Chapter 3

# Bipolar Junction Transistor (BJT)

Bipolar junction transistor (BJT) is a 3 terminal, three region & two junction device. The 3 terminals of a transistor are called Emitter (E), Base (B) & Collector (C).

Emitter (E):
This is the first region of a transistor which emits charge carriers. It is highly doped.

Base (B):
It lies between Emitter & Collector. It is narrower in size and ~~highly~~ doped. (lightly)

Collector (C):
It is 3rd region of transistor & is moderately doped. It collects the charge carriers emitted by Emitter. It is wider than emitter.

BJT consist of 2 PN junctions namely: Emitter Base (EB) junction & collector - Base (CB) junction.

In BJT current is conducted due to both electrons & holes, so it is named bipolar.

As EB junction is forward-biased depletion region at this junction becomes narrow. Once the applied voltage exceeds its barrier potential, charge carriers reach the base from the emitter.

The CB-junction is reverse-biased, & as a result depletion region widened. However reverse biasing doesnot stop the minority charge carriers but support to flow. So, the minority charge carriers easily cross the collector-to-base junction.

## Types of BJT

Based on BJT, there are two types of BJT:

a) NPN Transistor
b) PNP Transistor

### a) NPN Transistor

If P-type base is sandwiched between N-type Emitter and N-type Collector, then the transistor is known as NPN transistor.

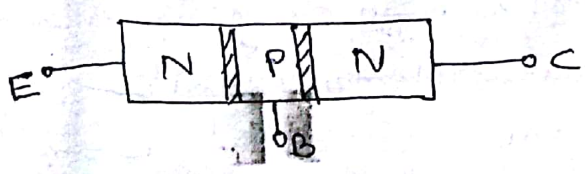



Fig: Structure of NPN transistor

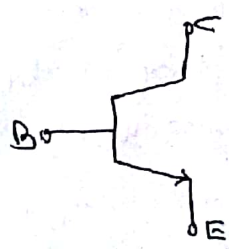



Fig: Symbol of NPN transistor

b) PNP Transistor

If N-type base is sandwiched between P-type Emitter and P-type collector, then a transistor is called PNP transistor.

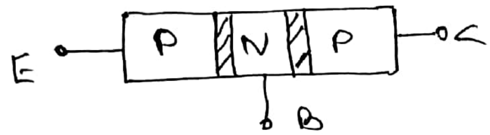



Fig: Structure of PNP transistor

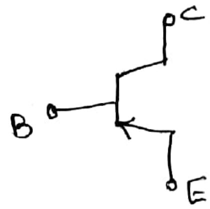



Fig: symbol of PNP transistor.

Operation of NPN Transistor
(Current flow mechanism in NPN Transistor)

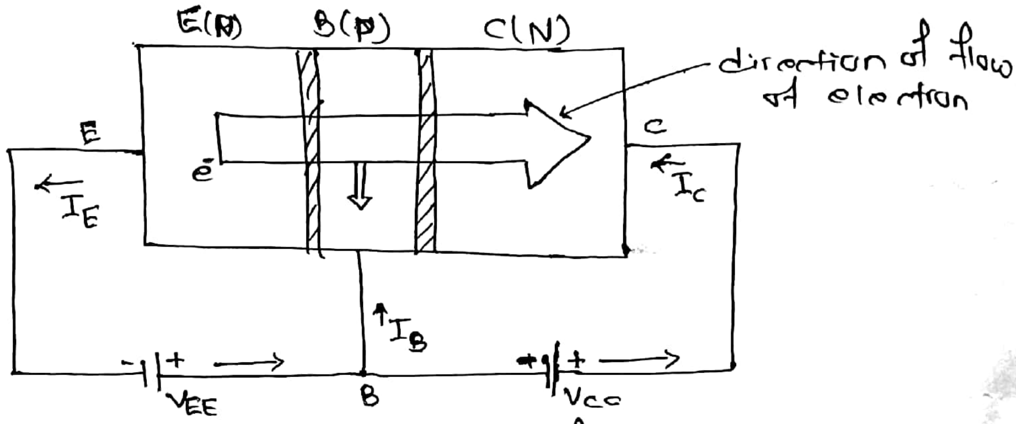



Fig: Basic operation of NPN transistor

For normal operation of transistor, Emitter-Base Junction must be forward biased & collector-Base Junction must be reverse biased, as shown in above fig.

The forward bias causes the e⁻s in N-type Emitter to flow towards Base, which gives Emitter current ($I_E$).

Among these e⁻s coming from Emitter to Base, only few electrons (about 5%) recombine with holes of P-type Base, & give rise to Base current $I_B$.

The remaining e⁻s (about 95%) cross the Base region and move towards collector. Since Collector is reverse biased the e⁻s crossing the Base (junction) region is attracted by positive terminal of a source $V_{cc}$. So e⁻s move from collector toward a source, & gives collector current $I_c$.

Thus, for a transistor, Emitter current is sum of Base current & Collector current.

$$\therefore I_E = I_B + I_C$$

Operation of PNP Transistor
( Current Flow mechanism in PNP Transistor)

