**Subject: Physics**

**Lesson: Bipolar junction transistor**

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# Bipolar junction transistor

Bipolar Junction Transistor (BJT) theory is very much dependent on the semiconductor and *pn*-junction theories covered in earlier chapters. Transistor essentially consists of two *pn*-junctions connected back-to-back or front-to-front. In the present chapter we will obtain physical characteristics of transistor operation and avoid the equations that describe the hole and electron density.

## 4.1 Types of BJT

The basic structure of transistor is a silicon or germanium bar crystal containing three separate regions. These regions are named as emitter, base and collector. The base region is placed at the middle of emitter and collector regions, which are outer regions. The two outer regions are made of same semiconductor type while middle base region is made of other semiconductor. There are two possibilities in which a transistor can be made. These are:

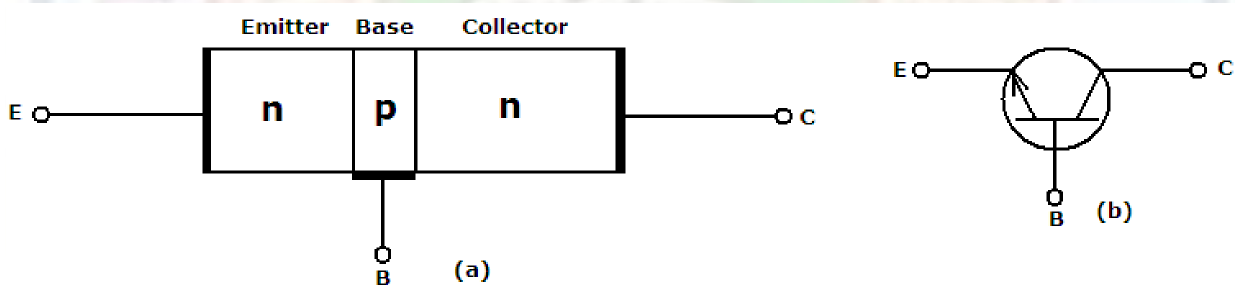
1. n-p-n
2. p-n-p

Let us discus these in detail.

### 4.1.1 n-p-n BJT

In n-p-n bipolar junction transistor, middle region base is made of p-type semiconductor while emitter and collector regions are made of n-type semiconductor. The cross-sectional view of n-p-n BJT is shown in figure 4.1 (a) and its symbolic representation is shown in figure 4.1 (b).

**Figure 4.1 (a) Cross-sectional view of n-p-n BJT and its (b) symbol.**



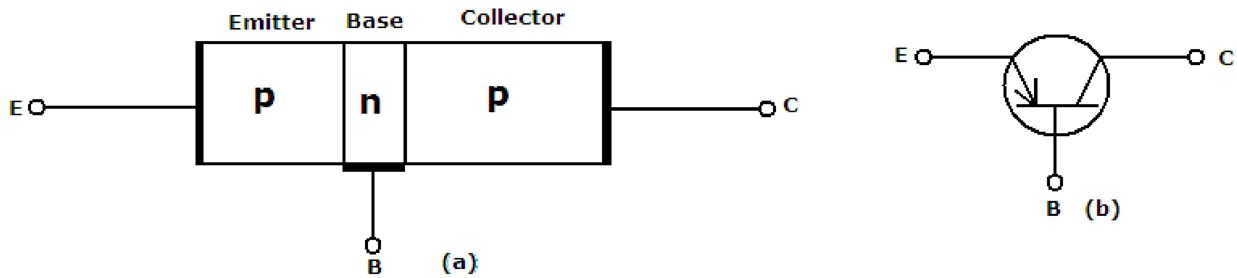

Even though two outer regions (emitter and collector) are made of, same types of semiconductor (n-type) but their function cannot be interchanged. The outer regions have different physical and electrical properties. The collector region is generally made larger than the emitter region. This is due to the fact that collector region is required to dissipate more heat than emitter region. The region on the other hand is made to be very thin. The doping is also not similar in three regions. In fact, the base region is very lightly doped while emitter region is heavily doped. The doping level in the collector region is in between emitter and base. The function of emitter region is to *emit* or *inject* the majority charge carrier *i.e.* electrons in the case of n-p-n transistor while that of collector is to *collect* these carriers.

Figure 4.1 (b) shows the symbolic representation for an n-p-n transistor. You can note that this symbol has an arrowhead at the emitter terminal (not on collector terminal). This arrowhead points in the direction of conventional emitter current (from p to n region).

## 4.1.2 p-n-p BJT

In p-n-p BJT, emitter and collector regions are made by p-type semiconductor while n-type semiconductor makes base region. All other specifications are similar to that of an n-p-n BJT. Figure 4.2 shows cross-sectional view of a p-n-p BJT with its symbolic representation. Here, the conventional current flows from p-type emitter region to n-type base region as indicated by arrow in the symbol.

**Figure 4.2 (a) Cross-sectional view of p-n-p BJT and its (b) symbol.**




From above discussion it should be clear that p-n-p transistor is just a complement of n-p-n transistor. However, both n-p-n and p-n-p transistors are widely used and sometimes together in a circuit. However in this chapter we will concentrate on the n-p-n transistor since p-n-p transistor is just a complement of n-p-n transistor. For a corresponding operation in p-n-p transistor it is merely necessary to read hole foe electron, electron for hole, negative for positive and positive for negative.

**Historical**

**Invention of bipolar junction transistor**

The BJT was invented in 1948 by John Bardeen, Walter Brattain and William Shockley at Bell Laboratory in USA. They were awarded Nobel prize for Physics as an recognition to their contribution. This discovery, which began as simple laboratory oddity, was proved to be sparking point in solid-state research that spread rapidly. The transistor demonstrated the process of amplification, which was earlier, achieved by electron vacuum tubes.

Transistors now have replaced bulky vacuum tubes in performing many applications. Transistor offers many advantages over vacuum tube counterparts, some of these are:

- Smaller in size, lighter in weight
- No heater or filament required so no heating delays and heating power needed
- Lower operating voltages
- Little power consumption
- Higher life-time with no ageing effects
- Mechanically strong and shock-proof
- Proper matched BJT fabrication possible which is added advantage in some specific applications such as push-pull and differential amplifiers

Transistor continues to perform numerous electronic applications with newer and improved designs. Also, this invention is rapidly expanded to lead to many other devices like FET, MOSFET, UJT, SCR *etc*.

## 4.2 Transistor action

Transistor has two pn-junctions-one between emitter and base and other between base and collector regions. The emitter-base junction sometimes referred as emitter junction while base-collector as collector junction. Let us now use the pn-junction theory to discuss the transistor action.

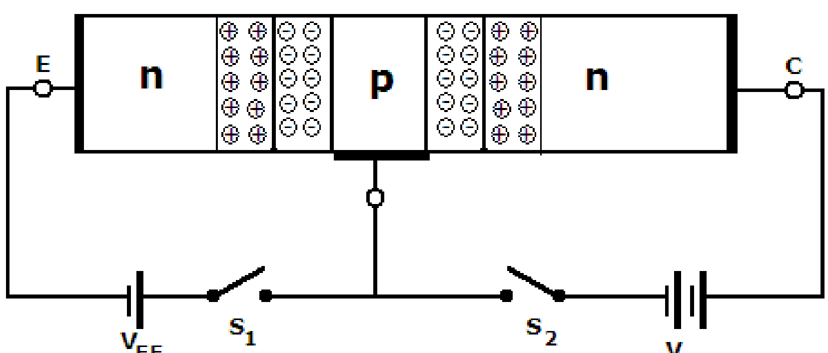
The two junctions present in a transistor can be biased in four different ways. These are tabulated in following table.

**Table 4.1 Biasing possibilities for two junctions in a BJT.**

| S. No. | Condition | Emitter junction | Collector junction | Region of operation |
|---|---|---|---|---|
| 1. | FR | Forward Biased | Reverse Biased | ACTIVE |
| 2. | FF | Forward Biased | Forward Biased | SATURATION |
| 3. | RR | Reverse Biased | Reverse Biased | CUTOFF |
| 4. | RF | Reverse Biased | Forward Biased | INVERTED |

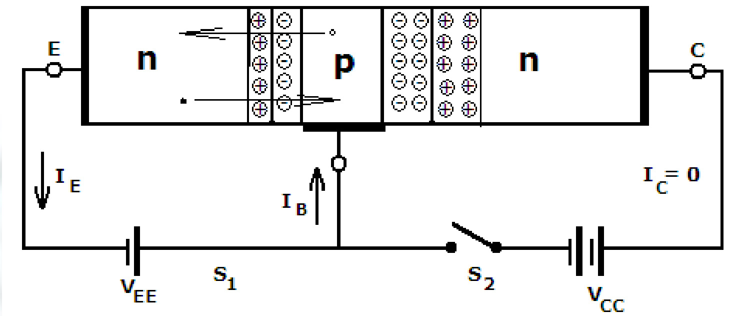
For this moment let us concentrate on the first FR condition *i.e.* emitter junction forward biased and collector junction reverse biased (Active region). Figure 4.3 shows the BJT connected for active mode operation. Note that base region is wider than the actual width. This is just for the sake of clarity. Battery $V_{EE}$ used to forward bias the emitter junction and battery $V_{CC}$ used to reverse bias the collector junction. Two switches $S_1$ and $S_2$ are employed in emitter and collector circuits to control the biasing of corresponding junction. When both the switches are open, both the junction will be unbiased and there will be depletion or space charge regions at two junctions.

