Transistors

Introduction

When a third doped element is added to a semiconductor diode in such a way that two pn junctions are formed, the resulting device is known as a transistor. The transistor is capable of achieving amplification of weak signals. Transistors are smaller in size. No need of heating power for its operation. Transistor has now becomes the heart of most electronic applications.

Transistor

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

i) n-p-n transistor
ii) p-n-p transistor

An n-p-n transistor is composed of two n-type semiconductors separated by a thin section of p-type as shown in Figure 1.3.1 (a). However, a p-n-p is formed by two p-sections separated by a thin section of n-type as shown in Figure 1.3.1 (b).

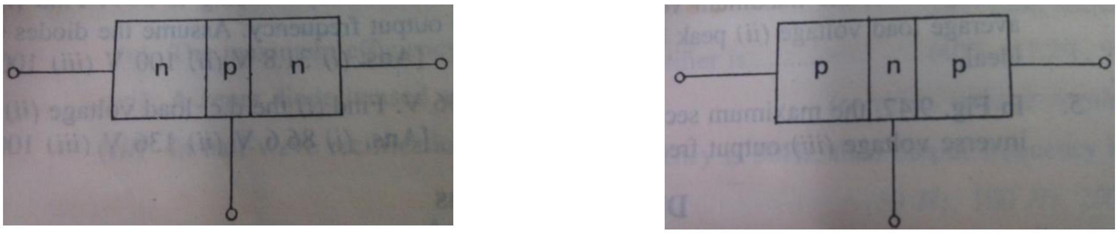


Figure 1.3.1

A transistor has two pn junctions. One junction is forward biased and the other is reverse biased. The forward biased junction has a low resistance path whereas a reverse biased junction has a high resistance path. The weak signal is introduced in the low resistance circuit and output is taken from the high resistance circuit. Therefore, a transistor transfers a signal from a low resistance to high resistance.

Naming the terminals

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

Emitter: The section on one side that supplies charge carriers (electron or holes) is called the emitter. The emitter is always forward biased w.r.t. base so that it can supply a large number of majority carriers.

Collector: The section on one side that collects charges is called the collector. The collector is always reverse biased w.r.t. base. Its function is to remove charges from its junction with the base.

Base: The middle section which forms two pn junctions between the emitter and the collector is called the base. The base-emitter junction is forward biased, allowing low resistance for the emitter circuit. The base-collector junction is reverse biased and provides high resistance in the collector circuit.
The emitter is heavily doped so that it can inject a large number of charge carriers into the base. The base is lightly doped and very thin. It passes most of the injected charges to the collector. The collector is moderately doped.

Transistor Action

Working of npn transistor: Figure 1.3.2 shows the npn transistor with forward bias to emitter base junction and reverse bias to collector-base junction. The forward bias causes the electrons in the n-type emitter to flow towards the base. This constitute the emitter current I_E. As these electrons flow through the p-type base, they tend to combine with holes. As the base is lightly doped and very thin, therefore, only a few electrons less than 5% combine with holes to constitute base current I_B. The remainder more than 95% cross over into the collector region to constitute collector current I_C. In this way, almost the entire emitter current flows in the collector circuit. The emitter current is the sum of collector and base currents i.e. $I_E = I_B + I_C$.

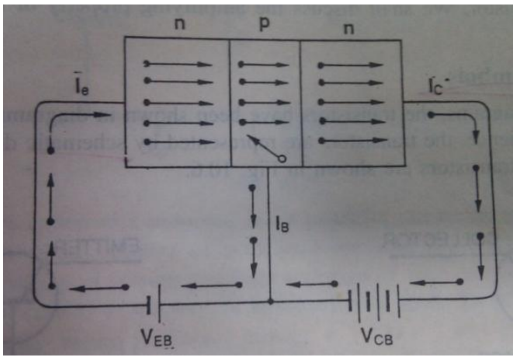


Figure 1.3.2

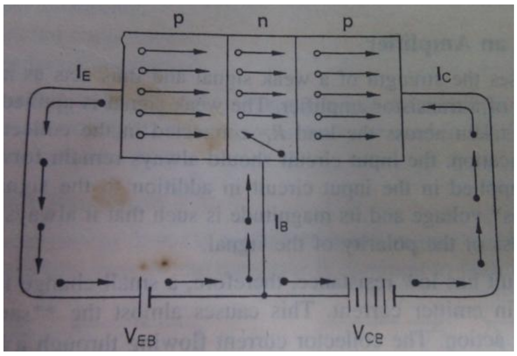


Figure 1.3.3

Working of pnp transistor: Figure 1.3.3 shows the pnp transistor. The forward bias causes the holes in the p-type emitter to flow towards the base. This constitute the emitter current I_E. As these holes cross into n-type base, they tend to combine with electrons. As the base is lightly doped and very thin, therefore, only a few holes combine with electrons. The remainder (more than 95%) cross over into the collector region to constitute collector current I_C. In this way, almost the entire emitter current flows in the collector circuit. The emitter current is the sum of collector and base currents i.e. $I_E = I_B + I_C$.

