Unit 01: Introduction to Analog Circuits

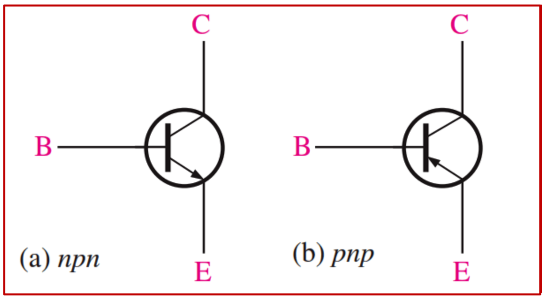
- **Transistor as an Amplifier**
- **Faithful Amplification**
- **What is Biasing? Need of biasing**
- **Potential Divider Bias Circuit**
- **Numerical [using Method-I and Method-II]**
- **Transistor as an Electronic Switch**
- **How to identify region of operation for transistor?**
- **What is FET? Difference between BJT & FET**
- **Construction and working of N-channel JFET.**

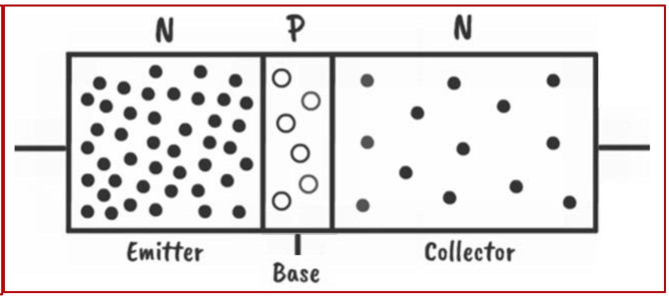
Bipolar Junction Transistor (BJT)

- A BJT is a three terminal semiconductor device used to amplify or switch electronic signals and electrical power.
- It is referred as one of the most important inventions in the 20th Century !
- It is invented in 1948 by American physicists John Bardeen and Walter Brattain while working under William Shockley at Bell Labs. The three shared the 1956 Nobel Prize in Physics for their achievement.
- Transistors revolutionized the field of electronics, and paved the way for smaller and cheaper radios, calculators, and computers !

Construction of a Transistor

A transistor consists of two PN junctions formed by sandwiching either P-Type or N-Type semiconductor between a pair of opposite types. There are two types of transistors, namely – NPN Transistor & PNP Transistor

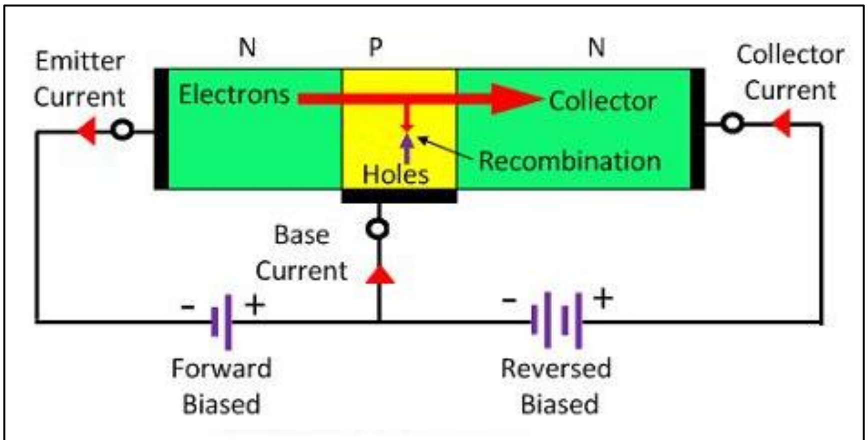




Size ➔ Collector > Emitter > Base
Doping ➔ Emitter > Collector > Base

Working of NPN Transistor

1. Emitter-Base junction should be Forward Biased and Collector-Base junction should be Reverse Biased
2. $I_E = I_B + I_C$ { Since, I_B is very small ➔ $I_E \cong I_C$ }



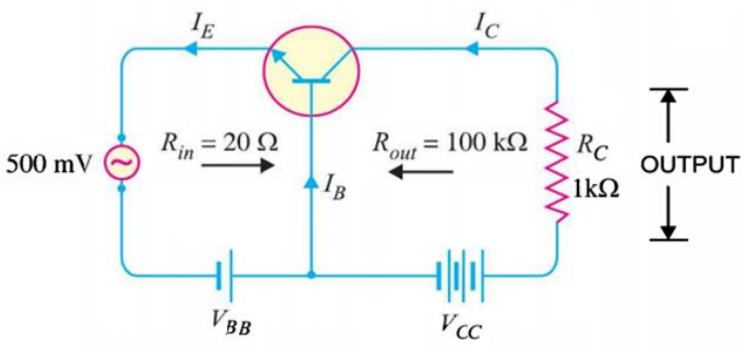
Working of Transistor

**Only majority charge carriers are discussed here !*

Transistor as an Amplifier

By understanding the working of transistor it can be stated that-
Basic amplifying action is produced by transferring a current {Since, $I_E \cong I_C$} from Low Resistance Path to High Resistance Path.

