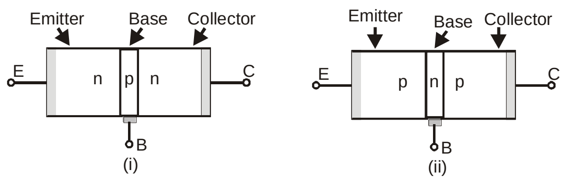
SEMICONDUCTOR ELECTRONICS

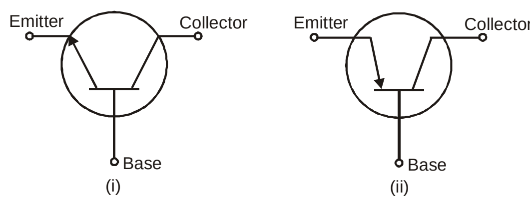
TRANSISTER

JUNCTION TRANSISTOR

Transistor structure and action:
A transistor is composed of three doped regions, giving rise to two p–n junctions situated between them. The figure illustrates two distinct types of transistors, each characterized by its arrangement of doped regions and semiconductor materials.



(a) Schematic representations of a n–p–n transistor and p–n–p transistor



(b) Symbols for n–p–n and p–n–p transistors.

(i) n–p–n transistor:
In this configuration, two segments of n–type semiconductor (specifically, the emitter and collector) are positioned on either side of a segment of p–type semiconductor, known as the base. The schematic representation of an n–p–n transistor is depicted in the figure.

(ii) p–n–p transistor:
In contrast, the p–n–p transistor features two segments of p–type semiconductor, identified as the emitter and collector, separated by a segment of n–type semiconductor acting as the base. The figure provides a visual representation of the schematic configuration for a p–n–p transistor.

Both types of transistors exhibit variations in the thickness and doping levels of their three segments. The schematic symbols employed to represent these p–n–p and n–p–n transistors, as shown in Figure (b), incorporate an arrowhead indicating the direction of conventional current flow within the transistor.

The distinctive characteristics of the three segments of a transistor are briefly outlined below, encompassing the emitter, base, and collector. These components play pivotal roles in the functionality of the transistor, influencing the control and amplification of electrical signals within electronic circuits.

Emitter:

This segment, depicted on one side of the transistor in Figure (a), exhibits a moderate size and is characterized by a high level of doping. Its primary function is to provide a substantial quantity of majority carriers, facilitating the flow of current throughout the transistor. The heavy doping ensures that this region contributes significantly to the availability of charge carriers, thereby influencing the overall conductivity and performance of the transistor.

Base:

This represents the central segment of the transistor. Notably, it possesses a slender profile and is characterized by a low doping level. The thinness and light doping of this segment are distinctive features. Despite its modest size, this central region plays a crucial role in the transistor's functionality, influencing the control and modulation of the current flow. Its unique characteristics contribute to the precision and sensitivity of the transistor's overall performance within electronic circuits.

Collector:

This segment, designated as the collector, plays a crucial role in the transistor's operation. It functions to gather a significant portion of the majority carriers supplied by the emitter. The collector region is characterized by being moderately doped and larger in size compared to the emitter. This size disparity is intentional, allowing for efficient dissipation of heat generated during the collection of charge carriers into the surrounding atmosphere.

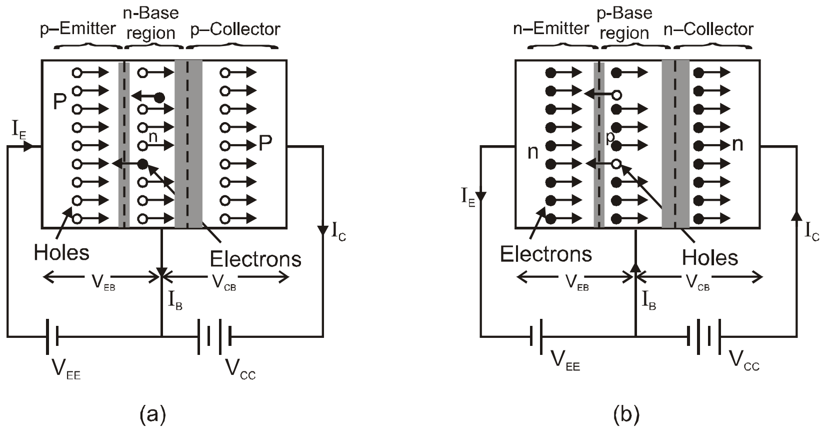
In the context of a p–n junction, the formation of a depletion region occurs across the junction. Similarly, in a transistor, two depletion regions are established: one at the emitter-base junction and the other at the base-collector junction.

