UNIT 2: TRANSISTORS

Bipolar Transistors

The arrangement of a bipolar transistor is shown schematically in Fig.1. It is quite simple. Between the two *p*-type regions there is a narrow region of the *n*-type semiconductor. That is why it is called the *p*-*n*-*p* transistor. The names of the two parts of the structure are known to us from the previous chapter: *emitter* and *base*. The name of the third part is the *collector*. In a similar way one can obtain a transistor of the *n*-*p*-*n* type. Then a narrow strip of a *p*-type semiconductor is to be placed between the two *n*-regions. The physical principles of operation of both structures (*p*-*n*-*p* and *n*-*p*-*n*) are absolutely the same. If one gets a good idea of the work of a *p*-*n*-*p* transistor, he or she will be able to quite easily analyse the work of the *n*-*p*-*n* structure.

The structure shown in Fig. 1 can be described in another way, and namely as a *p*-*n* junction which is quite familiar to us, to which one more *p*-region has been added. Or, otherwise, as two *p*-*n* junctions located very close to each other, and having a common base. How can this simple structure fulfill its main mission — to amplify the electric signals?

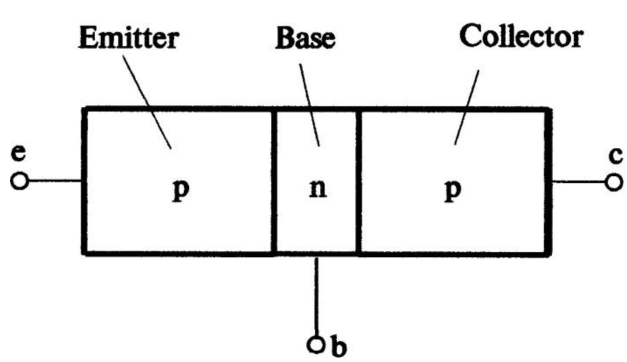


Fig. 1. Schematic diagram of the bipolar *p*-*n*-*p* transistor.

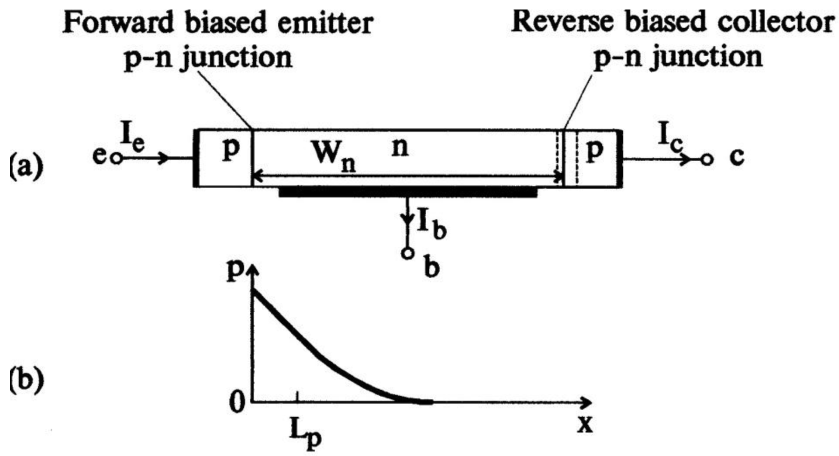


Fig. 2. Principle of operation of the structure with a "long" base. The base width W_n is much greater than the hole diffusion length L_p $(W_n/L_p \gg 1)$. (a) the *p-n-p* structure with a "long" base; (b) the hole distribution in the base . The holes which have entered the base from the emitter recombine without reaching the collector.

Principle of Operation of a Bipolar Transistor

For the transistor to be able to cope with its tasks, it is necessary that certain biases be applied to the *p-n* junctions forming the transistor structure.

The reverse bias must be applied to the collector *p-n* junction (the *p-n* junction between the base and the collector). On the opposite, the forward bias should be applied to the emitter junction of a transistor (the *p-n* junction between the emitter and the base).

To have the necessary biases at the junctions one must connect the transistor to the external circuit containing a bias source (or sources), resistors, capacitors, etc. Such circuits may vary in types. Some of them will be described below. But now we will concentrate our attention not on the ways of creating the necessary biases, but on how the transistor acquires an ability to amplify signals, provided the necessary conditions are satisfied.

In order to have a better idea of the working principle of the transistor, let us assume, at the beginning, that the base of the transistor is not short, but long (Fig. 2). However, it is necessary to define what is meant, strictly speaking, by the terms "long" and "short". What are they compared to?

The width of the *n*-base W_n of the transistor is always estimated according to its ratio to the diffusion length of the holes in the base L_p. Actually in the transistors the relation W_n/L_p is always much less than unity (the base is narrow).

But we wanted first to discuss the work of the structure with a long base, in which $W_n/L_p \gg 1$ (Fig. 2). We know everything about that structure. It presents just two diodes, one of which, the left one, is forward biased, while the other, the right diode, is reverse biased. The fact that they have a common base does not affect their work at all. Nevertheless, let us again fix our attention on the working peculiarities of the junctions which are most important when analysing the transistor. A small reverse current I_c flows across the collector junction of the structure. This current is formed firstly by electrons and holes, born in the space charge region (the generation current), and secondly, by minority carriers — holes of the *n*-base and electrons of the *p*-collector which happened to come too close to the junction (the diffusion current). Let us recall again (it is very important!) that any hole born in the *n*-base at a distance from the *p*-*n* junction, shorter than the diffusion length of the holes L_p, has a good chance of getting within the space charge region. Should that happen, the electric field of the reverse biased collector junction will immediately toss that hole out of the base into the collector .

Now let us turn our attention to the left forward biased emitter junction. The emitter of the transistor structure is always doped much stronger than the base. Therefore the mechanism of the current flowing across the emitter junction is exactly the same as that of the direct current flowing across the very asymmetric *p*-*n* junction, which had been analysed by us in detail. As we remember, the current across such a junction can be described in different ways. To analyse the work of the transistor, it is most convenient to start from the base electrode of the structure, as we had done before.

The fact that the current I_b is flowing across the base electrode of the structure means that every second $N = I_b/q$ electrons enter the base (from the external source not shown in the figure). They cannot be stored in the base in a steady state, because that state corresponds to the situation when nothing in the base changes in time, including the carrier concentration.

The electrons cannot go to the collector, because the strong field of the reverse biased collector junction forms a high potential barrier and pushes very energetically the electrons back to the base . Neither can they go to the highly doped emitter . So what happens to them? They perish in the base, recombining with the holes, entering the base from the emitter through the forward biased emitter *p*-*n* junction!

The number of electrons that pass per unit time through the base electrode is the same as the number of holes which enter the base in the same period of time through the *p*-*n* junction from the emitter to the base. Speaking figuratively, one can imagine that as soon as the negatively charged electrons enter the base, they provoke the positively charged holes to leave the emitter and, diffusing across the base, kill them at the cost of their own lives.

