UNIT-II

BIPOLAR JUNCTION TRANSISTORS

Transistor

A transistor consists of two pn junctions formed by sandwiching either p type or n-type semiconductor between a pair of opposite types. Accordingly, there are two types of transistors, namely

<I> n-p-n transistor <II> p-n-p transistor

An n-p-n transistor is composed of two n-type semiconductors seperated by a thin section of p-type as in Fig.1. However, a p-n-p transistor is formed by two p-sections seperated by a thin section of n-type as in Fig 2.

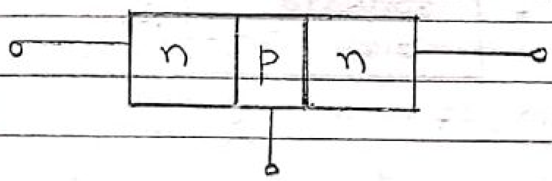


Fig. 1

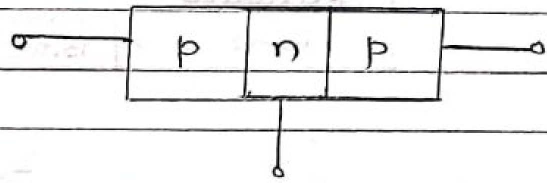


Fig. 2

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

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

(ii) There are three terminals,

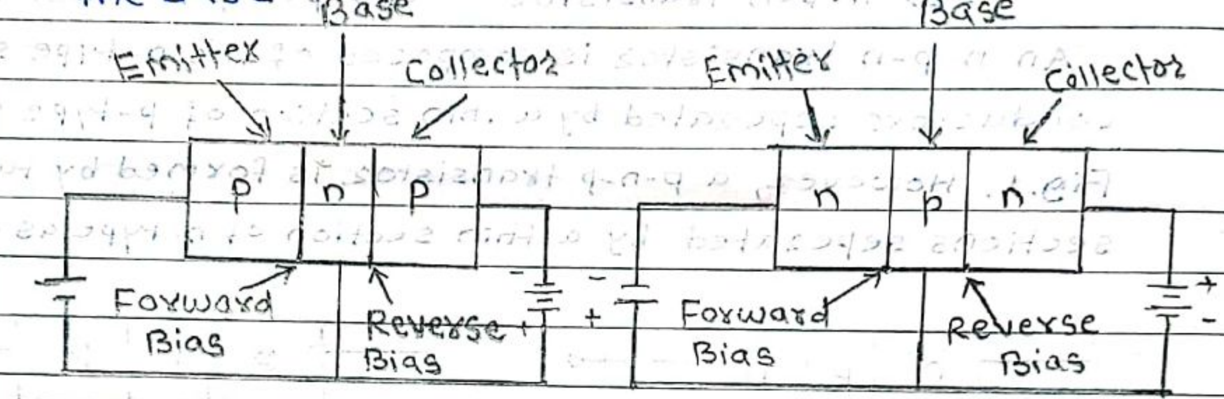
(iii) The middle section is a very thin layer. This is the most important factor in the function of a transistor.

A transistor (pnp or npn) has three sections of doped semiconductors. The section on one side is the emitter and the section on the opposite side is collector. The middle section is called the base and forms two junctions between the emitter and collector.

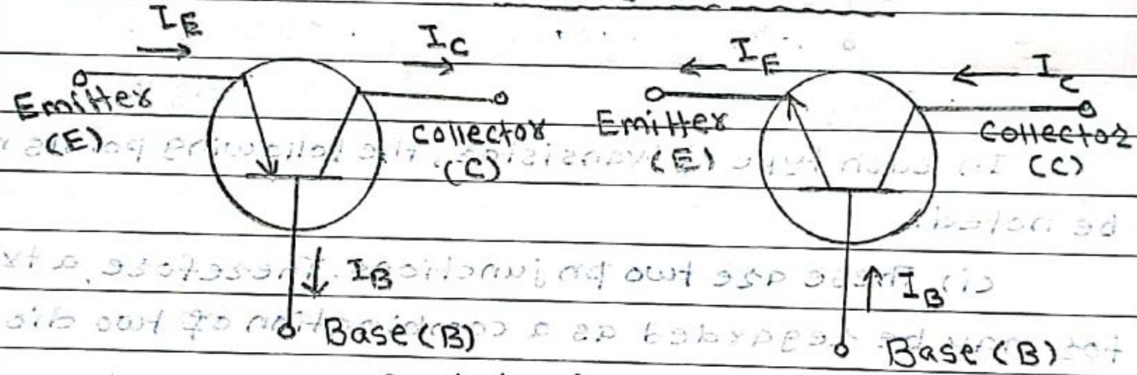
The transistor has three regions, namely: emitter, base and collector. The base is much thinner than the emitter while collector is wider than both. But for convenence it is customary to show emitter and collector to be of equal size.