The transistor operates as an amplifier with the emitter-base junction forward-biased and the base-collector junction reverse-biased. This biasing configuration is depicted in the figure, where VCC and VEE are utilized for creating the respective biases. When the transistor is biased in this manner, it is said to be in the active state.

The figure illustrates the voltage between the emitter and base as VEB and that between the collector and base as VCB. The base serves as a common terminal for two power supplies, represented as VEE' and VCC' respectively, where VEE' corresponds to the power supply between the base and emitter in circuits where the emitter is the common terminal.

The heavily doped emitter possesses a high concentration of majority carriers, which are either holes in a p–n–p transistor or electrons in an n–p–n transistor. These majority carriers enter the thin and lightly doped base region in large numbers. In the case of a p–n–p transistor, where the base is of n–type semiconductor, the majority carriers in the base are electrons. The substantial number of holes entering the base from the emitter overwhelms the limited number of electrons present.

As the base-collector junction is reverse-biased, the holes, considered as minority carriers at the junction, can easily traverse the junction and enter the collector. These holes in the base region can either move toward the base terminal to combine with electrons entering from outside or cross the junction to enter the collector, reaching the collector terminal. The thinness of the base is intentional, ensuring that a significant proportion of holes find themselves near the reverse-biased base-collector junction, facilitating their crossing of the junction rather than moving toward the base terminal. This strategic design enhances the efficiency of the transistor's operation.



Bias Voltage applied on : (a) p–n–p transistor and (b) n–p–n transistor

Note:
As a result of the forward bias, a substantial current flows into the emitter–base junction, with a significant portion of it being redirected towards the adjacent reverse-biased base–collector junction. Consequently, the current emerging from the base becomes a minute fraction of the total current that initially entered the junction. If we denote the hole current and electron current crossing the forward-biased junction by the sum $I_h + I_e$, we observe that the emitter current $I_E = I_h + I_e$, but the base current IB is considerably smaller than $I_h + I_e$. This is due to a major part of I_E being directed toward the collector instead of exiting through the base terminal. Therefore, the base current is a small fraction of the emitter current. It is evident from this explanation, and by applying Kirchhoff's law to Figure (a), that the emitter current is the sum of the collector current and base current: $I_E = I_C + I_B$. Additionally, we note that $I_C \approx I_E'$.

The description of the motion of holes aligns with the direction of conventional current. However, the motion of electrons is in the opposite direction to the current. In a p–n–p transistor, current enters from the emitter into the base, whereas in an n–p–n transistor, it enters from the base into the emitter. The arrowhead in the emitter denotes the direction of conventional current.

In the active state of the transistor, the emitter–base junction behaves as a low-resistance path, while the base–collector junction acts as a high-resistance path.

A transistor has only three terminals: emitter (E), base (B), and collector (C). Consequently, in a circuit, the input/output connections must be such that one of these terminals (E, B, or C) is common to both the input and output. Accordingly, transistors can be connected in one of three configurations: Common Emitter (CE), Common Base (CB), and Common Collector (CC).

Working of Transistor

(1) There exist four distinct methods for biasing the two P-N junctions, namely the emitter junction and the collector junction, of a transistor:

(i) Active Mode: Also recognized as linear mode operation, this mode entails the typical functioning of the transistor as an amplifier, allowing for a proportional amplification of the input signal.