In the structure with a long base, shown in Fig. 2(a) the holes practically fully recombine at a distance equal to several diffusion lengths L_p without reaching the collector junction. And what happens in an actual transistor structure with a short base?

Considering the processes in a real transistor structure with a short base ($W_n/L_p < 1$), it is important, first of all, to realize that the emitter and collector junctions in such a structure cannot be regarded as two isolated *p*-*n* junctions.

Why?

Because, as we have just now explained, as soon as the current appears in the base electrode of the structure, it is immediately followed by the injection of holes from the emitter into the base. On the other hand, as we know, any hole which appears in the base (its distance from the collector junction being smaller than the value L_p), has a good chance of being thrown by the field of the junction from the base into the collector. But in a transistor structure with a short base ($W_n/L_p < 1$) every hole in the base is at a distance shorter than L_p from the collector junction!

It is quite clear that part of the holes which come to the base from the emitter are sure to get to the space charge region of the collector junction. These holes will be thrown away to the collector. That means that the collector current I_c will now be determined not only (and even not so much) by the current of the reverse-biased collector junction, but also by the current of the holes flowing from the base to the collector.

The current of holes, captured by the collector, depends on the rate of the holes coming to the base, i.e. on the emitter current I_e. And that current, in its turn, depends on the magnitude of the base current I_b.

So, the currents, flowing across all the three electrodes of the structure, prove to be dependent on each other. Our task is to establish this dependence.

Current amplification

Let a structure with a short base have the base current I_b (Fig. 3). Every second $N = I_b/q$ electrons enter the base. Provoked by those electrons,

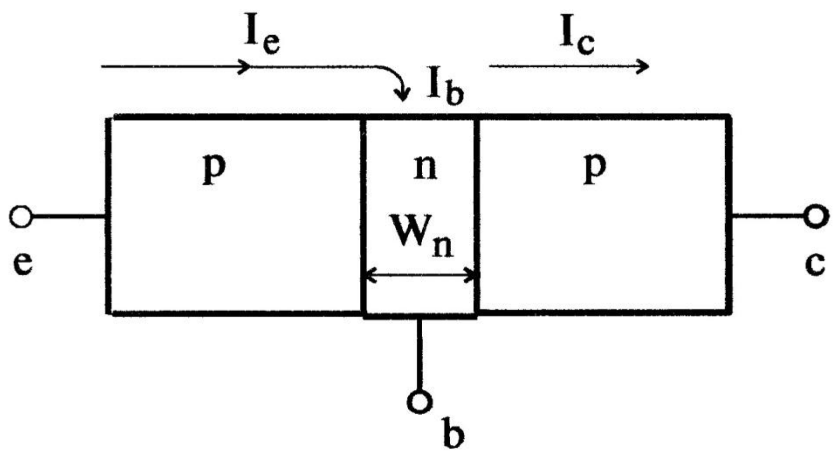


Fig. 3. The transistor structure with a “short” base. The greater part of holes passes into the collector, forming a collector current I_e. Only a small part of holes recombines in the base forming a small base current I_b.

the holes leave the emitter to kill the electrons and die. Should the base be long, the number of the electrons which might enter the base would be equal to the number of holes coming from the emitter. But in the structure with a short base it is not so. Part of the holes which enter the base will be intercepted by the field of the collector and will be thrown away from the base. They will have no time to recombine with the electrons.

Though all the electrons which enter the base must recombine by all means. They can neither leave the base, nor be stored there. That means that the number of holes which the emitter throws into the base must be greater than the number of the electrons which enter it. So, in spite of the fact that some holes will get to the collector, their number must be sufficient to provide the recombination of all the electrons that enter the base.

The thinner the base, the greater the portion of holes which enter the base, is intercepted by the collector.

If the base is short ($W_n/L_p \ll 1$), then the portion of the holes α, intercepted by the collector, is described by a simple expression

$$\alpha = 1 - W_n^2/2L_p^2 \qquad (1)$$

The less W_n/L_p, the shorter the distance from the collector to the emitter junction, the greater is, naturally, the part of the holes which pass through the base and which are then thrown into the collector without having time to recombine. The relation W_n/L_p in the transistors usually lies within the limits from ≈ 0.5 to 0.05, depending on their type and function. Thus, the value of the coefficient α, which is usually called the *base transport factor*, for different transistors may vary from ≈ 0.9 to 0.999. The term "*base transport factor*" sounds quite natural for the value α. Indeed, it is this value that determines the portion of the holes, transported across the base, due to the process of diffusion, from the emitter to the collector.

So, the collector intercepts the lion's share of the holes which arrive from the emitter — from 0.9 to 0.999. Only quite a small part of the holes, from 0.1 to 0.001 (Fig. 3), recombines with the electrons which come to the base.

But this conclusion, which in such wording sounds quite pessimistic, can be formulated differently, thus making it sounds like a victorious call deserving a Nobel Prize!

The current which gets to the transistor base causes the appearance of the emitter and collector current which is tens, hundreds and even thousands of times greater.

Thus, if the current which must be amplified is applied to the transistor base, and the output signal is registered in the collector or emitter circuit, the signal will be amplified tens, hundreds and even thousands of times. The current amplification factor (*current gain*) of the transistor β is determined by the ratio of the current of the collector to that of the base: $\beta = I_c/I_b$, and, naturally, the thinner the base, i.e. the less is the value of W_n/L_p, the larger the β.

Let us now define the relation between the currents flowing across the electrodes of the transistor. It is not difficult to do it: the current of the collector I_c is, as we know, a combination of two components — the reverse current of the junction and the current of the holes coming to the collector from the emitter. In the overwhelming majority of cases, the second component is many times larger.

Then

$I_c = \alpha I_e$ (2)

On the other hand

$Ie = Ib + Ic$ (3)

Equation (54) just reflects the fact, which is quite evident to us, that the holes which have left the emitter either recombine in the base (I_b) or leave for the collector (I_c). From Eqs. (53) and (54) it follows that

$$I_c = \frac{\alpha I_b}{1 \quad \alpha} = \beta I_b \qquad (4) -$$

where the current gain of the transistor β is equal to

$$\beta = \frac{\alpha}{\alpha - 1} \qquad (5)$$

With $\alpha = 0.9$, $\beta = 9$; $\beta = 999$ corresponds to the value $\alpha = 0.999$.

The above mechanism of amplifying the current by the transistor forms the basis of the operation of a bipolar transistor.