→ The emitter is always forward biased w.r.t. base so that it can supply a large number of majority carriers.

→ The collector is always reverse biased w.r.t. base. Its function is to remove charges from its junction with the base.



Biasing of transistor



Symbols of transistor

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 greater.

* Transistor connections

There are three leads in a transistor viz, emitter, base and collector terminals. However, when a transistor is to be connected in a circuit, we require four terminals; two for the input and two for the output. This difficulty is overcome by making one terminal of transistor common to both input and output terminals. The input is fed between this common terminal and one of the other two terminals. The output is obtained between the common terminal and the remaining terminal. Accordingly; a transistor can be connected in a circuit in the following three ways:

<I> common base connection

<II> common emitter connection

<III> common collector connection

<I> Common Base Connection (C-B)

In this circuit arrangement, input is applied between emitter and base and output is taken from collector and base. Here, base of the transistor is common to both input and output circuits and hence it is called common base connection. Fig.1 shows a common base npn transistor circuit.

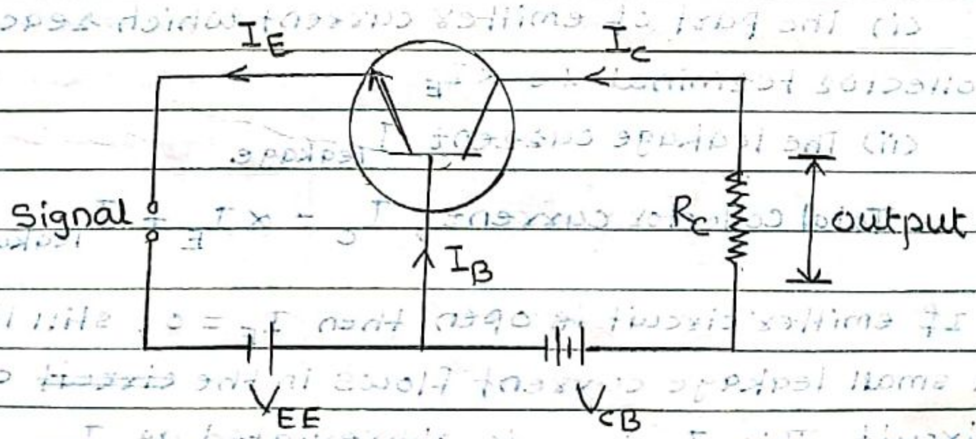


Fig.-1

1. Current amplification factor (α)

It is the ratio of output current to input current. In a common base connection, the input current is the emitter current I_E and output current is the collector current I_C.

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

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

It is clear that current amplification factor is less than unity. Practical values of α in commercial transistors range from 0.9 to 0.99.

2. Expression for collector current

The whole of the emitter current does not reach the collector. It is because as a result of electron-hole combinations occuring in base area a small percent of base current gives rise. Moreover, as the collector-base junction is reverse biased, some leakage current flows due to minority carriers. Hence, the total collector current consists of:

(i) The part of emitter current which reaches the collector terminal i.e αI_E

(ii) The leakage current $I_{leakage}$

∴ Total collector current, $I_C = \alpha I_E + I_{leakage}$ ——— (1)

If emitter circuit is open then $I_E = 0$, still there is a small leakage current flows in the ~~circuit~~ collector circuit. This $I_{leakage}$ is abbreviated as I_{CBO}

$$\therefore \quad I_C = \alpha I_E + I_{CBO} \quad \text{------- (2)}$$

Now, $\quad I_E = I_C + I_B$ --------- (3)

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

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

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

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

$$\therefore I_C = \frac{\alpha}{1-\alpha} I_B + \frac{I_{CBO}}{1-\alpha} \quad \text{------------ (4)}$$

The relation (2) or (4) can be used to find I_C.

* Characteristics of Common Base Connection

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

1. Input characteristic

It is the curve between emitter current I_E and emitter-base voltage V_{EB} at constant collector-base voltage V_{CB}. The emitter current is generally taken along Y-axis and emitter-base voltage along X-axis. The below Fig. 1 shows the input characteristics of a typical transistor in CB arrangement.

