

UNIT II

BIPOLAR JUNCTION TRANSISTOR

2.1 INTRODUCTION

A bipolar junction transistor (BJT) is a three terminal device in which operation depends on the interaction of both majority and minority carriers and hence the name bipolar. The BJT is analogous to vacuum triode and is comparatively smaller in size. It is used as amplifier and oscillator circuits, and as a switch in digital circuits. It has wide applications in computers, satellites and other modern communication systems.

A **Transistor** is a three terminal semiconductor device that regulates current or voltage flow and acts as a switch or gate for signals.

Why Do We Need Transistors?

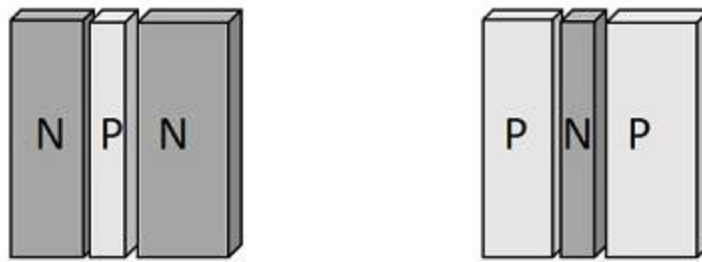
Suppose that you have a FM receiver which grabs the signal you want. The received signal will obviously be weak due to the disturbances it would face during its journey. Now if this signal is read as it is, you cannot get a fair output. Hence we need to amplify the signal. **Amplification** means increasing the signal strength.

This is just an instance. Amplification is needed wherever the signal strength has to be increased. This is done by a transistor. A transistor also acts as a **switch** to choose between available options. It also **regulates** the incoming **current and voltage** of the signals.

Constructional Details of a Transistor

The Transistor is a three terminal solid state device which is formed by connecting two diodes back to back. Hence it has got **two PN junctions**. Three terminals are drawn out of the three semiconductor materials present in it. This type of connection offers two types of transistors. They are **PNP** and **NPN** which means an N-type material between two P-types and the other is a P-type material between two N-types respectively.

The construction of transistors is as shown in the following figure which explains the idea discussed above.



Construction of PNP & NPN Transistors

The three terminals drawn from the transistor indicate Emitter, Base and Collector terminals. They have their functionality as discussed below.

Emitter

- The left hand side of the above shown structure can be understood as **Emitter**.
- This has a **moderate size** and is **heavily doped** as its main function is to **supply** a number of **majority carriers**, i.e. either electrons or holes.
- As this emits electrons, it is called as an Emitter.
- This is simply indicated with the letter **E**.

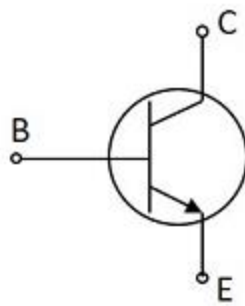
Base

- The middle material in the above figure is the **Base**.
- This is **thin** and **lightly doped**.
- Its main function is to **pass** the majority carriers from the emitter to the collector.
- This is indicated by the letter **B**.

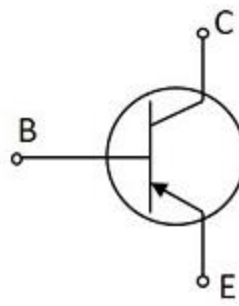
Collector

- The right side material in the above figure can be understood as a **Collector**.
- Its name implies its function of **collecting the carriers**.
- This is **a bit larger** in size than emitter and base. It is **moderately doped**.
- This is indicated by the letter **C**.

The symbols of PNP and NPN transistors are as shown below.



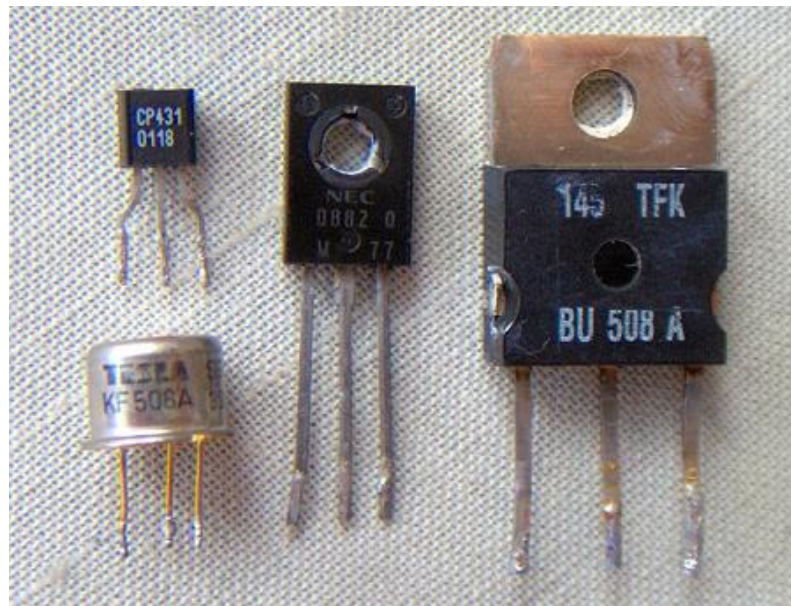
Symbol of
NPN transistor



Symbol of
PNP transistor

The **arrow-head** in the above figures indicated the **emitter** of a transistor. As the collector of a transistor has to dissipate much greater power, it is made large. Due to the specific functions of emitter and collector, they are **not interchangeable**. Hence the terminals are always to be kept in mind while using a transistor.