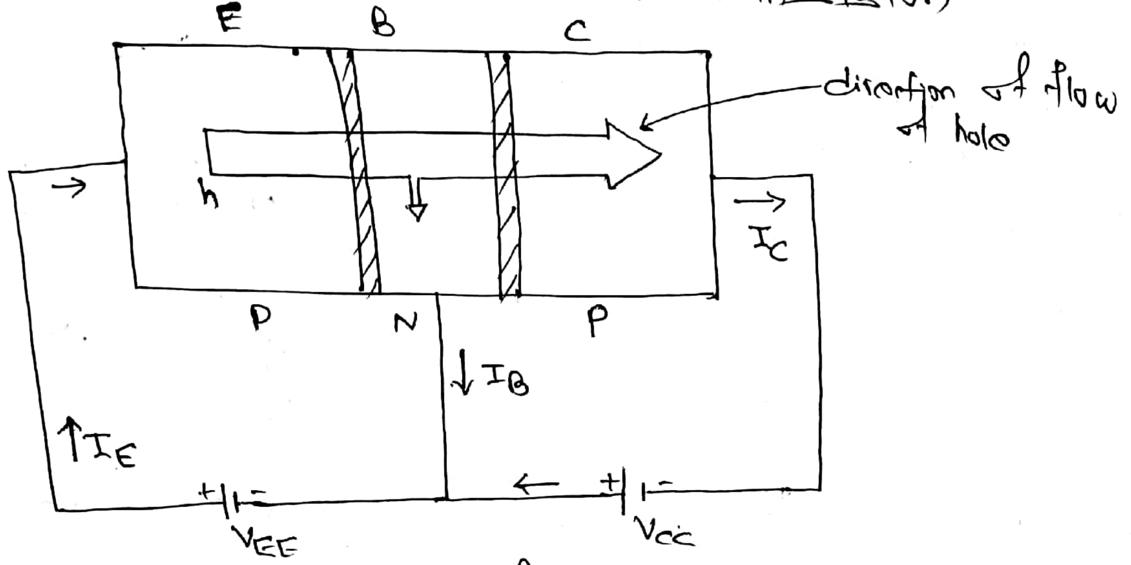



fig: Operation of PNP transistor

Figure shows the PNP transistor with Emitter-Base junction forward-biased & Collector-Base junction reverse-biased.

The +ve terminal of a source $V_{EE}$ repeals the holes from P-type Emitter. So the holes starts to move from Emitter towards a base & give rise to Emitter current $I_E$.

Among the holes coming from emitter to Base, only few holes (about 5%) recombine with the e⁻s of N-type Base & give rise to Base current ($I_B$)

The remaining holes (about 95%) cross the Base region and move to the collector. The -ve terminal of a source $V_{CC}$ attracts the holes from collector so that holes moves from collector towards the source $V_{CC}$. This gives rise to collector current ($I_C$).

Thus, for a transistor, Emitter current is sum of Base current & collector current.

[It may be noted that the current conduction in PNP transistor is by holes. However in the external connecting wires, the current is still by electrons.]

Modes of operation of BJT

A BJT can operate in any one of the following modes of operation.

a) Active mode (Normal mode)

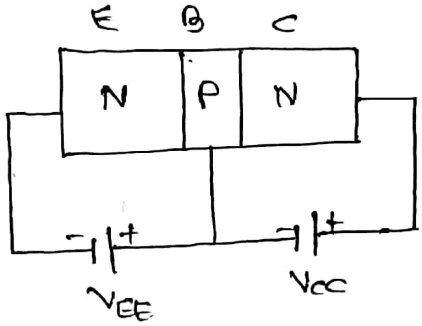
b) Cutoff mode

c) Saturation mode

a) Active Mode (Normal mode)

If EB junction of a BJT is forward biased & CB junction is reverse biased, then its mode of operation is called active mode.

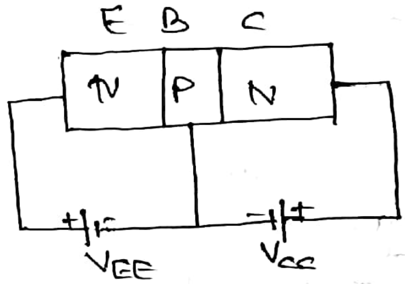
In this mode, BJT works as an amplifier.




b) Cutoff Mode

If both the EB & CB junction of a BJT is reverse-biased, then its modes of operation is called Cutoff mode.

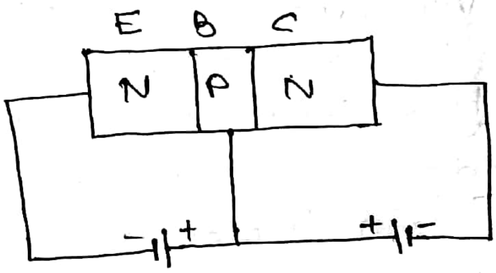
In this mode, BJT works as a open switch (switch OFF).




c) Saturation mode

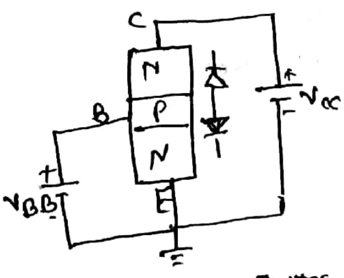
If both EB & CB junction of BJT is forward-biased, then its mode of operation is called saturation mode.

In this mode, BJT works as a closed switch (i.e. switch ON).




In summary,

| Mode | EB-Junction | CB Junction | Uses |
|---|---|---|---|
| Active | Forward | Reverse | Amplifier |
| Cutoff | Reverse | Reverse | Switch (OFF) |
| Saturation | Forward | Forward | Switch (ON) |




Common Emitter

# Transistor Configuration

The arrangement of I/p & O/p terminals in a circuit is called Transistor configuration. It can be performed in 3 ways:

1) Common Emitter (CE) configuration
2) Common Base (CB) Configuration
3) Common Collector (CC) configuration

## 1) Common Emitter (CE) configuration

I/p ⇒ $I_B$ & $V_{BE}$

O/p ⇒ $I_C$ & $V_{CE}$

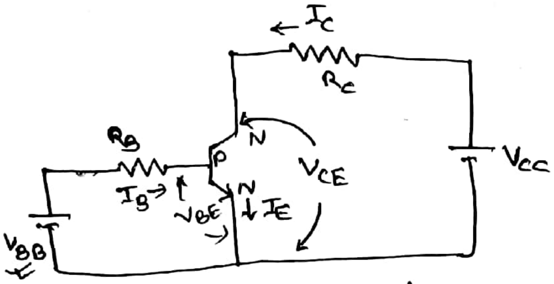



Fig: Ckt diagram for study of I/O characteristic curve for the CE configuration

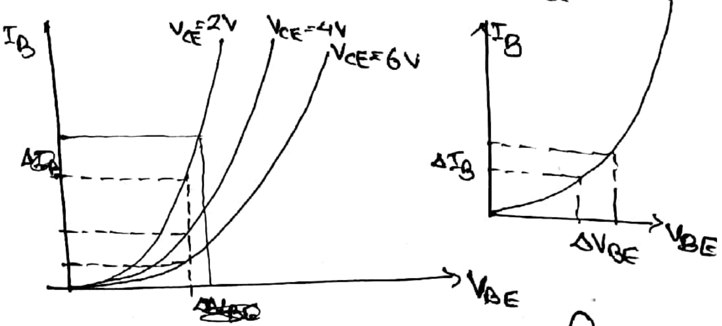



Fig: I/p characteristic for the CE configuration.