Transistor symbols: The symbols used for npn and pnp transistors are shown in Figure 1.3.4. Emitter is shown by an arrow which indicates the direction of conventional current flow with forward bias.

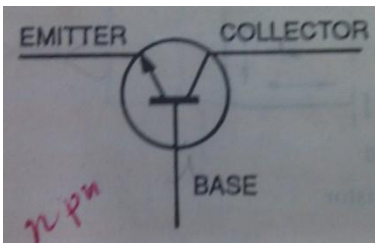
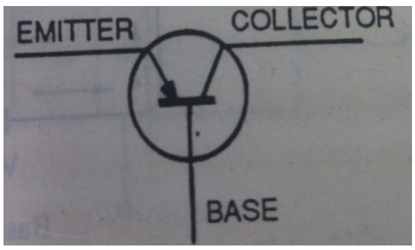


Figure 1.3.4



Transistor as an Amplifier

A transistor raises the strength of a weak signal and thus acts as an amplifier. Figure 1.3.5 shows the basic circuit of a transistor amplifier. The weak signal is applied between emitter base junction and output is taken across the load R_C connected in the collector circuit. For faithful amplification the input circuit should always remain forward biased. To do so, a dc voltage V_{EE} is applied in the input circuit in addition to the signal as shown. This dc voltage is known as bias voltage and its magnitude is such that it always keeps the input circuit forward biased regardless of the polarity of the signal.

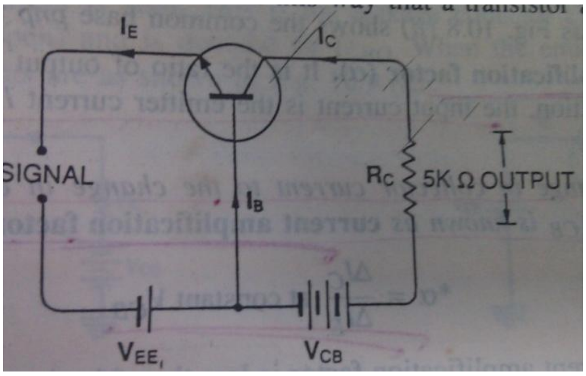


Figure 1.3.5

As the input circuit has low resistance, therefore, a small change in the signal voltage causes an appreciable change in emitter current. This causes almost the same change in collector current due to transistor action. The collector current flowing through a high load resistance R_C produces a large voltage across it. Thus, a weak signal applied in the input circuit appears in the amplified form in the collector circuit.

Illustration: Let R_C = 5 kΩ and a change of 0.1 V in signal voltages produces a change of 1 mA in emitter current. Obviously, the change in collector current would also be approximately 1 mA. This current flows through collector load R_C would produce a voltage = 5 kΩ X 1 mA = 5 V. Thus, a change of 0.1 V in the signal has caused a change of 5V in the output circuit. Voltage amplification is 5V/0.1 V = 50.

Transistor connections

A transistor can be connected in a circuit in following three configurations:

i. Common base connection (CB)
ii. Common emitter connection (CE)
iii. Common collector connection (CC)

Common Base Connection

In this 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 as shown in Figure 1.3.6. Here, (i) for npn and (ii) for pnp transistor.

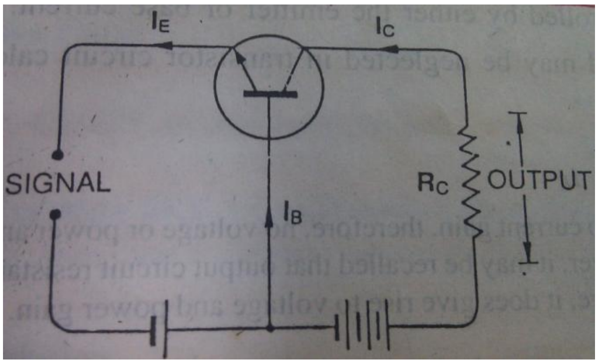


Figure 1.3.6

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.

$$\alpha = \Delta I_C / \Delta I_E \text{ at constant } V_{EB}$$

Current amplification factor is less than unity and practically α ranges from 0.9 to 0.99.