By the way, why do we say a bipolar transistor? As we know, the carriers of both types — electrons and holes — are equally important for the transistor operation. The electrons enter the *n*-base of the *p-n-p* transistor and cause the appearance of the hole current in both the emitter and collector, that current being much stronger.[1]

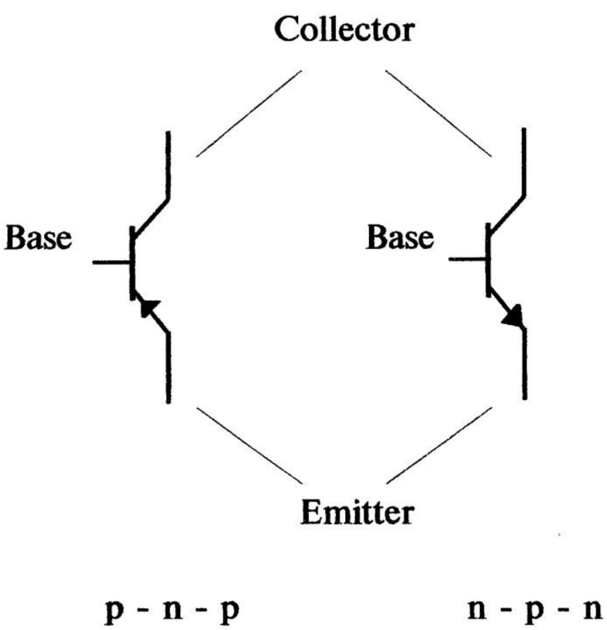


Figure 4: Circuit symbols of Bipolar junction transistors

Different Configurations of Transistors

In this transistor unit, we will learn about Different Configurations of Transistors. Since a Bipolar Junction Transistor is a 3-terminal device, there are three different configurations of Transistors possible with BJTs. Understanding these different configurations of transistors will help you in better implementation of your application.

Introduction

[1] In the transistor structure of the *n-p-n* type, whose work we hope you'll analyse yourself, the holes which enter the *p*-base cause the appearance of the electron current in both the emitter and collector, that current being many times stronger.

We know that generally the transistor has three terminals – emitter (E), base (B) and collector. But in the circuit connections we need four terminals, two terminals for input and another two terminals for output. To overcome these problems we use one terminal as common for both input and output actions.

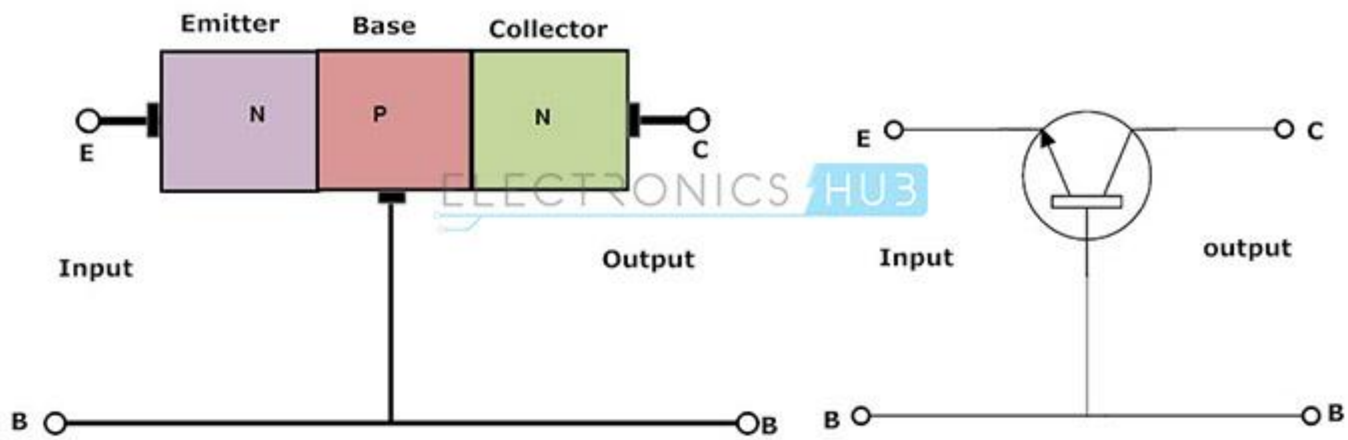
Using this property we construct the circuits and these structures are called transistor configurations. Generally there are three different configurations of transistors and they are common base (CB) configuration, common collector (CC) configuration and common emitter (CE) configuration.

The behavior of these three different configurations of transistors with respect to gain is given below.

- **Common Base (CB) Configuration**: no current gain but voltage gain
- **Common Collector (CC) Configuration**: current gain but no voltage gain
- **Common Emitter (CE) Configuration**: current gain and voltage gain

Now we discuss about these three different configurations of transistors with their input and output characteristics in the below sections.

Common Base Configuration



In this configuration we use base as common terminal for both input and output signals. The configuration name itself indicates the common terminal. Here the input is applied between the base and emitter terminals and the corresponding output signal is taken between the base and collector terminals with the base terminal grounded. Here the input parameters are V_{EB} and I_E and the output parameters are V_{CB} and I_C. The input current flowing into the emitter terminal must be higher than the base current and collector current to operate the transistor, therefore the output collector current is less than the input emitter current.

The current gain is generally equal or less than to unity for this type of configuration. The input and output signals are in-phase in this configuration. The amplifier circuit configuration of this type is called as non-inverting amplifier circuit. The construction of this configuration circuit is difficult because this type has high voltage gain values.

The input characteristics of this configuration are looks like characteristics of illuminated photo diode while the output characteristics represents a forward biased diode. This transistor configuration has high output impedance and low input impedance. This type of configuration has high resistance gain i.e. ratio of output resistance to input resistance is high. The voltage gain for this configuration of circuit is given below.