Input Characteristics:

→ Graph of $V_{BE}$ Vs $I_B$ for constant $V_{CE}$.

→ similar to that of forward biased diode.

[ I/p resistance

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

→ $I_B$ increases less rapidly with $V_{BE}$, so $r_{in}$ is HIGH.

→ As $V_{CE}$ is increased, $I_B$ decreases. The reason is that as $V_{CE}$ increases, the collector-base reverse voltage increases & effective base width is reduced. As a result recombination in base is reduced & base current is also reduced.

[As $V_{CE}$ is increased, the reverse-bias voltage at collector-Base (CB) junction increases which widens the depletion width of CB Junction. This depletion width increases the base region which is lightly doped compared to collector region. As a result, the effective base width reduces and the base current $I_B$ decreases. This effect is called Early (Early Effect) or Base width modulation]

If reverse-bias voltage is further increased, the effective base width tends to zero, causing excessive rise in collector current, $I_C$. This phenomenon is called 'Punch Through'. In this condition, Base does not exist & the emitter effectively behaves as short circuit with collector & cause voltage breakdown, & may damage transistor.

Output characteristics:

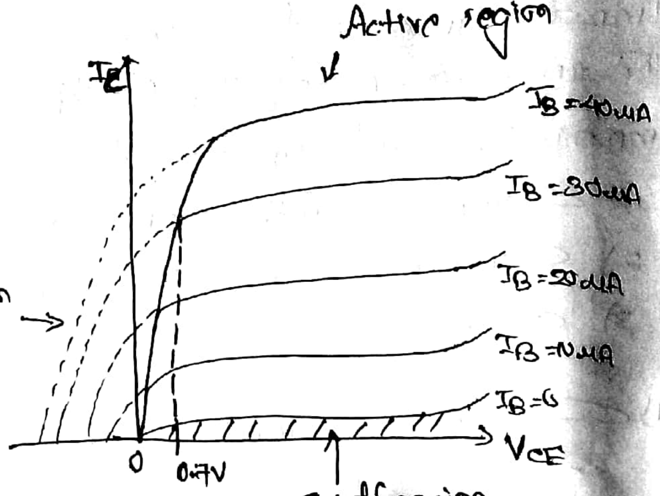



Fig: O/p characteristics curve for CE configuration.

→ For $V_{CE} < 0.7V$, CB junction is forward biased. So transistor is in saturation region, in which $I_C$ increases rapidly.

- Three regions of operation:

1) Active region
when EB junction is forward & CB junction is reverse-biased, it is in active region. For amplification purpose, the transistor must be operated in active region.

2) Saturation Region
when both the EB & CB junction are forward-biased, then transistor operates in saturation region.

3) Cut-off region
when both EB & CB junction are reverse-biased, then transistor operates in cut-off region.

## Common Base Configuration

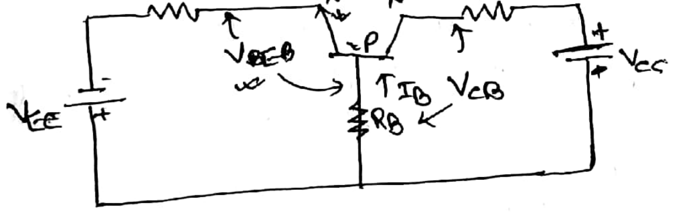



Fig: Common Base configuration

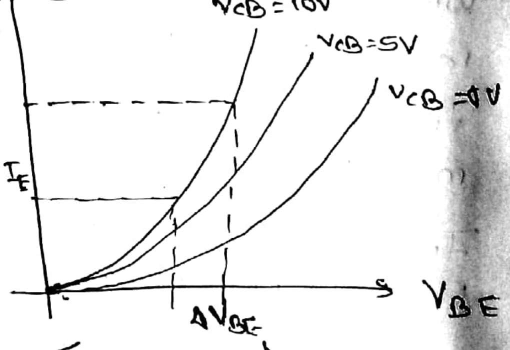



Fig: I/P characteristics for CB configuration

Input Characteristics:

→ plot between $I_E$ & $V_{BE}$ for constant voltage $V_{CB}$.

→ For a given I/p voltage $V_{BE}$, I/p current i.e. emitter current $I_E$ increases when higher value of collector-Base voltage is applied.

i.e. As $V_{CB}$ increases from 0V to 10V, the $I_E$ also increases, which is due to the reduction of the effective Base width.

Here, Input resistance, $r_{in} = \left.\dfrac{\Delta V_{BE}}{\Delta I_E}\right|_{V_{CB}=\text{constant}}$.

Since Emitter current increases rapidly with increase in $V_{BE}$. Thus i/p resistance for ~~CB~~ Common-Base configuration is very low.

Output Characteristics:

→ plot between o/p current $I_c$ & o/p voltage $V_{CB}$ for constant input current $I_E$.