Expression for collector current

The total collector current consists of

i. That part of emitter current which reaches the collector terminal i.e. αI_E
ii. The leakage current $I_{leakage}$. This current is due to the movement of minority carriers across base collector junction on account of it being reverse biased. This much smaller than αI_E.

So, total current $I_C = \alpha I_E + I_{leakage}$.

If $I_E = 0$, a small leakage current still flows in the collector circuit. This leakage current $I_{leakage}$ is abbreviated as I_{CB0}, meaning collector base current with emitter open.

So, $I_C = \alpha I_E + I_{CB0}$. Now $I_E = I_C + I_B$.

$$I_C = \alpha I_E + I_B + I_{CB0}. \qquad \text{Or,} \qquad I_C = \frac{\alpha}{1-\alpha} I_B + \frac{I_{CBO}}{1-\alpha}$$

So, the collector current can be controlled by either the emitter or base current. The current I_{CB0} is small and may be neglected in transistor circuit calculations.

Characteristics of Common Base Connection

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

Input characteristics: It is the curve between emitter current I_E and emitter base voltage V_{EB} at constant collector-base voltage V_{CB}. Figure 1.3.7 shows the input characteristics of a typical transistor. The input characteristics shows that

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}. So, I_E and hence I_C is almost independent of V_{CB}.

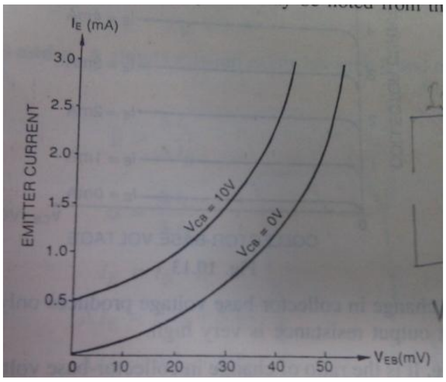


Figure 1.3.7.

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.

Input resistance, $r_i = \Delta V_{EB} / \Delta I_E$ at constant V_{CB}. Input resistance is small.

Output Characteristic: It is the curve between Collector current I_C and collector-base voltage V_{CB} at constant emitter current I_E. Figure 1.3.8 shows the input characteristics of a typical transistor. The input characteristics shows that

i. The collector current I_C varies with V_{CB} only at very low voltage $< 1V$. The transistor never operated in this region.
ii. When V_{CB} is raised above 1-2 V, the collector current becomes constant i.e. I_C is independent of V_{CB} and depends only on I_E only. 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 the output resistance is very high.

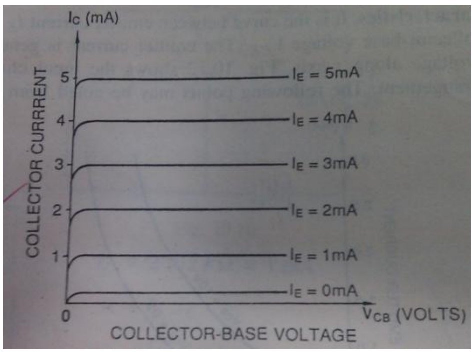


Figure 1.3.8.

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

Input resistance, $r_o = \Delta V_{CB} / \Delta I_C$ at constant I_E. Output resistance is very high.

Common Emitter Connection

In this arrangement input is applied between base and emitter and output is taken from collector and emitter. Here emitter of the transistor is common to both input and output circuits and as shown in Figure 1.3.9. Here, (i) for npn and (ii) for pnp transistor.

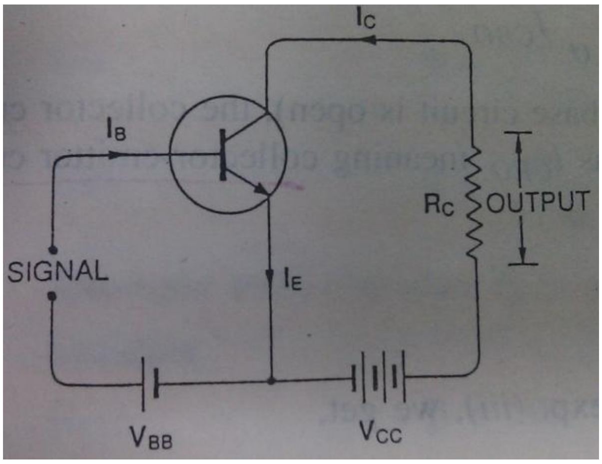


Figure 1.3.9

Base Current amplification Factor β : In this configuration, input current is I_B and output current I_C.