In a Practical transistor, there is a notch present near the emitter lead for identification. The PNP and NPN transistors can be differentiated using a Multimeter. The following figure shows how different practical transistors look like.

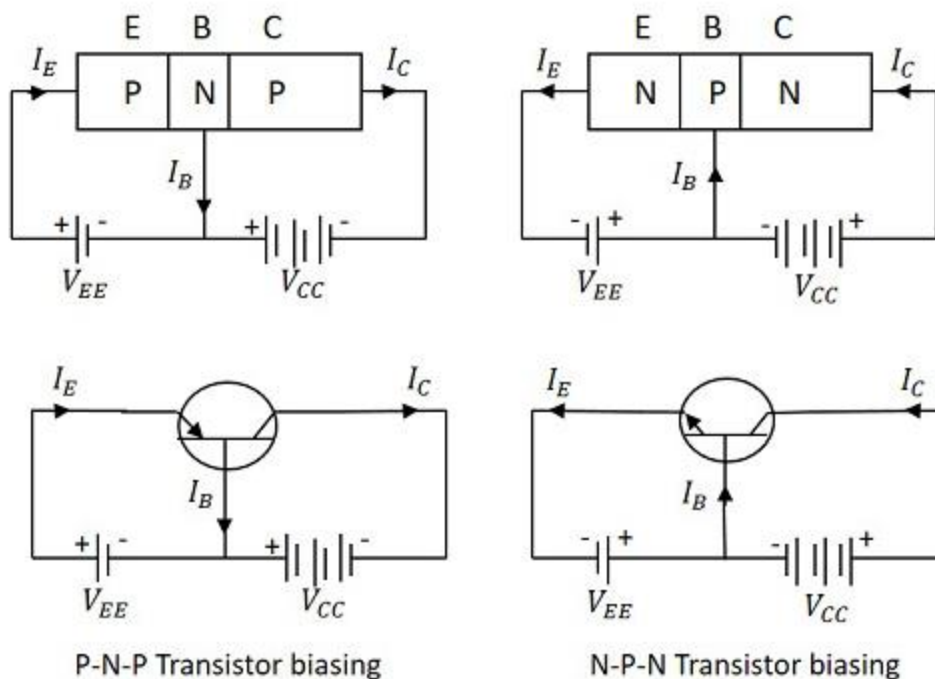


We have so far discussed the constructional details of a transistor, but to understand the operation of a transistor, first we need to know about the biasing.

Transistor Biasing

As we know that a transistor is a combination of two diodes, we have two junctions here. As one junction is between the emitter and base, that is called as **Emitter-Base junction** and likewise, the other is **Collector-Base junction**.

Biasing is controlling the operation of the circuit by providing power supply. The function of both the PN junctions is controlled by providing bias to the circuit through some dc supply. The figure below shows how a transistor is biased.



By having a look at the above figure, it is understood that

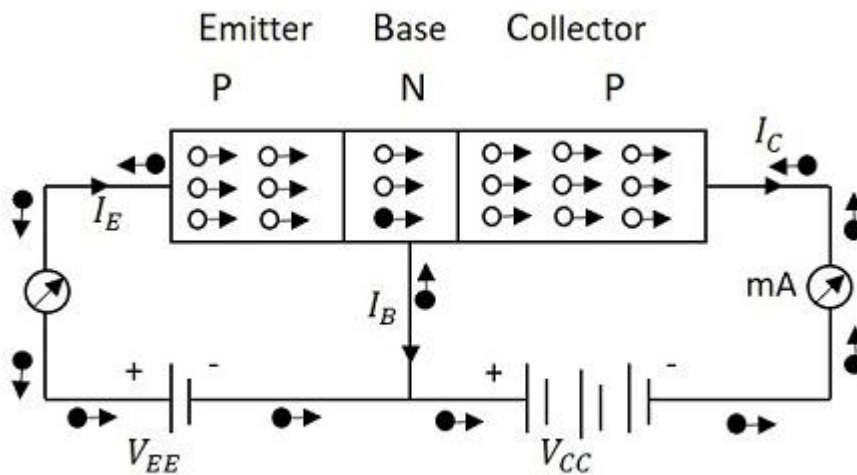
- The N-type material is provided negative supply and P-type material is given positive supply to make the circuit **Forward bias**.
- The N-type material is provided positive supply and P-type material is given negative supply to make the circuit **Reverse bias**.

By applying the power, the **emitter base junction** is always **forward biased** as the emitter resistance is very small. The **collector base junction** is **reverse biased** and its resistance is a bit higher. A small forward bias is sufficient at the emitter junction whereas a high reverse bias has to be applied at the collector junction.

The direction of current indicated in the circuits above, also called as the **Conventional Current**, is the movement of hole current which is **opposite to the electron current**.

Operation PNP Transistor

The operation of a PNP transistor can be explained by having a look at the following figure, in which emitter-base junction is forward biased and collector-base junction is reverse biased.



