Bipolar Junction Transistor: Operation and the Three Configurations

- Invention of BJT in 1948 led to the era of solid-state circuits, and also integrated circuits
- Till the early 80s, BJT was the device of choice in the design of both discrete and integrated circuits. Today the MOSFET is the most widely used electronic device.
- BJT is still the device of choice in some applications - discrete- amplifiers, automotive applications, etc.

1.0 BJT: Basic Structure

- BJT is a three-terminal device (needs at least two characteristics to characterize it) having three semiconductor regions: *emitter*, *base*, and *collector* regions
- The transistor consists of two junctions – the *emitter-base junction (EB jn.)* and the *collector-base junction (CB jn.)*
- Charge carriers of both polarities (electrons and holes) are involved in the BJT and hence the name – *bipolar junction transistor*.

- An *npn* transistor consists of an *n*-type emitter, a *p*-type base and *n*-type collector

- A *pnp* transistor consists an *p*-type emitter, a *n*-type base and *p*-type collector

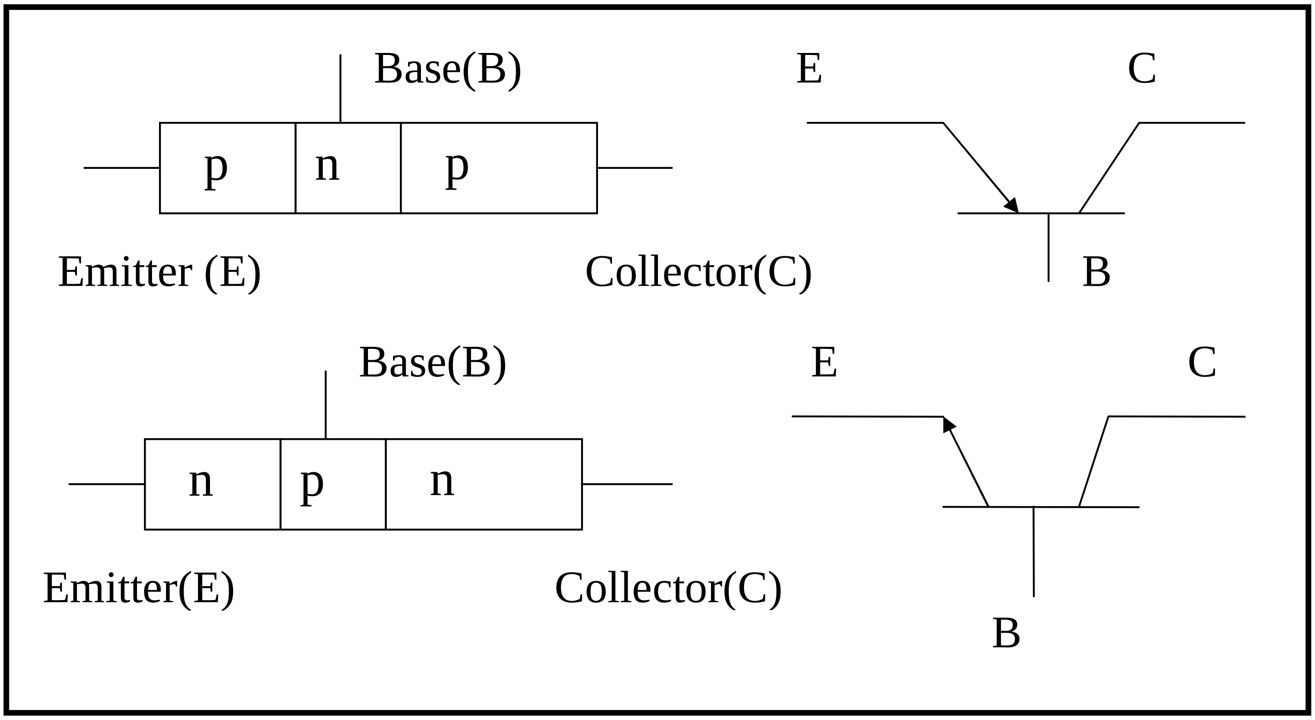


Fig.1 *npn* and *pnp* Transistors

1.1 Collector, Emitter, and Base regions

Collector has the largest area (to take care of the power dissipation requirement due to large current and large CB junction voltage), followed by emitter (less power dissipation requirements due to lower EB junction voltage).

Base is made very thin to minimize recombination.

The emitter region is heavily-doped, while the base region is lightly doped. Collector has a doping somewhere between the emitter and the base.

2.0 Modes of Operation of a BJT

Mode	**E-B junction**	**C-B junction**
Cutoff	Reverse biased	Reverse biased
Active	Forward biased	Reverse biased
Saturation	Forward biased	Forward biased
Reverse Active	Reverse biased	Forward biased

Forward Active mode: This mode is generally called the *active* mode, and is the most commonly used mode of operation for all kinds of linear applications, such as BJT amplifiers, sinusoidal oscillators, etc. In order to remain in active mode the BJT biasing circuits must ensure that EB junction is forward-biased and the CB junction is reverse-biased.

Cut-off mode : The BJT is cut-off when there is not sufficient forward bias at the EB junction. Practically no current flows through the device in this mode.

Saturation mode: When both the EB and the CB junctions of a BJT are forward biased the BJT is said to be in the saturation mode.

Reverse Active mode: This mode is not used in normal circuits. This mode can be thought of as a special active mode where the emitter and collector terminals are interchanged, resulting in the CB junction forward-biased and the EB junction reverse-biased.

2.1 Operation of an *npn* Transistor in the Active mode

The figure below shows the physical operation of an *npn* transistor. Two external voltage sources in the form of batteries are used for biasing the BJT.

As shown, the emitter-base (EB) junction is forward biased and the collector-base (CB) junction is reverse-biased.

