Bipolar Junction Transistor

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BJT

- The Bipolar Junction Transistor is a semiconductor device which can be used for switching or amplification.
- Transistors are three terminal active devices made from different semiconductor materials that can act as either an insulator or a conductor by the application of a small signal voltage.
- The transistor’s ability to change between these two states enables it to have two basic functions: “switching” (digital electronics) or “amplification” (analogue electronics).

BJT

Then bipolar transistors have the ability to operate within three different regions:

- **Active Region** – the transistor operates as an amplifier ; $I_c = \beta I_b$
- **Saturation Region** – the transistor is “Fully-ON” operating as a switch; $I_c = I(saturation)$
- **Cut-off** – the transistor is “Fully-OFF” operating as a switch; $I_c = 0$

BJT

- Bipolar Transistors are current regulating devices that control the amount of current flowing through them from the Emitter to the Collector terminals in proportion to the amount of biasing voltage applied to their base terminal, thus acting like a current-controlled switch.
- As a small current flowing into the base terminal controls a much larger collector current forming the basis of transistor action.

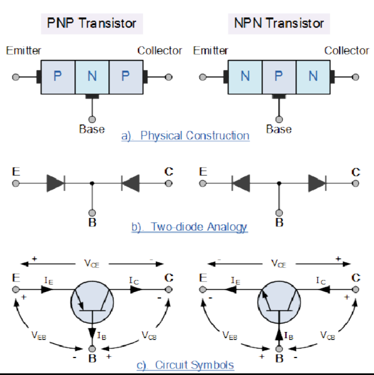
BJT

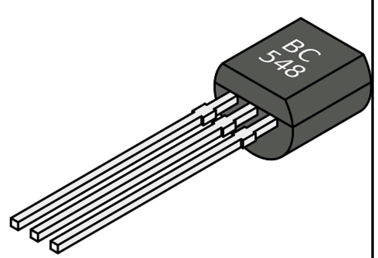
- The word transistor is derived from the words *Transfer* and *Resistor*. It describes the operation of a BJT i.e. the transfer of an input signal from a low resistance circuit to a high resistance circuit.
- Now as there are two junctions of different types of semiconductors, this is called junction transistor.
- It's called bipolar because the conduction takes place due to both electrons as well as holes.

BJT

- The transistor is made up of semiconductors. Now, in this type of transistor any one type of semiconductors is sandwiched between the other type of semiconductor.
- For example, an n - type can be sandwiched between two p-type semiconductors or similarly one p-type can be sandwiched between two n-type semiconductors.
- These are called p-n-p and n-p-n transistors respectively.

BJT





BJT

- From the above figure, we can see that every BJT has three parts named emitter, base and collector.
- The collector region is lightly doped than the emitter region, so the depletion layer width at the collector side is more than the depletion layer width at emitter side.
- The E/B and B/C represent junction of emitter and junction of collector respectively.
- Now initially it is sufficient for us to know that emitter based junction is forward biased and collector base junctions is reverse biased.

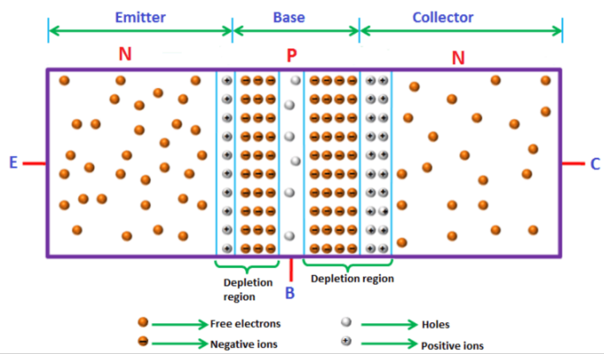
BJT - NPN

- For free electrons, n-region is the higher concentration region and p-region is the lower concentration region.
- Similarly, for holes, p-region is the higher concentration region and n-region is the lower concentration region.
- Therefore, the free electrons at the left side n-region (emitter) and right side n-region (collector) experience a repulsive force from each other. As a result, the free electrons at the left side and right side n-regions (emitter and collector) will move into the p-region (base).

BJT - NPN

- During this process, the free electrons meet the holes in the p-region (base) near the junction and fill them. As a result, depletion region (positive and negative ions) is formed at the emitter to base junction and base to collector junction.
- At emitter to base junction, the depletion region is penetrated more towards the base side, similarly; at base to collector junction, the depletion region is penetrated more towards the base side.