Operation of a PNP transistor

The voltage V_{EE} provides a positive potential at the emitter which repels the holes in the P-type material and these holes cross the emitter-base junction, to reach the base region. There a very low percent of holes recombine with free electrons of N-region. This provides very low current which constitutes the base current I_B . The remaining holes cross the collector-base junction, to constitute collector current I_C , which is the hole current.

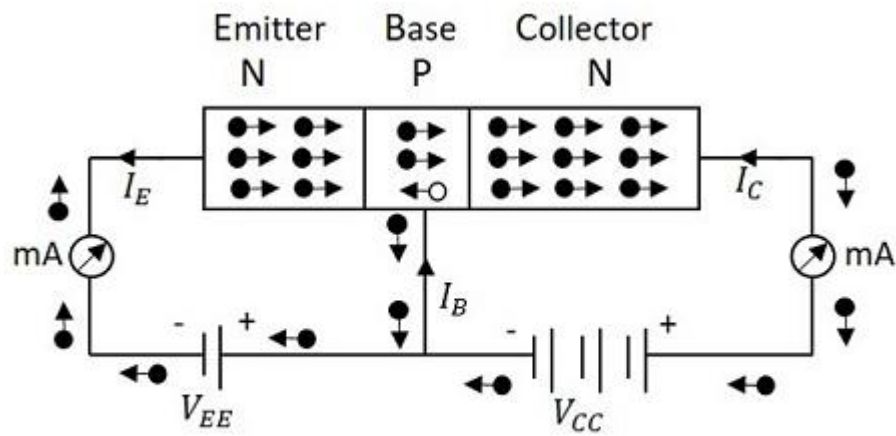
As a hole reaches the collector terminal, an electron from the battery negative terminal fills the space in the collector. This flow slowly increases and the electron minority current flows through the emitter, where each electron entering the positive terminal of V_{EE} , is replaced by a hole by moving towards the emitter junction. This constitutes emitter current I_E .

Hence we can understand that –

- The conduction in a PNP transistor takes place through holes.
- The collector current is slightly less than the emitter current.
- The increase or decrease in the emitter current affects the collector current.

Operation NPN Transistor

The operation of an NPN transistor can be explained by having a look at the following figure, in which emitter-base junction is forward biased and collector-base junction is reverse biased.



Operation of a NPN transistor

The voltage V_{EE} provides a negative potential at the emitter which repels the electrons in the N-type material and these electrons cross the emitter-base junction, to reach the base region. There a very low percent of electrons recombine with free holes of P-region. This provides very low current which constitutes the base current I_B . The remaining holes cross the collector-base junction, to constitute the collector current I_C .

As an electron reaches out of the collector terminal, and enters the positive terminal of the battery, an electron from the negative terminal of the battery V_{EE} enters the emitter region. This flow slowly increases and the electron current flows through the transistor.

Hence we can understand that –

- The conduction in a NPN transistor takes place through electrons.
- The collector current is higher than the emitter current.
- The increase or decrease in the emitter current affects the collector current.

Advantages

There are many advantages of a transistor such as –

- High voltage gain.
- Lower supply voltage is sufficient.
- Most suitable for low power applications.
- Smaller and lighter in weight.
- Mechanically stronger than vacuum tubes.
- No external heating required like vacuum tubes.
- Very suitable to integrate with resistors and diodes to produce ICs.

There are few disadvantages such as they cannot be used for high power applications due to lower power dissipation. They have lower input impedance and they are temperature dependent.

2.3 TRANSISTOR CURRENT COMPONENTS:

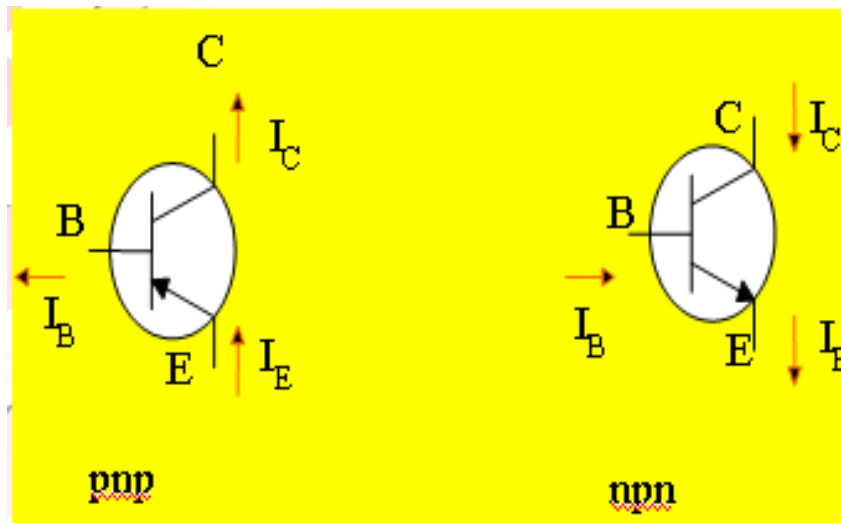


Fig 2.2 Bipolar Junction Transistor Current Components

The above fig 3.2 shows the various current components, which flow across the forward biased emitter junction and reverse- biased collector junction. The emitter current I_E consists of hole current I_{pE} (holes crossing from emitter into base) and electron current I_{nE} (electrons crossing from base into emitter). The ratio of hole to electron currents, I_{pE} / I_{nE} , crossing the emitter junction is proportional to the ratio of the conductivity of the p material to that of the n material. In a transistor, the doping of that of the emitter is made much larger than the doping of the base. This feature ensures (in p-n-p transistor) that the emitter current consists almost entirely of holes. Such a situation is desired since the current which results from electrons crossing the emitter junction from base to emitter do not contribute carriers, which can reach the collector.