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

$$\beta = \Delta I_C / \Delta I_B$$

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

Relation between β and α: A simple relation exists between β and α.

$$\beta = \Delta I_C / \Delta I_B \quad \text{(i)} \quad \text{and} \quad \alpha = \Delta I_C / \Delta I_E \quad \text{(ii)}$$

Now, $I_E = I_B + I_C$ Or, $\Delta I_E = \Delta I_B + \Delta I_C$ Or, $\Delta I_B = \Delta I_E - \Delta I_C$.

Substituting the value of ΔI_B in Eq.(i), $\beta = \Delta I_C / \Delta I_E - \Delta I_C$.

$$\beta = \alpha / 1 - \alpha$$

It is clear that when α approaches unity, β approaches infinity. That is, the current gain in CE connection is very high. Hence it is widely used configuration.

Expression for collector current

We know, $I_E = I_B + I_C$ and $I_C = \alpha I_E + I_{CB0}$.

From Eq. (ii), we get $I_C = \alpha I_E + I_{CB0} = \alpha (I_B + I_C) + I_{CB0}$.

Or, $$I_C = \frac{\alpha}{1-\alpha} I_B + \frac{1}{1-\alpha} I_{CBO} \quad \text{(iii)}$$

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

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

Substituting the value of

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

The current I_{CE0} is much larger than I_{CB0} is small and may be neglected in transistor circuit calculations.

Characteristics of Common Emitter Connection

The most important characteristics of common emitter configuration are *input characteristics* and *output characteristics*.

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

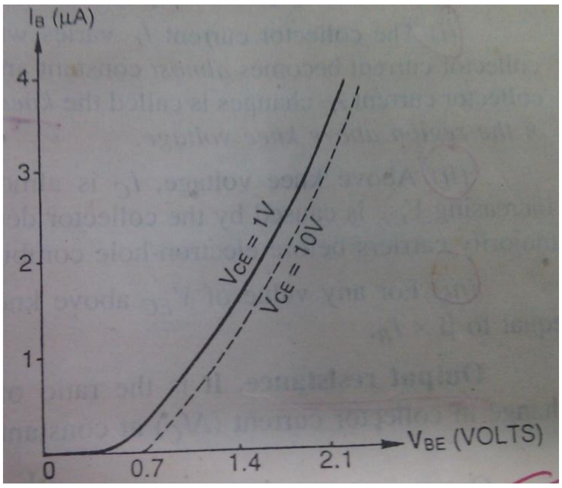


Figure 1.3.11

The input characteristics of a CE connection can be determined by the circuit shown in Figure1.3.10. Keeping V_{CE} constant base current I_B is measured for various V_{BE}. The plot of I_B versus V_{BE} gives the input characteristics. Figure 1.3.11 shows the input characteristics of a typical transistor. The input characteristics shows that

i The characteristic resembles that of a 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 that that of CB circuit.

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

Input resistance, $r_i = \Delta V_{BE} / \Delta I_B$ at constant V_{CE}. Input resistance ~ few hundred ohms

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

The output characteristics of a CE connection can be determined by the circuit shown in Figure1.3.10. Keeping base current I_B constant, collector current I_C is measured for various V_{CE}. The plot of I_C versus V_{CE} gives the output characteristics. Figure 1.3.12 shows the output characteristics of a typical transistor. The output characteristics shows that

i The collector current I_C varies with V_{CE} only for V_{CE} between 0 and 1 V only. After that collector current becomes almost constant and independent of V_{CE}. This value of V_{CE} is called the knee voltage V_{knee} .The transistors are always operated in the region above the 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 β X I_B .

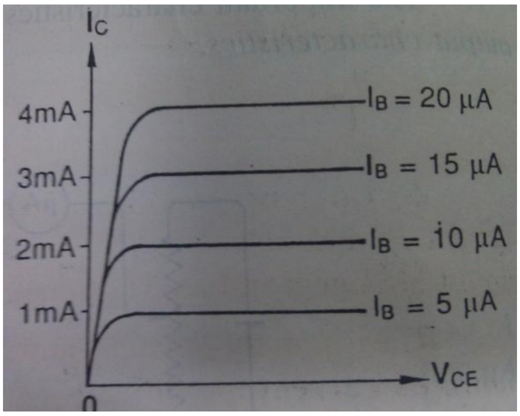


Figure 1.3.12.

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

Input resistance, $r_o = \Delta V_{CE} / \Delta I_C$ at constant I_B.

The output resistance of CE circuit is less than that of CB circuit.