TRANSfer + ResISTOR = TRANSISTOR !



$$I_E = \frac{500\text{ mV}}{20\Omega} = 25\text{mA}$$

we know that, $I_C \cong I_E$

output voltage = $I_C \times R_C$

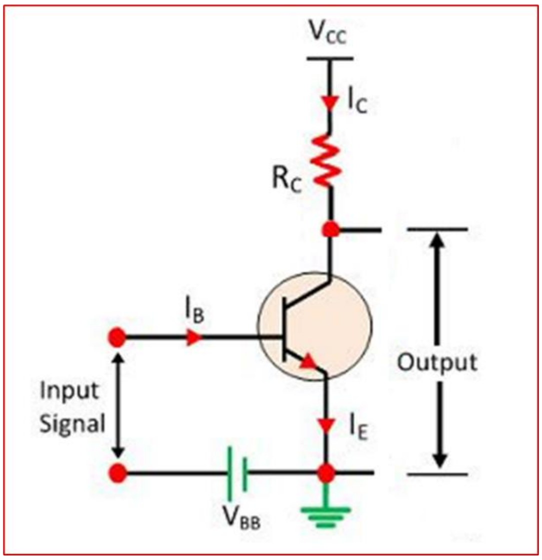
$$\therefore \text{output voltage} = 1\text{k}\Omega \times 25\text{mA} = 25\text{V}$$

Transistor Configurations

The transistor has three terminals: Emitter (E), Base (B) & Collector (C). But in the circuit connections we need four terminals, two terminals for input and another two terminals for output. To overcome this problem one terminal is used as common for both input and output actions. Using this property different circuits can be constructed and these structures are called Transistor Configurations. Generally there are three different configurations of transistors. They are:

1. Common Base (CB) Configuration: No current gain but voltage gain
2. Common Collector (CC) Configuration: Current gain but No voltage gain
3. Common Emitter (CE) Configuration: Both current gain and voltage gain

Common Emitter Configuration



- Input Current: I_B
- Input Voltage: V_{BE}
- Output Current: I_C
- Output Voltage: V_{CE}
- VBB : Forward Biasing Voltage
- VCC : Reverse Biasing Voltage

$$V_{CE} = V_{CC} - I_C R_C$$
$$I_C = \beta I_B$$

where, β is current amplification factor in CE configuration

**Generally, input is weak analog signal which requires amplification.*

Transistor Region of Operations

- The supply of suitable external DC voltage is called as **Biasing**. Either forward or reverse biasing is done to the emitter and collector junctions of the transistor.
- These biasing methods make the transistor circuit to work in four regions:

Sr. No.	Emitter-Base Junction	Collector-Base Junction	Region of Operation	Application
1.	Forward Bias	Reverse Bias	Active Region	Amplifier
2.	Forward Bias	Forward Bias	Saturation Region	Switch
3.	Reverse Bias	Reverse Bias	Cut-Off Region	
4.	Reverse Bias	Forward Bias	Inverse Active	---

Faithful Amplification

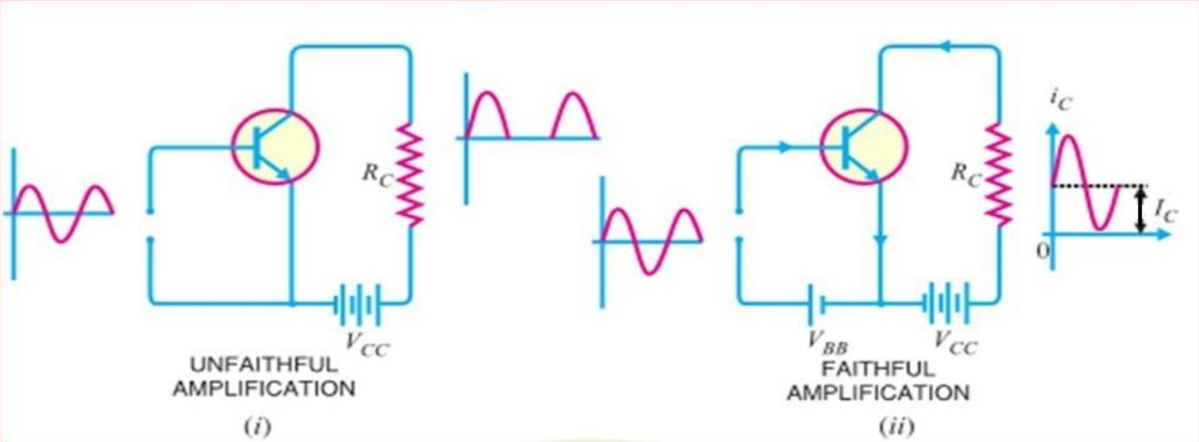
The process of raising the strength of a weak signal without any change in its general shape is known as a faithful amplification. (OR) The increase in magnitude of the signal without any change in its shape is known as faithful amplification.

The key factor for achieving the faithful amplification is that the base emitter junction of transistor remains forward biased and collector junction reverse biased. To ensure Faithful amplification following conditions must be specified.

1. **Proper Zero Signal Collector Current:** The value of zero signal collector current should be at least equal to the maximum collector current due to signal alone.

2. **Proper Minimum Base-Emitter Voltage (VBE):** In order to achieve faithful amplification, the base emitter voltage VBE should not fall below 0.3 V for Ge transistor and 0.7 V for Si transistor at any instant.

3. **Proper Minimum Collector-Emitter Voltage (VCE):** For faithful amplification, the collector emitter voltage VCE should not fall below 0.5 V for germanium and 1.0 V for silicon transistors at any instant.



Transistor Biasing

Transistor Biasing is the process of setting a transistors DC operating voltage or current conditions to the correct level so that any AC input signal can be amplified correctly by the transistor.