Not all the holes crossing the emitter junction J_E reach the collector junction J_C

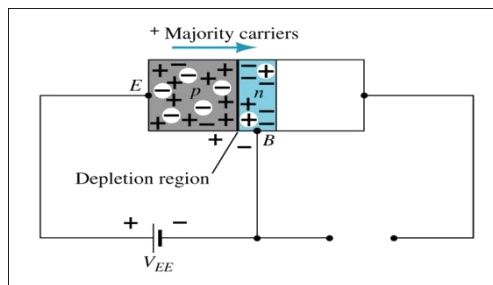
Because some of them combine with the electrons in n-type base. If I_{pC} is hole current at junction J_C there must be a bulk recombination current ($I_{pE} - I_{pC}$) leaving the base.

Actually, electrons enter the base region through the base lead to supply those charges, which have been lost by recombination with the holes injected in to the base across J_E . If the emitter were open circuited so that $I_E=0$ then I_{PC} would be zero. Under these circumstances, the base and collector current I_C would equal the reverse saturation current I_{CO} . If $I_E \neq 0$ then

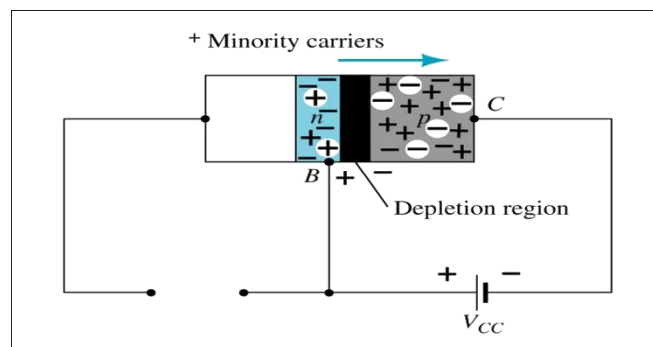
$$I_C = I_{CO} - I_{PC}$$

For a p-n-p transistor, I_{CO} consists of holes moving across J_C from left to right (base to collector) and electrons crossing J_C in opposite direction. Assumed referenced direction for I_{CO} i.e. from right to left, then for a p-n-p transistor, I_{CO} is negative. For an n-p-n transistor, I_{CO} is positive. The basic operation will be described using the pnp transistor. The operation of the pnp transistor is exactly the same if the roles played by the electron and hole are interchanged.

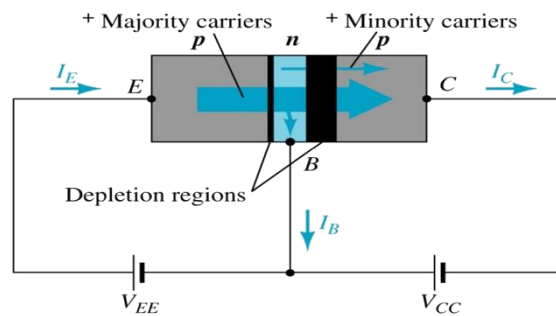
One p-n junction of a transistor is reverse-biased, whereas the other is forward-biased.



3.3a Forward-biased junction of a pnp transistor



2.3b Reverse-biased junction of a pnp transistor



2.3c Both biasing potentials have been applied to a pnp transistor and resulting majority and minority carrier flows indicated.

Majority carriers (+) will diffuse across the forward-biased p-n junction into the n-type material.

A very small number of carriers (+) will through n-type material to the base terminal. Resulting I_B is typically in order of microamperes.

The large number of majority carriers will diffuse across the reverse-biased junction into the p-type material connected to the collector terminal

Applying KCL to the transistor :

$$I_E = I_C + I_B$$

The comprises of two components – the majority and minority carriers

$$I_C = I_{C\text{majority}} + I_{C\text{minority}}$$

I_{CO} – I_C current with emitter terminal open and is called leakage current

Various parameters which relate the current components is given below

Emitter efficiency:

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

$$\gamma = \frac{I_{pE}}{I_{pE} + I_{nE}} = \frac{I_{pE}}{I_{nE}}$$

Transport Factor:

$$\beta^* = \frac{\text{injected carrier current reaching } J_C}{\text{injected carrier current at } J_E}$$

$$\beta^* = \frac{I_{pC}}{I_{nE}}$$

Large signal current gain:

The ratio of the negative of collector current increment to the emitter current change from zero (cut-off) to I_E the large signal current gain of a common base transistor.

$$\alpha = \frac{-(I_C - I_{CO})}{I_E}$$

Since I_C and I_E have opposite signs, then α , as defined, is always positive. Typically numerical values of α lies in the range of 0.90 to 0.995

$$\alpha = \frac{I_{pC}}{I_E} = \frac{I_{pC}}{I_{nE}} * \frac{I_{pE}}{I_E} \quad \alpha = \beta^* \gamma$$

The transistor alpha is the product of the transport factor and the emitter efficiency. This statement assumes that the collector multiplication ratio α^* is unity. α^* is the ratio of total current crossing J_C to hole arriving at the junction.