**Figure 4.3 Cross-sectional view of n-p-n BJT biased in active region.**



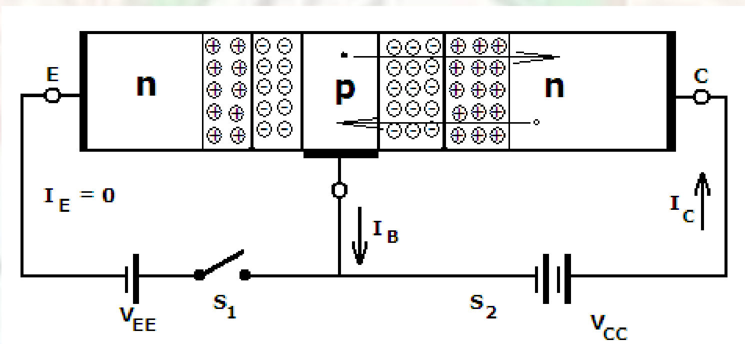

Let us first consider the case where switch $S_1$ is closed keeping switch $S_2$ open. This causes emitter junction to get forward biased and reduction in its width as shown in figure 4.4. The emitter-base junction is forward biased this causes a larger current flow across it. This current is made of majority charge carriers diffusing across the barrier *i.e.* electron from emitter to base and holes from base to emitter. The total current is sum of electron diffusion current and hole diffusion current. However in a transistor base region is doped very lightly compared to emitter region. Therefore a very small number of holes are present in the base region. As a result, about 99% of the current is carried by electrons (diffusing from emitter to base). The emitter current $I_E$ and base current $I_B$ in figure 4.4 are quite large. These two current must be equal $I_E = I_B$, while collector current is zero $I_C = 0$.

**Figure 4.4 Emitter junction forward biased keeping collector junction open.**




Now, consider the case where switch $S_2$ is closed keeping $S_1$ open as shown in figure 4.5. The collector junction gets reverse biased so that a very small current flows across it. This reverse saturation current is due to movement of minority carriers from *i.e.* electrons from p to n region and holes from n to p region. These carriers get accelerated by depletion layer electric field. This small current is called collector leakage current and denoted as $I_{CBO}$. The subscript CBO signify that this current flows between **C**ollector and **B**ase while third terminal (*i.e.* emitter) is **O**pen.

**Figure 4.5 Collector junction reverse biased keeping emitter junction open.**

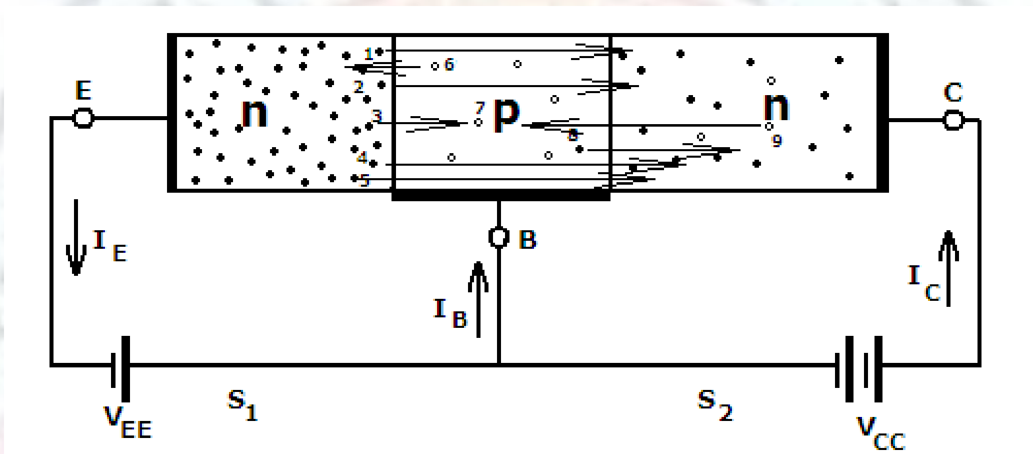



Again refer to figure 4.3, if both the switches $S_1$ and $S_2$ are closed, we expect current $I_E$ and $I_B$ to be large and $I_C$ to be small. But actually result of closing both the switches is surprising different. The emitter current $I_E$ is larger as expected while base current $I_B$ is smaller. The collector current $I_C$ turns out to be larger. This because of this unexpected result, transistor is considered to be a great invention. This phenomenon is referred as transistor action. In the next section we will investigate working of transistor in active mode and try to understand the transistor action.

## 4.3 Working of transistor

Consider an n-p-n transistor biased for the active mode operation *i.e.* emitter junction is forward biased and collector junction is reverse biased. The direction of current flow for such operation is shown in figure 4.6. As per convention the direction of flow of current is taken opposite to that of electron. In order to simplify the understanding, we have numbered some of the charge carriers present in the transistor.
The emitter junction is forward biased by few tenths of volts so that barrier at this junction gets reduced. The majority charge carriers diffuse across the junction. The current flow, thus consists of electrons movement from emitter to base region and holes traveling from base to emitter.

**Figure 4.6 n-p-n transistor biased for active mode operation.**




In figure 4.6, five electrons *i.e.* 1, 2, 3, 4 and 5 cross the emitter-base junction while hole numbered 6 move from base to emitter. These carrier together constitute the emitter current $I_E$. The emitter current due to flow of electrons is due to movement of electrons 1, 2, 3, 4 and 5 and due to flow of 6 hole. The ratio of emitter current due to electron flow to total emitter current is known as emitter efficiency or injection ratio ($\gamma_e$). The value of this is typically 0.995 which indicates that only 0.5% of the total emitter current is made of holes passing from base to emitter.

Electrons that are injected from emitter to base, loose their identity *i.e.* these cannot be separated from thermally generated electrons in base region itself. The base region is made to be very narrow and is lightly doped. This causes most of the injected electrons to reach collector region *e.g.* electrons 1, 2, 4 and 5, while a very few fraction of these recombine with holes present in the base region *e.g.* electrons 3 recombine with hole 7 of base region. The ratio of number of electrons arriving at collector to number of emitted electrons is known as base transportation factor ($\alpha_T$). The typical value of $\alpha_T$ is 0.995, which indicates only 0.5% of electrons get lost in base region and 99.5% reach the collector region.

In figure 4.6, movement of electron number 8 from base region to collector and that of hole number 9 from collector to base region constitute the leakage current $I_{CBO}$. While movement of electron 3 and hole 6 constitute a part of emitter current $I_E$. These two current components are not equal. In fact, current due to electron like 3 and hole like 6 crossing emitter-base junction is much more than the current due to electron like 8 and hole like 9 crossing base-collector junction. The difference between these two current components makes the base current $I_B$.

Thus, the carriers injected from emitter terminal into the forward biased emitter junction can result in large collector current in a reverse biased collector junction. This phenomenon is called transistor action.

From the above discussions it is clear that collector current is less than the emitter current but it is approximately equal to emitter current. The reasons for this are:

1. The emitter current has an additional component caused due to hole current, which is absent in collector current.
2. Not all the electrons injected into the base are successfully reach the collector region.

The first reason is mathematically illustrated by the factor emitter efficiency while second factor by base transport factor. The ratio of collector current to emitter current is represented by product of emitter efficiency and base transport factor *i.e.* $\alpha_{DC} = \gamma_e \alpha_T$. typically $\alpha_{DC} = 0.99$.

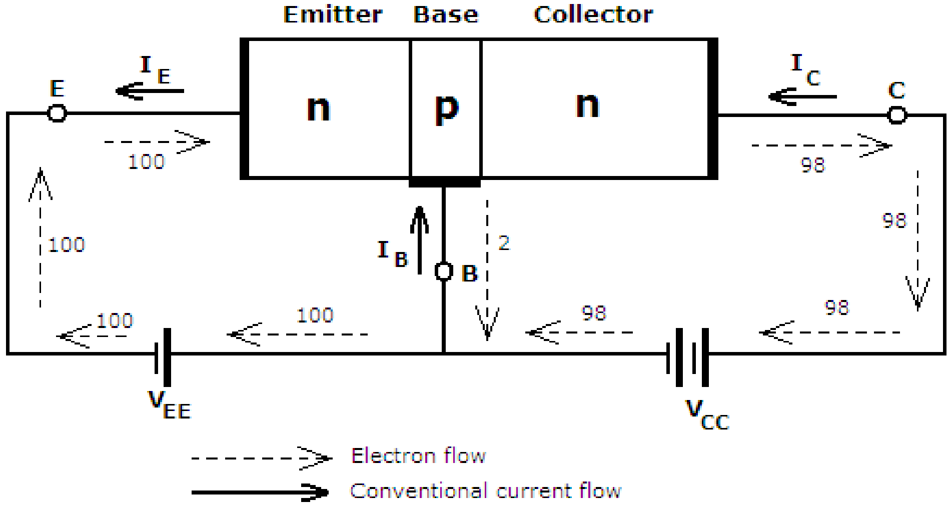
## 4.3.1 Role of biasing batteries

Now, let us examine the role played by batteries $V_{EE}$ and $V_{CC}$ in the biasing of transistor. These batteries used to maintain constant current flow in the transistor. The emitter region emits large number of electrons into the base region and some of the holes diffuse from base to the emitter region. These holes recombine with the electrons present in the emitter region and electrons-hole pairs get lost. In this way, the emitter region becomes short of electrons for some temporarily period. This shortage is immediately fulfilled by battery $V_{EE}$. The negative terminal of this battery supplies electrons to the emitter region.

| **Interesting fact** |
| --- |
| **Batteries** |
| Batteries are storehouse of charge so that these can supply as much charge as needed. |

To elaborate more, consider a hypothetical situation given in the figure 4.7. In this figure we will consider the journey of 100 electrons from $V_{EE}$.

**Figure 4.7 Role of biasing batteries.**




Let us assume 100 electrons supplied by negative terminal of the battery get injected into emitter region. These electrons constitute the total emitter current ($I_E$) in the emitter terminal. (In actual situation a large number of electrons are supplied by $V_{EE}$.) The conventional current flows in a direction opposite to that of electrons as indicated by dotted arrowhead. Note that emitter current $I_E$ comes out of emitter terminal. This is the reason why symbol of n-p-n transistor has arrow in the emitter lead points outward [figure 4.1(b)]. Out of injected 100 electrons, a majority of electrons say 99 electrons get injected into base region. One electron gets lost due to recombination with hole in the emitter region, which has been diffused from the base region. Now out of these 99 electrons, one get recombine with the hole present in the base region. The rest of the 98 electrons reach the collector region. So out of 100 injected emitter electrons 98 are able to reach the collector region. This is caused by special properties of the base region that it is lightly doped and very thin. The base region loose two holes, one diffuses into emitter region and other one lost in the base region due to recombination. The loss of two holes is fulfilled immediately by creation of fresh holes near the base terminal. The creation of holes leads to creation of two excess electrons also near the base terminal. These two electrons flows out of the base region through base terminal and constitute base current $I_B$. Since base electrons come out of base terminal, the conventional base current flows into the base terminal. The magnitude of the base current is very small as compared to that of emitter current.