Need for Biasing:

If a signal of very small voltage is given to the input of BJT, it cannot be amplified. Because, for a BJT, to amplify a signal, two conditions have to be met

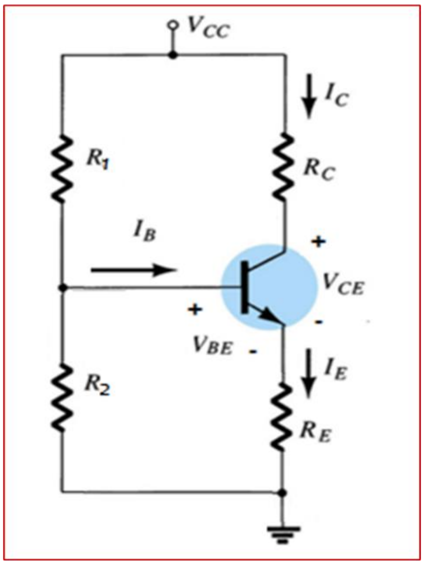
1. The input voltage should exceed cut-in voltage (VBE = 0.7V for Silicon transistor) for the transistor to be ON.
2. The BJT should be in the ACTIVE region, to be operated as an amplifier.

*In short, Biasing of transistor is required to achieve faithful amplification !

The basic purpose of transistor biasing is to keep base-emitter junction properly forward biased and collector-base junction properly reverse biased during the application of signal. This can be achieved with bias battery or associating circuit with a transistor. The latter method is more efficient and frequently employed! The circuit which provides transistor biasing is known as *Biasing Circuit*. There are different types of Biasing circuit:

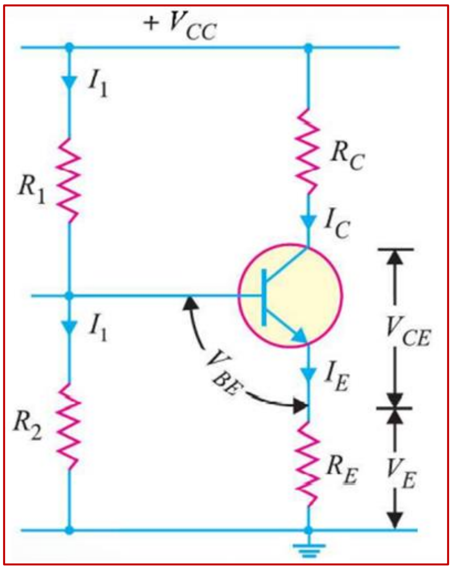
1. Base Resistor Method (or Fixed Biased Method)
2. Emitter Bias Method
3. Biasing with Collector Feedback Resistor
4. Potential Divider Biasing (or Voltage Divider Biasing)

Potential Divider Biasing



- This is most widely used method of biasing
- In this method two resistors R1 & R2 are connected across Vcc & provide biasing
- The name "potential divider" comes from the potential divider formed by R1 and R2
- The voltage drop across R2 forward biases the emitter base junction
- This causes base current and hence, collector current flow in the zero signal condition

Circuit Analysis: Method-I (Approximate Analysis)



Let, current flowing through R1 is I1. As base current is very small ($I_B \cong 0$), it will also flow through R2

$$\therefore I_1 = \frac{V_{CC}}{R_1 + R_2}$$

Hence voltage across R_2 is $V_2 = I_1 . R_2$

$$V_2 = \left(\frac{R_2}{R_1 + R_2}\right) V_{CC}$$

Applying KVL to the input side,

$$V_2 - V_{BE} - V_E = 0$$

i.e.,

$$V_2 = V_{BE} + V_E = V_{BE} + I_E R_E$$

$$I_E = \frac{V_2 - V_{BE}}{R_E}$$

But, we know that $I_C \cong I_E$

$$\therefore I_C = \frac{V_2 - V_{BE}}{R_E}$$

Applying KVL to the output side, we get

$$V_{CC} - I_C R_C - V_{CE} - I_E R_E = 0$$

i.e.,

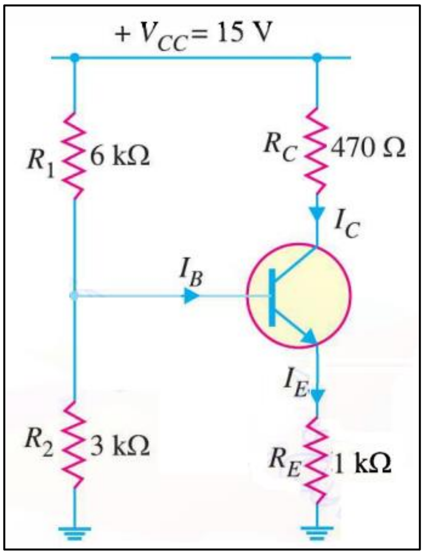
$$V_{CE} = V_{CC} - I_C R_C - I_E R_E$$

Since, $I_C \cong I_E$ above equation can be written as:

$$V_{CE} = V_{CC} - I_C (R_C + R_E)$$

Example on Potential Divider Biasing (Method-I)

Ex. The circuit shown in the figure uses Silicon transistor. Find out the values of V_{CE} and I_C.