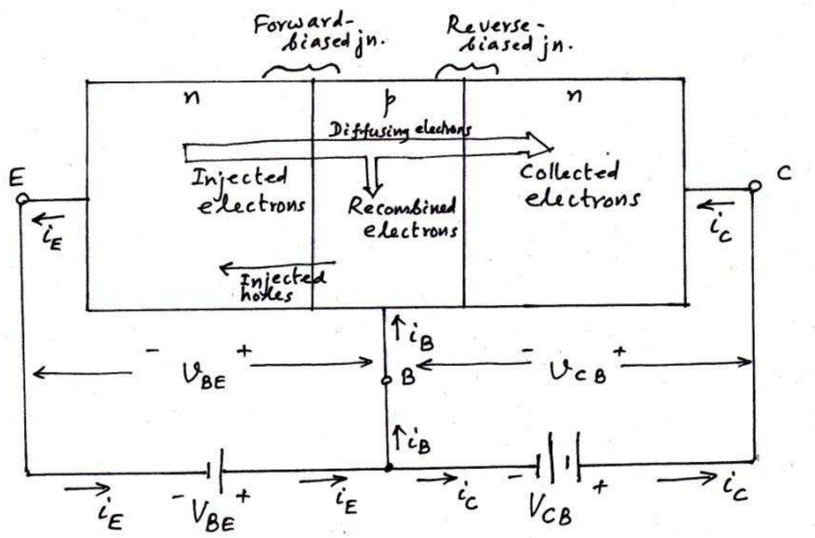


Fig. 2 Current flow in an *npn* transistor

2.2 Currents in a BJT:

Emitter Current: Because of the forward-bias at the EB jn., current will flow across this junction. This current has two components, viz. electrons injected from the emitter into the base, and holes injected from the base into the emitter. Because of the heavy doping of the emitter, and the light doping of the base, the current flow across the EB jn. will be largely due to the electrons injected from the emitter into the base. The emitter current i_E will be in the direction of the hole current and opposite to the direction of the electron current.

Collector Current: The electrons injected into the base will diffuse through the base region toward the collector. Most of the diffusing electrons will reach the boundary of the collector-base depletion region, while some injected electrons will recombine with the holes in the base region. Due to the higher collector potential, these electrons will be swept across the CB jn. into the collector. These collected electrons will result in the collector current i_C. The direction of the actual current will then be opposite to the electron current, i.e. into the collector.

Base Current: The base current i_B consists of two components. The first component is due to the holes injected from the base region into the emitter region. The second component is due to the holes that have to be supplied by the external circuit in order to replace the holes lost through the recombination process.

Saturation Current: One of the basic parameters of a BJT is its saturation current I_S (also called scale current). Saturation current is a function of the device parameters. It is inversely proportional to the base width and is directly proportional to the area of the EB jn. Typical range of I_S is 10^{-12} A to 10^{-18} A.

2.3 Forward Active Mode: Current Relationships

The forward-bias voltage between the base and emitter causes an exponential collector current i_C. This can be expressed as:

$$i_C = I_S \; e^{v_{BE}/V_T} \tag{1}$$

where I_S is the saturation current, v_{BE} is the base-emitter forward bias voltage and V_T the thermal voltage (26 mV approx at 300 K).

For an *npn* transistor, emitter current i_E leaves the device, while the collector i_C and the base current i_B enters the device. Hence applying KCL,

$$i_E = i_C + i_B \tag{2}$$

Also, $$i_B = \frac{i_C}{\beta} \quad \text{or} \quad i_C = \beta\, i_B \tag{3}$$

where β is called the **common-emitter current gain.** Since $i_C >> i_B$, $\beta >> 1$

Using eqns.(2) and (3),

$$i_E = \frac{(\beta+1)}{\beta} i_C \tag{4}$$

Eqn.(4) can be written as

$$i_C = \alpha\, i_E\,, \tag{5}$$

where $$\alpha = \frac{\beta}{\beta+1} \tag{6}$$

α is called the **common-base current gain.**
Since $i_E < i_C$, $\alpha < 1$.

From eqn.(6) we can write, $\beta = \dfrac{\alpha}{1-\alpha}$ (7)

α and β are the current gains in the forward-active mode. Occasionally these are also denoted as α_F and β_F to indicate that they are current gains in the forward-active mode.

For discrete transistors β is in the range of 50 – 400. For example if β = 100, then α = (100/101) = 0.9901.

Combining eqns.(1) and (5) we can write the emitter current i_E as,

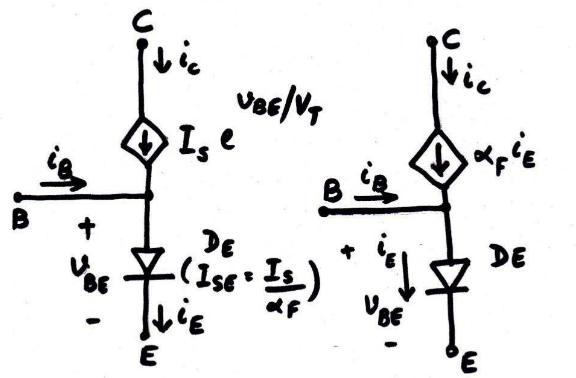
$$i_E = \frac{I_S}{\alpha_F} e^{v_{BE}/V_T} \qquad (8)$$

Summary: *npn* transistor in the forward-active mode

- The forward-bias voltage v_{BE} causes an exponentially rising collector current i_C to flow in the collector terminal
- The collector current i_C is independent of the value of the collector voltage as long as the collector-base junction is reverse-biased
- Thus in the active mode the collector terminal behaves as a controlled current source (controlled by v_{BE})
- The collector current is a fraction α_F of the emitter current. For $\beta_F >> 1$, $\alpha_F \approx 1$.