(ii) Saturation Mode: In this mode, the transistor experiences the maximum collector current flow, causing it to function as a closed switch from the collector to emitter terminals. This mode is characterized by the transistor being fully turned on.

(iii) Cut-off Mode: This mode corresponds to the operation of an open switch, where only minimal leakage current flows through the transistor. In this state, the transistor is effectively turned off.

(iv) Inverse Mode: In this mode, the positions of the emitter and collector are swapped or interchanged, resulting in a distinct operational configuration for the transistor. This mode is characterized by the emitter and collector roles being reversed from their typical orientations.

DIFFERENT MODES OF OPERATION OF A TRANSISTOR		
Operating mode	**Emitter base bias**	**Collector base bias**
Active	Forward	Reverse
Saturation	Forward	Forward
Cut off	Reverse	Reverse
Inverse	Reverse	Forward

(2) Typically, a transistor is employed in the active region of operation, wherein the emitter-base junction is forward biased, and the collector-base junction is reverse biased. This configuration is pivotal for the transistor to function as an amplifier, allowing it to modulate the current flowing through it in response to variations in the input signal.

(3) Observing the operation of a junction transistor reveals a direct relationship between changes in the current within the emitter circuit and corresponding alterations in the collector current. This connection underscores the transistor's role in amplifying signals, as variations in one part of the device lead to proportional adjustments in another.

(4) In every state of the transistor, there exists both an input port and an output port. Generally, the electrical quantities, be it voltage (V) or current (I), obtained at the output are controlled by the input. This characteristic is fundamental to the transistor's function as an active device that processes and amplifies signals based on the variations in its input.

Transistor Configurations

A transistor can be integrated into a circuit using one of three distinct configurations: Common Base (CB), Common Emitter (CE), and Common Collector (CC). Let's delve into the details of the Common Base configuration (CB):

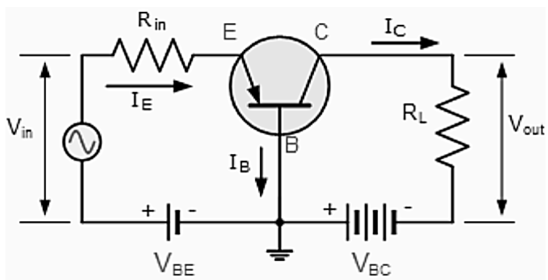
(1) Common Base (CB) Configuration:

- In the CB configuration, the base is shared as the common terminal for both the emitter and collector.

- Key electrical parameters in this configuration include.

(i) Input current (I_e),
(ii) Input voltage (V_{EB}),
(iii) Output voltage (V_{CB}),
(iv) Output current (I_C).

- A noteworthy characteristic of the CB configuration is that a small increase in the emitter-base voltage (V_{EB}) results in a rapid increase in the emitter current (I_e), owing to the small input resistance associated with this configuration.

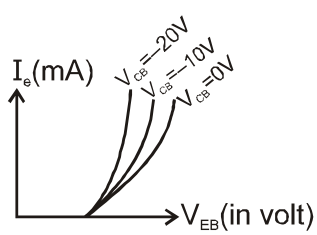


(v) Input Characteristics:

- When V_{CB} is held constant, the plot between I_e and V_{EB} is termed input characteristics. This graph is alternatively referred to as emitter characteristics.

- For an NPN transistor, the input characteristics are similar to the described figure, but both I_e and V_{EB} are negative, while V_{CB} is positive.

- The dynamic input resistance (R_i) of a transistor is defined as $R_i = \frac{V_{EB}}{I_e}$ with V_{CB} held constant. It is notable that R_i typically falls within the order of 100 ohms.

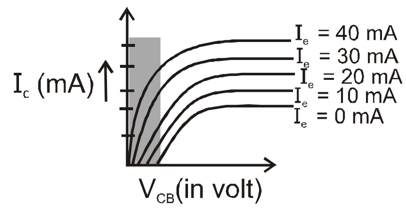


(vi) Output Characteristics:

- The output characteristics of the Common Base (CB) configuration are obtained by maintaining the emitter current (i_e) constant and plotting the curve between the collector current (I_C) and the collector-base voltage (V_{CB}).