98 electrons that reach the collector region experience an attractive force due to battery $V_{CC}$. These electrons come out of collector terminal and reach the positive terminal of the battery $V_{CC}$. The conventional collector current, which is made by 98 electrons, flows into the transistor collector terminal. Note that emitter current is made by 100 electrons and collector current made by 98 electrons, so these currents are almost equal but collector current is very slightly less than emitter current always.

The negative terminal of the battery $V_{CC}$ gives out as many electrons as received by the positive terminal of it *i.e.* 98 electrons. These 98 electrons from negative terminal of $V_{CC}$ combine, at the junction, with 2 electrons coming out of base terminal and make up a total of 100 electrons. These 100 electrons reach positive terminal of $V_{EE}$ so that this battery gets its 100 electrons as supplied by negative terminal of it. Thus the circuit gets completed.

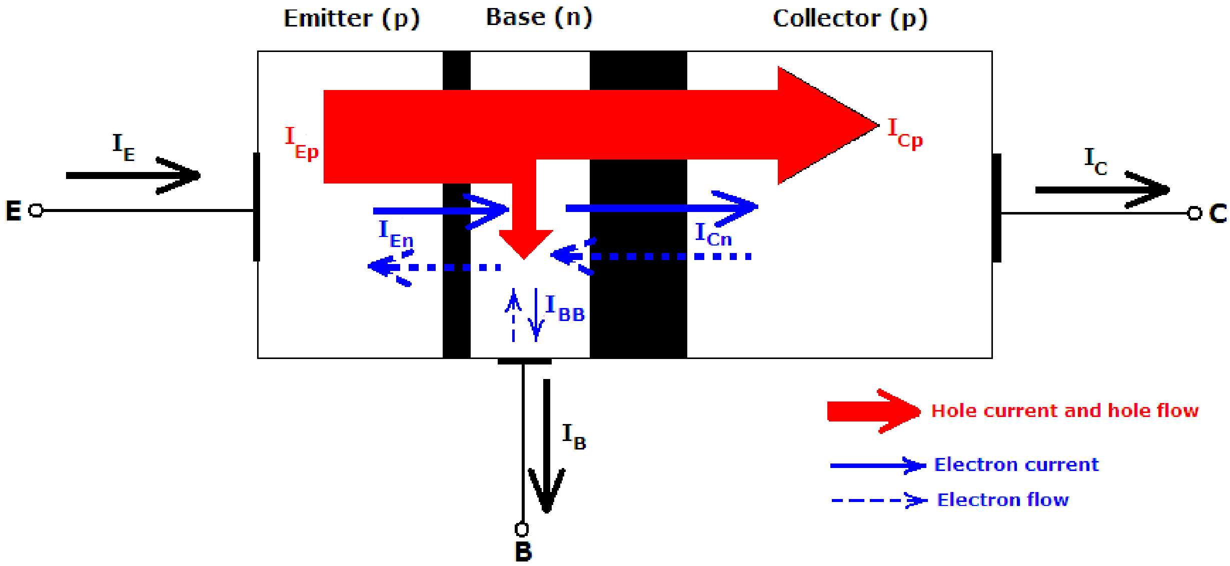
| **Interesting fact** |
|---|
| **Majority *vs* minority currents in bipolar transistors** |
| From the above discussions it should be clearly understood that in an n-p-n transistor, electrons make the major part of the transistor currents. Only a small fraction of current made by holes. So even though transistor is bipolar device *i.e.* both polarity charge carrier take part in the device performance, still main component of current is made of majority charge carrier. In case of n-p-n transistor these carriers are electrons. Therefore in an n-p-n BJT electron current is made larger than hole current by heavily doping of emitter region and light doping of base region. |

| **Misconception** |
|---|
| **Interacting *pn*-junctions** |
| The phenomenon of transistor action can only be achieved when two junctions are placed physically close to each other. That is when the base region is made to be very thin. This condition allows the two junctions (emitter-base and base-collector) to interact with each other and therefore some times referred as interacting-junctions. If the base width made larger then all injected electrons (in case of n-p-n transistor) will recombine in the base region before reaching the base-collector junction and transistor action being lost. This types of junctions are called non-interacting one. That is why we cannot achieve transistor action by placing two individual diodes back to back. |

## 4.3.2 Current components in p-n-p BJT

Let us describe the various current components present in the p-n-p transistor. This is just to simplify the description. The current components in n-p-n will also be similar to these. Figure 4.8 shows various current components present in a p-n-p transistor operated in active mode under the ideal conditions of no generation-recombination currents in depletion regions.

**Figure 4.8 Various current components in a p-n-p transistor under active mode of operation.**




The hole current which injected from the emitter terminal constitute emitter hole current component ($I_{Ep}$). This is the largest current component in a well-designed transistor. A large part of this is able to reach the collector region and give rise to collector hole current ($I_{Cp}$). The base current has three components as described below:

**$I_{BB}$:** This component arises due to electrons that must be supplied to the base to replace the electrons being recombined with the injected holes in the base region. In fact, $I_{BB} = I_{Ep} - I_{Cp}$.

**$I_{En}$:** This component is due to electrons, which get injected from base to the emitter. This is undesirable current component.

**$I_{Cn}$:** This component is due to thermally generated electrons that are near the base – collector junction edge and get drifted from collector to base.

As indicated in figure 4.8, the direction of conventional current flow is opposite to that of electron flow. Based on above description, various components of currents now can be expressed in terms of the terminal currents.

Emitter current, $I_E = I_{Ep} + I_{En}$

Collector current, $I_C = I_{Cp} + I_{Cn}$

Base current, $I_B = I_E - I_C = (I_{Ep} + I_{En}) - (I_{Cp} + I_{Cn}) = I_{En} + (I_{Ep} - I_{Cn}) - I_{Cp}$

We can now calculate three parameter, which we defined in the section 4.3. These are

Emitter efficiency: $\gamma = I_{Ep}/I_E = I_{Ep}/(I_{Ep} + I_{En})$

Base transport factor: $\alpha_T = I_{Cp}/I_{Ep}$

Common base DC current gain: $\alpha_{DC} = I_{Cp}/I_E$

| **Interesting fact** |
|---|
| **Well designed transistor** |
| In a well-designed transistor $I_{En} \approx 0$ so that $I_{Ep} \approx I_{Cp}$ and all $\gamma$, $\alpha_T$ and $\alpha_{DC}$ approach unity. $I_{En}$ can be minimized by heavier emitter doping or using a hetero-junction (junction formed between dissimilar semiconductors). |

Let us now express collector current in terms of $\alpha_{DC}$.

$$I_C = I_{Cp} + I_{Cn} = \alpha_T I_{Ep} + I_{Cn} = \gamma_e \alpha_T (I_{Ep}/\gamma_e) + I_{Cn} = \alpha_{DC} I_E + I_{Cn}$$

Note that $I_{Cn}$ is collector-base current flowing with emitter open-circuited ($I_E = 0$), which is same as $I_{CBO}$ described in the section 4.2. Thus, the collector current for common-base configuration is given by

$$I_C = \alpha_{DC} I_E + I_{CBO}$$

Above equation clearly states that the collector current is made up of two components. These are:

(i) The fraction of emitter current, which reaches collector *i.e.* $\alpha_{DC} I_E$
(ii) The normal reverse leakage current *i.e.* $I_{CBO}$

| **Numerical problem** |
|---|
| **Typical values** |
| Let for a typical n-p-n transistor, emitter electron current ($I_{En}$) is 3mA, emitter hole current ($I_{Ep}$) is 0.01mA, collector electron current ($I_{Cn}$) is 2.99mA and collector hole current ($I_{Cp}$) is 0.001mA. For this transistor,<br>Emitter efficiency, $\gamma_e = \frac{I_{En}}{I_{En} + I_{Ep}} = \frac{3}{3+0.01} = 0.9967$<br>Base transport factor, $\alpha_T = \frac{I_{Cn}}{I_{En}} = \frac{2.99}{3} = 0.9967$<br>Common base DC current gain, $\alpha_{DC} = \gamma_e \alpha_T = 0.9967 \times 0.9967 = 0.9934$<br>Total emitter current, $I_E = I_{En} + I_{Ep} = 3 + 0.01 = 3.01mA$<br>Total collector current, $I_C = I_{Cn} + I_{Cp} = 2.99 + 0.001 = 2.991mA$<br>Common base leakage current, $I_{CBO} = I_C - \alpha_{DC} I_E = 2.991 - 0.9934 \times 3.01 = 0.87\,\mu A$<br>Note $I_{CBO}$ is different from $I_{Cp}$, because $I_{CBO}$ is $I_{Cp}$ under the special condition of open circuited emitter. |

The total current, which flows into the transistor, must be equal to total current flowing out of it. Therefore, the emitter current is equal to sum of collector and base current *i.e.*

$$I_E = I_C + I_B$$

So the emitter current, just distribute itself to collector and base currents.

| **Interesting fact** |
|---|
| **Common base DC current gain ($\alpha_{DC}$)** |
| If the base region of a transistor is thinner and more lightly doped, the greater will be the value of common base DC current gain ($\alpha_{DC}$). Practically, however, its value cannot exceed unity. Almost all transistors have its value grater than 0.95 while some even have its value greater than 0.999. |

| **Numerical problem** |
|---|
| **Typical values** |
| BJT having $\alpha_{DC}$ = 0.98 and $I_{CBO}$ = 1μA, has emitter current $I_E$ = 1 mA, then<br>Collector current: $I_C = \alpha_{DC} I_E + I_{CBO} = 0.98 \times 1 \times 10^{-3} + 1 \times 10^{-6} = 0.981$ mA.<br>Base current: $I_B = I_E - I_C = 1 - 0.981 = 0.019$ mA = 19 μA<br>Note that collector and emitter currents are almost equal but base current is very small. |

## 4.3.3 Other modes of operation

Up till now we have concentrated on the active mode of operation for a BJT. In this mode emitter junction is kept forward biased and collector junction is reverse biased. There are three other modes of operation as tabulated in table 4.1. In order to fully understand working of transistor, we must briefly discuss other modes also.