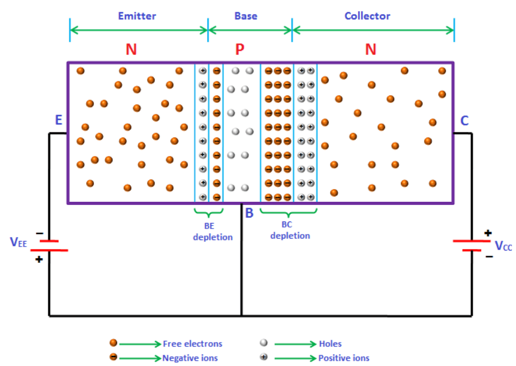
BJT - NPN



BJT - NPN

- This is because at emitter to base junction, the emitter is heavily doped and base is lightly doped so the depletion region is penetrated more towards the base side and less towards the emitter side.
- Similarly, at base to collector junction, the collector is heavily doped and base is lightly doped so the depletion region is penetrated more towards the base side and less towards the collector side.

BJT - NPN



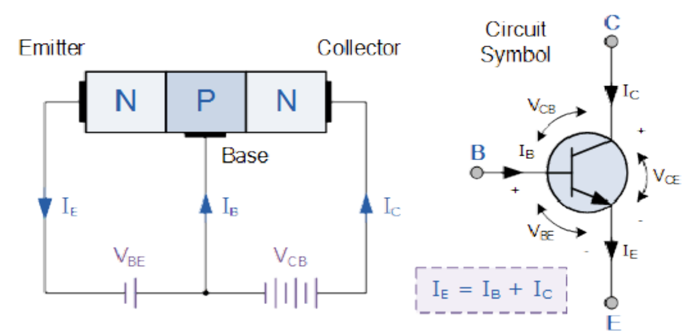
BJT - NPN

- In an n-p-n transistor biased in the active region, the emitter-base (E/B) junction is forward biased whereas the collector-base (C/B) junction is reversed biased.
- The width of the depletion region of the B/E junction is small as compared to that of the C/B junction.
- The forward bias at the B/E junction reduces the barrier potential and causes the electrons to flow from the emitter to base.

BJT - NPN

- As the base is thin and lightly doped it consists of very few holes so some of the electrons from the emitter (about 2%) recombine with the holes present in the base region and flow out of the base terminal.
- This constitutes the base current, it flows due to recombination of electrons and holes. The remaining large number of electrons will cross the reverse biased collector junction to constitute the collector current.

BJT - NPN



BJT - NPN

- Applying Kirchhoff's current law to the transistor, as if it were a single node, we obtain,

$$I_E = I_B + I_C$$

- We find that the emitter current is the sum of the collector and base currents. The base current is very small as compared to emitter and collector current. Therefore,

$$I_E \sim I_C$$

- Here, the majority charge carriers are electrons.

BJT - NPN

- The collector current is comprised of two components—the majority and minority carriers. The minority-current component is called the *leakage current*, and is given by the symbol I_{CO} (I_C current with emitter terminal Open).
- The collector current, therefore, is determined in total by

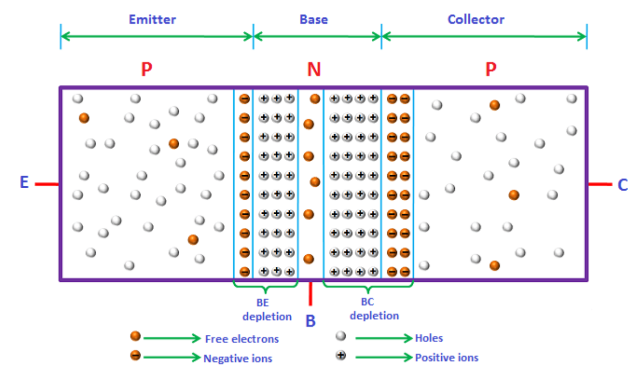
$$I_c = I_{C_{majority}} + I_{CO_{minority}}$$

- I_C is measured in milli-amperes, while I_{CO} is measured in micro-amperes or nano-amperes. I_{CO}, like I_s for a reverse-biased diode, is temperature sensitive.

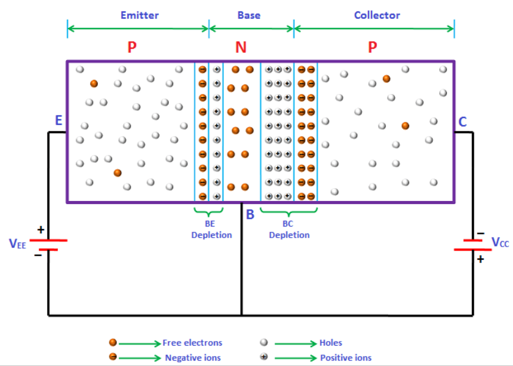
BJT - PNP

- The operation of a p-n-p transistor is same as of the n-p-n, the only difference is that the majority charge carriers are holes instead of electrons.
- Only a small part current flows due to majority carriers and most of the current flows due to minority charge carriers in a BJT. Hence, they are called as minority carrier devices.