Solution:

$$V_2 = \left(\frac{R_2}{R_1 + R_2}\right) V_{CC} = \left(\frac{3k\Omega}{6k\Omega + 3k\Omega}\right) 15V = 5V$$

Applying KVL to the input side,

$$V_2 - V_{BE} - V_E = 0$$

i.e.,

$$V_2 = V_{BE} + V_E = V_{BE} + I_E R_E$$

$$I_E = \frac{V_2 - V_{BE}}{R_E} = \frac{5 - 0.7}{1k\Omega} = 4.3 \text{ mA}$$

**Note: for Silicon transistor V_{BE}=0.7V*

But, we know that $I_C \cong I_E$

$$\therefore I_C = 4.3 \text{ mA}$$

Applying KVL to the output side, we get

$$V_{CC} - I_C R_C - V_{CE} - I_E R_E = 0$$

$$V_{CE} = V_{CC} - I_C R_C - I_E R_E$$

$\because I_C \cong I_E$ above equation can be written as:

$$V_{CE} = V_{CC} - I_C(R_C + R_E)$$

$$V_{CE} = 15V - 4.3mA\ (0.47k\Omega + 1k\Omega)$$

$$V_{CE} = 8.68 \text{ V}$$

Circuit Analysis: Method-II (Using Thevenin's Theorem)

Thevenin's Theorem states that it is possible to simplify any linear circuit, no matter how complex, to an equivalent circuit with just a single voltage source (V_{TH}) and series resistance (R_{TH}) connected to a load.

$$V_{TH} = \left(\frac{R_2}{R_1 + R_2}\right) V_{CC} \qquad \text{and} \qquad R_{TH} = R_1 || R_2 = \frac{R_1 . R_2}{R_1 + R_2}$$

Applying KVL to the input side,

$$V_{TH} - I_B R_{TH} - V_{BE} - I_E R_E = 0$$

$$V_{TH} = I_B R_{TH} + V_{BE} + I_C R_E \qquad \text{... since, } I_C \cong I_E$$

$$V_{TH} = I_B R_{TH} + V_{BE} + \beta\, I_B R_E \qquad \text{... since, } I_C = \beta\, I_B$$

$$V_{TH} = V_{BE} + I_B(\beta\, R_E + R_{TH})$$

$$\therefore I_B = \frac{V_{TH} - V_{BE}}{\beta\, R_E + R_{TH}} \quad \text{and} \quad I_C = \frac{V_{TH} - V_{BE}}{R_E + \frac{R_{TH}}{\beta}}$$

Applying KVL to the output side, we get

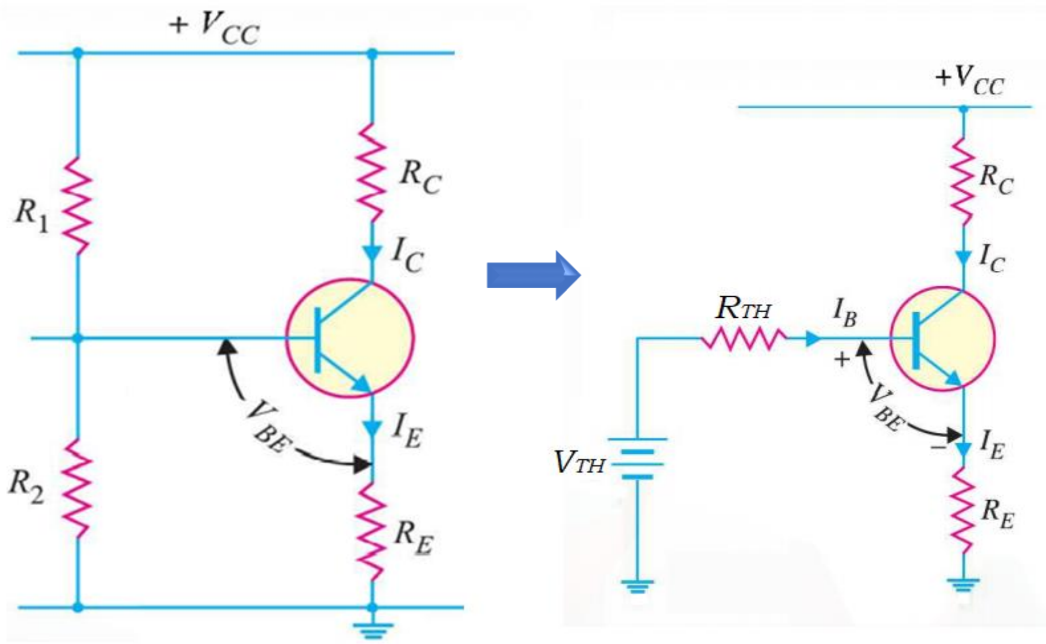
$$V_{CC} - I_C R_C - V_{CE} - I_E R_E = 0$$

i.e.,

$$V_{CE} = V_{CC} - I_C R_C - I_E R_E$$

Since, $I_C \cong I_E$ above equation can be written as:

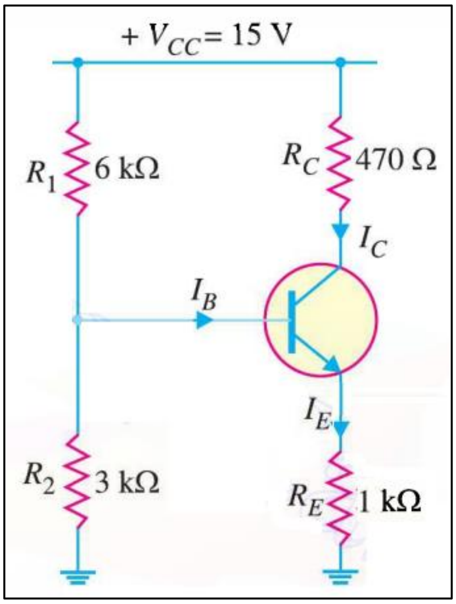
$$V_{CE} = V_{CC} - I_C(R_C + R_E)$$



Example on Potential Divider Biasing (Method-II)

Ex: The circuit shown in the figure uses Silicon transistor having β=100. Find out the values of I_B, I_C and V_{CE}.