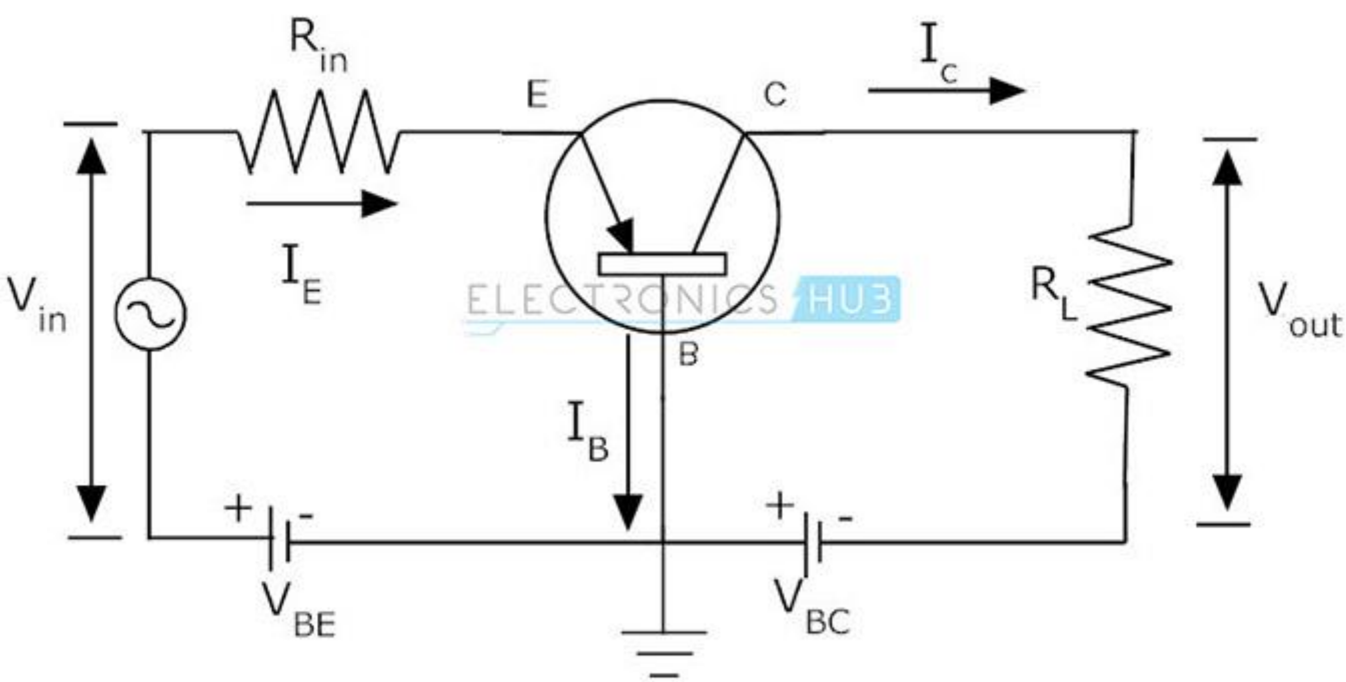
$A_V = V_{out}/V_{in} = (I_C*R_L) / (I_E*R_{in})$

Current gain in common base configuration is given as

α = Output current/Input current

$\alpha = I_C/I_E$

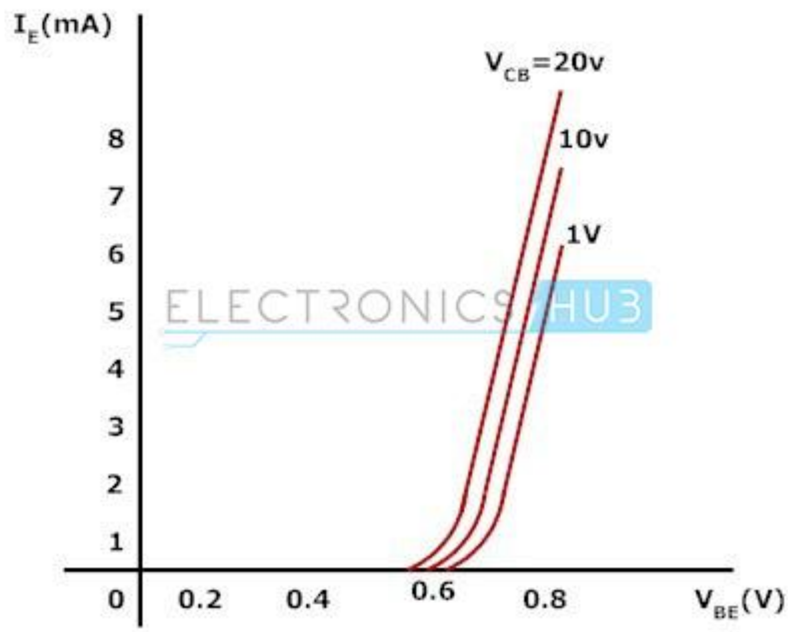
The common base circuit is mainly used in single stage amplifier circuits, such as microphone pre amplifier or radio frequency amplifiers because of their high frequency response. The common base transistor circuit is given below.



Input Characteristics

Input characteristics are obtained between input current and input voltage with constant output voltage. First keep the output voltage V_{CB} constant and vary the input voltage V_{EB} for different points then at each point record the input current I_E value. Repeat the same process at different output voltage levels. Now with these values we need to plot the graph between I_E and V_{EB} parameters. The below figure show the input characteristics of common base configuration. The equation to calculate the input resistance R_{in} value is given below.

$R_{in} = V_{EB} / I_E$ (when V_{CB} is constant)