Common Collector Connection

In this arrangement input is applied between base and collector and output is taken from emitter and collector. Here collector of the transistor is common to both input and output circuits and as shown in Figure 1.3.13. Here, (i) for npn and (ii) for pnp transistor.

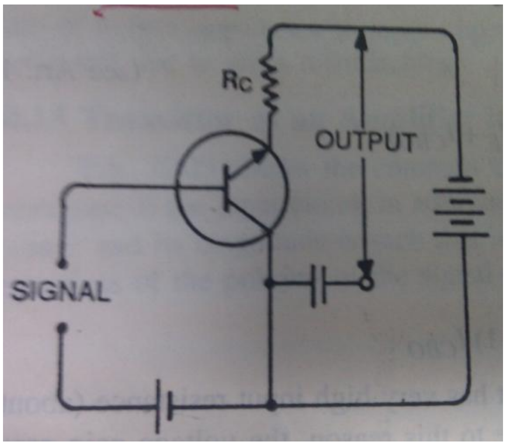


Figure 1.3.13

Current amplification Factor γ : In this configuration, input current is I_B and output current I_E.

The ratio of change in emitter current to the change in base current is known as base current amplification factor i.e.

$$\beta = \Delta I_E / \Delta I_B$$

This circuit provides about the same current gain as the CE circuit as $\Delta I_E = \Delta I_C$. However voltage gain is always less than 1..

Relation between γ and α:

$$\gamma = \Delta I_E / \Delta I_B \quad \text{(i)} \quad \text{and} \quad \alpha = \Delta I_C / \Delta I_E \quad \text{(ii)}$$

Now, $I_E = I_B + I_C$ Or, $\Delta I_E = \Delta I_B + \Delta I_C$ Or, $\Delta I_B = \Delta I_E - \Delta I_C$.

Substituting the value of ΔI_B in Eq. (i), $\gamma = \Delta I_E / \Delta I_E - \Delta I_C$.

$$\gamma = 1 / 1 - \alpha$$

Expression for collector current

We know, $I_C = \alpha I_E + I_{CB0}$ and $I_E = I_B + I_C$

From Eq. (ii), we get $I_C = I_E \ 1 - \alpha = I_B + I_{CB0}$.

Or,

Applications : CC circuit has very high input resistance (~ 750 kΩ) and very low output resistance (~ 25 Ω) and voltage gain is less than 1. CE arrangement is seldom used. for amplification. CC circuit is primarily used for impedance matching.

Comparison of Transistor connections

Sl No	Characteristic	Common Base	Common emitter	Common collector
1	Input resistance	Low ~ 100 Ω	Low ~ 750 Ω	Very high ~ 750 kΩ
2	Output resistance	Very high ~ 450 kΩ	High ~ 45 kΩ	Low ~ 50 Ω
3	Voltage gain	About 150	About 500	Less than 1
4	Applications	High Frequency applications	Audio Frequency applications	Impedance matching

Commonly Used Transistor Connection

CE circuit is the most efficient. It is used in about 90 to 95% of all transistor applications. Reasons are:

i) High current gain
ii) High voltage and power gain
iii) Moderate output to input impedance ratio

Transistor as an Amplifier in CE Arrangement

Figure 1.3.14 shows CE npn amplifier circuit. A battery V_{BB} is connected in the input circuit in addition to the signal voltage. This dc voltage is known as bias voltage and its magnitude is such that it always keeps the emitter-base junction forward biased regardless of the polarity of the signal source.

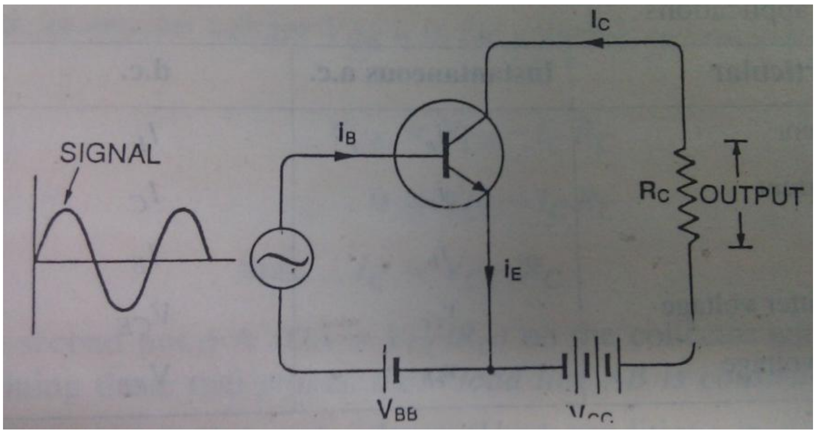


Figure 1.3.14

Operation: During the positive half cycle of the signal, the forward bias across the emitter-base junction is increased. Therefore, more electron flows from the emitter to the collector via the base. This causes an increase in collector current. The increased collector current produces a greater voltage drop across the collector load resistance R_C. During the negative half cycle, forward bias across emitter-base junction is decreased. So, collector current decreases. This results in the decreased output voltage. Hence an amplified output is obtained across the load.
Figure 1.3.15 shows the graph of total current i_C versus time.
Total collector current consists of two components, namely:

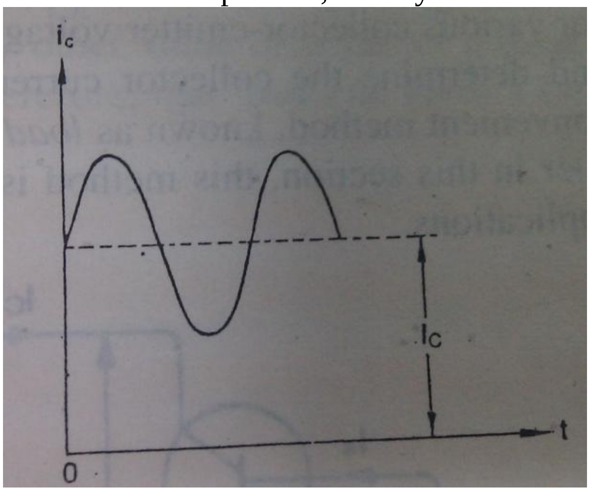


Figure 1.3.15

i The dc current I_C (zero signal collector current) due to the bias battery V_{BB}. This is the current that flows in the collector in the absence of signal.
ii The ac collector current i_C due to signal.

The useful output is the voltage drop across collector load R_C due to the ac component i_C . The purpose of zero signal collector current is to ensure that the emitter-base junction is forward biased at all times.

Transistor Load Line Analysis

In transistor circuit analysis, it is required to determine I_C for various V_{CE}. Plotting output characteristics, I_C can be determined at any desired V_{CE}. However, load line method can be used to solve such problems. This method is quite easy and is frequently used.

dc load line: Consider a CE npn transistor circuit shown in Figure 1.3.16(a) where no signal is applied. Therefore, dc conditions prevail in the circuit. The output characteristics of this circuit are shown in Figure 1.3.16(b) .

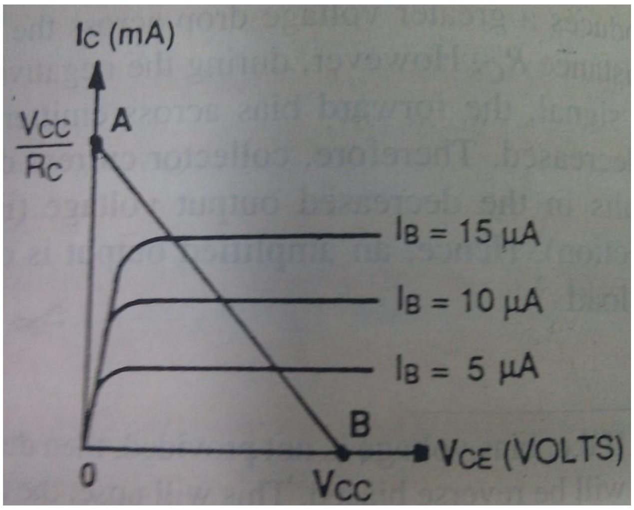


Figure 1.3.16

The value of collector-emitter voltage V_{CE} at any time is $V_{CE} = V_{CC} - I_C R_C$ (i)

As V_{CC} and R_C are fixed values, it can be represented by a straight line on the output characteristics. This is known as dc load line and determines the locus of V_{CE} - I_C points for any given value of R_C. To add load line, we need two end points. These two points can be located as:

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

$$\text{Maximum } V_{CE} = V_{CC} - I_C R_C = V_{CC}$$

This gives the first pint B, OB= V_{CC} on the collector-emitter voltage axis as shown in Figure 1.3.16 (b) .

ii When the collector–emitter voltage $V_{CE} = 0$, the collector current is maximum and is equal to V_{CC} / R_C i.e.

$$V_{CE} = V_{CC} - I_C R_C \quad \text{or,} \quad 0 = V_{CC} - I_C R_C \quad \text{Maximum} \quad I_C = V_{CC} / R_C$$

This gives the second point A, OA= V_{CC} / R_C on the collector current axis as shown in Figure 1.3.16(b). By joining these two points, dc load line AB is constructed.