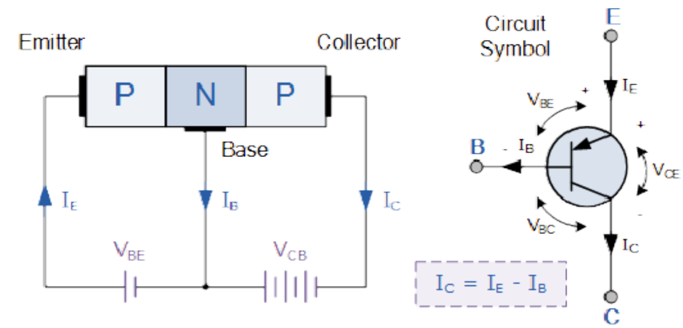
BJT - PNP



BJT - PNP



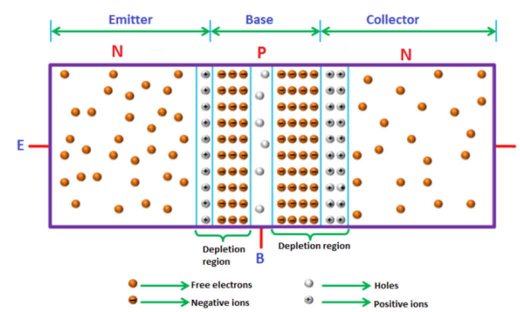
BJT - PNP



Base Width Modulation - Early effect

- Due to forward bias, the base-emitter junction acts as a forward biased diode and due to reverse bias, the collector-base junction acts as a reverse biased diode.
- Therefore, the width of the depletion region at the base-emitter junction is very small whereas the width of the depletion region at the collector-base junction is very large.

Base Width Modulation - Early effect



Base Width Modulation - Early effect

- If the output voltage V_{CB} applied to the collector-base junction is further increased, the depletion region width further increases.
- The base region is lightly doped as compared to the collector region. So the depletion region penetrates more into the base region and less into the collector region.
- As a result, the width of the base region decreases. This dependency of base width on the output voltage (V_{CB}) is known as an early effect.

Base Width Modulation - Early effect

- As a consequence of Early effect, a less number of carriers undergo recombination in the base region.
- Thus, the transfer factor β as well as the large signal current gain α increase.

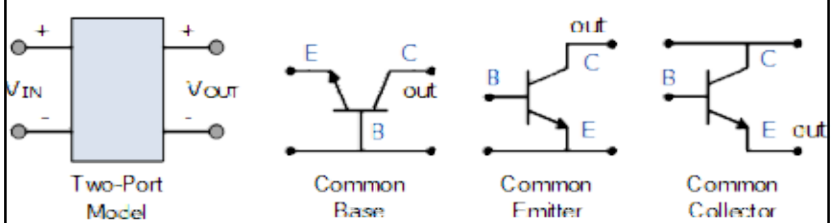
Bipolar Transistor Configurations

- When a transistor is to be connected in a circuit, one terminal is used as the input terminal, the other terminal is used as the output terminal and the third terminal is common to the input and output.
- The transistor does not have four terminals, therefore, one of the three terminals is used as common to both input and output.
- That means here input is applied between the input terminal and common terminal, and the corresponding output is taken between the output terminal and common terminal.

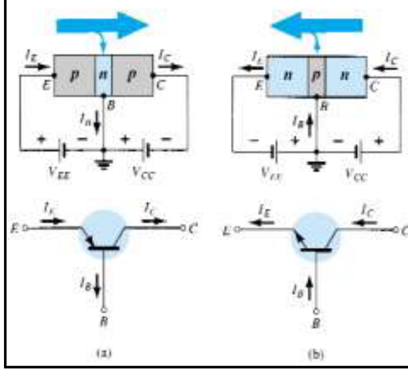
Bipolar Transistor Configurations

- Depending upon the terminal which is used as a common terminal to the input and output terminals, the transistor can be connected in the following three configurations. They are:
  - Common base (CB) configuration
  - Common emitter (CE) configuration
  - Common collector (CC) configuration
- In every configuration, the base-emitter junction B/E is always forward biased and the collector-base junction C/B is always reverse biased to operate the transistor as a current amplifier.