2.4 Bipolar Transistor Configurations

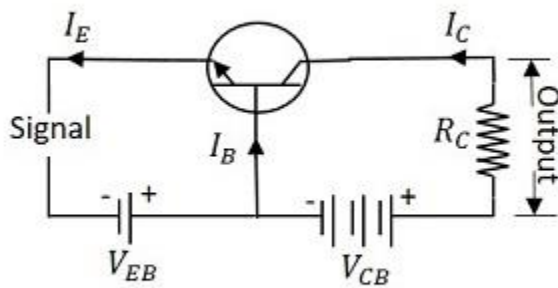
A Transistor has 3 terminals, the emitter, the base and the collector. Using these 3 terminals the transistor can be connected in a circuit with one terminal common to both input and output in a 3 different possible configurations.

The three types of configurations are **Common Base**, **Common Emitter** and **Common Collector** configurations. In every configuration, the emitter junction is forward biased and the collector junction is reverse biased.

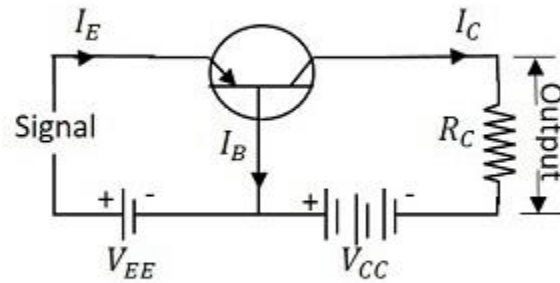
Common Base (CB) Configuration

The name itself implies that the Base terminal is taken as common terminal for both input and output of the transistor. The common base connection for both NPN and PNP transistors is as shown in the following figure.

Common Base Connection



Using NPN transistor



Using PNP transistor

For the sake of understanding, let us consider NPN transistor in CB configuration. When the emitter voltage is applied, as it is forward biased, the electrons from the negative terminal repel the emitter electrons and current flows through the emitter and base to the collector to contribute collector current. The collector voltage V_{CB} is kept constant throughout this.

In the CB configuration, the input current is the emitter current I_E and the output current is the collector current I_C .

Current Amplification Factor (α)

The ratio of change in collector current (ΔI_C) to the change in emitter current (ΔI_E) when collector voltage V_{CB} is kept constant, is called as **Current amplification factor**. It is denoted by α .

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

Expression for Collector current

With the idea above, let us try to draw some expression for collector current. Along with the emitter current flowing, there is some amount of base current I_B which flows through the base terminal due to electron hole recombination. As collector-base junction is reverse biased, there is another current which is flown due to minority charge carriers. This is the leakage current which can be understood as $I_{leakage}$. This is due to minority charge carriers and hence very small.

The emitter current that reaches the collector terminal is

$$\alpha I_E$$

Total collector current

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

If the emitter-base voltage $V_{EB} = 0$, even then, there flows a small leakage current, which can be termed as I_{CBO} (collector-base current with output open).

The collector current therefore can be expressed as

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

$$I_E = I_C + I_B$$

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

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

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

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

Hence the above derived is the expression for collector current. The value of collector current depends on base current and leakage current along with the current amplification factor of that transistor in use.

Characteristics of CB configuration

- This configuration provides voltage gain but no current gain.
- Being V_{CB} constant, with a small increase in the Emitter-base voltage V_{EB} , Emitter current I_E gets increased.
- Emitter Current I_E is independent of Collector voltage V_{CB} .
- Collector Voltage V_{CB} can affect the collector current I_C only at low voltages, when V_{EB} is kept constant.
- The input resistance r_i is the ratio of change in emitter-base voltage (ΔV_{EB}) to the change in emitter current (ΔI_E) at constant collector base voltage V_{CB} .

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

- As the input resistance is of very low value, a small value of V_{EB} is enough to produce a large current flow of emitter current I_E .

- The output resistance r_o is the ratio of change in the collector base voltage (ΔV_{CB}) to the change in collector current (ΔI_C) at constant emitter current I_E .

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

- As the output resistance is of very high value, a large change in V_{CB} produces a very little change in collector current I_C .
- This Configuration provides good stability against increase in temperature.
- The CB configuration is used for high frequency applications.