Importance: For any value of collector current the collector-emitter voltage can be determined from the dc load line.

Operating Point :

The zero signal values of I_C and V_{CE} are known as the *operating point*. It is called operating point because the variations of I_C and V_{CE} take place about this point when signal is applied. It is also called quiscent point or ***Q point*** because it is the point on I_C – V_{CE} characteristic in the absence of signal. The Q point must lie on the dc load line. That is, the coordinates of the point representing the Q point collector current I_C and the collector-emitter voltage V_{CE} must satisfy the dc load line. Therefore the Q point describes the actual state of affairs in the circuit in the absence of signal and called the operating point. Referring to Figure 1.3.17, for I =5 µA, the zero signal values are V_{CE} = OC V and I_C = OD mA

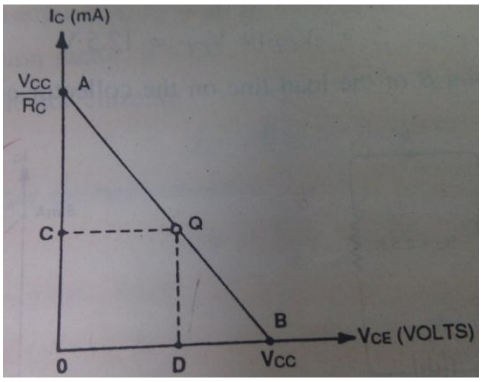


Figure 1.3.17

Drawing CE circuit and output from transistor amplifier

In practice the CE circuit is drawn as shown in Figure 1.3.18. A transistor acts as an amplifier and a CE amplifier is shown in Figure 1.3.19. The output can be taken either across R_C or across terminals 1 and 2.

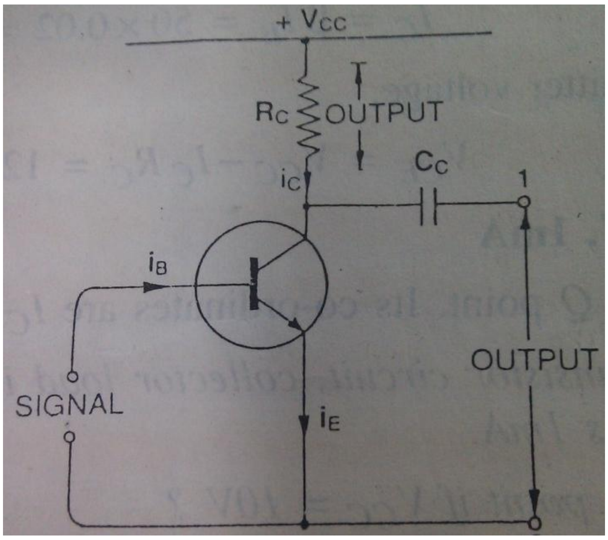


Figure 1.3.18

Output = Voltage across R_C = $i_C R_C$

Output = Voltage across terminals 1 and 2; = V_C - $i_C R_C$

As V is a direct voltage can not pass through capacitor C_C, therefore, only varying voltage $i_C R_C$ will appear across terminal 1 and 2

Output = - $i_C R_C$

Performance of Transistor Amplifier

The performance of a transistor depends upon input resistance, output resistance, effective collector load, current gain and power gain. Discussions are made with reference to CE connection.

Input resistance: It is the ratio of small change in base-emitter voltage ΔV_{BE} to the resulting change in base current ΔI_B at constant collector-emitter voltage i.e.

$$\text{Input resistance, } R_i = \frac{\Delta V_{BE}}{\Delta I_B}$$

The value of input resistance is quite small because the input circuit is always forward biased. It ranges from 500 to 5 Ω. In fact input resistance is the opposition offered by the base emitter junction to the signal flow. Figure 1.3.20 shows the general form of an amplifier. The input voltage V_{BE} causes an input current I_B.

$$\text{Input resistance, } R_i = \frac{\Delta V_{BE}}{\Delta I_B} = \frac{V_{BE}}{I_B}$$

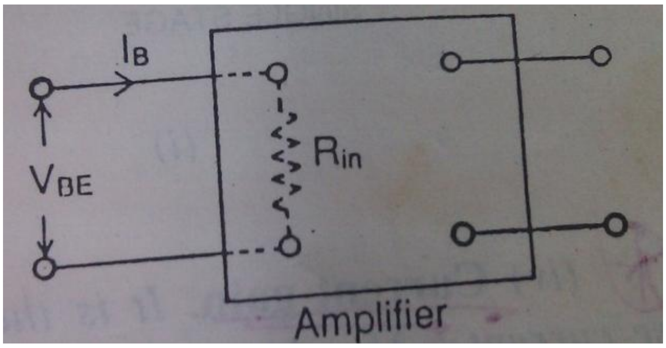


Figure 1.3.20

Output resistance: It is the ratio of small change in collector-emitter voltage ΔV_{CE} to the resulting change in base current ΔI_C at constant base current i.e.

$$\text{Output resistance, } R_O = \frac{\Delta V_{CE}}{\Delta I_C}$$

Output resistance of a transistor amplifier is very high of the order of several hundred kilo ohms and it is due to reverse bias.