Bipolar Transistor Configurations



Common Base



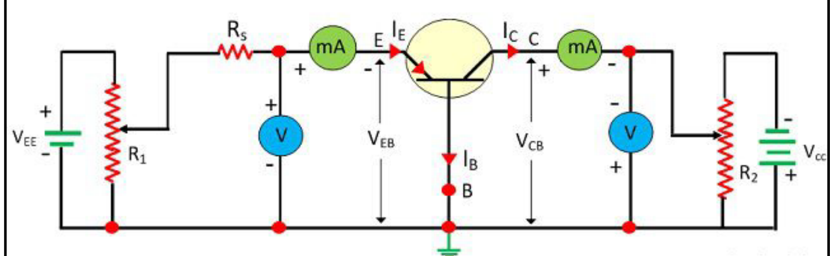
- The arrow in the graphic symbol defines the direction of emitter current (conventional flow) through the device.

$$I_E = I_B + I_C$$

- The emitter base junction is forward biased while collector base junction is reversed biased.

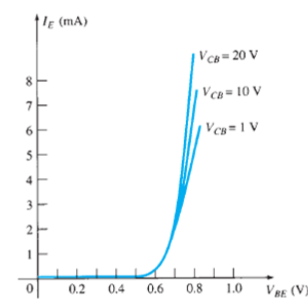
$$I_c = I_{C_{majority}} + I_{CO_{minority}}$$

Common Base Configuration



CB - Input Characteristics

- To fully describe the behavior of a three-terminal device requires two sets of characteristics—one for the input parameters and the other for the output side.
- The input set will relate an input current (I_E) to an input voltage (V_{BE}) for various levels of output voltage (V_{CB}).

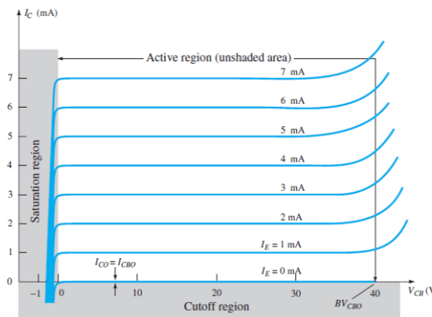


CB - Input Characteristics

- For fixed values of collector voltage(V_{CB}), as the base-to-emitter voltage increases, the emitter current increases in a manner that closely resembles the diode characteristics.
- When the output voltage (V_{CB}) is increased from zero volts to a certain voltage level (10 or 20 volts), the emitter current flow will be increased which in turn reduces the depletion region width at emitter-base junction.
- As a result, the cut in voltage will be reduced. Therefore, the curves shifted towards the left side for higher values of output voltage V_{CB}.

CB - Output Characteristics

- The output set will relate an output current (I_C) to an output voltage (V_{CB}) for various levels of input current (I_E).
- The output or collector set of characteristics has three basic regions of interest the *active, cutoff,* and *saturation regions.*



CB - Output Characteristics

- The active region is the region where the transistor operates normally. Here the emitter-base junction is forward biased while collector-base junction is reverse biased.
- Now the saturation region is the region where both the emitter -base & collector-base junctions are forward biased.
- And finally the cut off region is the region where both emitter-base and the collector-base junctions are reverse biased.

CB - Output Characteristics

- In the active region, the BJT is used as an amplifier. The V_{CB} has negligible effect on collector current for the active region.
- As the emitter current I_E increases above zero, the collector current I_C increases to a magnitude essentially equal to that of the emitter current as determined by the basic transistor-current relations.
- The curves clearly indicate that, $I_E \sim I_C$
- The current I_{CO} is so small (microamperes) in magnitude compared to the vertical scale of I_C (milliamperes) that it appears on virtually the same horizontal line as $I_C = 0$

CB - Output Characteristics

- The cutoff region is defined as that region where the collector current is $I_C = 0$ A.
- The saturation region is defined as that region of the characteristics to the left of $V_{CB} = 0$ V

Transistor parameters - CB

Dynamic input resistance (r_i)

- Dynamic input resistance is defined as the ratio of change in input voltage or emitter voltage (V_{BE}) to the corresponding change in input current or emitter current (I_E), with the output voltage or collector voltage (V_{CB}) kept at constant.

$$r_i = \frac{\Delta V_{BE}}{\Delta I_E}\bigg|_{V_{CB}=constant}$$

- The input resistance of common base amplifier is very low.

Transistor parameters - CB

Dynamic output resistance (r_o)

- Dynamic output resistance is defined as the ratio of change in output voltage or collector voltage (V_{CB}) to the corresponding change in output current or collector current (I_C), with the input current or emitter current (I_E) kept at constant.

$$r_O = \frac{\Delta V_{CB}}{\Delta I_C}\bigg|_{I_E=constant}$$

- The output resistance of common base amplifier is very high.

