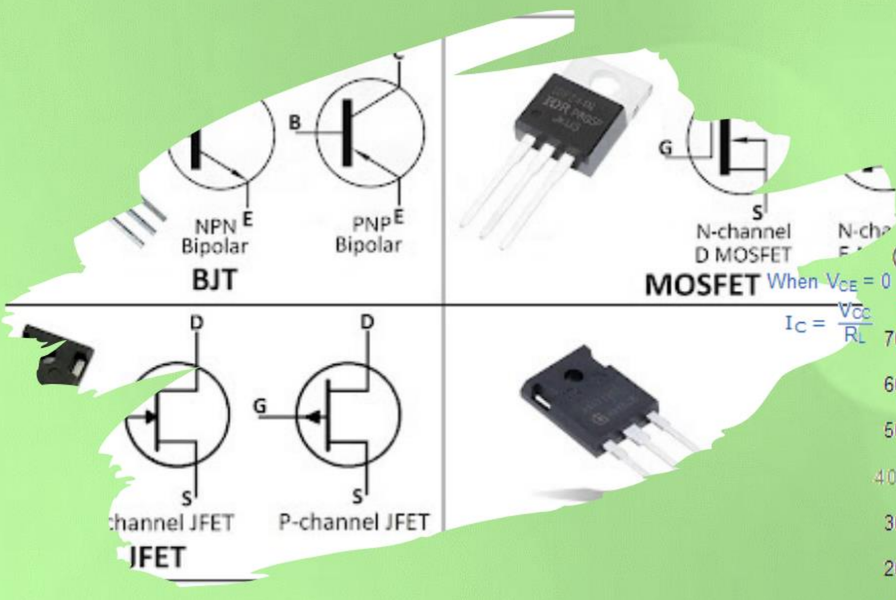
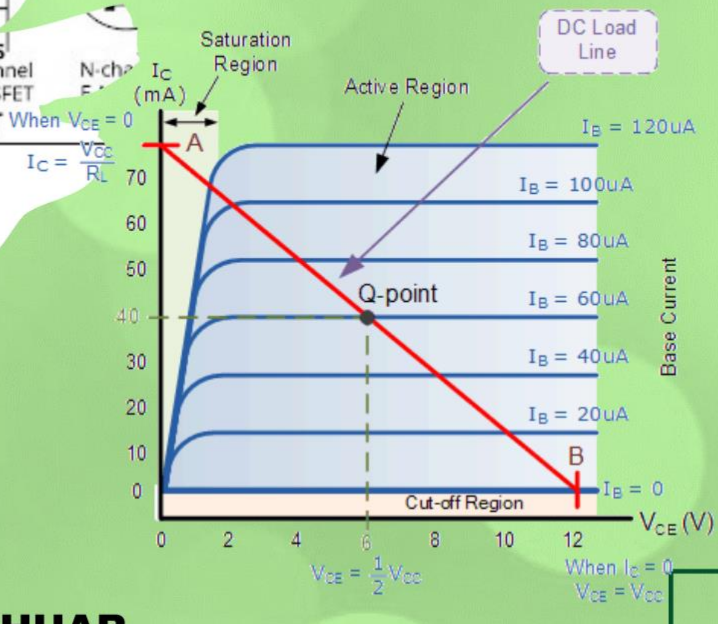
TRANSISTOR

CHARACTERISTICS AND APPLICATIONS





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This eBook is for the purpose basic reference at easy understand and category the types of diode. It is not intended for sale nor is it profitable.

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SYNOPSIS

The eBook is to provide a basic quick reference on the transistor construction, types of the transistor, working principle and their application. This eBook focuses on material of the transistor, types of the transistor, the transistor construction, working principle, and the transistor application in electronic circuits. It can be used as a supplementary material for the related courses such as electronic device, electronic circuit, and power electronic course as guide and basic knowledge.

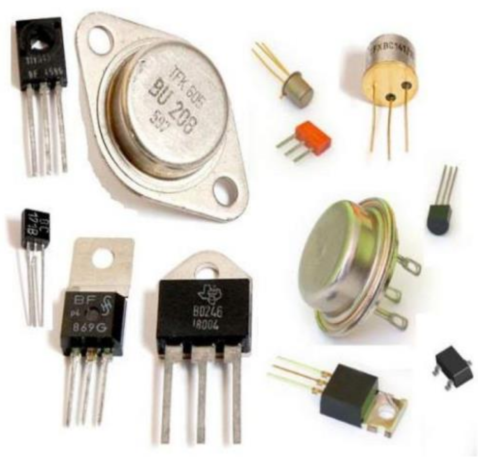
Contents

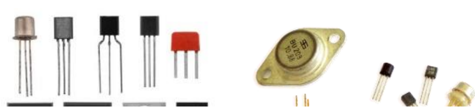
Chapter 1

Introduction to Transistor

Upon completion this chapter, you should be able to:

- Understand the history of transistor
- Explain the important of transistor
- Explain the basic transistor construction





1.0 Introduction

The transistor is a three terminal solid-state device made of semiconductor materials. The semiconductor materials discussed are P-type and the N-type which produces through the doping process. Three terminals are drawn out from the three layers semiconductor materials present in transistor structure. Mostly. the function of transistor is to regulates or controls current or voltage flow in, to amplify and generate these electrical signals and also act as a switch or gate for them. Transistor is a modern electronics component which working as an amplifier can make a weak signal strong enough to be useful in an electronic application, a transistor transforms a small input current into a bigger output current, as a switch can be in one of two distinct states on or off and also a device to control the flow of electronic signals through an electrical circuit or electronic device.