Effective collector load: It is the total load as seen by the ac collector current.

In case of single stage amplifiers, the effective collector load is a parallel combination of R_C and R_O as shown in Figure 1.3.21(i).

$$\text{Effective collector load, } R_{AC} = R_C \parallel R_O = \frac{R_C \times R_O}{R_C + R_O} = R_C$$

It follows that for a single stage amplifier, effective load is equal to collector load R_C.

However, in a multistage amplifier the input resistance R_i of the next stage also comes into picture as shown in Figure 1.3.21(ii). Therefore, effective collector load becomes parallel combination of R_C, R_O and R_i i.e.

$$\text{Effective collector load, } R_{AC} = RC \parallel R_O \parallel R_i = R_C \parallel R_i = \frac{R_C R_i}{R_C + R_i}$$

Since input resistance R is small.

Current gain: It is the ratio of change in collector current ΔI_C to the change in base current ΔI_B i.e.

$$\text{Current gain, } \beta = \Delta I_C / \Delta I_B$$

The value of β ranges from 20 to 500. The current gain indicates that input current becomes β times in the collector circuit.

Voltage gain: It is the ratio of change in output voltage ΔV_{CE} to the change in base current ΔV_{BE} i.e.

$$\text{Voltage gain, } A_V = \Delta V_{CE} / \Delta V_{BE}$$

$$= \beta \times \frac{R_{AC}}{R_i}$$

For single stage, $R_{AC} = R_C$. However for multistage, $R_{AC} = \frac{R_C \times R_i}{R_C + R_i}$

Power gain : It is the ratio of output signal power to the input signal power i.e.

$$\text{Power gain, } A_P = \frac{\Delta I_C}{\Delta I_B} \times \frac{\Delta I_C \times R_{AC}}{\Delta I_B \times R_i} \quad = \text{current gain X Voltage gain}$$

Cut off and saturation points

Cut off : The point where the load line intersects the $I_B = 0$ curve is known as *cut off*. At this point, I_B =0 and only small collector current exists. At cut off, the base emitter junction no longer remains forward biased and normal transistor action is lost. The collector emitter voltage is nearly equal to V_{CC} i.e. V_{CE} (cut off) $= V_{CC}$ (i)

Saturation: The point where the load line intersects the $I_B = I_{B(Sat)}$ curve is called saturation. At this point base current is maximum and so the collector current. At saturation, collector base junction no longer remains reverse biased and normal transistor action is lost.

$$I_C \text{ Sat} = V_{CC} / R_C \; ; \qquad V_{CE} = V_{CE} \text{ Sat} = V_{knee}$$

If base current is greater than $I_{B(Sat)}$, then collector current cannot increase because collector base junction is no longer reverse biased.

Active region: The region between the cut off and saturation is known as active region. In the active region, collector base junction remains reverse biased, while base emitter junction remains forward biased. Consequently, the transistor will function normally in this region.

Power Rating of Transistor: The maximum power that a transistor can handle without destruction is known as power rating of the transistor.

P_D = Collector current X Collector-base voltage = I_C X V_{CB}

P_D = I_C X V_{CE} since V_{BE} is very small.

Questions

1. What is a transistor? Why it is so called?
2. Describe transistor action in detail.
3. Explain the operation of a transistor as an amplifier.
4. Name the three possible transistor connections.
5. Define α. Show that it is always less than unity.
6. Draw the input and output characteristics of CB connection. What do you infer from these characteristics?
7. Define β. Show that β = α / 1 + α
8. How will you determine the input and output characteristics of CE connection experimentally.
9. Establish the following relations: a. $I_C = \alpha I_E + I_{CBO}$ b. $I_C = \frac{\alpha}{1-\alpha} I_B + \frac{1}{1-\alpha} I_{CBO}$
10. How will you draw dc lad line on the output characteristics of a transistor? What is its importance?
11. Explain the terms: Voltage gain, power gain, current gain, effective collector load, Operating point, dc load line.