2.4 Large-signal Model in the forward-active Mode

The above first-order model of the BJT in the forward-active mode can be represented by the large-signal equivalent circuit shown below



(a) (b)

Fig.3 Large-signal equivalent circuit models of an *npn* transistor in the forward-active mode

In the equivalent circuit the diode D_E has a scale current or saturation current, $I_{SE} = I_S/\alpha_F$ and the diode current i_E is related to v_{BE} by eqn.(8). The controlled source current shown in Fig.3(a) is controlled by v_{BE} and is the same as the collector current i_C as given by eqn.(1). The model can be thought of as a non-linear voltage controlled current source. Fig.3(b) shows the equivalent circuit as a current-controlled current-source equivalent circuit with ($\alpha_F I_E$) as the controlled source current.

We can think of the BJT as a two-port network, with the input port between E and B and the output port between C and B.

2.5 Structure of an actual BJT

A simplified cross-section of an *npn* BJT is shown below. The collector region surrounds the emitter and the base regions. Hence almost all the electrons injected into the base can be collected by the collector resulting in a α_F value close to unity. We also observe that the device is not symmetrical - the collector region is much larger than the emitter.

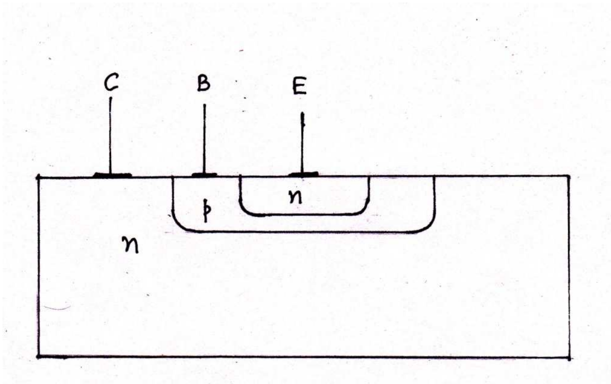


Fig.4 Cross-section of an *npn* BJT

2.6 *npn* Transistor in the Reverse-active Mode

As compared to a forward-active mode, in the reverse-active mode, the emitter and the collector terminals are interchanged. Since the BJT is not symmetrical, the current gains α_R and β_R will be different from α_F and β_F . Since the BJT is optimized for the forward-active mode operation, α_R and β_R values are much lower compared to α_F and β_F . α_R and β_R are related by equations identical to those for α_F and β_F

Typically, α_R is in the range of 0.01 to 0.5 and the corresponding range of β_R is 0.01 to 1.

2.7 Large-signal Model in the Reverse-active Mode

Model for an *npn* BJT operated in the reverse-active mode is shown in Fig.5.It is a current-controlled current source model. Here the diode D_C represents the collector-base junction having a scale current $I_{SC} = I_S / \alpha_R$. Since $\alpha_R << \alpha_F$, $I_{SC} >> I_{SE}$. The scale currents I_{SC} and I_{SE} have the same ratio as the areas of the collector and emitter.

The scale currents I_S, I_{SE} and I_{SC} and the current gains α_F and α_R are related by the equation

$$\alpha_F I_{SE} = \alpha_R I_{SC} = I_S \qquad (9)$$

Because of the larger I_{SC}, for the same current the CB jn. will have lower voltage drop when forward-biased than the forward drop of the EB jn. This difference in the junction voltages has its implications in the saturation mode of operation where both the junctions are forward biased.

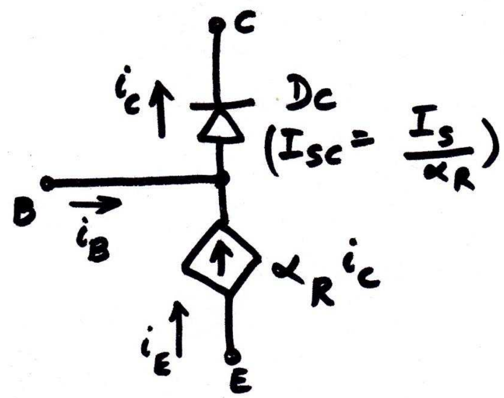


Fig.5 Equivalent circuit model for the *npn* transistor working in the reverse-active mode

2.8 Ebers-Moll (EM) Model

The Ebers-Moll model for an *npn* transistor is shown in Fig.6. It can be thought of as the combination of the current-controlled current source models for the forward-active and the reverse-active modes with the currents labeled as i_{DE} and i_{DC}. This model can be used to predict the operation of a BJT in all of its possible modes.

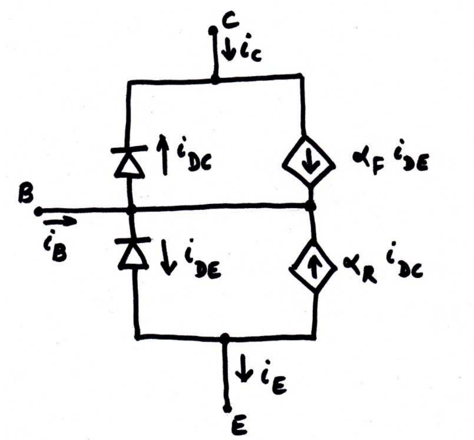


Fig.6 Ebers-Moll model of the *npn* transistor

From Fig.8 the terminal currents i_E, i_C, and i_B can be written as

$$i_E = i_{DE} - \alpha_R\, i_{DC} \qquad (10)$$

$$i_C = -i_{DC} + \alpha_F\, i_{DE} \qquad (11)$$

$$i_B = (1-\alpha_F)\, i_{DE} + (1-\alpha_R)\, i_{DC} \qquad (12)$$

Currents i_{DE} and i_{DC} can be written as

$$i_{DE} = I_{SE}\left(e^{v_{BE}/V_T} - 1\right) \qquad (13)$$

$$i_{DC} = I_{SC}\left(e^{v_{BC}/V_T} - 1\right) \qquad (14)$$

Substituting for i_{DE} and i_{DC} and using the relation between I_S, I_{SE} and I_{SC} (see eqn.9) the terminal currents can be written as

