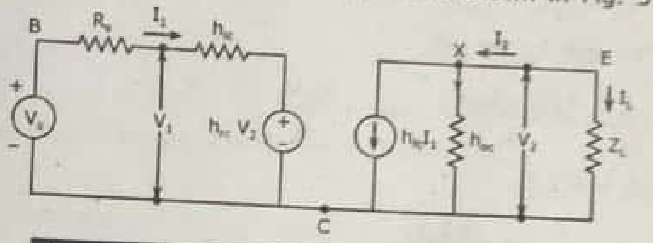


Fig. 3.8.6 Transistor Replaced by Hybrid Model

Current Gain (A_I) : Current gain is defined as the ratio of output current (I_2) to input current (I_1).

$$A_I = \frac{I_L}{I_1} = \frac{-I_2}{I_1}$$

From Fig. 3.8.6, Applying KCL at node X, we get,

$$I_2 = h_{fc}I_1 + h_{oc}V_2$$

Substituting, $V_2 = I_LZ_L = -I_2Z_L$ in I_2,

We get, $I_2 = h_{fc}I_1 + h_{oc}(-I_2Z_L)$

$\Rightarrow$ $I_2 = h_{fc}I_1 - h_{oc}I_2Z_L$

$\Rightarrow$ $I_2 + h_{oc}I_2Z_L = h_{fc}I_1$

$\Rightarrow$ $I_2(1 + h_{oc}Z_L) = h_{fc}I_1$

$\Rightarrow$ $\dfrac{I_2}{I_1} = \dfrac{h_{fc}}{1 + h_{oc}Z_L}$

$$\therefore \quad \boxed{A_I = \frac{-I_2}{I_1} = \frac{-h_{fc}}{1 + h_{oc}Z_L}}$$

Since, $h_{fc} = -(1 + h_{fe})$ and $h_{oc} = h_{oe}$. Then, current gain in terms of h-parameters of CE configuration is,

$$\therefore \quad \boxed{A_I = \frac{1 + h_{fe}}{1 + h_{oe}Z_L}} \qquad \text{... (3.8.19)}$$

Input Impedance (Z_i) : Input impedance is the ratio of input voltage to the input current at the input terminal.

$$Z_i = \frac{V_1}{I_1}$$

Applying KVL at input side of Fig. 3.8.6, we have,

$$V_1 = h_{ic}I_1 + h_{rc}V_2$$

Substituting V_1 and Z_i, we get,

$$Z_i = \frac{h_{ic}I_1 + h_{rc}V_2}{I_1} = h_{ic} + \frac{h_{rc}V_2}{I_1}$$

But, $V_2 = -I_2Z_L = A_II_1Z_L$.

Thus,
$$Z_i = h_{ic} + h_{rc}\frac{A_II_1Z_L}{I_1}$$
$$= h_{ic} + h_{rc}A_IZ_L$$

But, $A_I = \frac{-h_{fc}}{1 + h_{oc}Z_L}$.

Thus,
$$Z_i = h_{ic} - \frac{h_{rc}h_{fc}Z_L}{1 + h_{oc}Z_L}$$

$$\Rightarrow \quad Z_i = h_{ic} - \frac{h_{rc}h_{fc}}{Z_L\left(\frac{1}{Z_L} + h_{oc}\right)}Z_L$$

$$\therefore \quad \boxed{Z_i = h_{ic} - \frac{h_{rc}h_{fc}}{Y_L + h_{oc}}} \qquad \text{... (3.8.20)}$$

Since, $h_{ic} = h_{ie}$, $h_{rc} = 1$ and $h_{fc} = -(1 + h_{fe})$, $h_{oc} = h_{oe}$. Then we have,

$$\therefore \quad \boxed{Z_i = h_{ie} + \frac{(1 + h_{fe})}{Y_L + h_{oc}}}$$

Voltage Gain (A_V) : The ratio of output voltage to input voltage is known as 'voltage gain'. It is represented as 'A_V'.

$$A_V = \frac{V_2}{V_1}$$

But, $V_2 = A_I I_1 Z_L$

$$A_V = \frac{A_I I_1 Z_L}{V_1}$$

$$= \frac{A_I Z_L}{\frac{V_1}{I_1}}$$

$$= \frac{A_I Z_L}{Z_i}$$

$$\therefore \quad \boxed{A_V = \frac{A_I Z_L}{Z_i}} \qquad \text{... (3.8.21)}$$