Solution:



Replacing the given circuit by Thevenin's equivalent circuit,

$$V_{TH} = \left(\frac{R_2}{R_1 + R_2}\right) V_{CC}$$

$$V_{TH} = \left(\frac{3k\Omega}{6k\Omega + 3k\Omega}\right) 15V = 5V$$

Also,

$$R_{TH} = \frac{R_1 . R_2}{R_1 + R_2} = \frac{3 \times 6}{6 + 3} = 2\ k\Omega$$

Applying KVL to the input side,

$$V_{TH} - I_B R_{TH} - V_{BE} - I_E R_E = 0$$

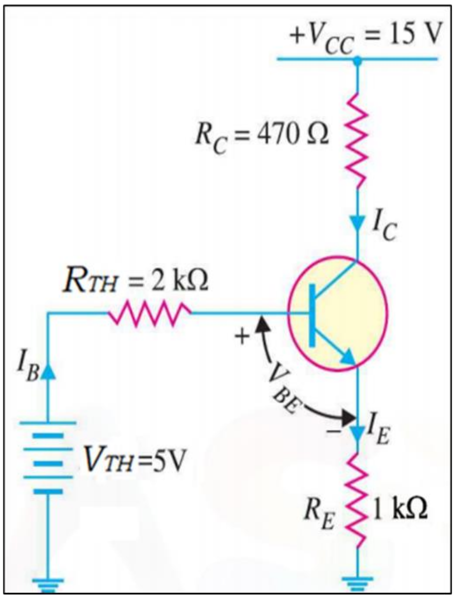
$$V_{TH} = I_B R_{TH} + V_{BE} + I_C R_E \qquad \because I_C \cong I_E$$

$$V_{TH} = I_B R_{TH} + V_{BE} + \beta\, I_B R_E \qquad \because I_C = \beta\, I_B$$

$$V_{TH} = V_{BE} + I_B(\beta\, R_E + R_{TH})$$

$$\therefore I_B = \frac{V_{TH} - V_{BE}}{\beta\, R_E + R_{TH}} = \frac{(5 - 0.7)V}{100 \times 1k\Omega + 2k\Omega}$$

$$I_B = \frac{4.3V}{102k\Omega} = 0.042\ mA$$



Now,

$$I_C = \beta\, I_B = 100 \times 0.042\ mA = 4.2\ mA$$

Applying KVL to the output side, we get

$$V_{CC} - I_C R_C - V_{CE} - I_E R_E = 0$$

i.e.,

$$V_{CE} = V_{CC} - I_C R_C - I_E R_E$$

Since, $I_C \cong I_E$ above equation can be written as:

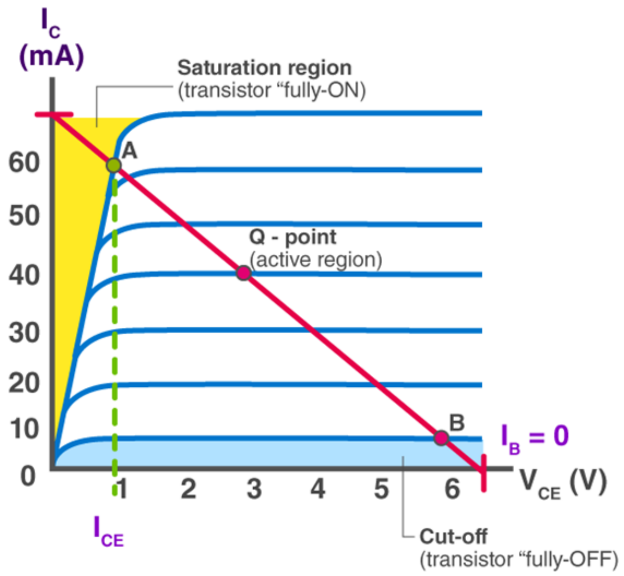
$$V_{CE} = V_{CC} - I_C(R_C + R_E)$$

$$V_{CE} = 15 - 4.2\ mA\ (470\Omega + 1k\Omega)$$

$$\therefore V_{CE} = 15 - 6.174 = 8.826\ V$$

Transistor as an Electronic Switch:

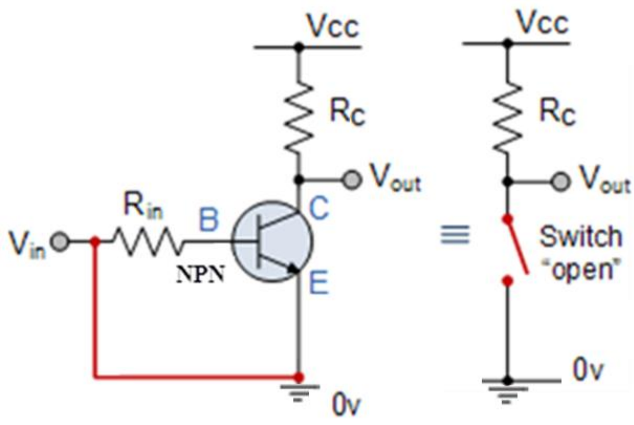
- A transistor can be operated in three modes: active region, saturation region and cut-off region.
- In the ACTIVE region, transistor works as an amplifier.
- The two operating regions of transistor Saturation Region (fully-ON) and the Cut-off Region (fully-OFF) are used to operate a transistor as a switch.