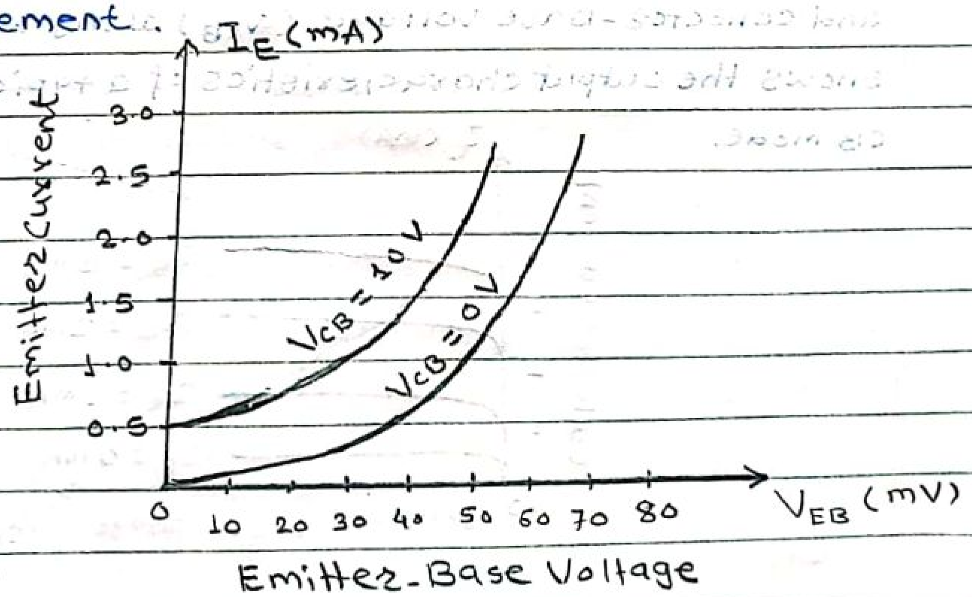

Fig-1

The following points may be noted from these characteristics:

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

(ii) The emitter current is almost independent of collector-base voltage V_{CB}. It leads that emitter current is almost independent of collector voltage

Input resistance

It is the ratio of change in emitter-base voltage (ΔV_{EB}) to the resulting change in emitter current (ΔI_E) at constant collector-base voltage (V_{CB}) i.e

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

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.

2. Output characteristic

It is the curve between collector current I_C and collector-base voltage V_{CB} at constant emitter current I_E. Generally, collector current is taken along y-axis and collector-base voltage (V_{CB}) along x-axis. Fig. 2 shows the output characteristics of a typical transistor in CB mode.

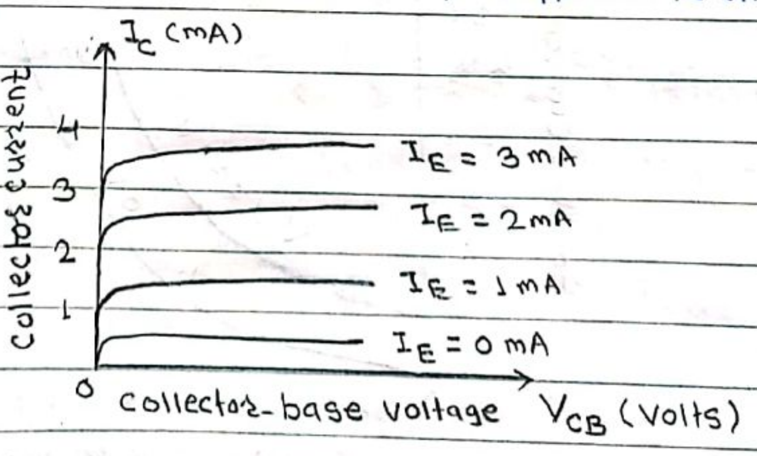

Fig. 2

The following points may be noted from the characteristics:

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

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

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

Output resistance

It is the ratio of change in collector-base voltage (ΔV_{CB}) to the resulting change in collector current (ΔI_c) at constant emitter current.

Output resistance,

$$r_o = \frac{\Delta V_{CB}}{\Delta I_c} \text{ at constant } I_E$$

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

<II> Common Emitter Connection (C-E)

In common emitter arrangement, input is applied between base and emitter and output is taken from the collector and emitter. Here, emitter of the transistor is common to both input and output circuits and hence the name common emitter connection. The below Fig.1 shows common emitter npn transistor circuit.