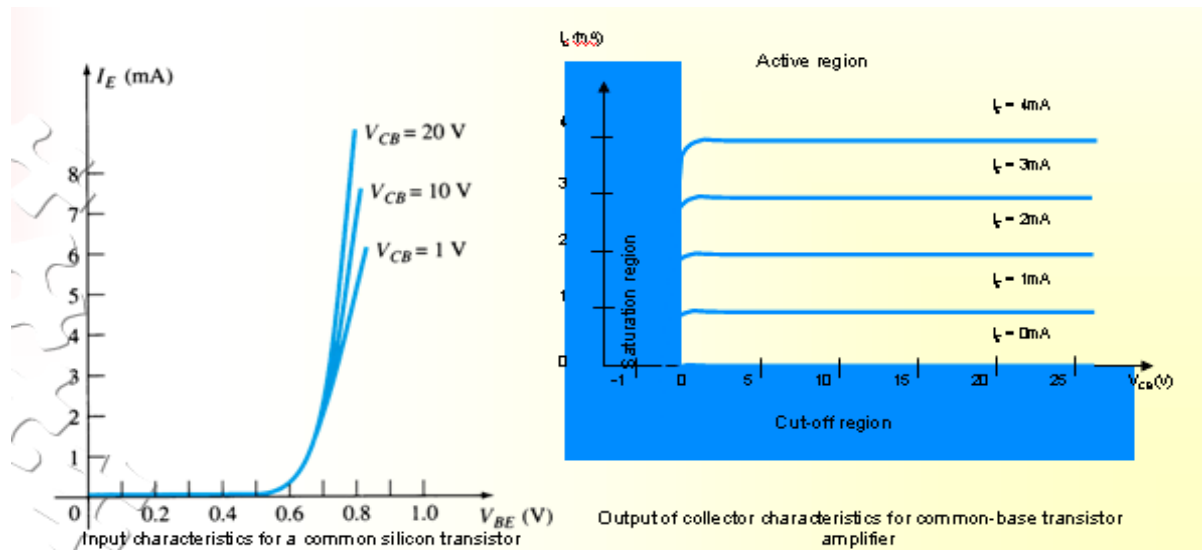
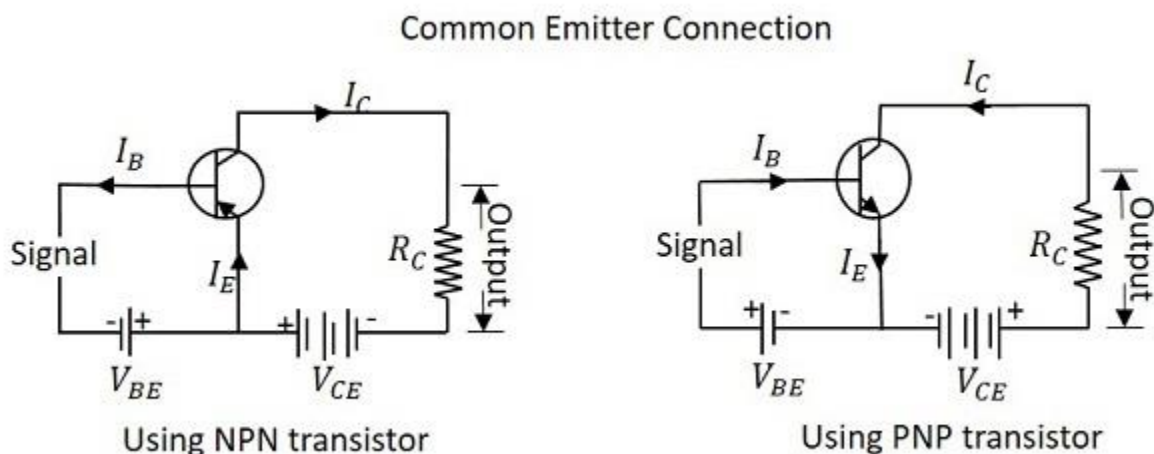


Fig 2.5 CB Input-Output Characteristics

| Active region | Saturation region | Cut-off region |
|----------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|----------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|--------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|
| <ul style="list-style-type: none"> I_E increased, I_C increased BE junction forward bias and CB junction reverse bias Refer to the graf, $I_C \approx I_E$ I_C not depends on V_{CB} Suitable region for the transistor working as amplifier | <ul style="list-style-type: none"> BE and CB junction is forward bias Small changes in V_{CB} will cause big different to I_C The allocation for this region is to the left of $V_{CB} = 0$ V. | <ul style="list-style-type: none"> Region below the line of $I_E = 0$ A BE and CB is reverse bias no current flow at collector, only leakage current |

Common Emitter (CE) Configuration

The name itself implies that the **Emitter** terminal is taken as common terminal for both input and output of the transistor. The common emitter connection for both NPN and PNP transistors is as shown in the following figure.



Just as in CB configuration, the emitter junction is forward biased and the collector junction is reverse biased. The flow of electrons is controlled in the same manner. The input current is the base current I_B and the output current is the collector current I_C here.

Base Current Amplification factor (β)

The ratio of change in collector current (ΔI_C) to the change in base current (ΔI_B) is known as **Base Current Amplification Factor**. It is denoted by β

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

Relation between β and α

Let us try to derive the relation between base current amplification factor and emitter current amplification factor.

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

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

$$I_E = I_B + I_C$$

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

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

We can write

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

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

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

We have

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

Therefore,

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

From the above equation, it is evident that, as α approaches 1, β reaches infinity.

Hence, **the current gain in Common Emitter connection is very high**. This is the reason this circuit connection is mostly used in all transistor applications.

Expression for Collector Current

In the Common Emitter configuration, I_B is the input current and I_C is the output current.

We know

$$I_E = I_B + I_C$$

And

$$\begin{aligned} I_C &= \alpha I_E + I_{CBO} \\ &= \alpha(I_B + I_C) + I_{CBO} \\ I_C(1 - \alpha) &= \alpha I_B + I_{CBO} \\ I_C &= \frac{\alpha}{1 - \alpha} I_B + \frac{1}{1 - \alpha} I_{CBO} \end{aligned}$$

If base circuit is open, i.e. if $I_B = 0$,

The collector emitter current with base open is I_{CEO}

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

Substituting the value of this in the previous equation, we get

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

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

Hence the equation for collector current is obtained.