Transistor parameters - CB

Current Gain

- The DC current gain, $\boldsymbol{\alpha}_{dc}$ of a transistor in CB configuration is defined as the ratio of output current or collector current (I_C) to the input current or emitter current (I_E).

$$\alpha_{dc} = \frac{I_C}{I_E}$$

- The DC current gain of a transistor in CB configuration is generally represented by $\boldsymbol{\alpha}$ and is less than unity. The typical current gain of a common base amplifier is 0.98.

Transistor parameters - CB

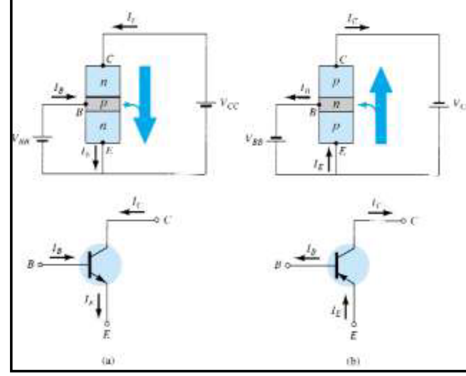
Current Amplification Factor

- The ratio of change in collector current to the change in emitter current at constant CB voltage is known as current amplification factor of a transistor in CB configuration. It is represented by $\boldsymbol{\alpha}_{ac}$. Its value is less than unity.

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

- The value reaches to unity when the base current reduces to zero. The base current becomes zero only when it is thin and lightly doped. The practical value of the current amplification factor varies from 0.95 to 0.99 in the commercial transistor.

Common Emitter

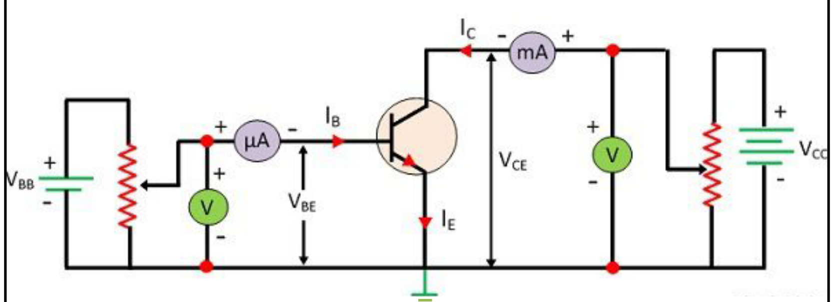


- Even though the transistor configuration has changed, the current relations developed earlier for the common-base configuration are still applicable. That is,

$$I_E = I_B + I_C$$

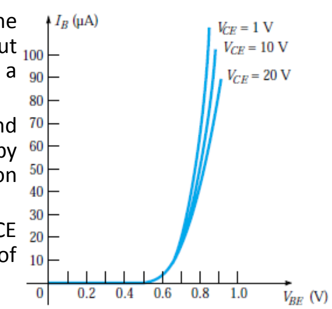
$$I_C = \alpha I_E$$

Common Emitter Configuration



CE - Input Characteristics

- For the common-emitter configuration the input characteristics are a plot of the input current (I_B) versus the input voltage (V_{BE}) for a range of values of output voltage (V_{CE}).
- When output voltage (V_{CE}) is at zero volts and emitter-base junction is forward biased by input voltage (V_{BE}), the emitter-base junction acts like a normal p-n junction diode.
- So the input characteristics of the CE configuration is same as the characteristics of a normal pn junction diode.

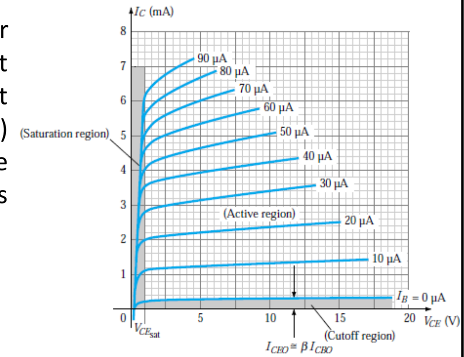


CE - Input Characteristics

- If the output voltage V_{CE} applied to the collector-base junction is further increased, the depletion region width further increases. As a result, the width of the base region decreases which in turn reduces the input current (I_B) produced in the base region.
- From the Input characteristics, we can see that for higher fixed values of output voltage V_{CE}, the curve shifts to the right side.
- This is because for higher fixed values of output voltage, the cut in voltage is increased above 0.7 volts. Therefore, to overcome this cut in voltage, more input voltage V_{BE} is needed than previous case.

CE - Output Characteristics

- For the common-emitter configuration the output characteristics are a plot of the output current (I_C) versus output voltage (V_{CE}) for a range of values of input current (I_B).