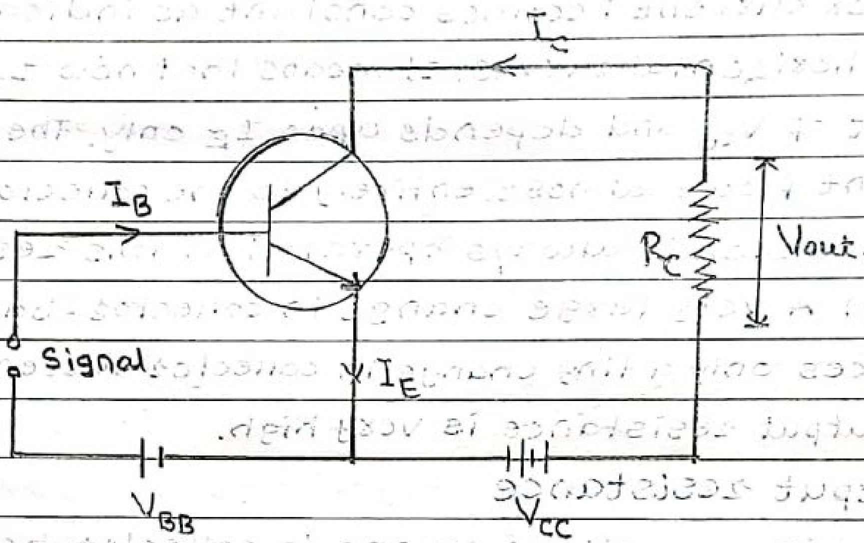

Fig.1

1. Base current amplification factor (β) –

In common emitter connection, input current is I_B and output current is I_C.

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

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

In almost any transistor, less than 5% of emitter current flows as the base current. Therefore, the value of β is generally greater than 20. Usually, its value ranges from 20 to 500. This type of connection is frequently used as it gives appreciable current gain as well as voltage gain.

Relation between β and α

A simple relation exist between β and α. This can be derived as follows:

$$\beta = \frac{\Delta I_C}{\Delta I_B} \quad \text{------------- (1)}$$

$$\alpha = \frac{\Delta I_C}{\Delta I_E} \quad \text{------------- (2)}$$

Now $I_E = I_B + I_C$ ---------- (3)

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

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

Substituting the value of ΔI_B in exp(1), we get

$$\beta = \frac{\Delta I_C}{\Delta I_E - \Delta I_C} \quad \text{------------- (4)}$$

Dividing the numerator and denominator of R.H.S. of exp (4) by ΔI_E; we get

$$\beta = \frac{\Delta I_C / \Delta I_E}{1 - \Delta I_C / \Delta I_E}$$

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

$$\therefore \beta = \frac{\alpha}{1-\alpha} \quad \text{------------- (5)}$$

It is clear that as α approaches unity, β approaches infinity. In other words, the current gain in common emitter connection is very high. Due to this reason CE arrangement is used in about 90 to 95 percent of all transistor application

Expression for collector current

In common emitter circuit, I_B is the input current and I_C is the output current.

we know $I_E = I_B + I_C$ -------- (1)

and $I_C = \alpha I_E + I_{CBO}$ -------- (2)

Put exp.(i) in exp.(ii), we get

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

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

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

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

$$\therefore I_C = \frac{\alpha}{1-\alpha} I_B + \frac{1}{1-\alpha} I_{CBO} \quad \text{------ (3)}$$

If $I_B = 0$, the collector current will be the current to the emitter. This is abbreviated as I_{CEO}.

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

Substituting the value of $\frac{1}{1-\alpha} I_{CBO} = I_{CEO}$ in exp.(3)