Knee Voltage

In CE configuration, by keeping the base current I_B constant, if V_{CE} is varied, I_C increases nearly to 1v of V_{CE} and stays constant thereafter. This value of V_{CE} up to which collector current I_C changes with V_{CE} is called the **Knee Voltage**. The transistors while operating in CE configuration, they are operated above this knee voltage.

Characteristics of CE Configuration

- This configuration provides good current gain and voltage gain.
- Keeping V_{CE} constant, with a small increase in V_{BE} the base current I_B increases rapidly than in CB configurations.
- For any value of V_{CE} above knee voltage, I_C is approximately equal to βI_B .
- The input resistance r_i is the ratio of change in base emitter voltage (ΔV_{BE}) to the change in base current (ΔI_B) at constant collector emitter voltage V_{CE} .

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

- As the input resistance is of very low value, a small value of V_{BE} is enough to produce a large current flow of base current I_B .
- The output resistance r_o is the ratio of change in collector emitter voltage (ΔV_{CE}) to the change in collector current (ΔI_C) at constant I_B .

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

- As the output resistance of CE circuit is less than that of CB circuit.

- This configuration is usually used for bias stabilization methods and audio frequency applications.

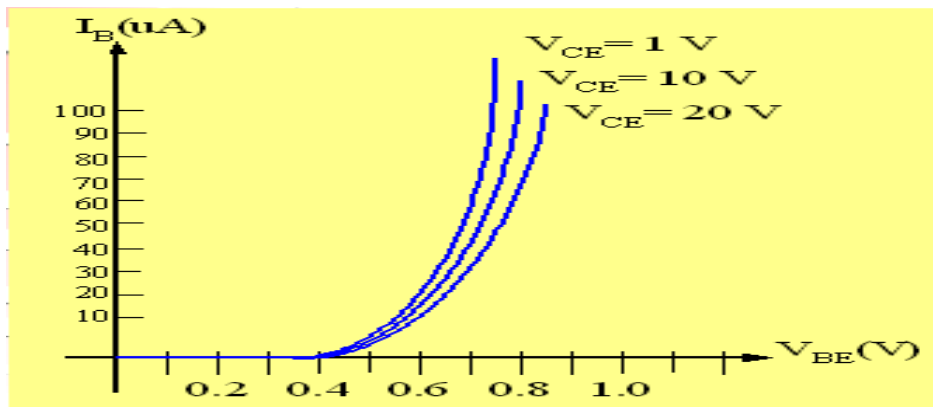


Fig 3.9a Input characteristics for common-emitter npn transistor

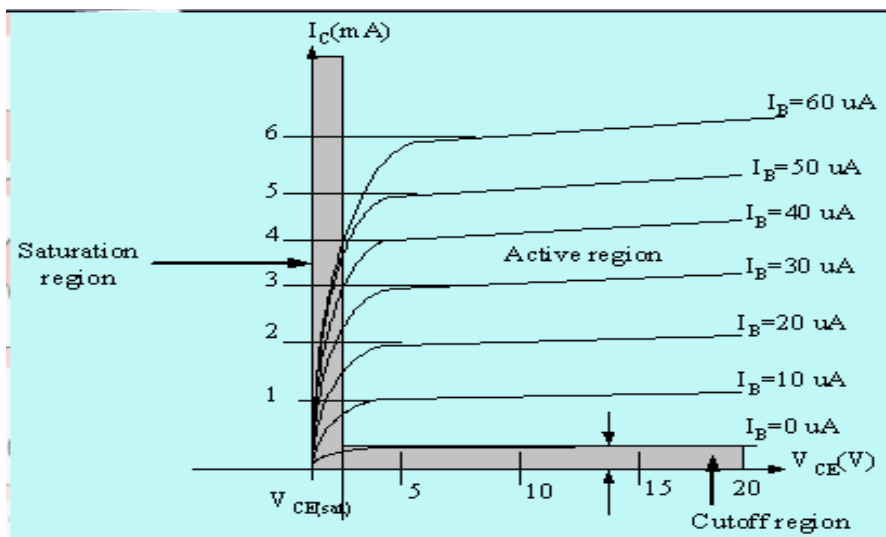


Fig 2.9b Output characteristics for common-emitter npn transistor

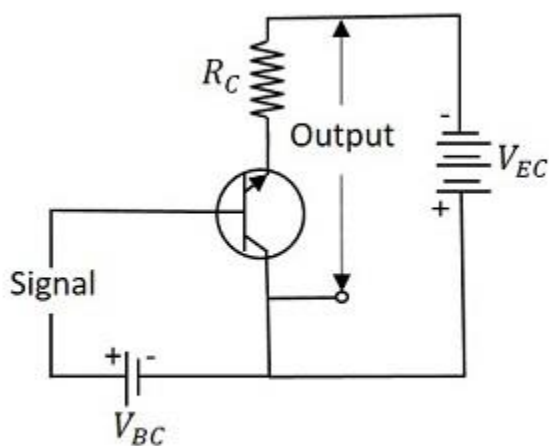
| Active region | Saturation region | Cut-off region |
|--------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|---------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|---------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|
| <ul style="list-style-type: none"> • B-E junction is forward bias • C-B junction is reverse bias • can be employed for voltage, current and power amplification | <ul style="list-style-type: none"> • B-E and C-B junction is forward bias, thus the values of I_B and I_C is too big. • The value of V_{CE} is so small. • Suitable region when the transistor as a logic switch. • NOT and avoid this region when the transistor as an amplifier. | <ul style="list-style-type: none"> • region below $I_B=0\mu A$ is to be avoided if an undistorted o/p signal is required • B-E junction and C-B junction is reverse bias • $I_B=0$, I_C not zero, during this condition $I_C=I_{CEO}$ where is this current flow when B-E is reverse bias. |