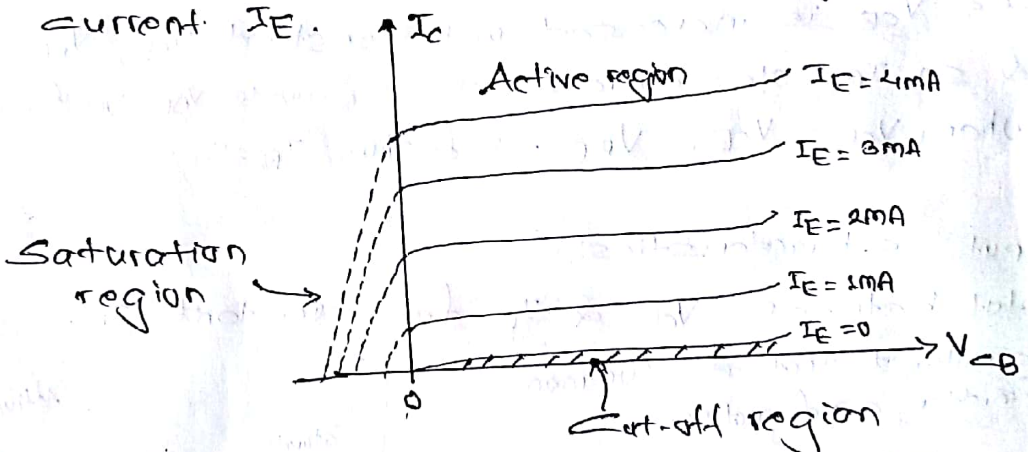



Fig: O/p characteristics curve for Common Base configuration.

→ $I_c$ is nearly equal to $I_E$ in active region. Thus o/p resistance is very high.

→ $I \simeq 0$ at cut-off region, i.e. only a small leakage saturation current flows.

→ For a small -ve voltage of $V_{CB}$, both EB & CB junctions remains in forward-biased ~~junction~~ condition & the region is in saturation region.

# Common Collector Configuration

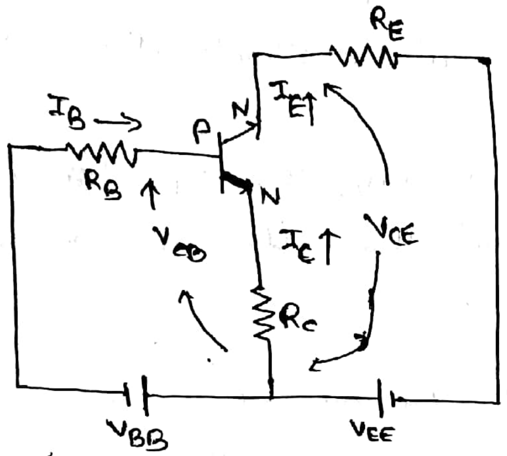



Fig: Common Collector Configuration

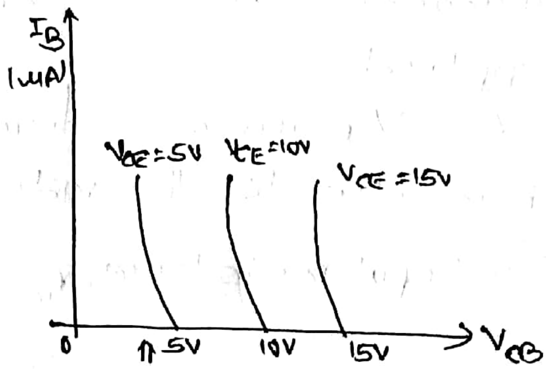



Fig: I/p characteristic of Common Collector Configuration

## Input Characteristics:

→ a graph betn $I_B$ & $V_{CB}$ for constant $V_{CE}$.

→ Here, $V_{BE} = V_{CE} - V_{CB}$ $(\because V_{CE} = V_{BE} + V_{CB})$

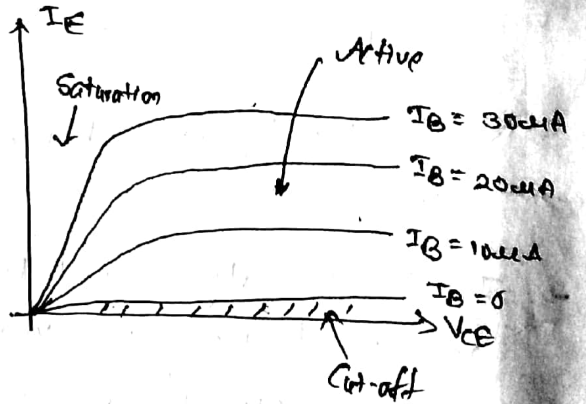
→ As $V_{CB}$ is increased with constant $V_{CE}$, $V_{BE}$ decreases & so $I_B$ also decreases. ($I_B$ due to $V_{BE}$, $V_{BE}$ forward bias)

→ When $V_{CB} = V_{CE}$, $V_{BE} = 0$ & thus $I_B = 0$

## Output Characteristics:

→ plot between $V_{CE}$ & $I_E$ for constant $I_B$.

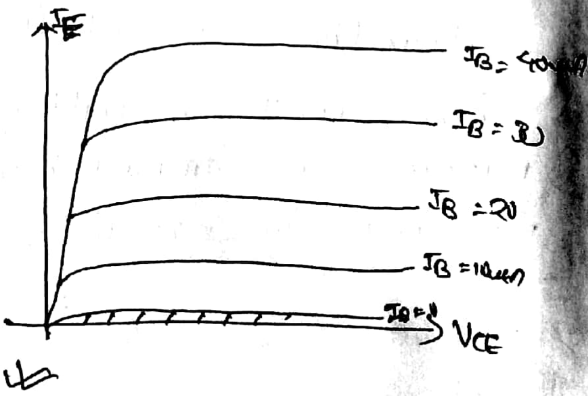
→ similar to that of Common Emitter configuration.




# This configuration is also known as emitter follower configuration because the Emitter voltage follows the base voltage.