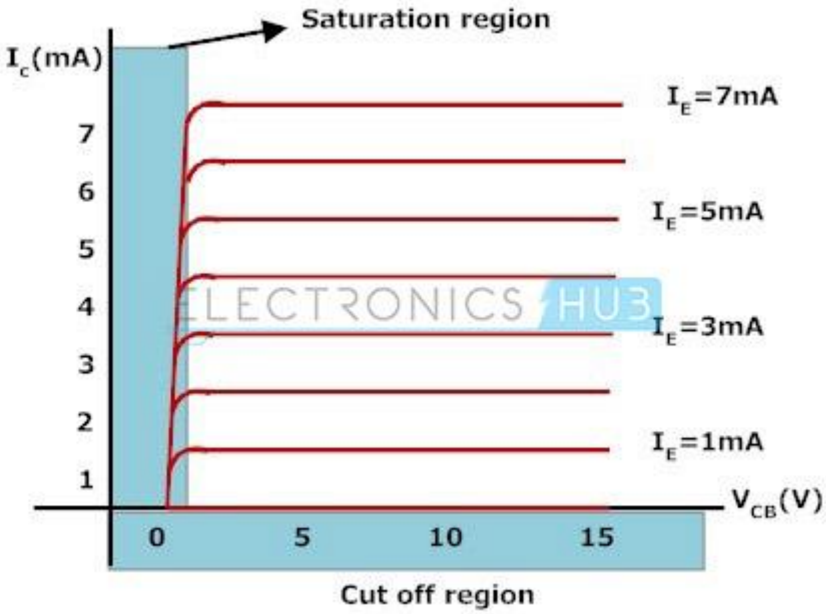


Output Characteristics

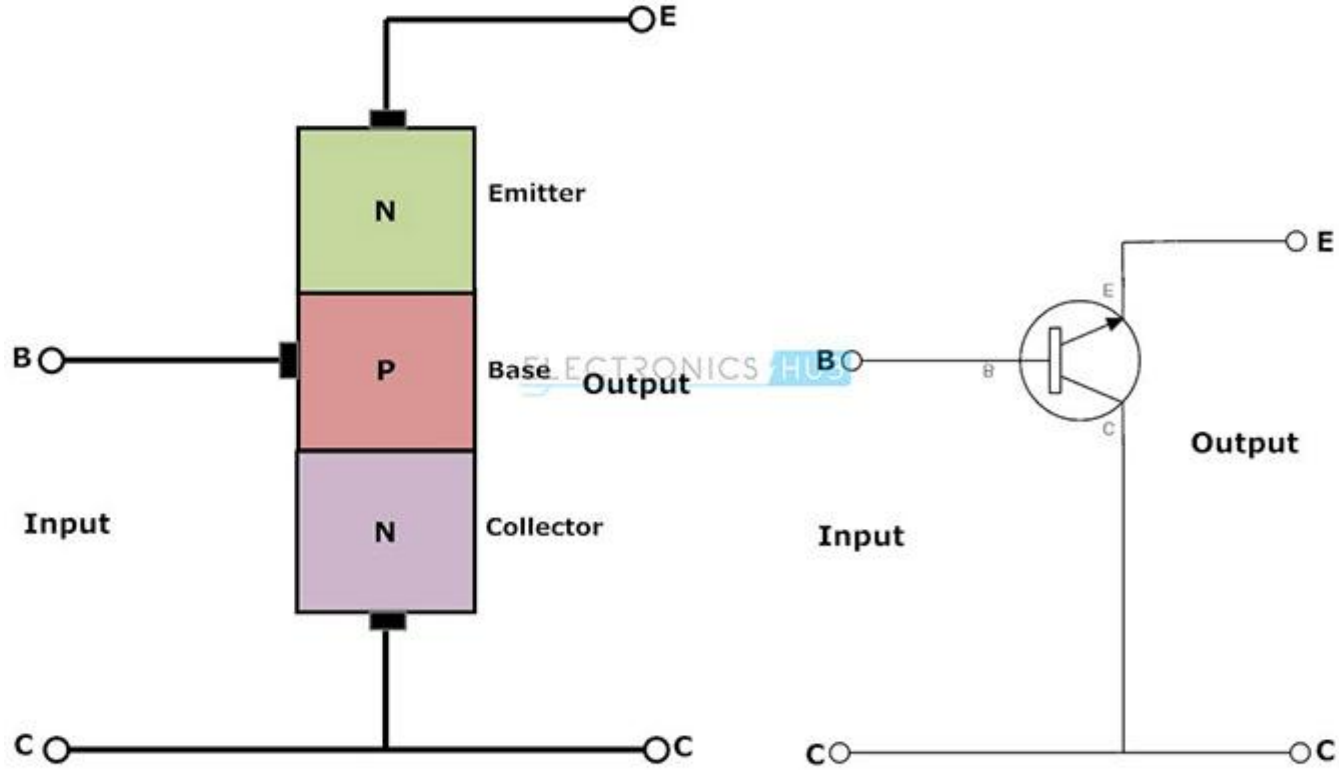
The output characteristics of common base configuration are obtained between output current and output voltage with constant input current. First keep the emitter current constant and vary the V_{CB} value for different points, now record the I_C values at each point. Repeat the same process at different I_E values. Finally we need to draw the plot between V_{CB} and I_C at constant

I_E. The below figure show the output characteristics of common base configuration. The equation to calculate the output resistance value is given below.

$R_{out} = V_{CB} / I_C$ (when I_E is constant)



Common Collector Configuration



In this configuration we use collector terminal as common for both input and output signals. This configuration is also known as emitter follower configuration because the emitter voltage follows the base voltage. This configuration is mostly used as a buffer. These configurations are widely used in impedance matching applications because of their high input impedance.

In this configuration the input signal is applied between the base-collector region and the output is taken from the emitter-collector region. Here the input parameters are VBC and IB and the output parameters are VEC and IE. The common collector configuration has high input impedance and low output impedance. The input and output signals are in phase. Here also the emitter current is equal to the sum of collector current and the base current. Now let us calculate the current gain for this configuration.