2.7 COMMON – COLLECTOR CONFIGURATION

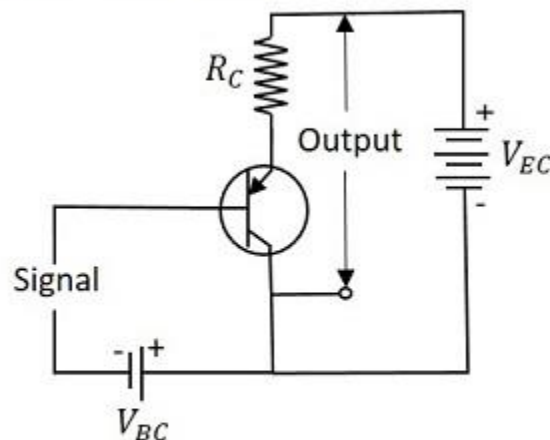
Common Collector (CC) Configuration

The name itself implies that the **Collector** terminal is taken as common terminal for both input and output of the transistor. The common collector connection for both NPN and PNP transistors is as shown in the following figure.

Common Collector Connection



Using NPN transistor



Using PNP transistor

Just as in CB and CE configurations, the emitter junction is forward biased and the collector junction is reverse biased. The flow of electrons is controlled in the same manner. The input current is the base current I_B and the output current is the emitter current I_E here.

Current Amplification Factor (γ)

The ratio of change in emitter current (ΔI_E) to the change in base current (ΔI_B) is known as **Current Amplification factor** in common collector (CC) configuration. It is denoted by γ .

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

- The current gain in CC configuration is same as in CE configuration.
- The voltage gain in CC configuration is always less than 1.

Relation between γ and α

Let us try to draw some relation between γ and α

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

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

$$I_E = I_B + I_C$$

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

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

Substituting the value of I_B , we get

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

Dividing by ΔI_E

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

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

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

Expression for collector current

We know

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

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

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

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

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

The above is the expression for collector current.

Characteristics of CC Configuration

- This configuration provides current gain but no voltage gain.
- In CC configuration, the input resistance is high and the output resistance is low.
- The voltage gain provided by this circuit is less than 1.
- The sum of collector current and base current equals emitter current.
- The input and output signals are in phase.
- This configuration works as non-inverting amplifier output.
- This circuit is mostly used for impedance matching. That means, to drive a low impedance load from a high impedance source.

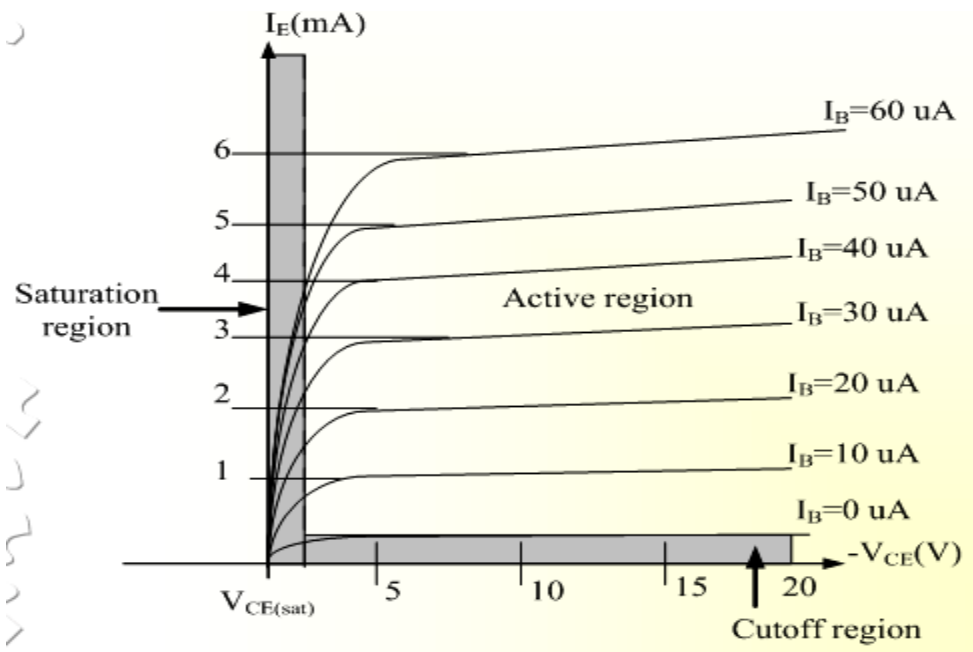


Fig 2.11 Output Characteristics of CC Configuration for npn Transistor