### Saturation mode

The second condition of table 4.1, when both emitter and collector junctions get forward biased, transistor is said to be in saturation mode. In this mode, collector current becomes almost independent of base current.

### Cut-off mode

The third condition of the table indicates both the junctions to get reverse biased. In these conditions transistor is said to be in cut-off mode. In this mode emitter does not inject carriers into the base region so that no carrier are collected at the collector. The collector current is thus zero, however a very small leakage current flow due to thermally generated minority carrier.

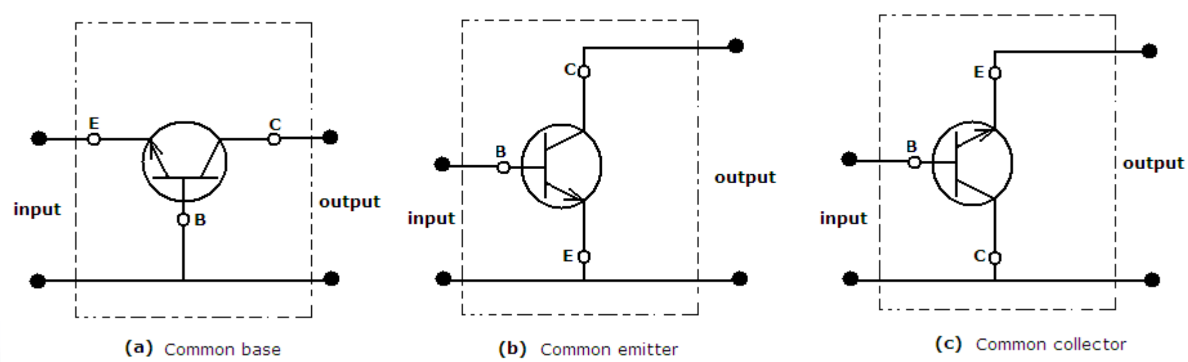
### Inverted mode

The forth condition of table 4.1 represents the transistor in which emitter junction is reverse biased and collector junction is forward biased, such transistor is said to be in inverted mode. Inverted mode is very different than the active mode operation. The emitter and collectors are not doped to the same extent; therefore these terminals cannot be interchanged. This mode of operation results in a poor transistor action, hence very rarely used in practice.
Saturation and cut-off modes of operations are used when transistor is used as an electronic switch while active mode is used when transistor acts as amplifier.

## 4.4 Transistor connection configurations

Transistor has three terminal namely emitter, base and collector. If one of these terminals is considered common to input and output then transistor can be considered as two-port device. Any of the three terminals of the transistor can be connected in common to input and output. The connection of the transistor then described in terms of this common terminal.
Figure 4.9 shows all possible configurations, total of three, of n-p-n transistor connection.

**Figure 4.9 Transistor connection configurations (a) common base (b) common emitter and (c) common collector.**




### Common base configuration

In common base (CB) configuration base terminal is taken as common electrode at both input and output ports as shown in figure 4.9 (a). The input signal is fed between emitter and base (so that input port is emitter-base terminals) while output signal is taken from collector and base terminal (*i.e.* output port is made at collector-base terminals).

### Common emitter configuration

When emitter terminal is common to the input and output ports as shown in figure 4.9 (b), the connection configuration is called common emitter (CE) configuration. In this configuration input is fed at base-emitter terminal and output taken from collector-emitter terminal.

### Common collector configuration

Figure 4.9 (c) shows common collector (CC) configuration used in transistor connections. In this connection the input signal is connected to base and collector terminals and output papers at emitter and collector terminal.

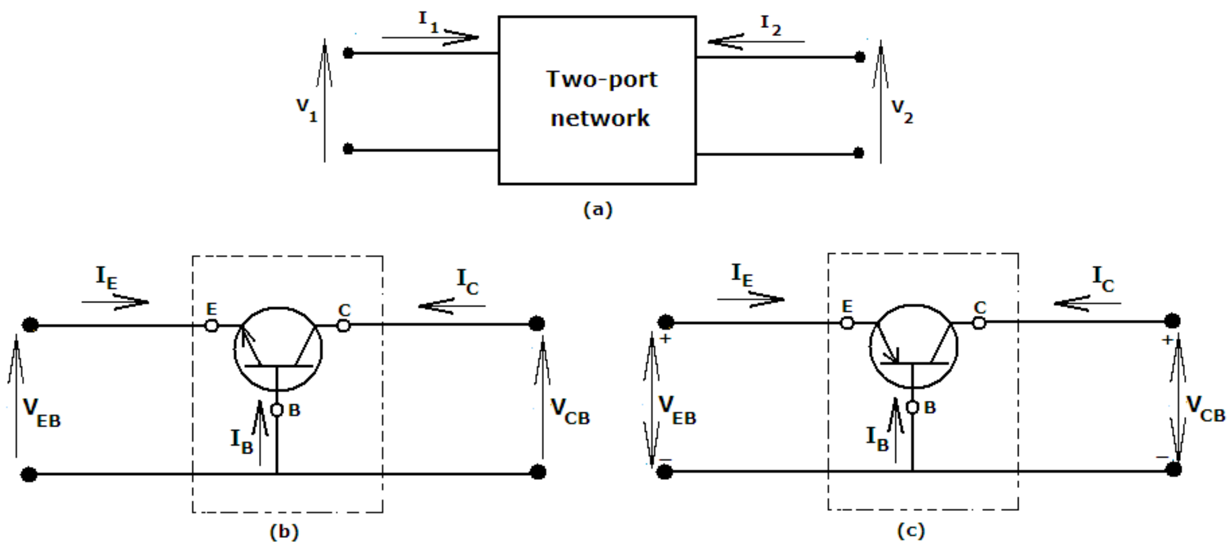
| **Interesting fact** |
| --- |
| **Common terminal** |
| The common terminal of transistor is generally grounded or connected to the chassis. |

It may be noted that transistor behaves differently in all different configurations. The configuration used for a transistor to be connected in a circuit, depends on its usage. A particular configuration may be suitable for one application might not be suitable for other. Different parameters like dynamic input resistance, output resistance, DC current gain, AC current gain AC voltage gain, leakage current *etc.* decides the transistor configuration in a circuit.

## 4.5 Sign conventions

The sign conventions used for voltages and currents in a transistor is same as that followed in the two-port networks. So let us first discuss the sign conventions for two port networks. Figure 4.10 (a) shows general two-port network with the sign conventions for input-output voltages and currents. Note in this figure current entering into the network is taken as positive and positive voltages are measured from upper with respect to lower terminal.

**Figure 4.10 Sign conventions (a) two-port network (b) n-p-n CB configuration and (c) p-n-p CB configuration.**




So as a convention all currents, which are entering into the transistor, are taken as positive and currents, which are coming out of transistor, are taken to be negative. Therefore for n-p-n transistor (see figure 4.10 (b)), $I_E$ is negative while $I_C$ and $I_B$ is positive. Similarly for p-n-p transistor (see figure 4.10 (c)), $I_E$ is positive while $I_C$ and $I_B$ is negative. But to avoid confusion, in many textbooks actual direction of current is indicated.

The voltages of transistor terminals are indicated with respect to common terminal. For example for CB configuration emitter and collector terminal voltages are indicated referenced to base. For example, $V_{EB}$ represents voltage of emitter terminal with respect to base. The reference directions used for voltage measurement are indicated by single-ended arrow (figure 4.10 (b)) or double-ended arrow with plus and minus signs (figure 4.10 (c)).

The sign convention for transistor terminal voltage is such that if the common (reference) terminal is at higher potential, the voltage is given negative sign. For example, for an n-p-n transistor biased in CB active mode operation will have $V_{EB}$ negative (since emitter np junction is forward biased) and $V_{CB}$ positive (since collector pn junction is reverse biased). Similarly, a p-n-p transistor working in active mode will have $V_{EB}$ positive and $V_{CB}$ negative.

# 4.6 Transistor characteristics

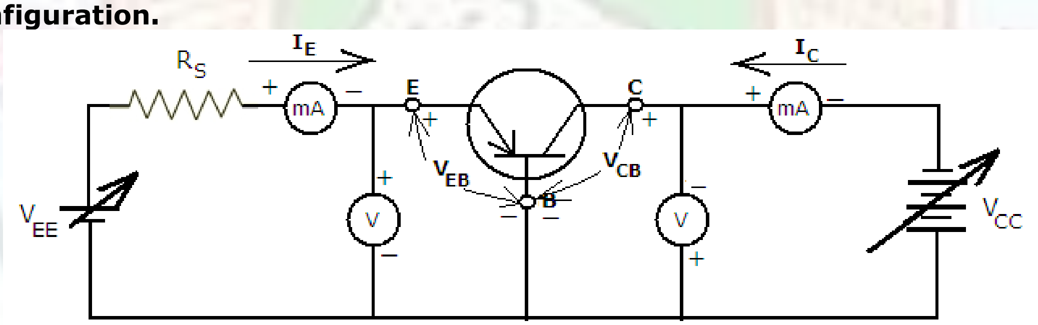
Details of a transistor can be studied with the help of curves that relates the current and voltages of the transistor. These curves are called static characteristics of the transistor. There are many possible sets of characteristics curves but two most important sets are input characteristics and output characteristic. These two sets when taken together, completely describe the static operation of the transistor. The input characteristics curve relates the input current as a function of input voltage keeping output voltage constant. The output characteristics curve, on the other hand, relates output current as a function of output voltage keeping input current constant.

Let us now discuss the input and output characteristics for three configurations of transistor. For the simplicity of biasing scheme we will take the transistor to be p-n-p type.

## 4.6.1 CB configuration

Figure 4.11 shows the circuit arrangement used for the characteristics for CB configuration of p-n-p transistor. The variable power supplies $V_{EE}$ and $V_{CC}$ are used for varying $V_{EB}$ and $V_{CB}$ respectively. The particular setting of power supply can be seen from the readings of corresponding voltmeter or ammeter. A series resistance $R_S$ (typically 1kΩ) is connected at the emitter-base input port since $V_{EB}$ is just a fraction of volt. This resistance limits the emitter current $I_E$ to lower value in case when power supply $V_{EE}$ is varied.