Current gain,

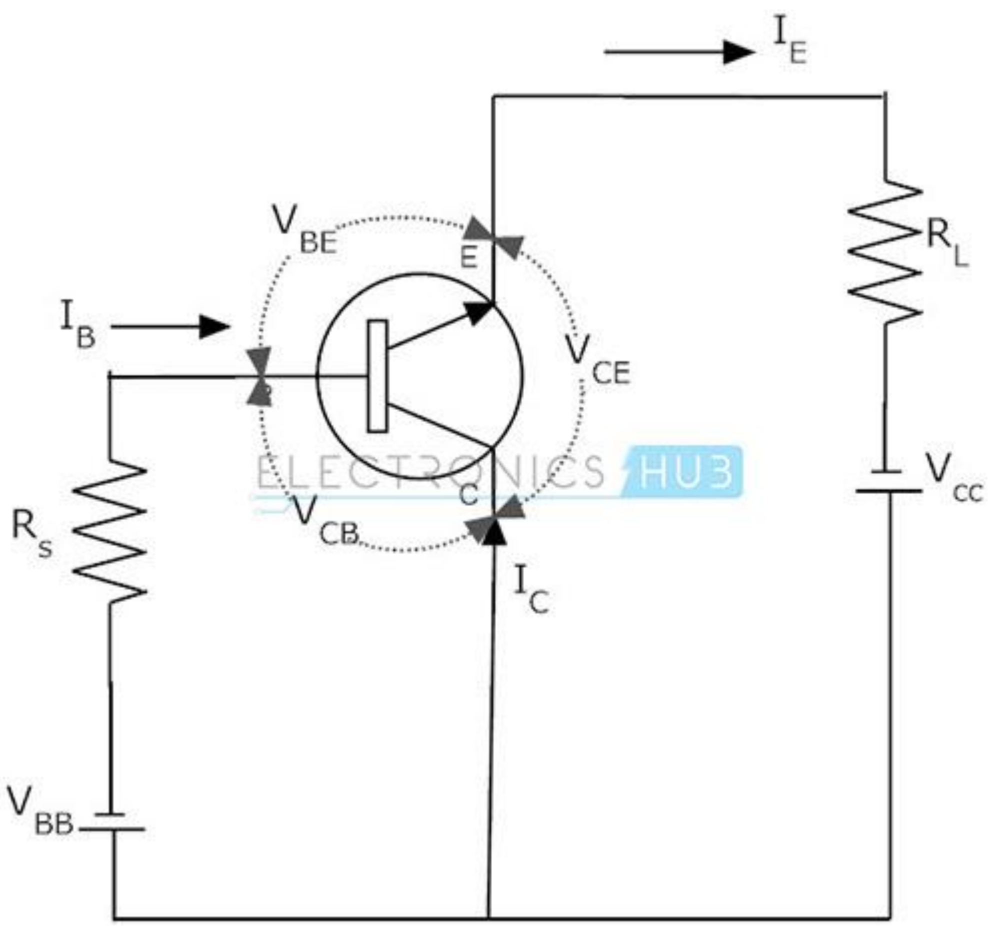
A_i = output current/Input current

$$A_i = I_E/I_B$$

$$A_i = (I_C + I_B)/I_B$$

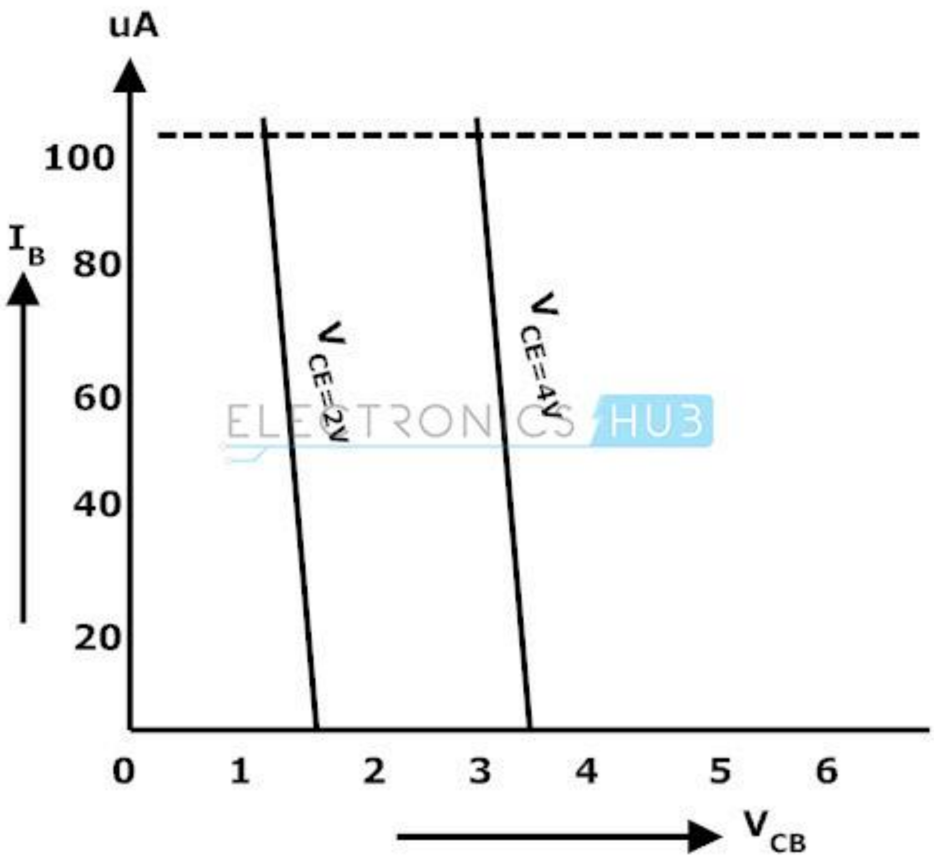
$$A_i = (I_C/I_B) + 1$$

$$A_i = \beta + 1$$



The common collector transistor circuit is shown above. This common collector configuration is a non inverting amplifier circuit. The voltage gain for this circuit is less than unity but it has large current gain because the load resistor in this circuit receives both the collector and base currents.

Input Characteristics



The input characteristics of a common collector configuration are quite different from the common base and common emitter configurations because the input voltage V_{BC} is largely determined by V_{EC} level. Here,

$V_{EC} = V_{EB} + V_{BC}$

$V_{EB} = V_{EC} – V_{BC}$

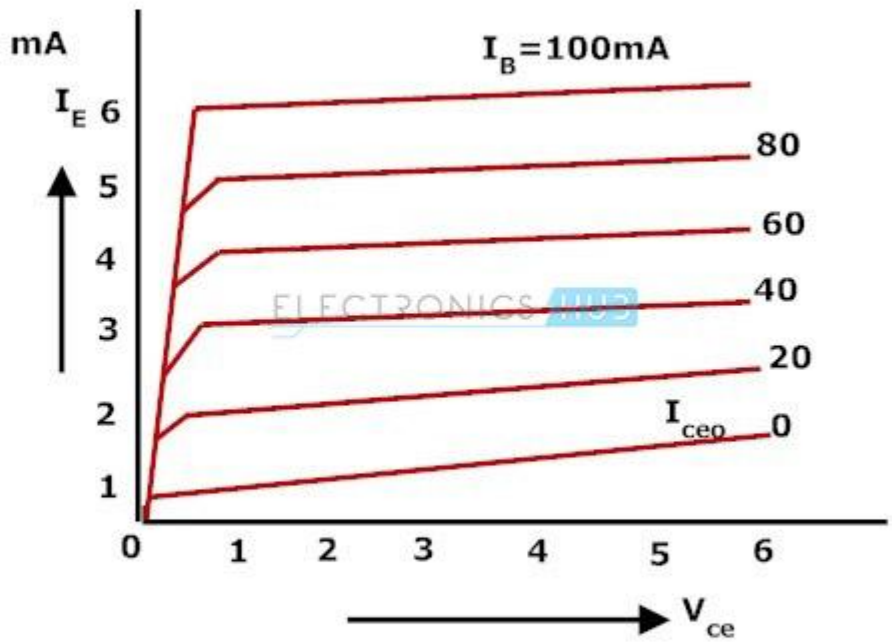
The input characteristics of a common-collector configuration are obtained between inputs current I_B and the input voltage V_{CB} at constant output voltage V_{EC}. Keep the output voltage

V_{EC} constant at different levels and vary the input voltage V_{BC} for different points and record the I_B values for each point. Now using these values we need to draw a graph between the parameters of V_{BC} and I_B at constant V_{EC}.

Output Characteristics

The operation of the common collector circuit is same as that of common emitter circuit. The output characteristics of a common collector circuit are obtained between the output voltage V_{EC} and output current I_E at constant input current I_B. In the operation of common collector circuit if the base current is zero then the emitter current also becomes zero. As a result no current flows through the transistor