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

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

* Characteristics of Common Emitter Connection

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

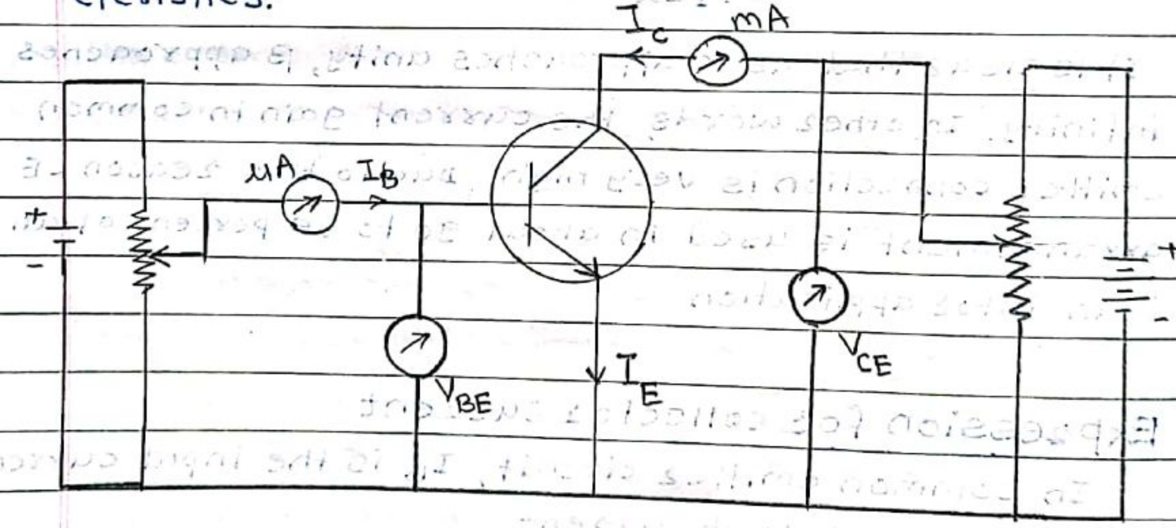

Fig. 1

1. Input characteristic

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

The input characteristics of CE connection can be determined by the circuit shown in above Fig 1. Keeping V_{CE} constant, 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 characteristics at V_{CE} = const as shown in Fig. 2.

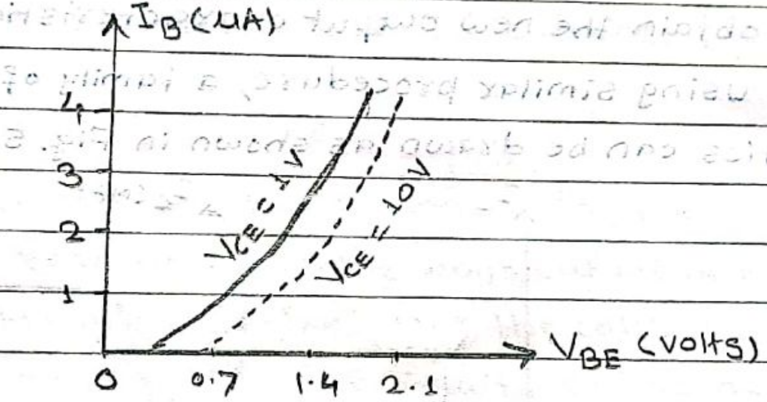

Fig 2

The following points may be noted from the characteristics:

(i) These curves are similar to that of forward biased diode curve.

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

Input resistance -

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

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

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

2. Output characteristic

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

The output characteristics of CE circuit can be drawn with the help of circuit shown in Fig. 1. Keeping the base current I_B fixed at some voltage 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 on y-axis and V_{CE} along x-axis. This gives the output characteristic at $I_B = 5\mu A$ as shown in Fig. 3. The test can be repeated for $I_B = 10 \mu A$ to obtain the new output characteristic as shown in Fig. 4. Using similar procedure, a family of output characteristics can be drawn as shown in Fig. 5.

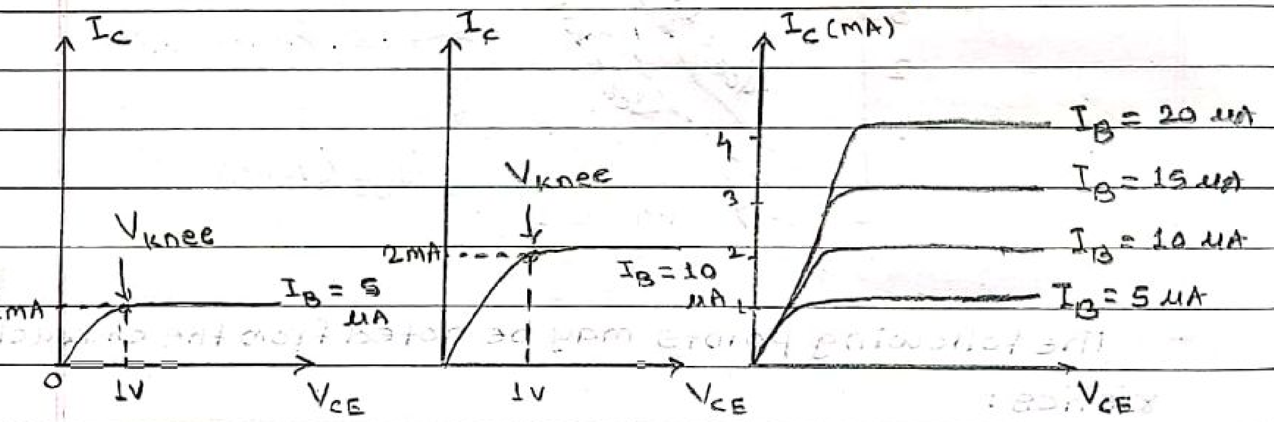

Fig 3 Fig 4 Fig 5

The following points may be noted from the characteristics:

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

(ii) Above knee voltage, I_C is almost constant.