**Figure 4.11 Circuit diagram for determining the current-voltage characteristics for CB configuration.**




## Input characteristics

The common-base input characteristics are plotted between emitter current and emitter-base voltage keeping collector base voltage to a constant value. Generally, emitter current is taken as dependent variable (so plotted over Y-axis) and emitter-base voltage taken as independent variable (so plotted over X-axis). A typical input characteristic of for CB mode p-n-p transistor is shown in figure 4.12. We can note following point from these:

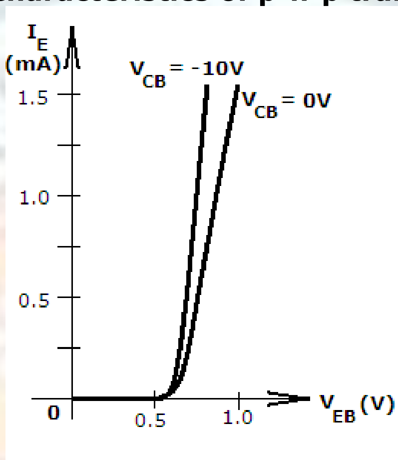
1. For a given value of $V_{CB}$, the input curve is just like the diode characteristics in forward biased conditions.
2. The emitter current increases rapidly, with a small fractional increase in the emitter-base voltage ($V_{EB}$). The input resistance is therefore very small. The input dynamic resistance for configuration can be calculated from slope of input characteristics curve and it is given by

$$r_i = \left.\frac{\Delta V_{EB}}{\Delta I_E}\right|_{V_{CB}=\text{constant}}$$

Input resistance is of the order of few ohms.

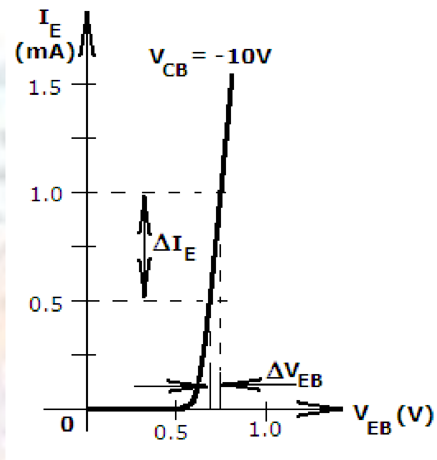
3. The emitter current (and therefore collector current) is almost independent of collector-base voltage ($V_{CB}$). So we can conclude that emitter current is independent of collector voltage.

**Figure 4.12 Typical input characteristics of p-n-p transistor in CB configuration.**



| **Graphical calculation** |
|---|
| **Input dynamic resistance in CB configuration** |

Let us calculate the input dynamic resistance for p-n-p transistor, which has input characteristics as shown in figure 4.12 for $V_{CB}$ = -10V.




Dynamic input resistance $r_i$ around $I_E$ = 7.5mA, can be calculated by taking ratio of small change in emitter current *i.e.* $\Delta I_E$ to corresponding change in $V_{CB}$ *i.e.* $\Delta V_{CB}$. So

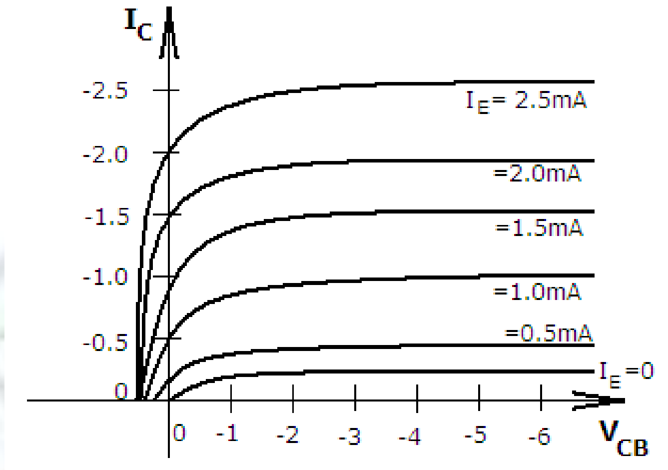
$$r_i = \left.\frac{\Delta V_{EB}}{\Delta I_E}\right|_{V_{CB}=-10V} = \frac{0.06}{0.5\times10^{-3}} = 120\Omega$$

This value is somewhat little higher than the expected value. In actual practice when transistor is operated as an amplifier, the emitter current is at higher values. At higher values of emitter currents, the input characteristics curve becomes steeper. Therefore input resistance $r_i$ becomes very less about 20-30Ω.

## Output characteristics

The common-base output characteristics are plotted between collector current and collector-base voltage keeping emitter current to a constant value. Generally, collector current is taken as dependent variable (so plotted over Y-axis) and collector -base voltage taken as independent variable (so plotted over X-axis). A typical output characteristic of for CB mode p-n-p transistor is shown in figure 4.13. Each output characteristic curve indicate the way collector current ($I_C$) varies with collector to base voltage ($V_{CB}$) for a given emitter current ($I_E$).

**Figure 4.13 Typical output characteristics of p-n-p transistor in CB configuration.**




The following points can be noted from these characteristics:

1. The collector current varies ($I_C$) with collector to base voltage ($V_{CB}$) only at very low voltage (<1V). When $V_{CB}$ is raised further (<1-2V), $I_C$ becomes independent of $V_{CB}$ as indicated by the horizontal lines and depends only on $I_E$. In fact, $I_C$ is approximately equal to $I_E$. Theoretically, also it is the emitter current, which flows almost entirely to collector. This region of operation is active-region.
2. When $V_{CB}$ is positive, the collector-base junction get forward biased and $I_C$ decreases sharply. This is called saturation region, in this region is $I_C$ is independent of $I_E$.
3. $I_C$ has a non-zero value, when $I_E = 0$, *i.e.* when emitter is open circuited. This is the reverse saturation current $I_{CBO}$, as explained earlier. This region is the cutoff region.
4. In active region very large change in $V_{CB}$ produces a very little change in the $I_C$ therefore dynamic output resistance ($r_o$) is very high. It is defined as the ratio of change in the collector-to-base voltage ($\Delta V_{CB}$), to resulting change in the collector current at constant emitter current ($\Delta I_C$) *i.e.*

$$r_o = \left.\frac{\Delta V_{CB}}{\Delta I_C}\right|_{I_E = constant}$$

   Output resistance is of the order of few mega-ohms.

We have already studied about the DC current gain ($\alpha_{DC}$) but it loses its significance when applied signal is variable *i.e.* like AC signal rather than absolute constant DC. For such situations we define, the AC current gain. Let us now define AC current gain ($\alpha$) for CB configuration.

The AC current gain ($\alpha$) for CB configuration is defined as ratio of small change in $\Delta I_C$ to corresponding change in $\Delta I_E$ required bringing about this change for a given collector to base voltage ($V_{CB}$) *i.e.*

$$\alpha = \left.\frac{\Delta I_C}{\Delta I_E}\right|_{V_{CB} = constant}$$

The value of $\alpha$ can be calculated from output characteristics of the transistor in CB configuration. Its value comes out to be less than unity in the range 0.95-0.995.

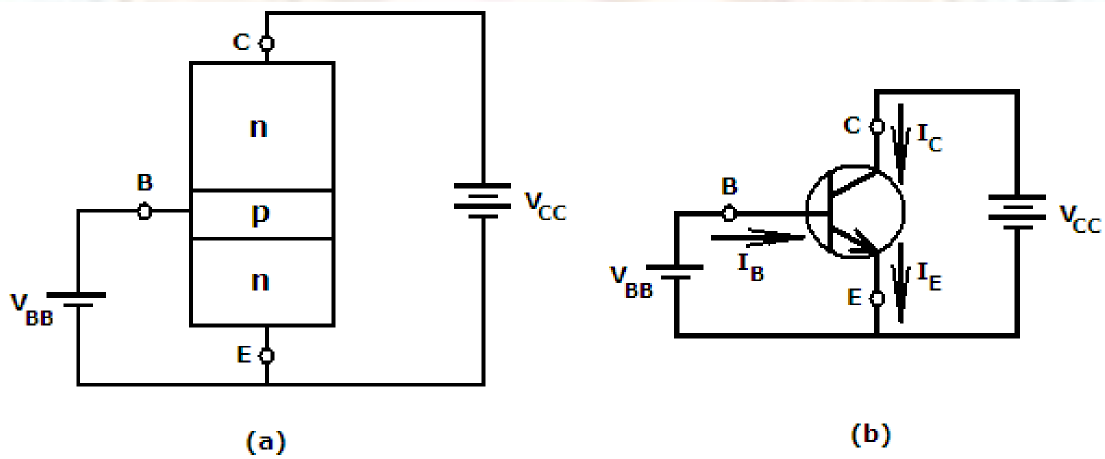
| **Do you know?** |
|---|
| **$h_{fb}$** |
| AC current gain ($\alpha$) for a transistor is also specified as $h_{fb}$ in the text. This symbol is based on h-parameter (hybrid-parameter). The first letter *f* in the subscript indicates *forward* and letter *b* indicates common-base configuration. So it represents common base forward (*i.e.* output to input) current gain. |

## 4.6.2 CE configuration

So far we only have concentrated on CB configuration however most popular configuration is CE configuration. Therefore before discussing the IV characteristics of these let us first elaborate this configuration.

No matter what the configuration of transistor is used, it has to be biased to operate in active mode *i.e.* emitter junction forward biased and collector junction reverse biased. In CE configuration this is done by using two batteries, these are $V_{BB}$ and $V_{CC}$ respectively. Figure 4.14 (a) shows an n-p-n transistor connected in CE configuration.

**Figure 4.14 Active mode biasing for n-p-n transistor in CE mode.**




It is clear from the circuit that base is at $+V_{BB}$ potential with respect to emitter while collector is at $+V_{CC}$ potential with respect to emitter. So the net potential of collector with respect to base is ($V_{CC}$ - $V_{BB}$). The collector junction is reverse-biased by this potential. Since $V_{BB}$ is very lesser than $V_{CC}$, therefore ($V_{CC}$ - $V_{BB}$) ≈ $V_{CC}$. Figure 4.14 (b) shows transistor symbol in the circuit and directions of the various current.