Output Admittance (Y_0) : Output admittance is defined as,

$$Y_0 = \left.\frac{I_2}{V_2}\right|_{V_S = 0}$$

From Fig. 3.8.6. Applying KCL at node X, we get,

$$I_2 = h_{fc} I_1 + h_{oc} V_2 \qquad \text{... (3.8.22)}$$

Dividing Eq. (3.8.22) by V_2,

$$\frac{I_2}{V_2} = h_{fc} \frac{I_1}{V_2} \times h_{oc} \qquad \text{... (3.8.23)}$$

On applying KVL to input circuit with $V_s = 0$, we get,

$$R_s I_1 + h_{ie} I_1 + h_{rc} V_2 = 0$$

$$\Rightarrow \quad I_1 (R_s + h_{ic}) + h_{rc} V_2 = 0$$

$$\Rightarrow \quad \frac{I_1}{V_2} = \frac{-h_{rc}}{R_s + h_{ic}} \qquad \text{... (3.8.24)}$$

Substituting Eq. (3.8.24) in Eq. (3.8.23),

We get, $$\frac{I_2}{V_2} = h_{fc}\left(\frac{-h_{rc}}{R_s + h_{ic}}\right) + h_{oc}$$

$$\therefore \quad \boxed{Y_0 = h_{oc} - \frac{h_{fc}h_{rc}}{h_{ic} + R_s}} \quad \cdots (3.8.25)$$

Since, Output impedance, $Z_0 = \frac{1}{Y_0}$

$$\therefore \quad Z_0 = \frac{1}{\left[h_{oc} - \frac{h_{fc}h_{rc}}{h_{ic} + R_s}\right]}$$

Since, $h_{ic} = h_{ie}$, $h_{rc} = 1$, and $h_{fc} = -(1 + h_{fe})$, $h_{oc} = h_{oe}$

Then, Z_o in terms of h-parameters of CE configuration is,

$$\therefore \quad \boxed{Z_0 = \frac{1}{\left[h_{oe} + \frac{1 + h_{fe}}{h_{ie} + R_s}\right]}}$$

EXAMPLE PROBLEM 1

For a single stage transistor amplifier, R_s = 10 k and R_L = 10 k. The h-parameter values are h_{fc} = –51, h_{ic} = 1.1 kΩ, h_{rc} = 1, h_{oc} = 25 μA/V. Find A_I, A_V, A_{VS}, Z_i, and Z_o for the CC transistor configuration.

SOLUTION

Given Data : R_s 10 k

R_L = 10 k

h_{fc} = –51

h_{ic} = 1.1 kΩ

h_{rc} = 1

h_{oc} = 25 μA/V

Current gain,

$$A_I = \frac{-h_{fc}}{1 + h_{oc}R_L}$$

$$= \frac{51}{1 + 25 \times 10^{-6} \times 10^4}$$

$$= 40.8$$

Input impedance,

$$Z_i = h_{ie} + h_{re}A_IR_L$$

$$= 1.1 \times 10^3 + 1 \times 40.8 \times 10^4$$

$$= 409.1 \text{ k}\Omega$$

Voltage gain,

$$A_V = \frac{A_I Z_L}{Z_i}$$

$$= \frac{40.8 \times 10^4}{409.1 \times 10^3}$$

$$= 0.998$$

Output impedance,

$$Z_o = \frac{1}{h_{oC} - \frac{h_{fC}h_{rC}}{h_{iC} + R_s}}$$

$$= \frac{1}{25 \times 10^{-6} + \frac{51 \times 1}{(1.1 + 10)10^3}}$$

$$= \frac{1}{4.625 \times 10^{-3}}$$

$$= 217 \ \Omega$$

We know that, overall voltage gain (A_{VS}) is defined by,

$$A_{VS} = \frac{A_V.Z_i}{Z_i + R_S}$$

$$= \frac{0.998 \times 409.1 \times 10^3}{409.1 \times 10^3 + 10^3}$$

$$= 0.995$$

❖ ❖ ❖