$$i_E = \left(\frac{I_S}{\alpha_F}\right)\left(e^{v_{BE}/V_T} - 1\right) - I_S\left(e^{v_{BC}/V_T} - 1\right) \qquad (15)$$

$$i_C = I_S\left(e^{v_{BE}/V_T} - 1\right) - \left(\frac{I_S}{\alpha_R}\right)\left(e^{v_{BC}/V_T} - 1\right) \qquad (16)$$

$$i_B = \left(\frac{I_S}{\beta_F}\right)\left(e^{v_{BE}/V_T} - 1\right) + \left(\frac{I_S}{\beta_R}\right)\left(e^{v_{BC}/V_T} - 1\right) \qquad (17)$$

In the above Ebers-Moll (EM) equations the first term in all the current expressions is the current due to the forward-biased EB junction, while the second term gives the current contribution due to the forward-biased CB junction.

2.8.1 EM Model: Active and saturation Modes of an *npn* BJT

Consider the equation for i_C. When the BJT is operating in the active mode v_{BE} will be in the range of 0.6 to0.8V. Junction voltage v_{BC} will be zero or negative (or equivalently $v_{CB} \geq 0$). Hence only the first term contributes towards i_C , as the second term would be negligibly small. Hence, for the active mode the second term can be neglected for all the three currents.

What is the range of voltages for which the CB junction remains reverse-biased? So far we assumed $v_{CB} \geq 0$. However a *pn* junction becomes forward-biased only when the forward voltage exceeds 0.5V. For the CB jn, this means that as long as $v_{BC} \leq 0.5$V (or $v_{CB} \geq -0.5$V) the junction cannot conduct any significant current. Hence we can safely say that as long as $v_{CB} \geq -0.4$V the *npn* BJT would remain in the forward-active region. A plot of i_C vs v_{CB} is shown in Fig.7 below. We see that for $v_{CB} \geq -0.4$V i_C is constant at the active mode value.

Once $v_{CB} < -0.4$V the CB junction begins to conduct and the BJT gets into the saturation mode. We see clearly that as v_{CB} decreases (or v_{BC} increases) i_C also decreases. This is due to the fact that as v_{BC} increases, the second term in the EM equations becomes larger and subtracts from the first term causing i_C to reduce, eventually reaching zero. Note that in saturation i_C will be lower than the value in the active mode.

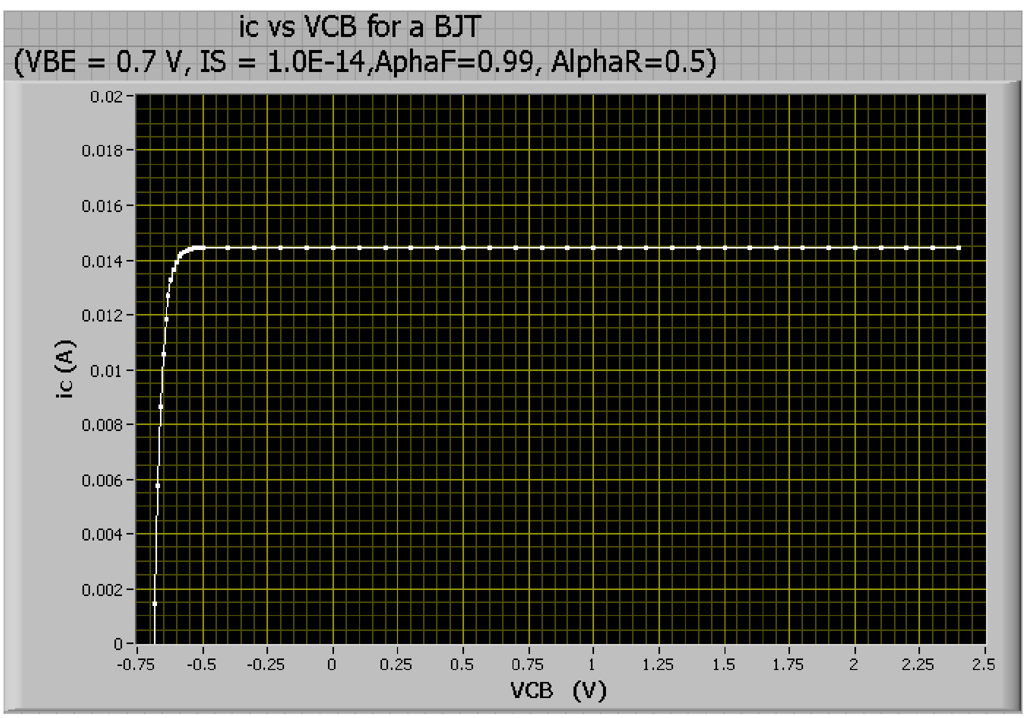


Fig.7 Plot of i_C vs v_{CB} for an *npn* transistor

2.8.2 EM Model: Reverse Active Mode of an *npn* BJT

In the EM equations if the CB junction is forward-biased by making v_{BC} positive (in the range 0.6 to 0.8V) and the EB junction is reverse-biased by making $v_{BE} < 0.4$V, we can evaluate the BJT currents for the reverse-active mode.

2.8.3 EM Model: Cutoff Mode

BJT will be cutoff when both EB and CB junctions are reverse-biased. In the EM equations this situation is realized by making both v_{BE} and v_{BC} negative (or $v_{BE} < 0.5$V and v_{BC} negative). For this case i_C will be negligibly small.