## Current expressions in CE configuration

In CB configuration, input current is $I_E$ and $I_C$ is output current. These current are related as

$$I_E = I_C + I_B$$
$$I_C = \alpha_{DC} I_E + I_{CBO}$$

Now in CE configuration, input current becomes $I_B$ and $I_C$ is output current. We should express the output current $I_C$ in terms of input current $I_B$ *i.e.* $I_C = f(I_B)$. This expression can be obtained by putting $I_E$ of first expression into the second one *i.e.*

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

Let us define, $\beta_{DC} = \frac{\alpha_{DC}}{1-\alpha_{DC}}$ and $I_{CEO} = \frac{I_{CBO}}{1-\alpha_{DC}}$

Substituting this, we get

$$I_C = \beta_{DC} I_B + I_{CEO}$$

This equation states that the collector current has two components. These are:

(i) The input base current multiplied by $\beta_{DC}$, which reaches collector *i.e.* $\beta_{DC}$ $I_B$
(ii) $I_{CEO}$

The factor $\beta_{DC}$ is called common emitter DC current gain. It is the ratio of output collector DC current to input base DC current. The relation between $\beta_{DC}$ and $\alpha_{DC}$ clearly indicate $\beta_{DC}$ is very large *e.g.*

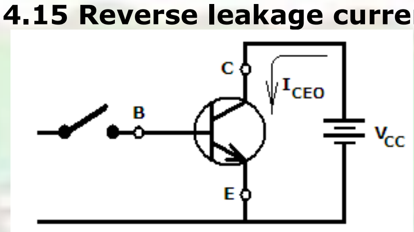
$$\alpha_{DC} = 0.98, \text{ gives } \beta_{DC} = \frac{0.98}{1-0.98} = 49$$

Typically $\beta_{DC}$ range from 20-300.

| **Mathematical rearrangement** |
| --- |
| **$\alpha_{DC}$ in terms of $\beta_{DC}$** |
| We defined $\beta_{DC}$ in terms of $\alpha_{DC}$ as $$\beta_{DC} = \frac{\alpha_{DC}}{1-\alpha_{DC}}$$ $$\Rightarrow \beta_{DC}(1-\alpha_{DC}) = \alpha_{DC}$$ $$\Rightarrow \beta_{DC} - \beta_{DC}\,\alpha_{DC} = \alpha_{DC}$$ $$\Rightarrow \beta_{DC} = \alpha_{DC} + \beta_{DC}\,\alpha_{DC}$$ $$\Rightarrow \beta_{DC} = \alpha_{DC}(1+\beta_{DC})$$ So, $\alpha_{DC}$ in terms of $\beta_{DC}$ expressed as $$\alpha_{DC} = \frac{\beta_{DC}}{\beta_{DC}+1}$$ |

$I_{CEO}$ is the leakage current which flow between collector and emitter, if third terminal *i.e.* base is open as illustrated in figure 4.15.

**Figure 4.15 Reverse leakage current, $I_{CEO}$.**




The relation between $I_{CEO}$ and $I_{CBO}$ indicates $I_{CEO}$ is very larger than $I_{CBO}$ *e.g.*

$\alpha_{DC}$ = 0.98, gives $I_{CEO} = \frac{I_{CBO}}{1-0.98} = 50 \times I_{CBO}$

That means $I_{CEO}$ is fifty times to that of $I_{CBO}$ for $\alpha_{DC}$ = 0.98.

| **Mathematical rearrangement** |
|---|
| **$I_{CEO}$ in terms of $I_{CBO}$** |
| Earlier we defined $$I_{CEO} = \frac{1}{1-\alpha_{DC}} I_{CBO} = \frac{1}{1-\frac{\beta_{DC}}{1+\beta_{DC}}} I_{CBO} = (1+\beta_{DC}) I_{CBO}$$ So $I_{CEO}$ in terms of $I_{CBO}$ expressed as $$I_{CEO} = (1+\beta_{DC}) I_{CBO}$$ |

For a Si-transistor $I_{CEO}$ would be typically in few microamperes (typically 20μA) while for Ge transistor it is in few hundred microamperes (typically 500μA).

## CE current-voltage characteristics

For CE configuration, $I_B$ and $V_{BE}$ are the input variables while $I_C$ and $V_{CE}$ are the output variables. Figure 4.16 shows the circuit arrangement used to determine current-voltage characteristics of p-n-p type BJT.

## Input characteristics

Typical input characteristics are shown in figure 4.17. These are the curve, which shows the variation of input current $I_B$ with respect to input voltage $V_{BE}$ for a given value of output voltage $V_{CE}$. These curves are similar to that obtained for CB configuration (figure 4.12).

**Figure 4.16 Circuit diagram for determining the current-voltage characteristics for CE configuration.**

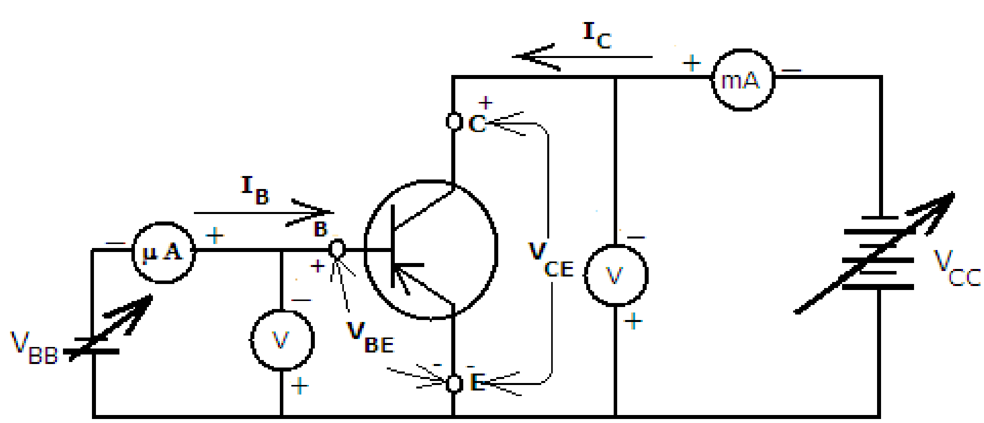
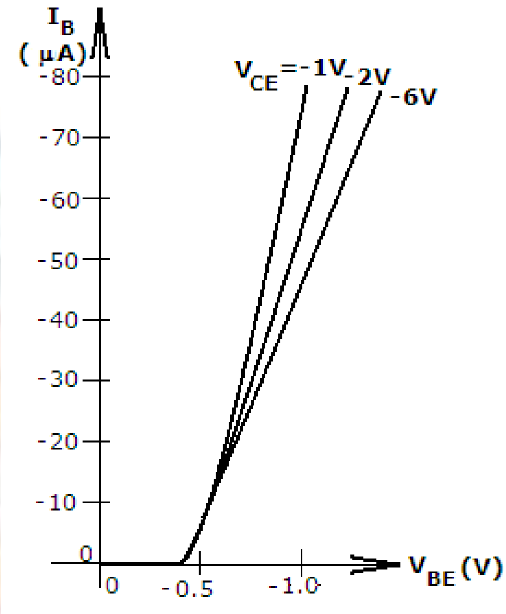


**Figure 4.17 Typical input characteristics of p-n-p transistor in CE configuration.**




It can be noted that change in the output voltage $V_{CE}$ does not result larger change in the curve. In fact we can ignore the effect of changing $V_{CE}$ on the input characteristics.
As defined earlier also for CB configuration, the dynamic input resistance ($r_i$) for CE configuration is

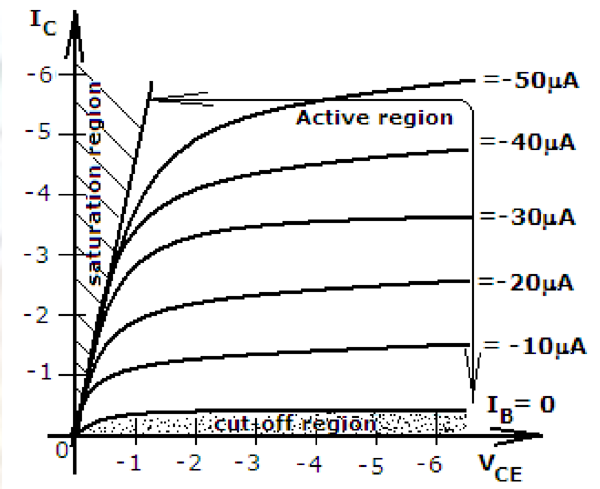
$$r_i = \left.\frac{\Delta V_{BE}}{\Delta I_B}\right|_{V_{CE}=constant}$$

The typical value of $r_i$ is 1kΩ but practically it ranges in 800 to 3kΩ.

## Output characteristics

Figure 4.18 shows the typical output characteristics in CE configuration of a p-n-p transistor. Note that all quantities $I_B$, $V_{BE}$ and $V_{CE}$ all are negative for p-n-p transistor. If transistor would have been n-p-n type then terminals of the batteries $V_{BB}$ and $V_{CC}$ have to be reversed so that $I_B$, $V_{BE}$ and $V_{CE}$ will be positive.

**Figure 4.18 Typical output characteristics of p-n-p transistor in CE configuration.**




We can note the following points about output-characteristics for CE configuration:

1. In active region, $I_C$ depends little on $V_{CE}$, in fact is increases very slowly with increasing $V_{CE}$. This behavior is similar to that found in CB configuration. Here, however the slope of the curve is greater than the CB output characteristics.
2. $\beta_{DC}$ is given by $I_C/I_B$. As can be seen from figure 4.18 that for each curve $I_B$ is constant, but $I_C$ increases with $V_{CE}$. This clearly indicates that $\beta_{DC}$ increases with $V_{CE}$ in active region.
3. If $V_{CE}$ is less than few tenths of volt, $I_C$ decreases rapidly as $V_{CE}$ drops. This occurs as $V_{CE}$ drops below the value of $V_{BE}$ so that the collector junction becomes forward biased. Under these conditions both the junctions are forward biased and therefore transistor is said to be working in saturation mode. In this mode, $I_C$ is no longer dependent on $I_B$.
4. When $I_B$ is zero $I_C$ is non-zero, this value of $I_C$ is reverse leakage current $I_{CEO}$.