→ I/p from base & collector

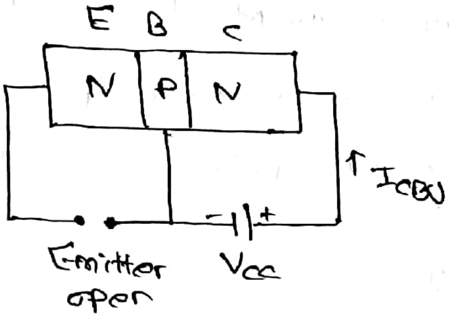
→ O/p from emitter & collector



Leakage Current in Transistor

1) Collector-Base Leakage Current ($I_{CBO}$)

In common-base configuration, small current flows from collector to base due to minority carriers even when emitter is open. This current is called collector-base leakage current.




From eqn (2), $I_C = \alpha I_E + I_{CBO}$

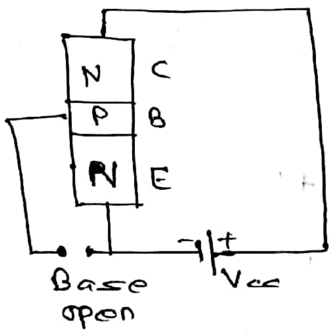
$= \alpha(I_C + I_B) + I_{CBO}$

or, $(1-\alpha) I_C = \alpha I_B + I_{CBO}$

$\therefore I_C = \frac{\alpha}{1-\alpha} I_B + \frac{1}{1-\alpha} I_{CBO}$

2) Collector-Emitter Leakage Current ($I_{CEO}$)

In common-emitter configuration, small current flows from collector to emitter even when base is open. This current is called Collector-Emitter leakage current.




We know,

$I_C = \frac{\alpha}{1-\alpha} I_B + \frac{1}{1-\alpha} I_{CBO}$

Since Base is open,

$I_B = 0$

$\therefore I_{CEO} = \frac{1}{1-\alpha} I_{CBO}$

$\because \alpha < 1$, $I_{CEO} > I_{CBO}$.

Current Gain in Transistors

1) Common Base Current Gain ($\alpha$)

It is defined as the ratio of collector current resulting from carrier injection to the total emitter current.

$$\text{Current Gain}(\alpha) = \frac{\text{Output current } [I_{C(INJ)}]}{\text{Input current } (I_E)}$$

or, $\frac{I_C}{I_E} = \alpha \Rightarrow I_{C(INJ)} = \alpha I_E$ —— (1)

Total Collector current is given by,

$I_C = I_{C(INJ)} + I_{CBO}$

$\therefore I_C = \alpha I_E + I_{CBO}$ —— (2)

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Since $I_{CBO}$ is very small & can be neglected.

Thus, $I_C = \alpha I_E$

$$\therefore \alpha = \frac{I_C}{I_E}$$

Thus common-base current gain can be defined as the ratio of collector current to emitter current.

2) Common Emitter Current Gain ($\beta$)

It can be defined as the ratio of collector current to base current.

i.e. $$\beta = \frac{I_C}{I_B}$$

Relationship between $\alpha$ and $\beta$

We know that, the total emitter current is the sum of base current & collector current.

i.e. $I_E = I_B + I_C$

On dividing both sides by $I_C$, we get

$$\frac{I_E}{I_C} = \frac{I_B}{I_C} + 1$$

$$\text{or, } \frac{1}{I_C/I_E} = \frac{1}{I_C/I_B} + 1$$

$$\text{or, } \frac{1}{\alpha} = \frac{1}{\beta} + 1 = \frac{1+\beta}{\beta}$$

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

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

$$\text{or, } \frac{1-\alpha}{\alpha} = \frac{1}{\beta}$$

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

3) Common- Collector Current Gain($\gamma$)

It is defined as the ratio of Emitter current to base current.

$$\text{i.e. } \gamma = \frac{I_E}{I_B} = \frac{I_B + I_C}{I_B} = 1 + \frac{I_C}{I_B} = 1+\beta$$

$$\therefore \gamma = 1+\beta$$

Avalanche Effect (Breakdown)

For amplification purpose, Emitter-Base Junction must be forward biased & CB junction must be reverse-biased. [The current may increase suddenly if the reverse-bias voltage is made sufficiently large. This process is known as Avalanche effect or breakdown.

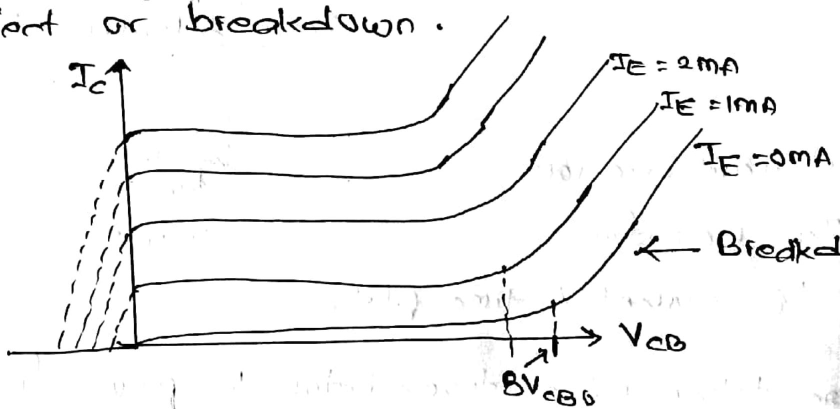


Fig: Common Base O/p characteristic within Breakdown region.

Breakdown may also occur due to the Punch-Through effect. As the reverse voltage increases, the depletion width across CB junction increases. However the depletion region penetrates deeper into the base due to its light doping. As a result, effective base width reduces (& $I_B$ decreases). This effect is called Early effect.

On further increase in reverse-biased voltage, the effective base width reduces to zero i.e. collector short circuits with emitter and excessive collector current flows. This is known as Punch-Through or Reach-Through.

Here, $BV_{CBO}$ is the breakdown voltage when $I_E = 0$.