3.0 *pnp* Transistor

The schematic shown in Fig.8 below is that of a *pnp* transistor biased to operate in the active mode. Here the emitter is more positive than the base while the collector is more negative w.r.t. the base.

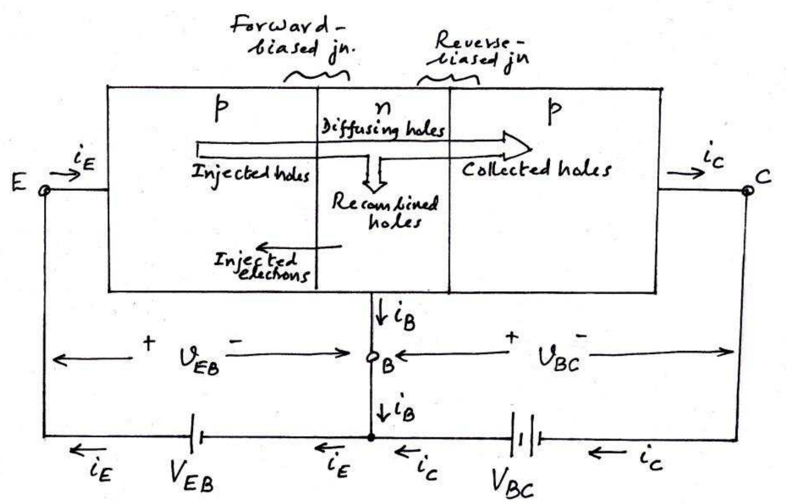


Fig.8 Current flow in a *pnp* transistor

In a *pnp* transistor the current is mainly due to holes injected from the emitter into the base by the forward-biased EB junction. Since the base is lightly doped the emitter current is mostly due to the holes. A number of holes injected into the base recombine with the electrons in the base. The holes reaching the boundary of the depletion region of the collector-base junction will be attracted by the negative voltage on the collector. These holes will be swept across the collector region to the collector and becomes the collector current.

The EM equations we wrote for the *npn* transistor can be used for the *pnp* transistor by replacing v_{BE} by v_{EB} and v_{BC} by v_{CB}.

4.0 BJT Configurations

We learned earlier, while drawing an equivalent circuit model for the BJT, that the BJT is a two-port network with an input port and an output port. There are three distinct ways a BJT can be connected as a two-port network, with one of the terminals becoming the common terminal for the input and output ports.

The following three configurations are named based upon which terminal is made the common terminal.

Configuration	Common terminal	Input port	Output port
Common Emitter (CE)	Emitter	between Base and Emitter	between Collector and Emitter
Common base (CB)	Base	between Emitter and Base	between Collector and Base
Common Collector (CC)	Collector	between Base and Collector	between Emitter and Collector

As seen earlier, the dc gain parameters α and β are defined as follows:

α is called the common-base current gain. $$\alpha = \frac{I_C}{I_E}$$

In the common-base configuration I_E is the input current and I_C the output current

β is called the common-emitter current gain. $$\beta = \frac{I_C}{I_B}$$

In the common-emitter configuration, I_B is the input current and I_C the output current

BJTs when used as amplifiers can be configured in one of the above three configurations. Each BJT amplifier configuration gives different performance parameters.

5.0 Current-Voltage Characteristics: CE Configuration

Two current-voltage characteristics are in common use – the input and output characteristics, to describe the BJT behaviour in the chosen configuration. The most commonly used configuration is the common-emitter (CE) configuration. We shall study the input and output characteristics in the common-emitter configuration.

5.1 Common-Emitter Characteristics

i) input characteristic: i_B - v_{BE}

ii) output characteristic: i_C - v_{CE}

5.1.1 Input characteristic: i_B - v_{BE}

The input characteristic is exponential and is given by

$$i_B = \left(\frac{I_S}{\beta_F}\right) e^{v_{BE}/V_T}$$

A typical plot of the input characteristic is shown below.