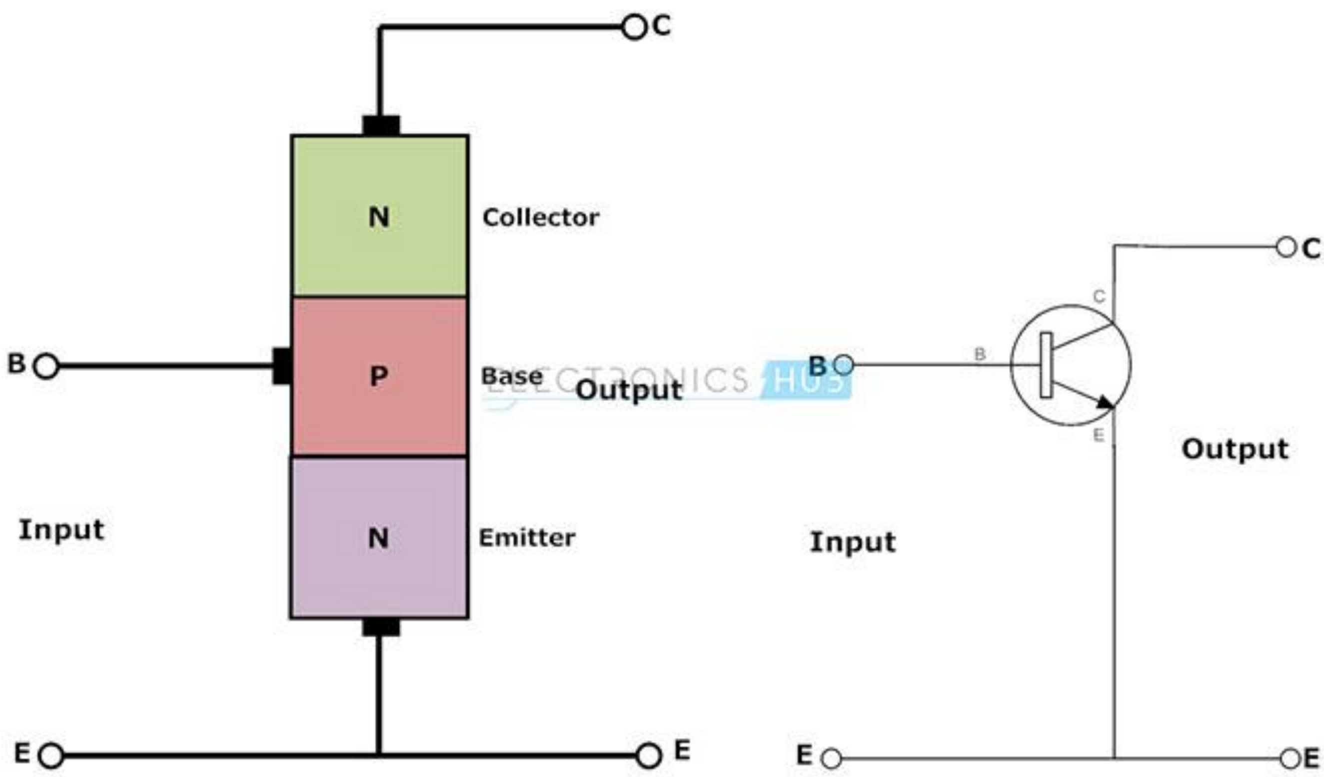
If the base current increases then the transistor operates in active region and finally reaches to saturation region. To plot the graph first we keep the I_B at constant value and we will vary the V_{EC} value for various points, now we need to record the value of I_E for each point. Repeat the same process for different I_B values. Now using these values we need to plot the graph between the parameters of I_E and V_{CE} at constant values of I_B. The below figure show the output characteristics of common collector.



Common Emitter Configuration

In this configuration we use emitter as common terminal for both input and output. This common emitter configuration is an inverting amplifier circuit. Here the input is applied between base-emitter region and the output is taken between collector and emitter terminals. In this configuration the input parameters are V_{BE} and I_B and the output parameters are V_{CE} and I_C.

This type of configuration is mostly used in the applications of transistor based amplifiers. In this configuration the emitter current is equal to the sum of small base current and the large collector current. i.e. $I_E = I_C + I_B$. We know that the ratio between collector current and emitter current gives current gain alpha in Common Base configuration similarly the ratio between collector current and base current gives the current gain beta in common emitter configuration.



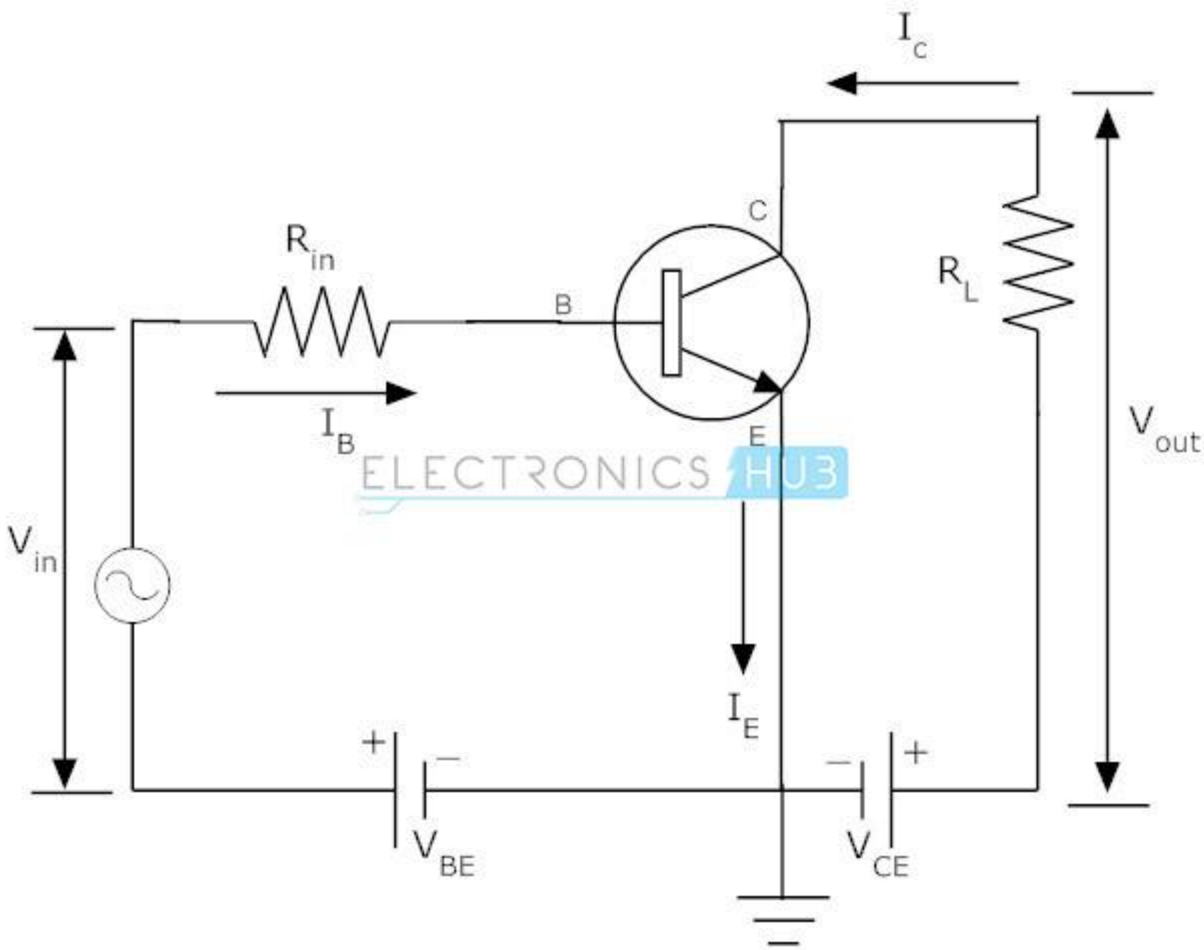
Now let us see the relationship between these two current gains.