Also, as $I_E$ increases, the breakdown occurs at lower input voltage ($V_{CB}$)

# BJT Switching Time

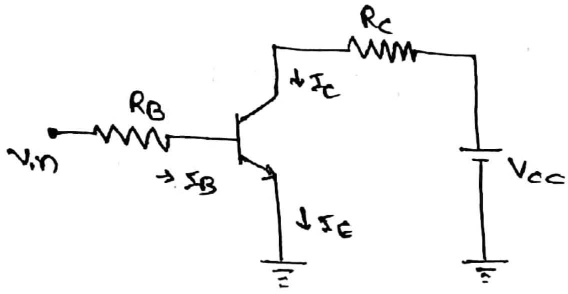


Fig: (a)

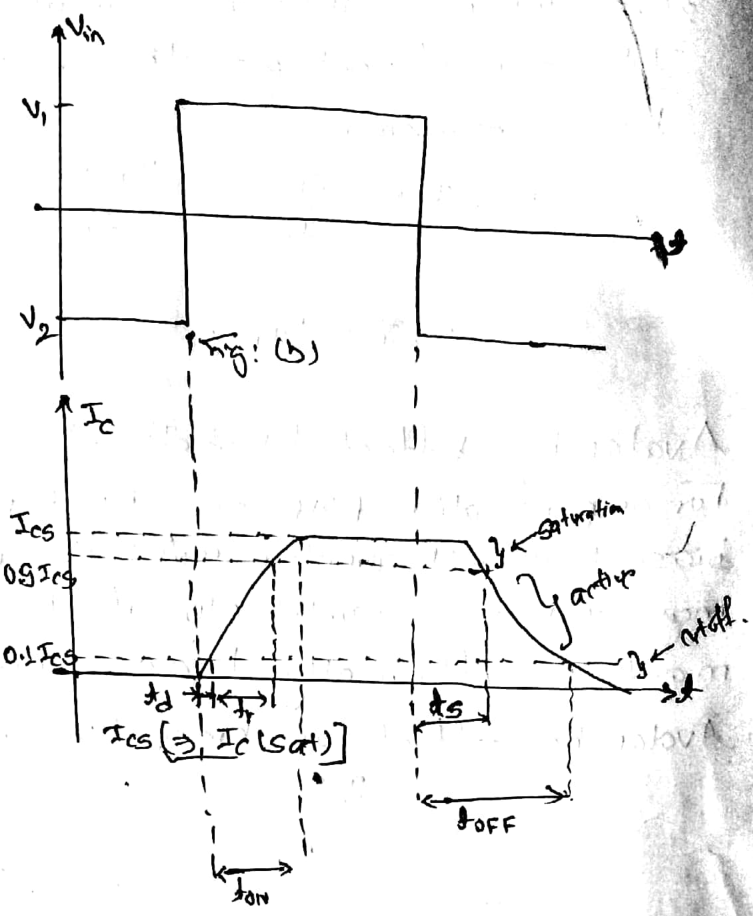


Fig (c)

Fig (a): Circuit diagram
Fig (b): I/P waveform
Fig (c) = O/P current $V_s$ time plot.

— The time taken by a transistor to move from cutoff mode (OFF switch) to saturation mode (switch ON) or move from saturation to cutoff mode is called transistor switching time.

Transistor switching times are
1) Turn ON Time ($t_{ON}$)
2) Turn OFF Time ($t_{OFF}$)

1) Turn ON Time ($t_{ON}$)

The time taken by a transistor to move from cutoff to saturation is called turn-ON time. It can also be defined as the time taken by transistor to change its current from 0 (zero) to $I_C$(sat). $t_{ON} = t_d + t_r$

It consist of 2 time periods: diffusion & rise time.

i) Diffusion Time ($t_d$)

It is the time taken by transistor to enter into active mode from cut-off mode. It can also be defined as the time taken by a transistor to increase its current from 0 to 10% of $I_C$(sat).

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ii) Rise Time ($t_r$)

It is the time taken (spend) by transistor in active mode while moving from cutoff mode to saturation. It can also be defined as the time taken by transistor to increase its current from 10% to 90% of $I_C(sat)$ while moving from cutoff to saturation.

2) Turn OFF Time ($t_{OFF}$)

The time taken by a transistor to move from saturation to cut-off mode is called Turn-OFF time. It can also be defined as the time taken by a transistor to decrease its current from $I_C(sat)$ to 0. $T_{OFF} = t_s + t_f$

It consist of 2 time periods:- storage time & fall time.

i) Storage time ($t_s$)

It is the time taken by a transistor to enter into active mode from saturation mode while moving from saturation to cutoff. It can also be defined as the time taken by a transistor to decrease its current from $I_C(sat)$ to 90% of $I_C(sat)$.

ii) Fall Time ($t_f$)

It is the time spend by a transistor in active region while moving from saturation to cut-off. It can also be defined as the time taken by a transistor to decrease its current from 90% to 10% of $I_C(sat)$.

- Ebers Moll Model of the BJT

Ebers Moll model is a transistor model which describes the operating states of a transistor. This model is useful to obtain information about the DC characteristics of a transistor.

This model generalizes the behaviour of a transistor by taking into account the inverted mode of operation of the transistor.

- This model involves two ideal diodes placed back-to-back & two dependent current controlled current source shunting the ideal diodes.

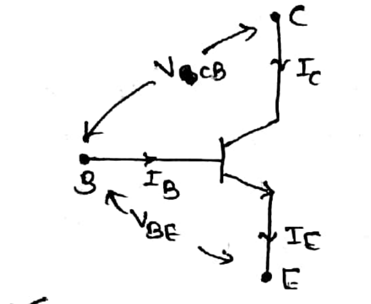



Fig: NPN Transistor.