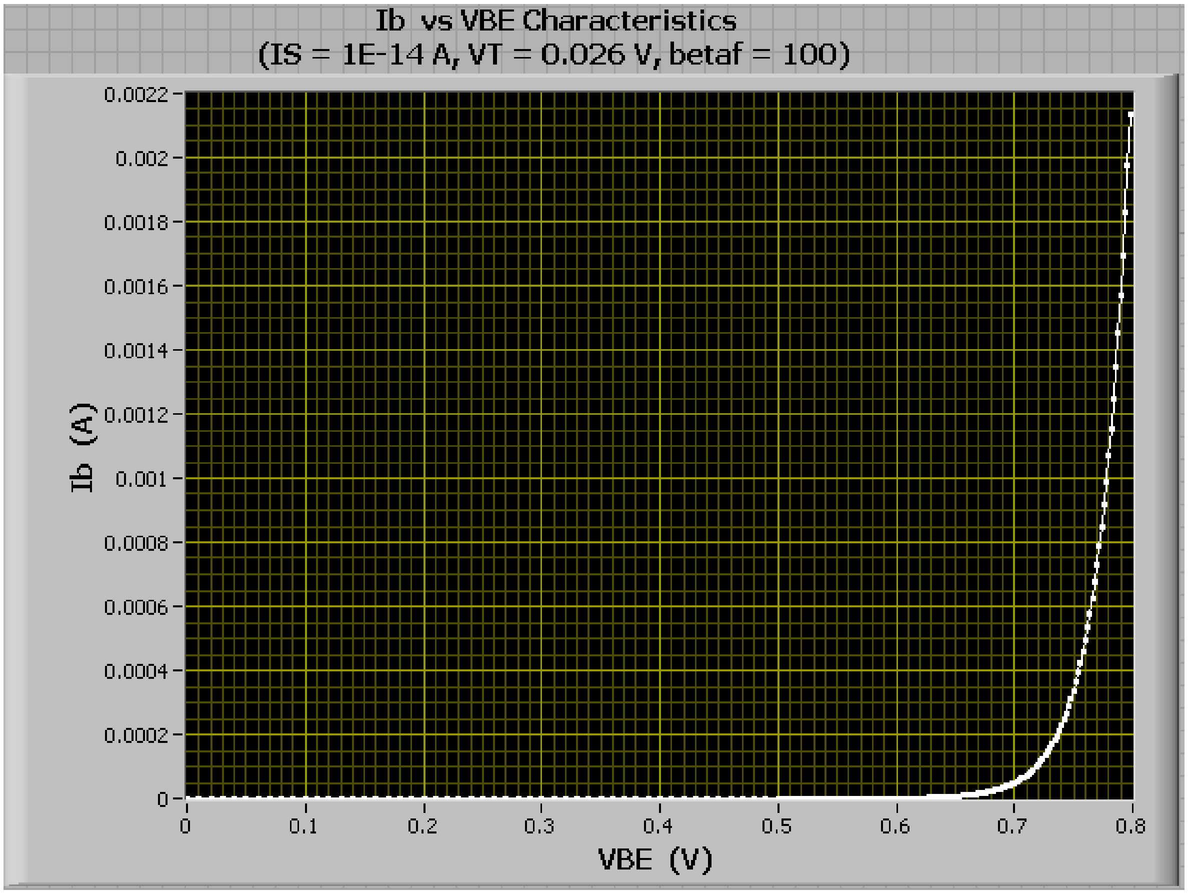


Fig.9 Input characteristic: i_B - v_{BE} in the CE configuration

For v_{BE} smaller than 0.5V, the current is negligible. For most of the typical current range v_{BE} lies in the range of 0.6 to 0.8V. hence, for most cases, especially for first-order DC calculations, we take $V_{BE} \approx 0.7$V.

Similar to silicon diodes, v_{BE} decreases by about 2 mV per °C rise in temperature, when the junction is operating at a constant current.

5.1.2 Common-Emitter (CE) Output characteristics: i_C - v_{CE}

In the common emitter output characteristics, the base current is used as a parameter. For different values of I_B , the collector current is measured as a function of v_{CE}. Typical i_C - v_{CE} characteristics are shown in Fig.10.

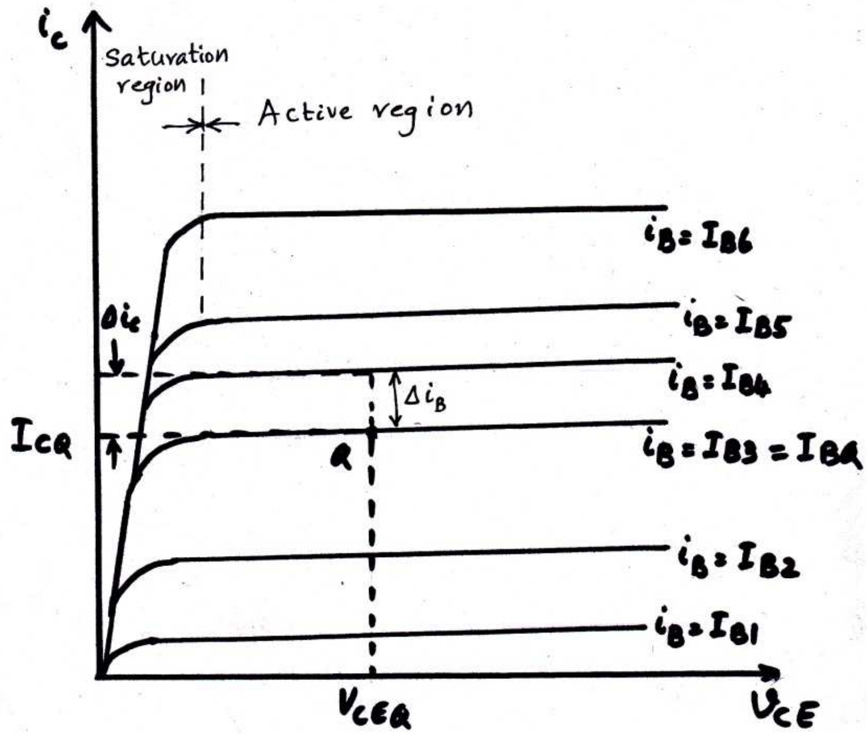


Fig.10 $\boldsymbol{i_C}$ - $\boldsymbol{v_{CE}}$ characteristics

Active and Saturation Regions

We see that, for each value of i_{B}, the collector current of the BJT would reach a steady value once the v_{CE} exceeds a certain value. The region with steady i_C values is the active region.

The region closer to the y-axis is the saturation region where i_C value for each i_C-v_{CE} characteristic is less than the active region value. As a first order approximation, especially for DC circuits, a particular v_{CE} value is specified as the boundary value between the active and saturation regions. This value is called V_{CEsat}, which is generally taken in DC circuits to be 200mV.

CE Current Gain $\boldsymbol{\beta}$

The CE current gain β_F (or β) is an important transistor parameter. The *large signal or dc β* is defined as

$$\beta_{dc} = \frac{I_{CQ}}{I_{BQ}}$$

where I_{CQ} and I_{BQ} correspond to a particular value of V_{CEQ} for the operating point Q on a particular $\boldsymbol{i_C}$ **-** $\boldsymbol{v_{CE}}$ characteristic.