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

Output resistance -

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

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

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

* Common Collector Connection

In common collector arrangement, input is applied between base and collector while output is taken between the emitter and collector. Here, the collector is common to both input and output circuits so the name common collector connection. The Fig 1 shows common collector npn transistor circuit.

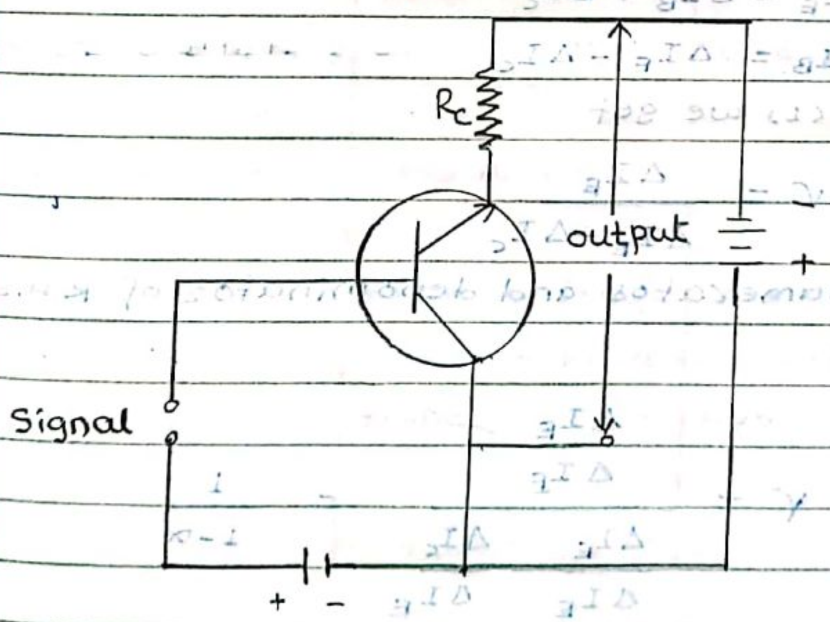

Fig. 1

(i) Current amplification factor (γ)

In common collector circuit, input current is the base current I_B and output current is the emitter current I_E.

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

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

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

Relation between γ and α:

$$\gamma = \frac{\Delta I_E}{\Delta I_B} \quad \text{------} \quad (1)$$

$$\alpha = \frac{\Delta I_c}{\Delta I_E} \quad \text{------} \quad (2)$$

Now $\quad I_E = I_B + I_c$

$$\therefore \quad \Delta I_E = \Delta I_B + \Delta I_c \quad \text{------} \quad (3)$$

$$\Delta I_B = \Delta I_E - \Delta I_c \quad \text{------} \quad (4)$$

Put exp. (4) in (1) we get

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

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

$$\gamma = \frac{\frac{\Delta I_E}{\Delta I_E}}{\frac{\Delta I_E}{\Delta I_E} - \frac{\Delta I_c}{\Delta I_E}} = \frac{1}{1-\alpha}$$

$$\therefore \boxed{\gamma = \frac{1}{1-\alpha}} \quad \text{------} \quad (5)$$

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(ii) Expression for collector current

We know

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

$$I_E = I_B + I_C$$

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

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

$$I_E - \alpha I_E = I_B + I_{CBO}$$

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

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

Comparision of Transistor Connections

Sr. No.	Characteristic	Common Base	Common Emitter	Common Collector
1.	Input resistance	Low (about 100 Ω)	Low (about 750 Ω)	Very high (about 750 kΩ)
2.	output resistance	Very high (about 450 kΩ)	High (about 45 kΩ)	Low (about 50 Ω)
3.	Voltage gain	about 150	about 500	less than 1
4.	current gain	Less than 1	High (β)	Appriciable
5	Applications	For high frequency applications	For audio frequency applications	For impedance matching.

* Hybrid Parameters (h-parameters)

Every linear circuit having input and output terminals can be analysed by four parameters (one measured in ohm, one in mho and two dimensionless) called hybrid or h-parameters.

Hybrid means 'mixed'. Since these parameters have mixed dimensions, they are called hybrid parameters.

Consider the two port network as in below Fig 1.