- This graphical representation is essential for understanding the behavior of the transistor in the CB configuration under varying external conditions.

- The dynamic output resistance (R_0) is expressed as $R_0 = \frac{V_{CB}}{I_C}$ with i_e held constant. The value of R_0 remains consistent under these conditions.



Note:

Transistor as Common Base (CB) Amplifier:

(i) AC Current Gain (α_c):

- It is defined as the ratio of a small change in collector current (i_c) to a small change in emitter current (i_e).

- Mathematically, $\alpha_c = \frac{\triangle i_e}{\triangle i_e}$.

(ii) DC Current Gain ($\alpha_{dc}\ or\ \alpha$) :

- This gain is expressed as the ratio of collector current (i_c) to emitter current (i_e).

- α_{dc} Typically falls within the range of 0.95 to 0.99.

(iii) Voltage Gain (A_v):

- It is defined as the ratio of the change in output voltage (V_0) to the change in input voltage (V_i).

- Mathematically, $A_v = \alpha_{ac} \times Resistance\ Gain$.

(iv) Power Gain:

- It is expressed as the ratio of the change in output power (P_0) to the change in input power (P_i).

- $Power\ Gain = \alpha_{ac}^2 \times Resistance\ Gain$.

(v) Phase Difference (between Output and Input):

- The phase difference is in the same phase.

(vi) Application:

- Common Base (CB) configuration is commonly employed for high-frequency applications.

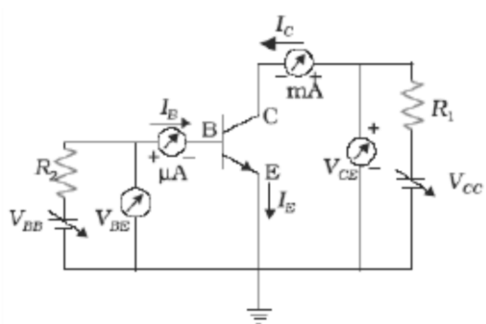
Common Emitter (CE):

The Common Emitter (CE) configuration is the most prevalent application of transistors. In this configuration, the input is applied between the base and the emitter, while the output is taken between the collector and the emitter. The relationship between the base current (I_B) and the base–emitter voltage (V_{BE}) is known as the input characteristic.

In the Common Emitter configuration, the input characteristics play a pivotal role in governing the output characteristics. This signifies that variations in the collector current are contingent upon changes in the base current. The CE configuration is widely utilized due to its favorable characteristics and versatility in amplifying signals in electronic circuits.

CE configurations:

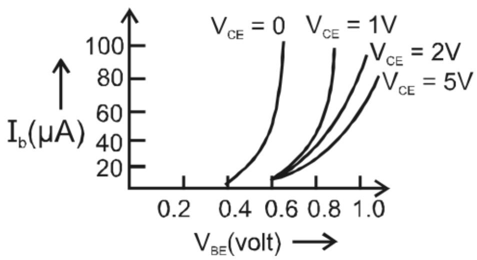
In the Common Emitter (CE) configuration of a transistor, the emitter serves as the common terminal shared by both the base and the collector. Graphical representations depicting the relationships between voltages and currents in scenarios where the emitter of a transistor is common to both the input and output circuits are termed as CE characteristics. These characteristics provide insights into the behavior of the transistor in the CE configuration, offering a visual representation of how various electrical parameters vary with changes in input and output conditions. The CE characteristics are crucial for understanding the transistor's performance and are frequently employed in the analysis and design of electronic circuits.



Input characteristics:

The input characteristics curve is established by plotting the relationship between the base current (I_B) and the emitter-base voltage (V_{EB}) while maintaining a constant collector-emitter voltage (V_{CE}). This graphical representation is pivotal for understanding the behavior of a transistor in the Common Emitter (CE) configuration.