We can define the *incremental or ac β* as

$$\beta_{ac} = \left.\frac{\Delta i_C}{\Delta i_B}\right|_{v_{CE=cons\tan t}}$$

The magnitudes of β_{dc} and β_{ac} differ typically by about 10 to 20%. The small-signal β or β_{ac} is also known by the alternate symbol h_{fe} which is called the *short-circuit common-emitter current gain.*

<u>5.1.3 Early Effect and Early Voltage</u>

We see from Fig.10 that the i_C-v_{CE} characteristics have a finite slope, i.e we observe that when v_{CE} increases the collector current of a particular i_C - v_{CE} characteristic also increases. The characteristic curves when extrapolated meet at a point on the negative v_{CE} axis, at v_{CE} = -V_A. The voltage V_A is a positive number and is a parameter for the particular BJT. Typical values of V_A are in the range of 50 to 200V. V_A is called the Early voltage.

Since $v_{CE} = v_{BE} + v_{CB}$, increasing v_{CE} for a given v_{BE} results in increased reverse bias v_{CB}. The increased reverse bias results in an increased depletion region width which reduces the effective base width. Since the scale current I_S is inversely proportional to the base width, i_C increases proportionately. This is called the Early effect.

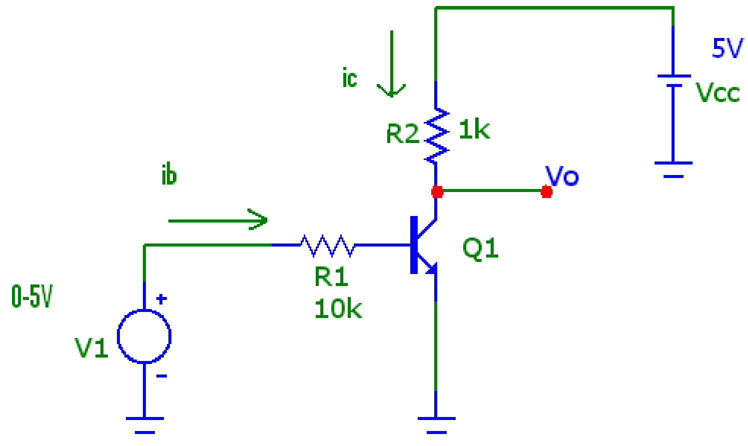
6.0 Illustration of Cutoff, Active, Saturation modes: BJT Inverter Circuit

Assume: $V_{BE} = 0.7$ V, $\beta = 50$, $V_{CEsat} = 0.2$ V

As V_{in} (=V_1) is varied from 0 to V_{cc} (=5V), the BJT goes from cut-off to active-mode and finally on to saturation.

6.1 Plot the V_o vs V_{in} Transfer characteristic

Case 1: $V_{in} < V_{BE}$
Since $V_{in} < V_{BE}$, BE junction is not forward-biased
The BJT is **cut-off**
Hence $i_B = 0$, and $i_C = 0$, resulting in $V_o = V_{cc}$
Hence for V_{in} values from 0 to V_{BE}, $V_o = V_{cc}$



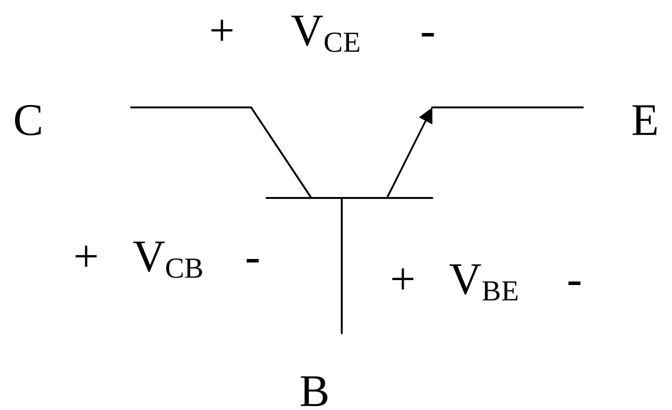
<u>Case 2</u> $V_{BE} \le V_{in} \le V_{IH}$
Since $V_{in} > V_{BE}$, the BJT would turn ON.
$i_B = (V_{in} - V_{BE})/R1$; $i_C = \beta\, i_B$
In the output loop, $V_{CC} = i_C R2 + V_{CE}$
i.e., $V_o = V_{CE} = V_{cc} - i_C R2$

Hence as V_{in} is increases, V_o will keep decreasing from V_{cc}.

How low can V_o ($=V_{CE}$) become? Can it become 0V or negative?

The BJT inverter circuit is a CE configuration; hence $V_{CE} > 0$. From the i_C - v_{CE} characteristics in the CE configuration we know that small values of V_{CE} corresponds to the saturation region. In the saturation mode both the EB and CB junctions are forward-biased. The lowest possible value for V_{CE} will be the difference between the two forward biased junctions as shown below:

Applying KVL, we can write the terminal voltage V_{CE} in terms of the other terminal voltages V_{BE} and V_{CB} as:



$V_{CE} = V_{BE} + V_{CB}$, where V_{BE} and V_{CB} are both positive (when the BE jn is forward-biased and the CB jn is reverse-biased). Initially, $V_{CB} >> V_{BE}$. As i_c increases the collector potential V_C ($=V_{CE}$) and V_{CB} decreases.

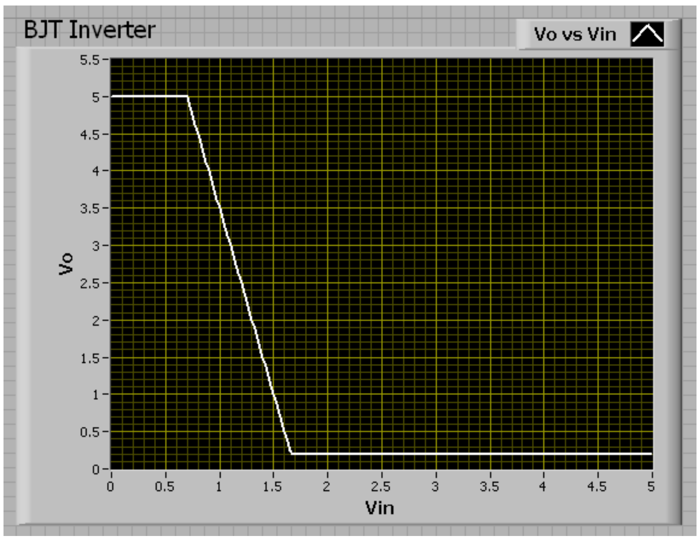
The lowest value of V_{CE} in an *npn* transistor is called the V_{CEsat}, which is typically in the range of 50 to 200 mV. Importantly V_{CE} cannot be negative in an *npn* transistor.