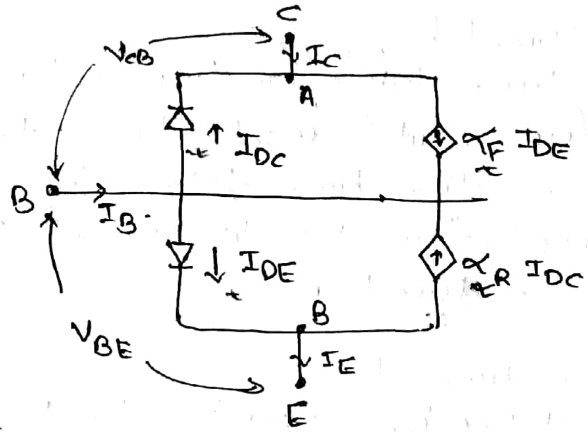



Fig: Ebers Moll model of BJT

We know that, the current through a diode is given by,

$$I_D = I_S(e^{V/\eta V_T} - 1)$$

Take $\eta = 1$, then

$$I_D = I_S(e^{V/V_T} - 1)$$

For Emitter Diode,

$$I_{DE} = I_{SE}(e^{V_{BE}/V_T} - 1) \quad \text{—— (i)}$$

For Collector Diode,

$$I_{DC} = I_{SC}(e^{V_{CB}/V_T} - 1) \quad \text{—— (ii)}$$

Using KCL at node A,

$$I_{DC} + I_C = \alpha_F I_{DE}$$

$$\Rightarrow I_C = -I_{DC} + \alpha_F I_{DE}$$

$V_{CB}$

$$= -I_{SE}(e^{V_{BE}/V_T} - 1) + \alpha_F I_{SE}(e^{V_{BE}/V_T} - 1) \quad \text{—(iii)}$$

Similarly, applying KCL at node B,

$$I_{DE} + I_E - \alpha_R I_{DC} = 0$$

$$\Rightarrow I_E = I_{DE} - \alpha_R I_{DC}$$

$$= I_{SE}(e^{V_{BE}/V_T} - 1) - \alpha_R I_{SC}(e^{V_{CB}/V_T} - 1) \quad \text{— (iv)}$$

Also, we know that,

$$I_E = I_B + I_C$$

$$\Rightarrow I_B = I_E - I_C$$

$$= I_{SE}(e^{V_{BE}/V_T} - 1) - \alpha_R I_{SC}(e^{V_{CB}/V_T} - 1)$$

$$- \{-I_{SC}(e^{V_{CB}/V_T} - 1) + \alpha_F I_{SE}(e^{V_{BE}/V_T} - 1)\}$$

or, $I_B = I_{SE}\left(e^{V_{BE}/V_T}-1\right)(1-\alpha_F) + I_{SC}\left(e^{V_{CB}/V_T}-1\right)(1-\alpha_R)$ —(v)

$\therefore I_B = (1-\alpha_F) I_{SE}\left(e^{V_{BE}/V_T}-1\right) + (1+\alpha_R) I_{SC}\left(e^{V_{CB}/V_T}-1\right)$.

## Transistor as a Switch (BJT Inverter)

A BJT can be used as a switch or a inverter when it is operated in cutoff or saturation mode.

A transistor is called closed switch (Switch ON), if it is in saturation mode, whereas it is called open switch (switch OFF) if it is in cutoff mode.

The circuit diagram & operation of BJT switch inverter is as shown below:

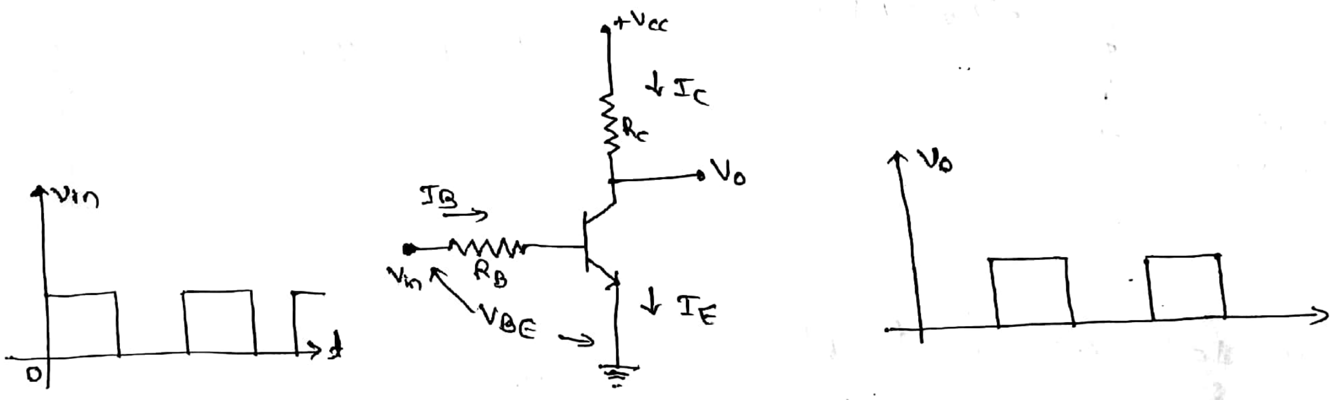
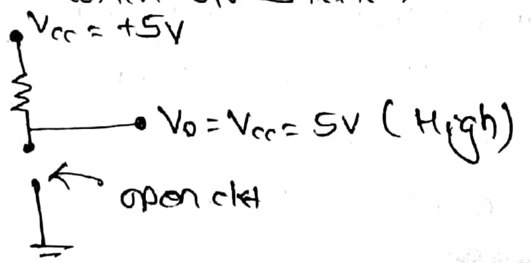



fig: BJT inverter switch (with I/p & o/p pulse).

To use BJT as a inverter / switch, the input voltage ($V_{in}$) is supplied to the base through $R_B$ & output voltage ($V_o$) is taken from the collector through $R_C$.

Case I: when i/p is low ($V_{in} = 0V$) [ $V_{BE} < 0.5V$ for Si ]

- If $V_{in} = 0V$ (or $V_{in} <$ Barrier potential, $V_{BE} < 0.5V$ for Si), it is not sufficient to forward bias EB Junction. The supply $V_{CC}$ reverse biased CB junction. Thus both EB & CB junction are ~~forward~~ reverse biased due to which transistor will be in cutoff mode. In cutoff mode, transistor doesn't conduct current from Collector to Emitter. So the collector & Emitter are said to be open circuited. In this case o/p voltage becomes high. & is switch ON state.