Working of Transistor in Cut-off Region

The operating conditions of the transistor are zero input base current (IB=0), zero output collector current (Ic=0) and maximum collector voltage (VCE=VCC)

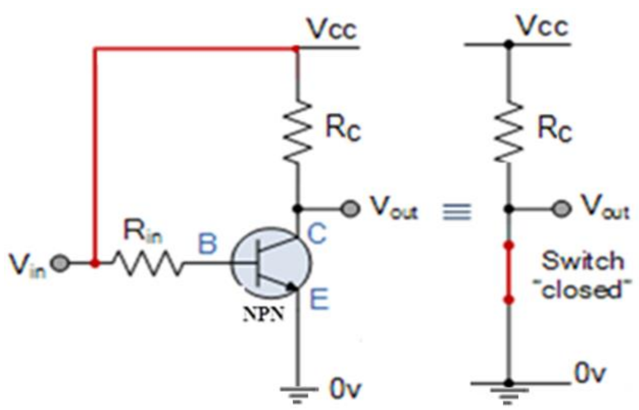
Therefore, the transistor is switched to "Fully-OFF".



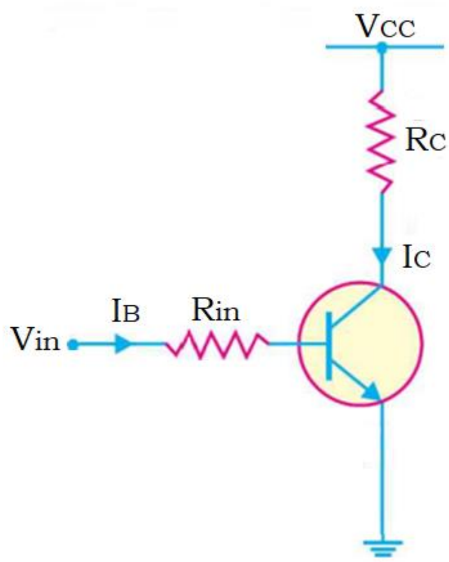
Working of Transistor in Saturation Region

The operating conditions of transistor are maximum base current (IB), resulting in maximum collector current (IC = Icsat) and minimum collector-emitter voltage (VCE = 0).

Therefore, transistor is switched to "Fully-ON".



How to identify Region of operation?



Step I: Calculate the base current

$I_B = \frac{V_{in} - V_{BE}}{R_{in}}$

If $I_B \leq 0$ ➔ Cut-off Region

If $I_B > 0$ ➔ Active or Saturation

Step II: Let, transistor is working in Active Region and find out values of I_{Csat} and I_C

Where, $I_{Csat} = \frac{V_{CC}}{R_C}$ and $I_C = \beta I_B$

Step III: Compare values of I_{Csat} and I_C

If $I_C \geq I_{Csat}$ ➔ Saturation

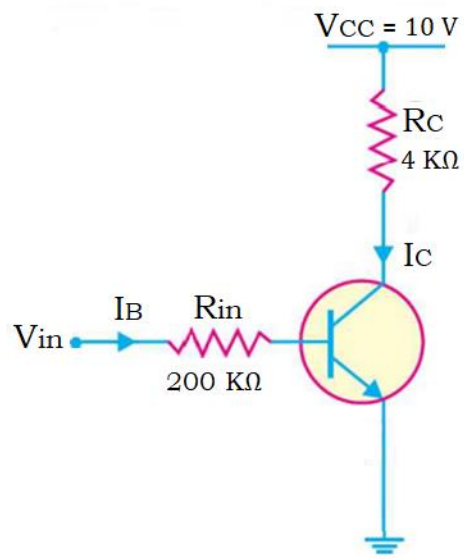
If $I_C < I_{Csat}$ ➔ Active

Example: Find the region of operation, I_C & V_{CE}.

A] Vin = 0.2V

B] Vin = 3.7V

C] Vin = 7.7V



Solution:

A] By applying KVL to input side, we get

$$I_B = \frac{V_{in} - V_{BE}}{R_{in}} = \frac{0.2 - 0.7}{200\ k\Omega} = -2.5\ \mu A$$

Since, $I_B < 0$, it is in Cut-off Region !

Hence, $I_B = 0$, $I_C = 0$ and $V_{CE} = V_{CC} = 10V$

B] By applying KVL to input side, we get

$$I_B = \frac{V_{in} - V_{BE}}{R_{in}} = \frac{3.7 - 0.7}{200\ \text{k}\Omega} = 15\ \mu\text{A}$$

Since, $I_B > 0$, it should be in either active/saturation Region

Let, transistor is working in Active Region

$\therefore I_{Csat} = \frac{V_{CC}}{R_C} = \frac{10}{4\ \text{k}\Omega} = 2.5$ mA and $I_C = \beta I_B = 100 \times 15\ \mu\text{A} = 1.5$ mA

Since, $I_C < I_{Csat}$, it is in Active Region !

Hence, $I_C = 1.5$ mA and

$$V_{CE} = V_{CC} - I_C R_C = 10 - 1.5\ \text{mA} \times 4\text{k}\Omega = 4\ \text{V}$$

C] By applying KVL to input side, we get

$$I_B = \frac{V_{in} - V_{BE}}{R_{in}} = \frac{7.7 \ - 0.7}{200\ k\Omega} = 35\ \mu A$$

Since, $I_B > 0$, it should be in either active/saturation Region

Let, transistor is working in Active Region

$\therefore\ I_{Csat} = \frac{V_{CC}}{R_C} = \frac{10}{4\ k\Omega} = 2.5\ mA$ and $I_C = \beta I_B = 100 \times 35\ \mu A = 3.5\ mA$

Since, $I_C > I_{Csat}$, it is in Saturation Region !