CE - Output Characteristics

- A curve is drawn between output current I_C and output voltage V_{CE} at constant input current I_B (say, from 0 to 90µA).
- When the base current or input current I_B = 0 µA, the transistor operates in the cut-off region. In this region, both junctions are reverse biased.
- Next, the input current (I_B) is increased from 0 µA to 90 µA by adjusting the input voltage (V_{BE}).

CE - Output Characteristics

- The input current (I_B) is kept constant and, the output voltage (V_{CE}) is increased from zero volts to different voltage levels.
- For each voltage level of output voltage (V_{CE}), the corresponding output current (I_C) is plotted.
- This steps are repeated for higher fixed values of input current I_B (*i.e.* 10 µA, 20µA, 30 µA and so on).
- This region is known as the active region of a transistor. In this region, emitter-base junction is forward biased and the collector-base junction is reverse biased.

CE - Output Characteristics

- When output voltage V_{CE} is reduced to a small value (0.2 V), the collector-base junction becomes forward biased. This is because the output voltage V_{CE} has less effect on collector-base junction than input voltage V_{BE}.
- As we know that the emitter-base junction is already forward biased. Therefore, when both the junctions are forward biased, the transistor operates in the saturation region. In this region, a small increase in output voltage V_{CE} will rapidly increases the output current I_C.

Transistor parameters - CE

Dynamic input resistance (r_i)

- Dynamic input resistance is defined as the ratio of change in input voltage or base voltage (V_{BE}) to the corresponding change in input current or base current (I_B), with the output voltage or collector voltage (V_{CE}) kept at constant.

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

- In CE configuration, the input resistance is very low.

Transistor parameters - CE

Dynamic output resistance (r_o)

- Dynamic output resistance is defined as the ratio of change in output voltage or collector voltage (V_{CE}) to the corresponding change in output current or collector current (I_C), with the input current or base current (I_B) kept at constant.

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

- In CE configuration, the output resistance is high.

Transistor parameters - CE

Current gain (β)

- The DC current gain of a transistor in CE configuration is defined as the ratio of output current or collector current (I_C) to the input current or base current (I_B).

$$\beta_{dc} = \frac{I_C}{I_B}$$

- The DC current gain of a transistor in CE configuration is high. Therefore, the transistor in CE configuration is used for amplifying the current.

Transistor parameters - CE

Current Amplification Factor

- The ratio of change in collector current to the change in base current at constant CE voltage is known as current amplification factor of a transistor in CE configuration. It is represented by β_{ac}. Its value is more than unity.

$$\beta_{ac} = \frac{\Delta I_C}{\Delta I_B}\bigg|_{V_{CE}=constant}$$

- The current amplification factor of the common emitter transistor configuration is quite large. It has a value between 20 and 200 for most general purpose transistors..

Current Amplification

- Relation between α and β:

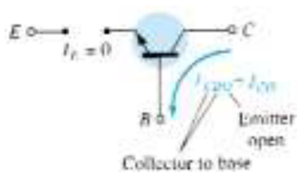
$$\alpha = \frac{\beta}{1+\beta}$$

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

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

Transistor Leakage Current - CB

- **Collector to Base Leakage Current**



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

$$I_E = I_B + I_C$$

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

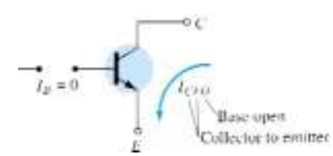
Transistor Leakage Current - CE

- **Collector to Emitter Leakage Current:**

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

- If $I_B = 0$
- then $I_{CEO} = (1+\beta) I_{CBO}$

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

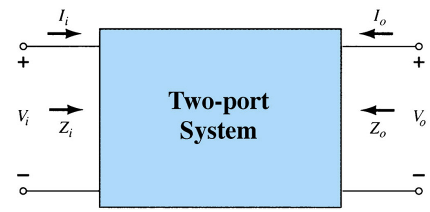


Bipolar Transistor Configurations

Characteristic	Common Base	Common Emitter	Common Collector
Input Impedance	Low	Medium	High
Output Impedance	Very High	High	Low
Phase Shift	0°	180°	0°
Voltage Gain	High	Medium	Low
Current Gain	Low	Medium	High
Power Gain	Low	Very High	Medium

TWO PORT NETWORKS

- The circuit of the basic two port network is shown on the right. Depending on the application, it may be used in a number of different ways to develop different models.
- We will use it to develop the h-parameter model.