Current gain (α) = I_C/I_E

Current gain (β) = I_C/I_B

Collector current $I_C = \alpha I_E = \beta I_B$

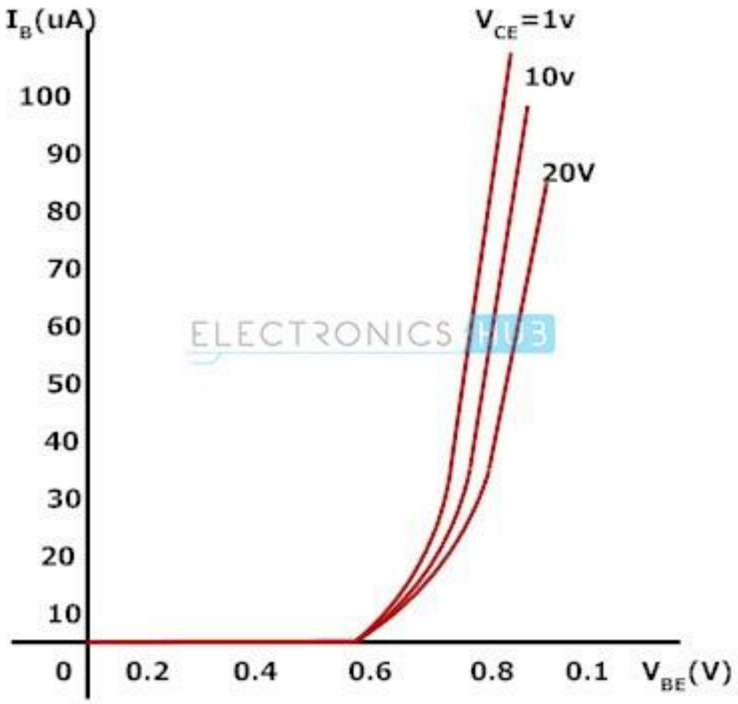
This configuration is mostly used one among all the three configurations. It has medium input and output impedance values. It also has the medium current and voltage gains. But the output signal has a phase shift of 1800 i.e. both the input and output are inverse to each other.



Input Characteristics

The input characteristics of common emitter configuration are obtained between input current I_B and input voltage V_{BE} with constant output voltage V_{CE}. Keep the output voltage V_{CE} constant and vary the input voltage V_{BE} for different points, now record the values of input current at each point. Now using these values we need to draw a graph between the values of I_B and V_{BE} at constant V_{CE}. The equation to calculate the input resistance R_{in} is given below.

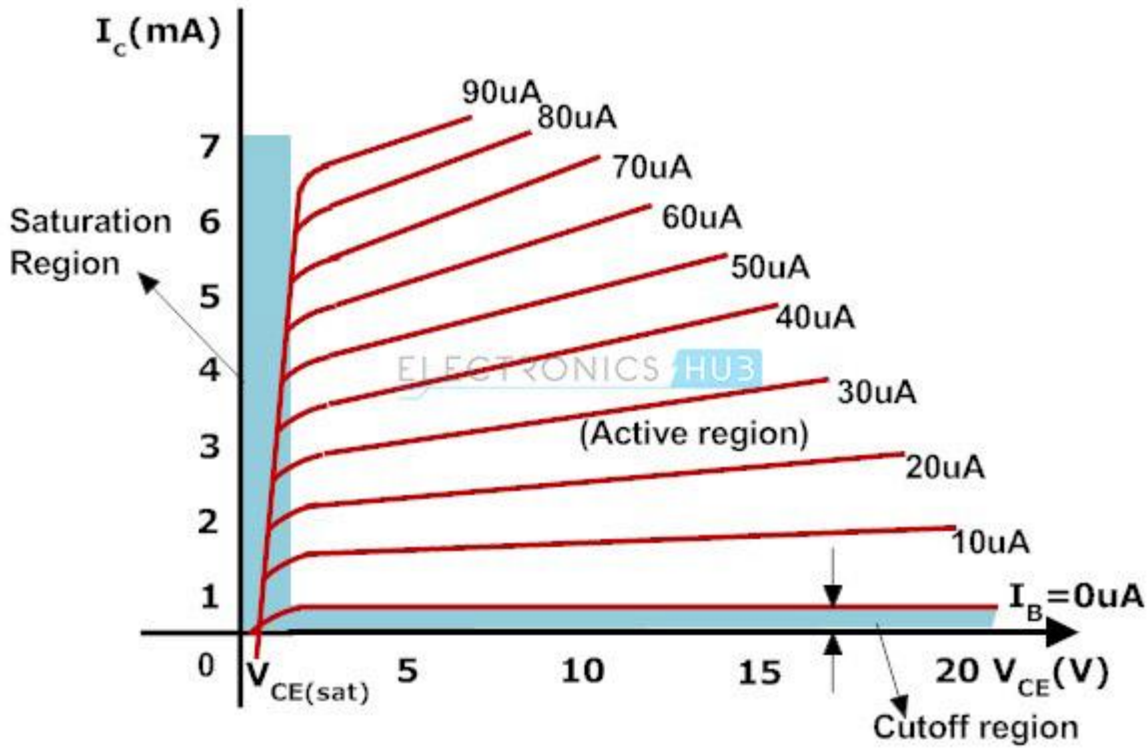
$R_{in} = V_{BE}/I_B$ (when V_{CE} is at constant)



Output Characteristics

The output characteristics of common emitter configuration are obtained between the output current I_C and output voltage V_{CE} with constant input current I_B. Keep the base current I_B constant and vary the value of output voltage V_{CE} for different points, now note down the value of collector I_C for each point. Plot the graph between the parameters I_C and V_{CE} in order to get the output characteristics of common emitter configuration. The equation to calculate the output resistance from this graph is given below.

$R_{out} = V_{CE}/I_C$ (when I_B is at constant)



Configurations of Transistors Summary

Transistor Configuration Summary Table			
Transistor Configuration	**Common Base**	**Common Collector (Emitter Follower)**	**Common Emitter**
Voltage Gain	High	Low	Medium
Current Gain	Low	High	Medium
Power Gain	Low	Medium	High
Input / Output Phase Relationship	0°	0°	180°
Input Resistance	Low	High	Medium
Output Resistance	High	Low	Medium

The table which gives the main characteristics of a transistor in the three configurations is given above. The BJT transistors have mainly three types of configurations. They are common-emitter, common-base and common-collector configurations. Among all these three configurations common-emitter configuration is mostly used type. These three have different characteristics corresponding to both input and output signals. And also these three configurations have few similarities.