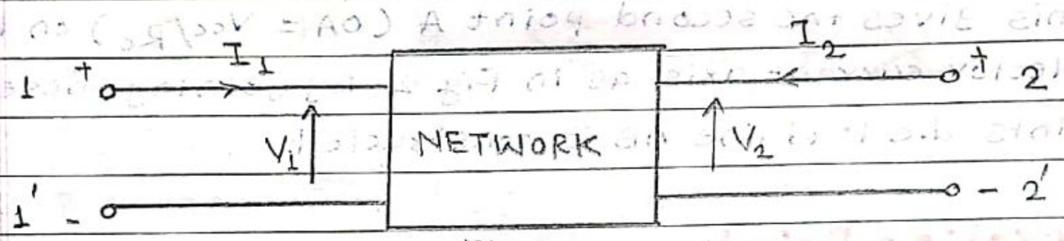

Fig 1

The voltage at input port and the current at the output port is taken as independent variables.

If the voltage at port 1-1' and current at port 2-2' are taken as dependent variables, we can express them in terms of I_1 and V_2

$$V_1 = h_{11} I_1 + h_{12} V_2 \quad \text{------ (1)}$$

$$I_2 = h_{21} I_1 + h_{22} V_2 \quad \text{------ (2)}$$

The coefficients in the above equations are called hybrid parameters. These parameters have a mixture of units rather than a single unit such as ohm or siemens

* Determination of h-parameters

The major reason for the use of h-parameters is the relative ease with which they can be measured.

(i) If we short-circuit the output terminals, $V_2 = 0$.

putting $V_2 = 0$ in eq^n (1) and (2) we get

$V_1 = h_{11} I_1 + h_{12} \times 0$	$I_2 = h_{21} I_1 + h_{22} \times 0$
$\therefore V_1 = h_{11} I_1$	$I_2 = h_{21} I_1 + 0$
$\therefore h_{11} = \dfrac{V_1}{I_1}$ for $V_2 = 0$	$\therefore h_{21} = \dfrac{I_2}{I_1}$ for $V_2 = 0$

$\therefore \; h_{11} = \frac{V_1}{I_1}$ for $V_2 = 0$ i.e output shorted

and $h_{21} = \frac{I_2}{I_1}$ for $V_2 = 0$ i.e output shorted

Now we see the physical meaning of h_{11} and h_{21}. Since h_{11} is the ratio of voltage and current (i.e V_1/I_1), it is an impedance and is called "input impedance with output shorted". similarly, h_{21} is the ratio of output and input current (i.e I_2/I_1), it will be dimensionless and is called current gain with output shorted.

(ii) The other two h parameters i.e. h_{12} and h_{22} can be found by making $I_1 = 0$. This can be done by keeping the input terminals open. when $I_1 = 0$ the eq^n (1) and (2) becomes

$V_1 = h_{11} \times 0 + h_{12} V_2$	$I_2 = h_{21} \times 0 + h_{22} V_2$
$\therefore \; V_1 = h_{12} V_2$	$\therefore \; I_2 = h_{22} V_2$
$\therefore \; h_{12} = \frac{V_1}{V_2}$	$\therefore \; h_{22} = \frac{I_2}{V_2}$

$\therefore \; h_{12} = \frac{V_1}{V_2}$ for $I_1 = 0$ i.e input open

and $h_{22} = \frac{I_2}{V_2}$ for $I_1 = 0$ i.e input open

Since h_{12} is a ratio of input and output voltages i.e (V_1/V_2) it is dimensionless and is called "voltage feedback ratio with input terminals open." similarly, h_{22} is a ratio of output current to output voltage (i.e I_2/V_2) it will be admittance and is called "output admittance with input terminals open."

The h parameters are generally written as

$h_{11} = h_i$, $h_{12} = h_r$, $h_{21} = h_f$ and $h_{22} = h_o$

where $h_i = \left.\frac{V_1}{I_1}\right|_{V_2 = 0}$ = input impedance with output shorted

$h_r = \frac{V_1}{V_2}\Big|_{I_1=0}$ = reverse voltage gain with input open

$h_f = \frac{I_2}{I_1}\Big|_{V_2=0}$ = forward current gain with output shorted

$h_o = \frac{I_2}{V_2}\Big|_{I_1=0}$ = output admittance with input open

* Analysis of CE amplifier using h-parameters

The circuit diagram of CE amplifier and its trans-conductance model is shown in below Fig. 1 and Fig. 2. respectively.