From the output characteristics we can determine the dynamic output resistance, which is defined as ratio of change in $V_{CE}$ to corresponding change in $I_C$ keeping $I_B$ constant *i.e.*

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

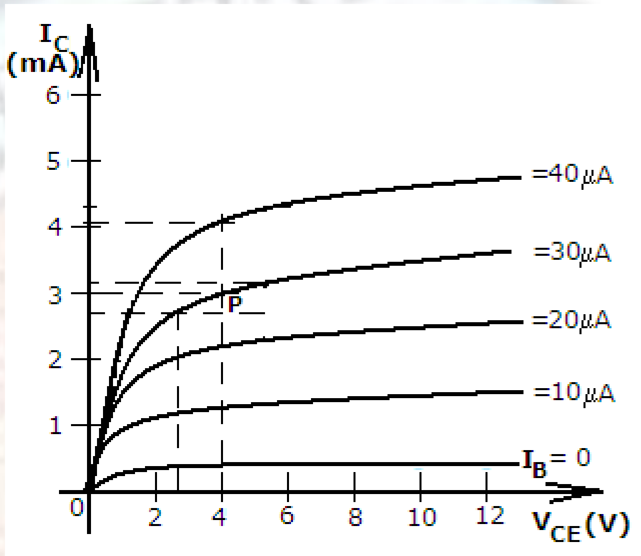
Its typical value of $r_o$ is about few tens of *kilo*-ohms.

The AC current gain ($\beta$) for CE configuration is ratio of small change in the output collector current ($\Delta I_C$) to corresponding change in input base current ($\Delta I_B$) required bringing about this change for constant output voltage collector to emitter voltage ($V_{CE}$) *i.e.*

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

| **Graphical calculations** |
|---|
| **$r_O$, $\beta_{DC}$ and $\beta$** |

Following figure gives the output characteristics of an n-p-n transistor. Let us determine $r_O$, $\beta_{DC}$ and $\beta$ for this when it is operated at $V_{CE}$ = 4V and $I_B$ = 30μA.




First make a vertical line at $V_{CE}$ = 4V, it cuts the output curve for $I_B$ = 30μA at point P. The collector current at this point is $I_C$ = 3mA.

In order to determine dynamic output resistance ($r_o$), we take small change in $V_{CE}$ *i.e.* 2.7V to 5.5V for a constant $I_B$ of 30μA. The corresponding change in $I_C$ can be noted as 2.8 mA to 3.1 mA. So the output resistance is given as

$$r_o = \left.\frac{\Delta V_{CE}}{\Delta I_C}\right|_{I_B=30\mu A.} = \frac{5.5-2.7}{(3.1-2.8)\times 10^{-3}} = 9.3k\Omega$$

$\beta_{DC}$ can be found by the value of DC collector current corresponding to $I_B$ = 30μA *i.e.*

$$\beta_{DC} = \frac{I_C}{I_B} = \frac{3mA}{30\mu A} = 100$$

The value of β can be found by making vertical line at $V_{CE}$ = 4V. From the characteristic curves it is clear that when base current changes from 30μA to 40μA, collector current changes from 3 mA to 4.1 mA. Therefore, the AC current gain is given by

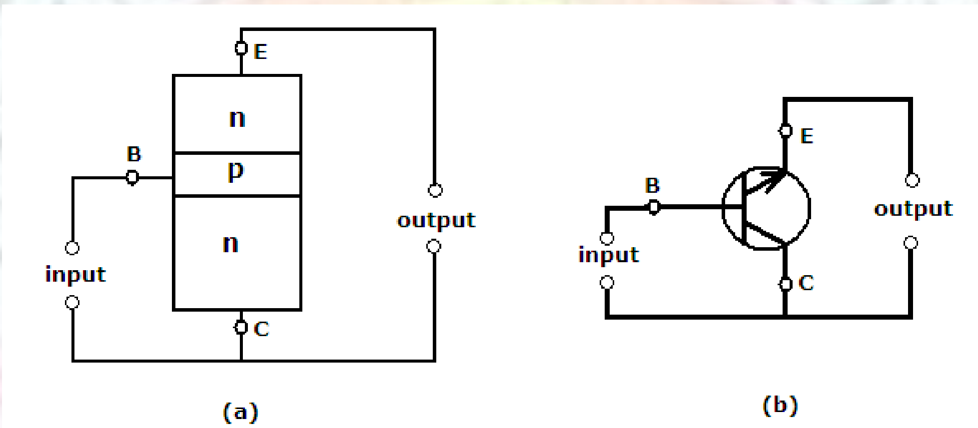
$$\beta = \left.\frac{\Delta I_C}{\Delta I_B}\right|_{V_{CE}=4V} = \frac{(4.1-3.0)\times 10^{-3}}{(40-30)\times 10^{-6}} = 110$$

Note that β and $\beta_{DC}$ are different in definition and values.

### 4.6.3 CC configuration

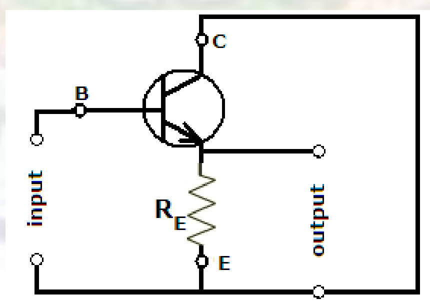
In this arrangement, input port is made by base-collector while output port made by emitter- collector so that collector terminal is common terminal. Figure 4.19 shows n-p-n transistor connected in common collector (CC) configuration.

**Figure 4.19 n-p-n transistor connected in CC configuration (a) cross-sectional view (b) circuit with symbol.**




| Adaptation |
|---|
| **CC configuration** |

The same circuit as shown in figure 4.19 can also be drawn in a different way as shown below:




In this figure the transistor is shown to be in conventional manner *i.e.* collector terminal at upper end and emitter terminal at lower end. This circuit looks alike that of common emitter configuration. Here the only difference is that the output is taken from emitter rather than collector.

The biasing arrangement is same as that used for CE configuration *i.e.* two power supplies $V_{BB}$ and $V_{CC}$ are used to forward bias emitter and collector junctions respectively.

## Current expressions in CE configuration

In CC configuration, input current is $I_B$ and $I_E$ is output current. The output current should be written as a function of input current *i.e.*

$$I_E = f(I_B)$$

To find the required expression, let us start with basic current equations:

$$I_E = I_C + I_B$$
$$I_C = \alpha_{DC} I_E + I_{CBO}$$

We should eliminate collector current $I_C$, so substituting collector current expression from first equation into second,

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

Let us define, $\gamma_{DC} = \frac{1}{1-\alpha_{DC}}$ and $I_{CEO} = \frac{I_{CBO}}{1-\alpha_{DC}}$

$$\Rightarrow \quad I_E = \gamma_{DC} I_B + I_{CEO}$$

This is the required expression of currents for CC configuration. The factor $\gamma_{DC}$ is called common collector DC current gain. It is the ratio of output emitter DC current to input base DC current.

| **Mathematical rearrangement** |
| --- |
| **$\gamma_{DC}$ in terms of $\beta_{DC}$** |
| $\gamma_{DC} = \frac{1}{1-\alpha_{DC}} = \frac{(1-\alpha_{DC})+\alpha_{DC}}{1-\alpha_{DC}} = 1 + \frac{\alpha_{DC}}{1-\alpha_{DC}} = 1 + \beta_{DC}$ |

## CC current-voltage characteristics

Generally, CC configuration is not studied separately as an independent circuit. The usual practice is to consider CC circuitry as a special case of CE configuration. However input-output characteristics can also be drawn for CC configuration also. These will look exactly like that for CE configuration. In the present case we will skip this part, as it does not matter much.

However, from output characteristics we can define common collector current gain ($\gamma$) as ratio of change in emitter current to corresponding change in base current at a constant emitter to collector voltage *i.e.*

$$\gamma = \left.\frac{\Delta I_E}{\Delta I_B}\right|_{V_{EC}=constant}$$

and output resistance ($r_o$) as

$$r_o = \left.\frac{\Delta V_{EC}}{\Delta I_E}\right|_{I_B=constant}$$

## 4.7 Relations between current gains

In the last section, we defined various current gains for the transistor, these are $\alpha$, $\beta$, and $\gamma$.

$$\alpha = \frac{\Delta I_C}{\Delta I_E} \qquad \beta = \frac{\Delta I_C}{\Delta I_B} \qquad \gamma = \frac{\Delta I_E}{\Delta I_B}$$

These are also known as current amplification factors for CB, CE and CC configurations respectively. Let us now determine various relations between these.

### 4.7.1 $\alpha$ and $\beta$

Consider

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

Dividing by $\Delta I_C$:

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

This can be re-written as:

$$\alpha = \frac{\beta}{\beta + 1} \qquad \text{OR} \qquad \beta = \frac{\alpha}{1-\alpha}$$

### 4.7.2 $\gamma$ and $\alpha$

Consider

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

By definition of $\gamma$:

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

So

$$\gamma = \frac{1}{1-\alpha} \qquad \text{OR} \qquad \alpha = \frac{\gamma - 1}{\gamma}$$

### 4.7.3 γ and β

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

So $\gamma = 1+\beta$ OR $\beta = \gamma - 1$

| Mathematical rearrangement |
|---|
| **α, β and γ** |
| Expression showing relation between α, β and γ: $\gamma = 1+\beta = \frac{1}{1-\alpha}$ |

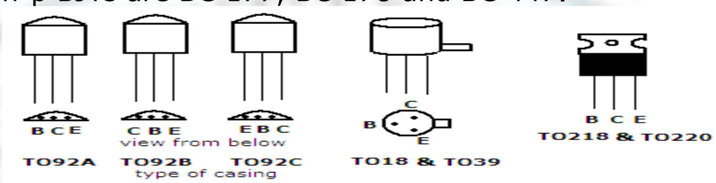
## 4.8 Comparison between three configurations

We have seen that transistor can be connected in any one of three possible configurations. Its behavior is different in different configuration. The particular configuration of a transistor in a circuit depends on the application it is being used. The different parameters like input dynamic resistance, output dynamic resistance, DC current gain, AC current gain and leakage current decides the application of configuration. Table 4.2 tabulate various parameters of each configurations:

**Table 4.2 Comparison of various parameters for CB, CE and CC configurations.**

| S. No. | Parameters | Common Base | Common Emitter | Common Collector |
|---|---|---|---|---|
| 1. | Input resistance | Very low (~20Ω) | Low (~1kΩ) | Very high (~1MΩ) |
| 2. | Output resistance | Very high (~1MΩ) | High (~10kΩ) | Low (~50Ω) |
| 3. | Current gain (DC/AC) | Less than unity (~0.98) | High (~100) | High (100) |
| 4. | Leakage current | Very small (~1μA for Si) | Very large (~20μA for Si) | Same as CE configuration |

Of these three configurations, CE configuration is most efficient and it is used about 90% of all transistor applications. The main reason for this is its higher current gains, which gives highest power gain among the three configurations. Moreover it also has moderate output to input impedance ratio which make this arrangement ideal one for coupling between various transistor stages. But for other coupling needs, this ratio proves to be very large hence becomes bad mismatch and highly inefficient. For obtaining good impedance matching, CC configuration is used. CC configuration has highest input and lowest output resistances and therefore offers best output to input impedance ratio. The higher leakage current in CE mode is disadvantage for this arrangement since it makes circuit thermally unstable. However, CB configuration has lowest leakage current therefore it is thermally stable configuration. Also Si transistors offers lesser leakage current compared to Ge transistor, therefore Si-BJTs are more preferred one.

| |
|---|
| **Terminal identification** |
| **Commonly used transistor** |
| Some of the commonly used n-p-n BJTs in the laboratories are BC 107, BC 108 and BC 547 while p-n-p BJTs are BC 177, BC 178 and BC 447.  |

# Bipolar junction transistor

## Summary


- Bipolar Junction Transistor (BJT) is a three terminal and three layer device. These are named as emitter, base and collector.
- Emitter region is heavily doped while base region is lightly doped. The doping level of collector region is made to be in between emitter and base.
- Base region of transistor is made to be very thin and collector region is made very thick. The thickness of emitter region is in between that of collector and base.
- Depending on the doping profile, BJT can be either n-p-n or p-n-p type.
- In n-p-n transistor, electrons are the majority charge carriers that decide the overall operation while in p-n-p transistor holes decides the operation.
- There are two junction in a transistor-one is between emitter and base region (called emitter junction) while other one between base and collector region (called collector junction).
- Base current caused by recombination of majority carriers (electrons in case of n-p-n and holes in case of p-n-p transistors) and diffusion of minority carriers (holes in case of n-p-n and electors in case of p-n-p transistors) present in the base region.
- Base current is only a small fraction of emitter current while collector current is only that fraction short of emitter current.
- Transistor action refers to phenomenon of larger current flow though a reverse biased collector junction.
- The phenomenon of transistor action can only be achieved when pn-junctions are of interacting type.
- Emitter efficiency ($\gamma$) of a transistor decides the fraction of minority carriers contributing to emitter current.
- Base transport factor ($\alpha_T$) decides the faction of majority charge carriers being lost in the base region.
- Common base DC current gain ($\alpha_{DC}$) is the ratio of collector current to emitter current. It is represented by product of emitter efficiency and base transport factor *i.e.*

$$\alpha_{DC} = \gamma\ \alpha_T.$$

- The collector current is made up of two components (i) fraction of emitter current, which reaches collector *i.e.* $\alpha_{DC}\ I_E$ and (ii) normal reverse leakage current *i.e.* $I_{CBO}$. Thus, $I_C = \alpha_{DC}\ I_E + I_{CBO}$
- The emitter current is equal to sum of collector and base current *i.e.* $I_E = I_C + I_B$. So the emitter current, just distribute itself to collector and base currents.
- Each input characteristics curve relates the input current as a function of input voltage keeping output voltage constant.

# Bipolar junction transistor

- Each output characteristics curve, on the other hand, relates output current as a function of output voltage keeping input current constant.
- The output collector current $I_C$, for CE configuration is $I_C = \beta_{DC} I_B + I_{CEO}$
- The output emitter current $I_E$, for CC configuration is $I_E = \gamma_{DC} I_B + I_{CEO}$
- The AC current gains for CB, CE and CC configurations are these are $\alpha$, $\beta$, and $\gamma$ respectively, defined as

$$\alpha = \frac{\Delta I_C}{\Delta I_E} \qquad \beta = \frac{\Delta I_C}{\Delta I_B} \qquad \gamma = \frac{\Delta I_E}{\Delta I_B}$$

- Various AC current gains are related as

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

- The CE configuration is most often used connection is the electronic circuitry (about 90%). This is due to its higher current gains (both AC and DC), which gives highest power gain among the three configurations.
- The CC configuration has highest input and lowest output resistances and therefore offers best output to input impedance ratio and used for impedance matching.

## Exercises

4.1 What are bipolar junction transistors? Why these are called so?

4.2 Discuss the schematic cross-section structure of BJT explaining doping profile and size considerations of various regions.

4.3 What is the meaning of transistor action in a BJT? Explain your answer.

4.4 What are the conditions imposed on pn-junctions to achieve transistor action?

4.5 Explain the working of p-n-p transistor biased in active mode. How is it different than that for n-p-n transistor?

4.6 Explain the hypothetical journey of 100 electrons from $V_{EE}$ battery in p-n-p transistor, which is biased in active mode.

4.7 Why cannot we replace a transistor by two pn-junction diodes? Explain.

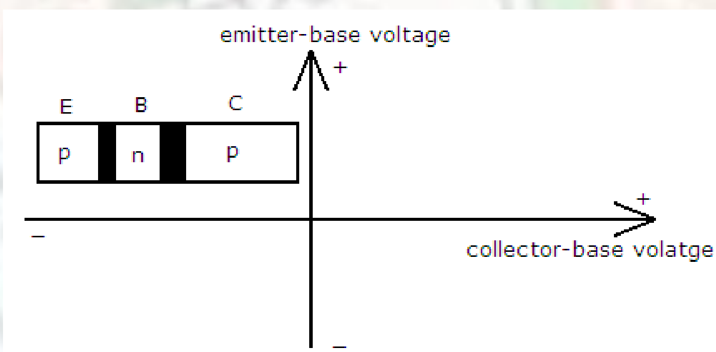
4.8 Define emitter efficiency, base transport factor and common base DC current gain. Also establish relation between these.

4.9 Write the physical significance of emitter efficiency and base transport factor. What are their ideal values? Explain.

4.10 Describe various current components present in the transistor.

4.11 Describe various modes of operations for a n-p-n transistor.

4.12 Following figure shows active mode for a p-n-p BJT to be in II quadrant, find out the quadrants for other three modes.




4.13 What are the possible configurations for BJT to be connected in a circuit? Is configuration used, in a transistor circuit is immaterial? Explain.

4.14 Draw the circuitry used for determining input and output characteristics for n-p-n transistor connected in CB mode.

4.15 Draw typical CB input-output characteristics for n-p-n transistor by labeling all the variables. Also explain how input, output dynamic resistances, AC, DC current gain are determined from these characteristics.

4.16 Draw the circuitry used for determining input and output characteristics for n-p-n transistor connected in CE mode.

4.17 Draw typical CE input-output characteristics for n-p-n transistor by labeling all the variables. Also explain how input, output dynamic resistances, AC, DC current gain are determined from these characteristics.

4.18 Define the DC and AC current gains for various configurations of transistor connection.

4.19 Establish relationship between various AC current gains.

4.20 Give the qualitative comparison between various configurations of the transistor used in the electronic circuitry.

4.21 Explain why does CE configuration is most preferred one in electronic circuitry.

## Glossary

**$\alpha$:** Common base AC current gain. It is the ratio of change in collector current to change in emitter current for a given collector-to-base voltage. Also referred as $h_{fb}$.

**$\alpha_{DC}$:** Common base DC current gain. It is the ratio of collector current to emitter current for a given collector-to-base voltage.

**$\beta$:** Common emitter AC current gain. It is the ratio of change in collector current to change in base current for a given collector-to-emitter voltage. Also referred as $h_{fe}$.

**$\beta_{DC}$:** Common emitter DC current gain. It is the ratio of collector current to base current for a given collector-to-emitter voltage.

**Base transportation factor ($\alpha_T$):** The ratio of number of majority charge carriers arriving at collector to number of emitted majority charge carriers.

**CB configuration:** Common base configuration *i.e.* base terminal is common to both input and output ports.

**CC configuration:** Common collector configuration *i.e.* collector terminal is common to both input and output ports.

**CE configuration:** Common emitter configuration *i.e.* emitter terminal is common to both input and output ports.

**Collector junction:** *pn*-junction present in between base and collector regions of transistor.

**Emitter efficiency ($\gamma_e$):** The ratio of emitter current due to majority charge carriers (electrons in case of n-p-n and holes in case of p-n-p transistors) flow to total emitter current.

**Emitter junction:** *pn*-junction present in between emitter and base regions of transistor.

**$\gamma$:** Common collector AC current gain. It is the ratio of change in emitter current to change in base current for a given emitter-to-collector voltage. Also referred as $h_{fc}$.

**$\gamma_{DC}$:** Common collector DC current gain. It is the ratio of emitter current to base current for a given emitter-to-collector voltage.

**$I_{CBO}$:** Collector leakage current in common base configuration. Subscript CBO signifies that this current flows between **C**ollector and **B**ase while third terminal (*i.e.* emitter) is **O**pen.

**$I_{CEO}$:** Collector leakage current in common emitter configuration. Subscript CEO signifies that this current flows between **C**ollector and **E**mitter while third terminal (*i.e.* base) is **O**pen.

**Injection ratio:** Same as emitter efficiency.

**Interacting junctions:** The two semiconductor pn-junctions, which can achieve transistor action *e.g.* emitter-base junction and base-collector junction.

**Non-interacting junctions:** The two semiconductor pn-junctions, which cannot achieve transistor action *e.g.* two back-to-back connected diodes.

# Bipolar junction transistor

**Transistor action:** Phenomenon in which majority charge carriers injected from emitter terminal into the forward biased emitter junction can result in large collector current in a reverse biased collector junction.

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