Hence, $I_C = I_{Csat} = 2.5\ mA$ and $V_{CE} = 0V$

Field Effect Transistors [FET]

BJT has two principle disadvantages:

1. Low input resistance because of forward emitter-base junction
2. Considerable noise level because of its bipolar nature !

The field-effect transistor (FET) is a type of transistor which uses an electric field to control the flow of current. It has three terminals: Source, Gate and Drain. FETs are also known as unipolar transistors since, they involve single carrier-type operation. That is, FETs use either electrons or holes as charge carriers in their operation, but not both. There are two basic types of FETs:

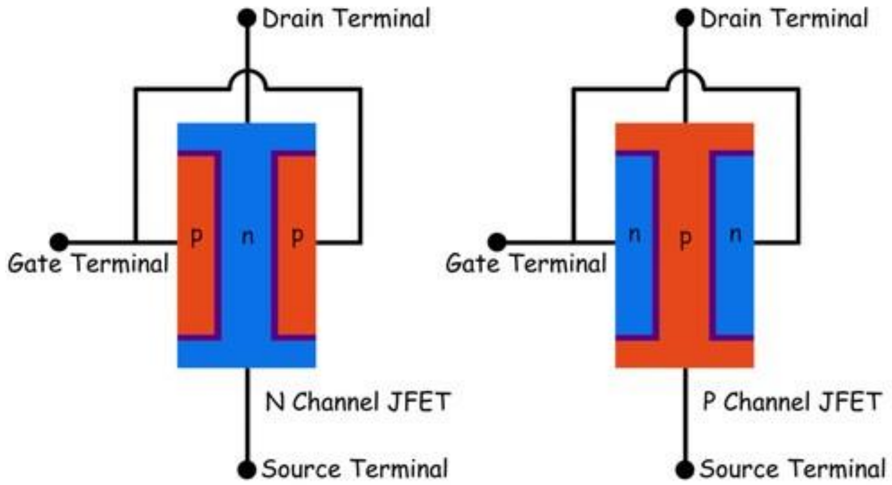
- JFET (Junction Field Effect Transistor)
- MOSFET (Metal Oxide Semiconductor Field Effect Transistor)

Difference between BJT & FET:

SN	BJT (Bipolar Junction Transistor)	FET (Field Effect Transistor)
01	BJT is bipolar device. Its operation depends on both majority charge carriers and minority charge carriers. Hence, it is more noisy.	FET is a unipolar device. Its operation depends on majority charge carriers [either holes or electrons]. Hence, it is less noisy.
02	Input impedance of BJT is very small.	Input impedance of FET is very large.
03	It has high output impedance.	It has low output impedance.
04	It is the current control device.	It is the voltage controlled device.
05	It is temperature dependent device.	It has better heat stability.
06	It is bigger in size than FET.	It is smaller in size than BJT.
07	BJT has three terminals (base, Emitter and Collector). It has different sizes and doping. Hence, it is asymmetric.	FET has three terminals (Drain, Source and Gate). It is symmetric [means drain & source can be interchanged]

Junction Field Effect Transistors [JFET]

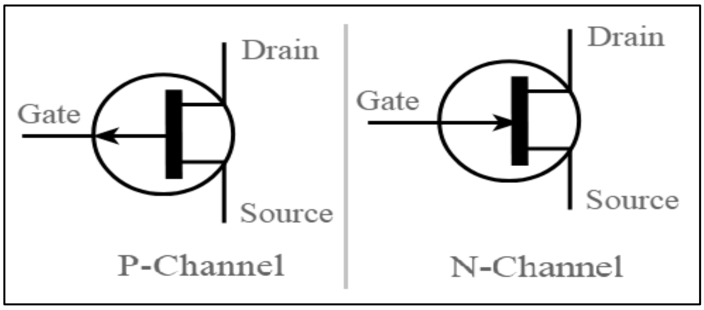
- JFET consists of a p-type or n-type silicon bar containing two PN junctions at the sides as shown in figure. Bar forms conducting channel for charge carriers.
- If bar is n-type then it is called as n-channel JFET and if the bar is p-type then it is called as p-channel JFET. The two PN junction forming diodes are connected internally and common terminal called GATE is taken out.



N-channel JFET:

Important points to be remembered:

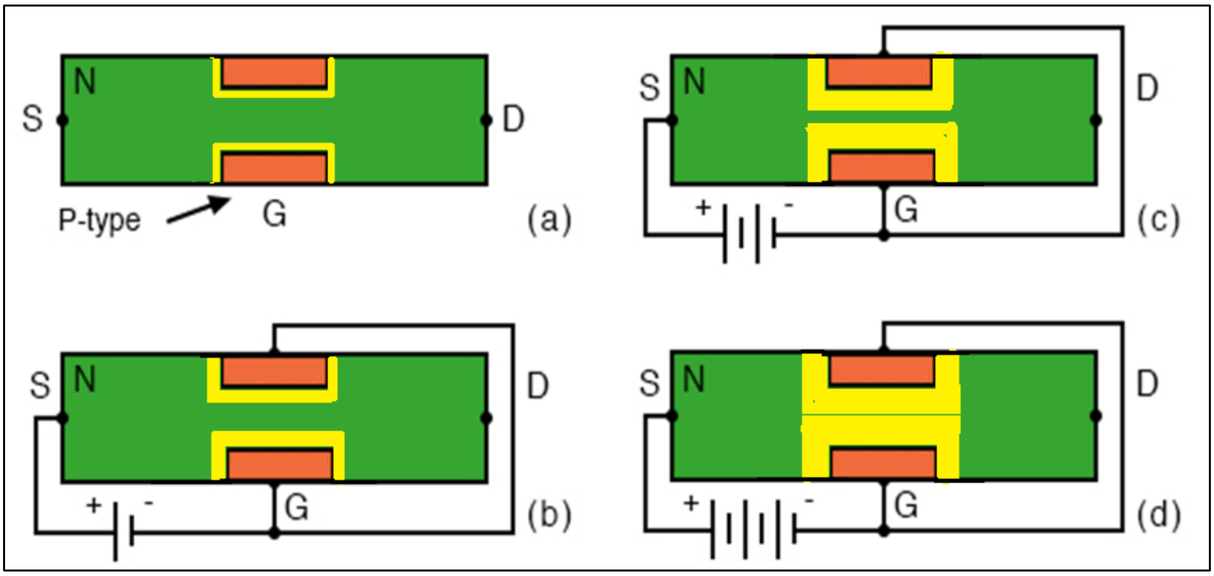
1. The input circuit (i.e., gate to source) of JFET is reversed biased (VGS is negative). Hence, device has high input impedance.
2. The drain is biased with respect to source such that drain current flows from drain to source (VDS is positive)
3. In all JFETs, source current is equal to the drain current ! [ID = IS]