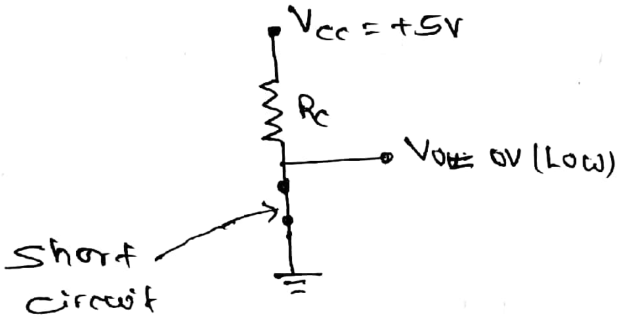



Here, $V_o = V_{CC} = V_C$

Case II: When I/p is high ($V_{in}$ = +5V) ($V_{BE}$ > 0.7 V)

When $V_{in}$ = +5V (OR when $V_{BE}$ > 0.7 V for Si), it is sufficient to forward biased both EB & CB junction due to which transistor will be in saturation mode.

In saturation mode, transistor conduct constant current $I_{c(sat)}$ from collector to Emitter. i.e. collector & Emitter are short circuited (close switch). Thus output voltage becomes low (i.e. $V_o$ = 0 V(H)). i.e. switch OFF.




Here, $I_B = \frac{V_{in} - V_{BE}}{R_B}$

& $I_C = \beta I_B$

$V_o = V_{cc} - I_c R_c$

Transistor as an Amplifier.

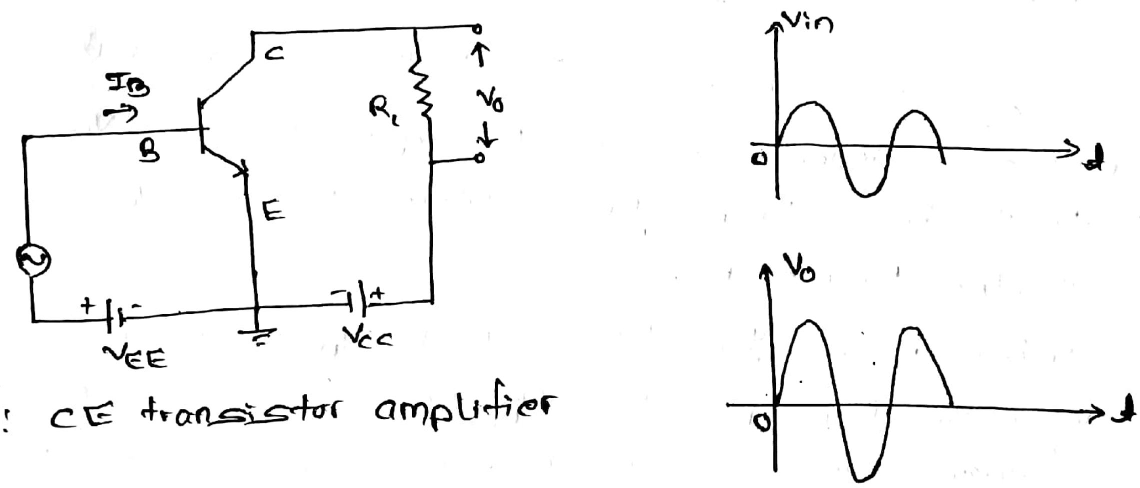



fig: CE transistor amplifier

fig: I/O waveform

To use transistor as an amplifier, it must be operated in active mode i.e. EB junction must be forward biased & CB junction must be reverse-biased.

Consider a CE transistor amplifier circuit as shown above where $V_s$ is the low amplitude AC signal to be amplified. The DC voltage sources $V_{EE}$ & $V_{cc}$ are connected in such a way that they always forward-biased EB junction and reverse-biased CB junction despite of source voltage $V_s$.

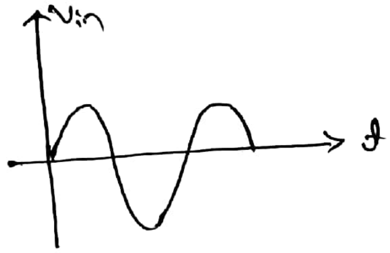
Operation:

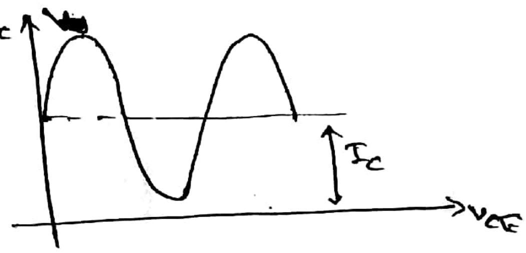
For the +ve half cycle of source signal $V_s$, Base will be more positive i.e. forward biasing of EB junction is increased due to which more current flow into Base. This causes o/p current (i.e. collector current, $I_c$) to increase. Thus the o/p voltage, $V_o = I_c R_c$ also increases.

For the -ve half cycle of source signal $V_s$, Base will be less positive i.e. the forward biasing of EB junction is decreased due to which less current flows into Base. This cause the o/p current to decrease sharply. Thus the o/p voltage, $V_o = I_c R_c$ also decreases.

Thus amplified signal is obtained at the o/p.

[∴ Small change in i/p voltage (i/p current) causes large change in o/p current (collect current, $I_c$)]




The i/p circuit being forward biased has low resistance, so a small change in i/p voltage can cause large change in $I_B$. This cause almost same change in $I_c$ ($I_c = \beta I_B$). This large collector current $I_c$ flowing through $R_c$ develops a large voltage drop across it. Thus a weak signal applied at i/p circuit appears in the amplified form at the o/p. In this way transistor acts as a amplifier.

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