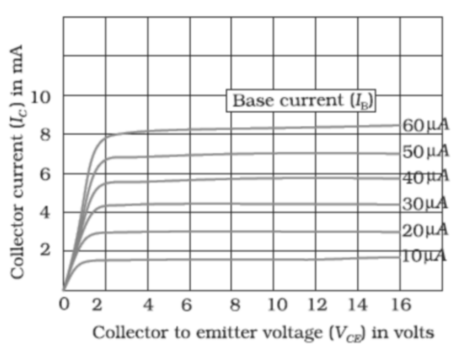
The dynamic input resistance (R_i) is calculated as the ratio of the change in emitter-base voltage (V_{BE}) to the corresponding change in base current (I_B), with the collector-emitter voltage (V_{CE}) held constant. Mathematically,$R_i = \frac{V_{BE}}{I_B}$ where V_{CE} is maintained at a consistent value throughout the analysis. This dynamic input resistance provides valuable insights into the transistor's responsiveness to changes in the input conditions and is a critical parameter in the characterization of transistor behavior in electronic circuits.



Output characteristics:

The change in collector current (I_C) concerning collector-emitter voltage (V_{CE}) is observable within the range of V_{CE} from 0 to 1 volt. The specific value of V_{CE} up to which I_C exhibits variation is referred to as the knee voltage. The transistor is effectively operated in the region above the knee voltage.

The dynamic output resistance (R_0) is calculated as the ratio of the change in collector-emitter voltage (V_{CE}) to the corresponding change in collector current (I_C), with the base current (I_B) held constant. Mathematically, $R_0 = \frac{V_{CE}}{I_C}$ where I_B remains consistent. This dynamic output resistance is a crucial parameter for understanding how the transistor responds to alterations in the output conditions, particularly in the Common Emitter (CE) configuration.



(a) Transistor as a device:

The application of a transistor as a functional device is contingent upon several factors, including the chosen configuration (Common Base, Common Collector, or Common Emitter), the biasing conditions applied to the emitter-base (E-B) and base-collector (B-C) junctions, and the specific operation region—namely, cut-off, active region, or saturation.

The transistor, when operated in the cut-off or saturation state, functions as a switch. In these states, it can either be in a fully turned-off condition (cut-off) or fully turned-on condition (saturation), effectively acting as an electronic switch.

Conversely, to utilize the transistor as an amplifier, it must operate in the active region. The active region is characterized by appropriate biasing conditions and allows the transistor to amplify input signals. The choice of configuration, biasing, and operational region thus determines the transistor's role, whether as a switch or an amplifier, offering versatility in its applications within electronic circuits.

(i) Transistor as a switch:

We aim to comprehend the transistor's functionality as a switch by scrutinizing the behavior of a base-biased transistor in the Common Emitter (CE) configuration, as illustrated in figure (a). By applying Kirchhoff’s voltage rule to both the input and output sides of this circuit, the following relationships are established:

1. Input Side Equation:

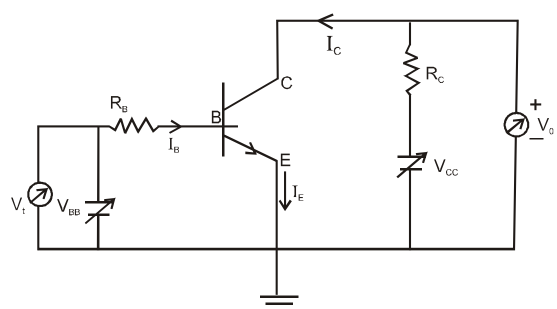
- $V_{BB} = I_B \cdot R_B + V_{BE}$

- This equation reflects the Kirchhoff's voltage rule applied to the input side, where V_{BB} is considered as the dc input voltage (V_i), I_B is the base current, R_B is the base resistance, and V_{BE} is the base-emitter voltage.