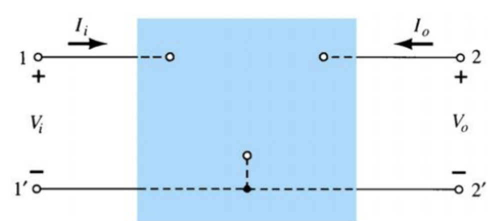


h-PARAMETER BJT MODEL

- The h-parameter model is typically suited to transistor circuit modeling. It is important because:
  - Its values are used on specification sheets.
  - It is one model that may be used to analyze circuit behavior.
  - It may be used to form the basis of a more accurate transistor model.
- The h-parameter model has values that are complex numbers that vary as a function of:
  - Frequency
  - Ambient temperature
  - Q-Point

h-PARAMETER BJT MODEL

- Our description of the hybrid equivalent model for transistor will begin with the general two port system.



h-PARAMETER BJT MODEL

- The terminal behaviour of such a two port system is usually determined by four variables: two signal currents I_i and I_o, and two signal voltages V_i and V_o.
- For transistors, the input current I_i and the output voltage V_o are taken as the independent variables, and the input voltage V_i and the output current I_o as the dependent variables.

h-PARAMETER BJT MODEL

- The dependent variables are related to the independent variables by the four variables h_{11}, h_{12}, h_{21} and h_{22}, which are called hybrid parameters,

$$\begin{vmatrix} V_i \\ I_o \end{vmatrix} = \begin{vmatrix} h_{11} & h_{12} \\ h_{21} & h_{22} \end{vmatrix} \begin{vmatrix} I_i \\ V_o \end{vmatrix}$$

- Using KVL and KCL

$$V_i = h_{11} I_i + h_{12} V_o$$

$$I_o = h_{21} I_i + h_{22} V_o$$

h-PARAMETER BJT MODEL

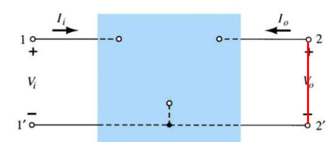
- The parameters relating the four variables are called h-parameters, from the word hybrid.
- The term hybrid was chosen because the mixture of variables (V and I) in each equation results in a *hybrid* set of units of measurement for the h-parameters.
- A clearer understanding of what the various h-parameters represent and how we can determine their magnitude can be developed by isolating each and examining the resulting relationship.

h-PARAMETER BJT MODEL

Short Circuit **Input Impedance:**

With output shorted, set $V_o = 0$, solving $V_i = h_{11} I_i + h_{12} V_o$ for h_{11},

$$h_{11} = \left.\frac{V_i}{I_i}\right|_{V_o=0}$$



1. Short terminals 2 2’
2. Apply test source V_i to terminal 1 1’
3. Measure I_i
4. Calculate h_{11}

***h_{11}* → Ohms**

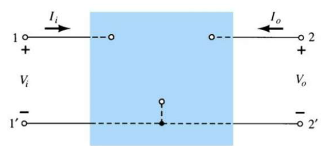
h-PARAMETER BJT MODEL

- Open Circuit **Reverse Voltage Gain:**

If I_i is set equal to zero by opening the input leads, we get expression for h_{12}:

$$V_i = h_{11}I_i + h_{12}V_o$$

$$h_{12} = \left.\frac{V_i}{V_o}\right|_{I_i=0}$$

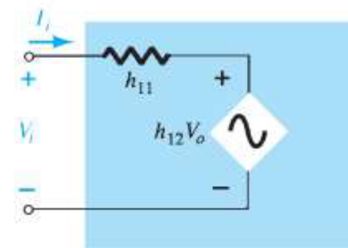


1. Open terminals 1 1’
2. Apply test source V_o to terminal 2 2’
3. Measure V_i and
4. Measure V_o
5. Calculate h_{12}

***h*₁₂ → dimensionless**

Hybrid Input Equivalent Circuit

- Since each term of equation has the unit volt, let us apply Kirchhoff’s voltage law in reverse to find a circuit that fits the equation.
- Performing this operation will result in this circuit. Since the parameter h_{11} has the unit ohm, it is represented by a resistor.
- The quantity h_{12} is dimensionless and therefore simply appears as a multiplying factor of the feedback” term in the input circuit.