This lowest value of $V_o = V_{CEsat}$ gives us the maximum possible value of i_C in the BJT inverter.

$i_{C\,(max)} = (V_{cc} - V_{CEsat})/R2$

When V_o first becomes V_{CEsat}, the corresponding value of i_B is, $i_{Cmax}/\beta = i_{B2}$.

Since $i_B = (V_{in}\text{-}V_{BE})/R1$, the corresponding V_{in} value is:
$V_{in}\ (at\ i_{Cmax}) = V_{BE} + (i_{B2}\ R2) = V_{IH}$



So we define the point $V_{in} = V_{IH}$ as the point where the output voltage V_o first becomes V_{CEsat}
Hence for $V_{BE} \leq V_{in} \leq V_{IH}$, the BJT is in **active** mode.

For this range of V_{in} values, i_C varies linearly with i_B

Case 3: $V_{in} > V_{IH}$

For values of $V_{in} > V_{IH}$, i_B will keep increasing but i_C cannot increase; i_C will be clamped at $i_C = i_{C\,(max)}$. Also V_o cannot decrease; it will be clamped at V_{CEsat}

This is the **saturation** region.

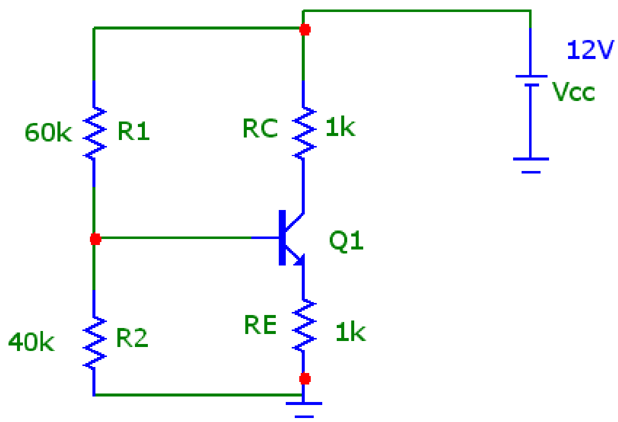
As we wrote earlier, $V_{CE} = V_{BE} + V_{CB}$, *or* $V_{CB} = V_{CE} - V_{BE}$
For V_{BE} = 0.7V and V_{CEsat} = 0.2 V,
V_{CB} = -0.5V or V_{BC} = 0.5V
Hence both BE and CB junctions are forward biased.

Features of the saturation mode:

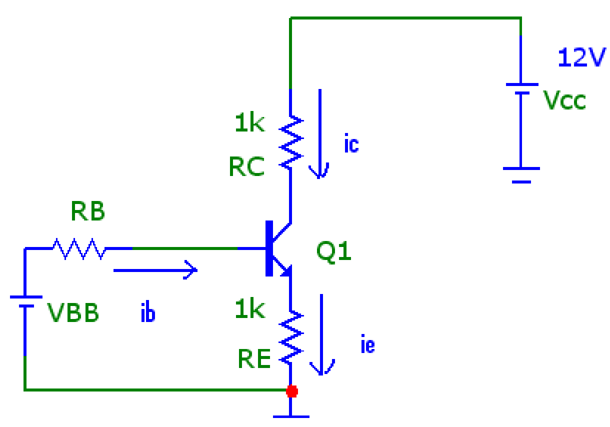
i) $i_C < i_B.\,\beta_{dc}$ (i_C gets saturated)
ii) Both BE and BC junctions get forward-biased

BJT DC Circuits

Common Emitter Biasing Circuit



Simplified circuit for current calculation



Using Thevenin's theorem in the BE loop, we can get:
$V_{BB} = (V_{CC} R_2)/(R_1+R_2)$; $RB = (R_1 R_2)/(R_1+R_2)$
Assuming BJT to be active, and applying KVL in the BE loop we can write

$$V_{BB} = i_B R_B + V_{BE} + i_B (\beta+1) R_E$$

Or $i_b = (V_{BB} – V_{BE})/[R_B + (\beta+1) R_E]$
$i_C = \beta\ i_B$; $i_E = (\beta+1)\ i_B$

$V_C = V_{CC} – i_C R_C$; $V_E = i_E R_E$
$V_{CE} = V_C – V_E$

If $V_{CE} > V_{CEsat}$ then the BJT is active; else it is in saturation.
If in saturation, then two equations need to be written (one for the input loop and one for the output loop. Another equation is $i_E = i_C + i_B$. $V_{CE} = V_{CEsat} = 0.2$ V. The above equations can be solved to get all the currents.

<u>Role of R_C and R_E</u>
For a given i_C there is a maximum value for R_C, above which the BJT will be saturation. This value can be found out by making $V_C = V_E + V_{CEsat}$ and using $V_C = V_{CC} – i_C R_C$.

Similarly, for circuit with a given R_1, R_2, R_C, and V_{CC}, if R_E is reduced, then the circuit will go into saturation after a certain value. This situation is more tricky as R_E value would affect both i_C and i_E .

Reference Text Book

AS Sedra and KC Smith, Microelectronic Circuits, 5th edition, Oxford University Press, Indian edition, 2007.