2. Output Side Equation:

- $V_{CE} = V_{CC} - I_C \cdot R_C$

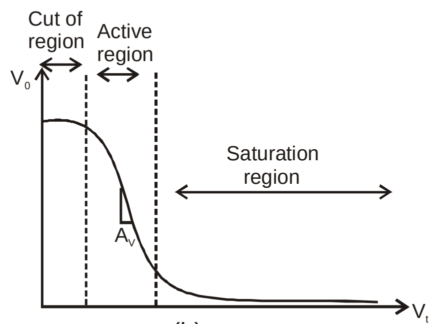
- This equation represents the Kirchhoff's voltage rule applied to the output side, where V_{CE} is considered as the dc output voltage (V_o), V_{CC} is the collector supply voltage, I_C is the collector current, and R_C is the collector resistance.



(a)

Treating V_BB as the dc input voltage (V_i) and V_CE as the dc output voltage (V_o), we can express the relationships as $V_i = I_B \cdot R_B + V_{BE}$ and$V_o = V_{CC} - I_C \cdot R_C$.

Examining how V_o changes as V_i increases reveals interesting behavior. When V_i is less than 0.6 V, corresponding to the cut-off state, V_o remains at V_{CC} with I_C being zero? As V_i surpasses 0.6 V, the transistor enters the active state, resulting in a linear decrease in V_o due to the increase in I_c. However, beyond a certain point, the change becomes nonlinear, marking the transition to the saturation state. The transition regions exhibit nonlinearity, indicating that the shift from cut-off to active and from active to saturation is not sharply defined.



(b)

In the context of the Si transistor, when V_i is low, unable to forward-bias the transistor, V_o is high (at V_{CC}). When V_i is sufficiently high to drive the transistor into saturation, V_o decreases nearly to zero. The transistor is considered switched off when not conducting and switched on when driven into saturation. Therefore, defining low and high states based on certain voltage levels corresponding to cut-off and saturation allows us to assert that a low input switches the transistor off, and a high input switches it on.

(ii) Transistor as an Amplifier (CE-Configuration):

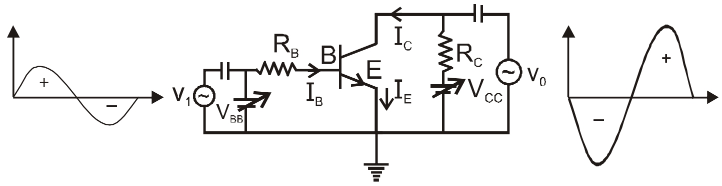
To utilize the transistor as an amplifier effectively, it is crucial to establish its operating point within the middle of its active region. Setting the value of V_{BB} at a point in the linear section of the transfer curve ensures that the DC base current (I_B) and the corresponding collector current (I_C) remain constant. Consequently, the DC voltage $V_{CE} = V_{CC} - I_C R_C$ also stays constant. The operating values of V_{CE} and I_B collectively determine the operating point of the amplifier.

Introducing a small sinusoidal voltage with amplitude v_s on top of the DC base bias, achieved by connecting the source of the signal in series with the V_{BB} supply, results in sinusoidal variations in the base current superimposed on the DC value of I_B. Consequently, the collector current also exhibits sinusoidal variations superimposed on the value of I_C, leading to corresponding changes in the value of V_o. The AC variations across the input and output terminals can be measured by blocking the DC voltages using larger capacitors.

In the preceding amplifier description, the consideration of an AC signal was not taken into account. Generally, amplifiers are designed to amplify alternating signals. By introducing an AC input signal (v_i) to be amplified on top of the DC bias V_{BB}, the output is extracted between the collector and the ground. Understanding the amplifier's operation is facilitated by assuming $v_i = 0$ initially. Applying Kirchhoff's law to the output loop yields $V_{CC} = V_{CE} + I_C\ R_L$, while the input loop gives $V_{BB} = V_{BE} + I_B\ R_B$.

When v_i is not zero, the expression becomes $V_{BE} + v_i = V_{BE} + I_B R_B + \triangle I_B (R_B + r_i)$. The change in V_{BE} is related to the input resistance r_i and the change in I_B, yielding $v_i = \triangle I_B (R_B + r_i) = r \triangle I_B$.