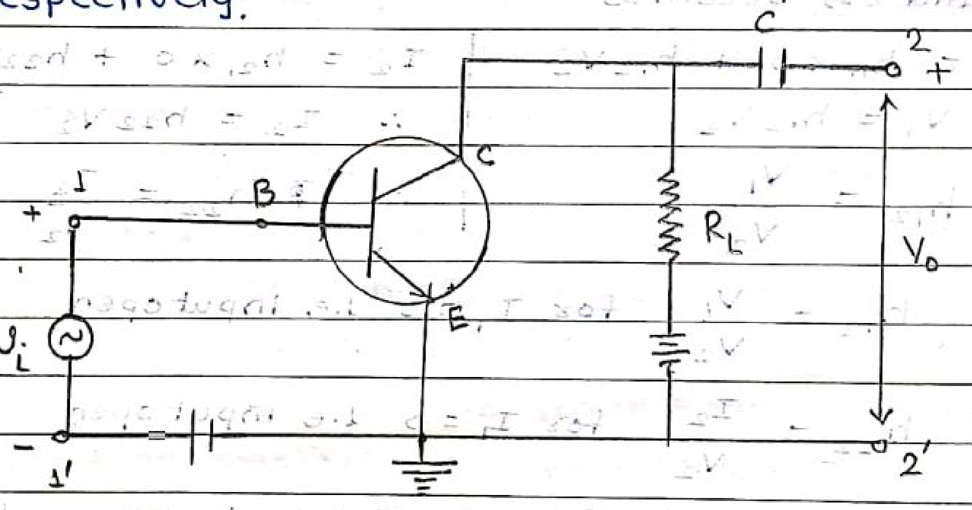

Fig. 1

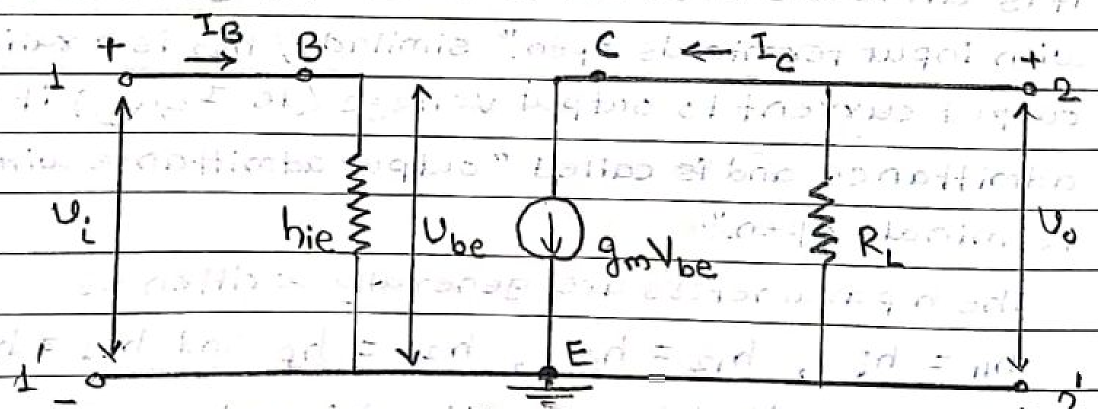

Fig. 2

From above Fig. we can express the output voltage as

$$v_o = -I_c R_L \quad \text{-------------} (1)$$

$$= -g_m v_{be} R_L$$

$$= -g_m v_i R_L \quad (\because v_i = v_{be})$$

$$\therefore \quad v_o = -g_m v_i R_L$$

$$\therefore \quad \frac{v_o}{v_i} = -g_m R_L$$

or $$A_{ve} = -g_m R_L \quad \text{-------------} (2)$$

The above expression is the voltage gain.

The current in the load is

$$I_c = g_m v_{be}$$

$$I_c = h_{fe} I_b \quad (\because g_m v_{be} = h_{fe} I_b)$$

$$\therefore \quad \frac{I_c}{I_b} = h_{fe}$$

or $$A_{ie} = \frac{I_c}{I_b} = h_{fe} \quad \text{-------------} (3)$$

The above eqn is an expression for the current gain

The input impedance is a ratio of input voltage to the input current thus

$$R_{ie} = \frac{v_i}{I_b} = \frac{v_{be}}{I_b} = h_{ie} \quad \text{------} (4)$$

The above eqn is an expression for the input impedance.

The output impedance is a ratio of output voltage to the output current. In practice, the output port is shunted by large resistance $\frac{1}{h_{oe}}$, Thus

$$R_{oe} = \frac{1}{h_{oe}} \quad \text{-------------} (5)$$

The power gain is defined as the product of the voltage gain and current gain magnitude, i.e

$$\text{power gain} = |A_{ve}||A_{ie}|$$

using equation (2) and (3), we get

$$\text{Power gain} = g_m R_L \cdot h_{fe}$$

$$= \frac{h_{fe}}{h_{ie}} R_L h_{fe}$$

$$P.G. = \frac{h_{fe}^2}{h_{ie}} R_L$$

Because of the large current gain, voltage gain, and power gain CE amplifiers are widely used in variety of applications.