$$V_i = h_{11}I_i + h_{12}V_o$$

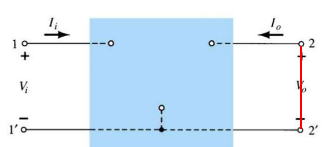
h-PARAMETER BJT MODEL

- Short Circuit **Forward Current Gain:**

Again by setting V_o to zero by shorting the output terminals, we get h_{21}

$$I_o = h_{21}I_i + h_{22}V_o$$

$$h_{21} = \left.\frac{I_o}{I_i}\right|_{V_o=0}$$



1. Short terminals 2 2’
2. Apply test source V_i to terminal 1 1’
3. Measure I_i and
4. Measure I_o
5. Calculate h_{21}

h_{21} → dimensionless

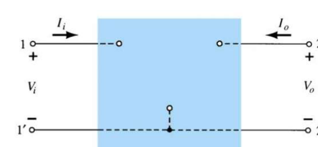
h-PARAMETER BJT MODEL

- Open Circuit **Output Admittance:**

Again by setting $I_i = 0$ by opening the input leads,

$$I_o = h_{21}I_i + h_{22}V_o$$

$$h_{22} = \left.\frac{I_o}{V_o}\right|_{I_i=0}$$

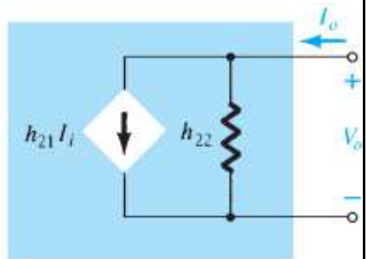


- Open terminals 1 1’
- Apply test source V_o to terminal 2 2’
- Measure I_o
- Measure V_o
- Calculate h_{22}

h_{22} → Siemens

Hybrid Output Equivalent Circuit

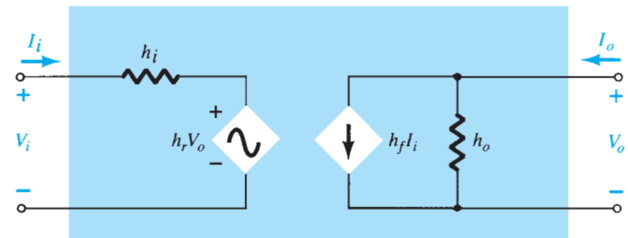
- Since each term of equation has the units of current, let us now apply Kirchhoff's current law in reverse to obtain this circuit.
- Since h_{22} has the units of admittance, which for the transistor model is conductance, it is represented by the resistor symbol.
- However, that the resistance in ohms of this resistor is equal to the reciprocal of conductance ($1/h_{22}$).



$$I_o = h_{21}I_i + h_{22}V_o$$

Complete Hybrid Equivalent Circuit

- The revised two port network for the h-parameter model is shown below. At low and mid-band frequencies, the h-parameter values are real values.



h-PARAMETER BJT MODEL

- The complete ac equivalent circuit for the basic three-terminal linear device is indicated in last figure with a new set of subscripts for the *h*-parameters.

$$h_{11} \rightarrow \textit{input resistance} \rightarrow h_i$$
$$h_{12} \rightarrow \textit{reverse transfer voltage ratio} \rightarrow h_r$$
$$h_{21} \rightarrow \textit{forward transfer current ratio} \rightarrow h_f$$
$$h_{22} \rightarrow \textit{output conductance} \rightarrow h_o$$

Hybrid Equivalent Circuit

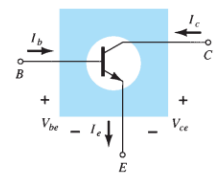
- The equivalent circuit of is applicable to any linear three-terminal electronic device or system with no internal independent sources.
- For the transistor, therefore, even though it has three basic configurations, they are all three-terminal configurations, so that the resulting equivalent circuit will have the same format as shown in last figure.

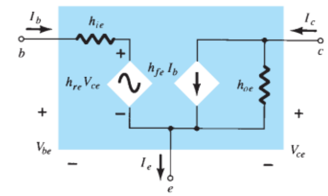
Hybrid Equivalent Circuit

- The *h-parameters* will change with each configuration.
- To distinguish which parameter has been used or which is available, a second subscript has been added to the *h-parameter* notation.
- For the common-base configuration, the lowercase letter *b* was added, while for the common-emitter and common-collector configurations, the letters *e* and *c* were added, respectively.

Hybrid Equivalent Circuit - CE

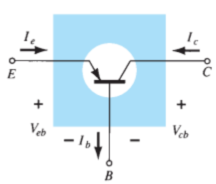
- The hybrid equivalent network for the CE configuration.
- Note that $I_i = I_b$, $I_o = I_c$, and through an application of Kirchhoff's current law, $I_e = I_b + I_c$. The input voltage is now V_{be}, with the output voltage V_{ce}.

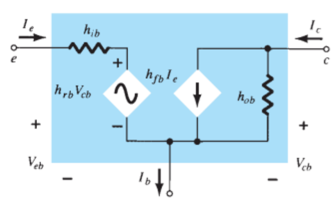




Hybrid Equivalent Circuit - CB

- The hybrid equivalent network for the CB configuration.
- For the common-base configuration, $I_i = I_e$, $I_o = I_c$ with $V_i = V_{eb}$ and $V_o = V_{cb}$.
- The h-circuits of CE and CB are applicable for *pnp or npn* transistors.





Unit II

END