The change in I_B causes a corresponding change in I_C. We introduce a parameter β_{ac}, similar to β_{dc}defined in the equation, as $\beta_{ac} = \frac{\triangle I_C}{\triangle I_B} = \frac{\triangle i_c}{\triangle i_b}$



This parameter, denoted as β_{ac} , is also recognized as the AC current gain (A_i), and in the linear region of the output characteristics, β_{ac} typically closely approximates β_{dc}.

The alteration in I_C resulting from a change in I_B induces variations in V_{CE} and the voltage drop across resistor R_L, considering V_{CC} is constant. These variations can be expressed using the equation:

$\triangle V_{CC} = \triangle V_{CE} + R_L \cdot \triangle I_C = 0$ Or $\triangle V_{CE} = -R_L \cdot \triangle I_C$

The change in V_CE corresponds to the output voltage v_o, and from the equation, we obtain:

$v_o = \triangle V_{CE} = -\beta_{ac} R_L \triangle I_B$

The voltage gain (A_v) of the amplifier is calculated as:

$$A_v = \frac{\triangle V_{CE}}{\triangle V_i} = -\beta_{ac} R_L \frac{\triangle I_B}{\triangle V_i}$$

The negative sign indicates that the output voltage is phase-opposite to the input voltage.

Considering the transistor characteristics discussed earlier, which involve a current gain β_{ac} in the Common Emitter (CE) configuration, and the introduction of the voltage gain (A_v), the power gain (A_p) can be expressed as the product of the current gain and voltage gain. Mathematically, $A_p = \beta_{ac} \times A_v$. As both β_{ac} and A_v are greater than 1, this yields an AC power gain. It is crucial to recognize, however, that the transistor does not function as a power-generating device; the energy for the increased AC power at the output is supplied by the battery.

Note:

Operating as a Common Emitter (CE) amplifier, the transistor exhibits various characteristics:

- AC Current Gain (β_{ac}): The AC current gain is expressed as $\beta_{ac} = \frac{i_c}{i_b}$ at constant V_{CE}.

- DC Current Gain (β_{dc}): The DC current gain is defined as $\beta_{dc} = \frac{i_c}{i_b}$.
- Voltage Gain (A_v): The voltage gain is calculated as $A_v = \frac{V_0}{V_i} = \beta_{ac} \times Resistance\ gain$.
- Power Gain $\left(A_p\right)$: The power gain is given by $A_p = \frac{P0}{P_i} = \beta_{ac}^2 \times Resistance$.
- Tran's conductance (g_m): This parameter is the ratio of the change in collector current to the change in emitter-base voltage, denoted as $g_m = \frac{i_c}{V_{EB}}$. Additionally, $g_m = \frac{A_v}{R_L}$ where R_L is the load resistance.
- Phase Difference (Between Output and Input): The phase difference between the output and input signals is opposite.
- Application: Typically used for audible frequency amplification.

(iii) Interrelation between α and β: The relationship is given $\beta = \frac{\alpha}{1-\alpha}\ \ or\ \alpha = \frac{\beta}{1+\beta}$.

Example.

In the realm of a common base transistor amplifier, wherein the input and output resistances measure 500 ohms and 40,000 ohms, and the emitter current attains a value of 1.0 milliampere, one is tasked with determining the input and output voltages. The provided value for the common base current gain (α) is 0.95.

Solution.

The input voltage is determined by multiplying the emitter current by the input resistance, expressed as:

$$V_{in} = i_E \times R_{in} = (1.0 \times 10^{-3} A) \times 500\Omega = 0.5V$$

Similarly, the output voltage is calculated as:

$$V_{out} = i_C \times R_{out} = \alpha \times i_E \times R_{out} = 0.95 \times (1.0 \times 10^{-3} A) \times (40 \times 103\Omega) = 38V$$

Thus, the input voltage (V_{in}) is 0.5 volts, and the output voltage (V_{out}) is 38 volts.