Symbol for P-channel and N-channel JFET

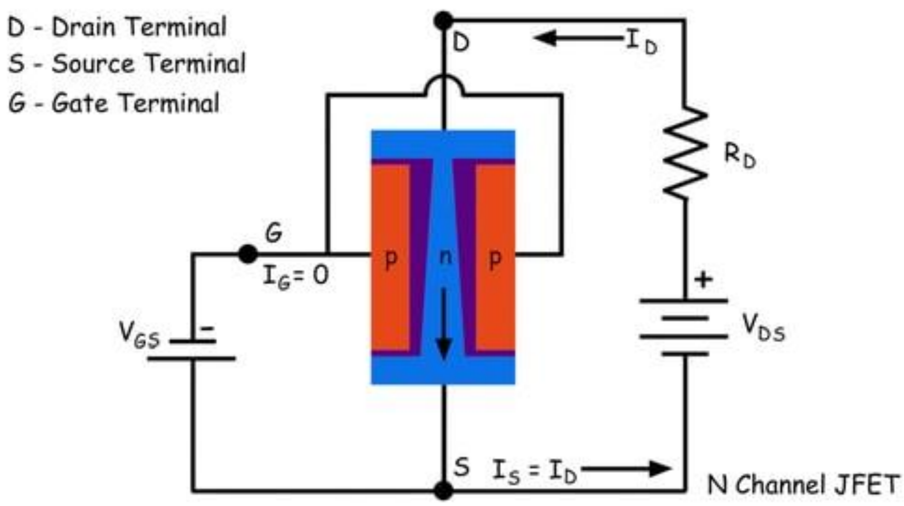
Construction and Working of N-channel JFET

The gate is reverse biased. If a voltage applied between the source and drain, the N-type bar would conduct in either direction because of the doping. Figure (a) shows the depletion region at the gate junction. The depletion region extends more deeply into the channel side due to the heavy gate doping and light channel doping.



The thickness of the depletion region can be increased by applying moderate reverse bias (fig. b). This increases the resistance of the source to drain channel by narrowing the channel. Increasing the reverse bias further increases the depletion region, decreases the channel width, and increases the channel resistance (fig. c). Finally increasing the reverse bias voltage VGS will pinch-off the channel current (fig. d). The channel resistance will be very high. This VGS at which pinch-off occurs is called as pinch-off voltage (VP). In summation, the channel resistance can be controlled by the degree of reverse biasing on the gate. It is clear from the discussion that current from drain to source can be controlled by the application of potential (electric field) on the gate. Hence, the device is known as Field Effect Transistors.

The drain source voltage VDS, not shown in previous figures, distorts the depletion region, enlarging it on the drain side of the gate. As drain voltage VDS increased, the gate depletion region expands toward the drain as shown in figure.



Difference between JFET & BJT

- In a JFET, there is only one type of carrier (i.e., holes in p-type channel and electrons in n-type channel). For this reason it is also called Unipolar Transistor. However, in an ordinary BJT, both electrons and holes play role in conduction. Therefore, it is called as bipolar transistor.
- As the input circuit of a JFET is reverse biased, therefore, it has a high input impedance. However, the input circuit of a BJT is forward biased and hence has low input impedance.
- The primary functional difference between the JFET and BJT is that no current enters the gate of JFET ($I_G = 0$). However, in typical BJT base current might be a few μA.
- A BJT uses the current into its base to control a large current between collector and emitter. Whereas, a JFET uses voltage on the gate terminal to control the current between drain and source.
- In JFET, there is no junction. Therefore, noise level in JFET is very small.

Advantages of JFET

A JFET is a voltage controlled, constant current device in which variation in input voltage control the output current. Some of the advantages of JFET are:

- It has a very high input impedance. This permits high degree of isolation between the input and output circuits.
- The operation of a JFET depends upon the bulk material current carriers that do not cross junctions. Therefore, the inherent noise of transistors are not present in a JFET.
- JFET has a negative temperature co-efficient of resistance. This avoids the risk of thermal runaway.
- JFET has a very high power gain. This eliminates the necessity of using driver stages.
- A JFET has a smaller size, longer life and high efficiency

Important Questions:

1. Describe the working of BJT connected in common emitter configuration.
2. What is biasing? Explain the need of biasing.
3. Explain the working of transistor as switch.
4. Explain Potential Divider Biasing method with a circuit diagram.
5. Explain the construction and working of n-channel JFET.
6. Distinguish between BJT and FET.