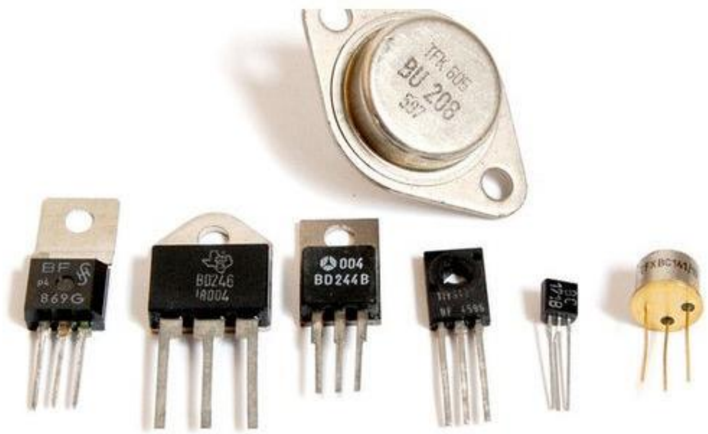


Figure 1.1: transistors

1.1 A Bit of History

The principle of a field-effect transistor was proposed by Physicist Julius Edgar Lilienfeld in 1925. but it was not success in work at that time. The first transistor was successfully tested on 23 December 1947 at Bell Laboratories in Murray Hill, New Jersey. William Shockley, John Bardeen and Walter Brattain credited with the invention of the transistor. Shockley introduced the improved bipolar junction transistor in 1948 which started production in the early 1950s and led to the first widespread use of transistors.

Figure 1.2: John Bardeen, William Shockley and Walter Brattain at Bell Labs, 1948

The transistor emerged from war-time efforts to produce extremely pure germanium crystal mixer diodes used in radar units as a frequency mixer element in microwave radar receivers at the Bell Labs. UK researchers had produced models using a tungsten filament on a germanium disk, but these were difficult to manufacture and not particularly robust. Bell's version was a single-crystal design that was both smaller and completely solid. A parallel project on germanium diodes at Purdue University succeeded in producing the good-quality germanium semiconducting crystals that were used at Bell Labs. Early tube-based circuits did not switch fast enough for this role, leading the Bell team to use solid-state diodes instead.

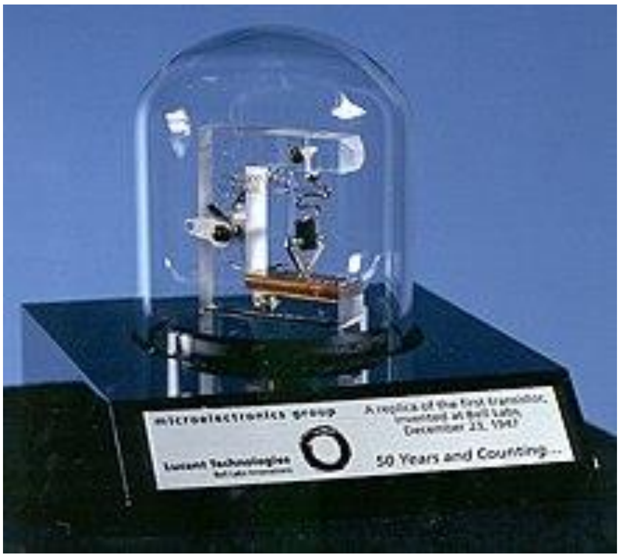


Figure 1.3: A stylized replica of the first transistor

The MOSFET was invented at Bell Labs between 1955 and 1960, after Frosch and Derick discovered surface passivation by silicon dioxide and used their finding to create the first planar transistors, the first in which drain and source were adjacent at the same surface. This breakthrough led to mass-production of MOS transistors for a wide range of uses becoming the basis of processors and solid memory devices.

The MOSFET was introduced in 1959. In 2020, it was still the dominant transistor type in use, with an estimated total of 13 sextillion (1.3×1022) MOSFETs manufactured between 1960 and 2018. The key advantages of a MOSFET transistors over BJTs are that they consume no current except when switching states and they have faster switching speed (ideal for digital signals). After that, the MOSFET become the most widely manufactured device in electronic technology industries.

1.2 Important of the Transistor

A transistor allows current flow in one direction and block in other way. This make the transistors be the simple switching device in circuit. From that, transistor as the basic elements in logic gate and integrated circuits (ICs) which consist one or more of transistors interconnected with circuitry and baked into a single silicon microchip. From microchip, transistors in large numbers are used to create microprocessors where millions of transistors are embedded into a single IC. They also drive computer memory chips and memory storage devices for MP3 players, smartphones, cameras and electronic games. Transistors are embedded in nearly all ICs, which are part of every electronic device. Transistors are also used for low-frequency, high-power applications, such as power-supply inverters that convert alternating current into direct current. Additionally, high-frequency applications use transistors, such as the oscillator circuits that to generate radio signals.

The MOSFET is the most widely used in applications ranging from computers and electronics gadgets to communications technology such as smartphones and Internet on things (IoT). The demand of transistor be possibly the most important invention in electronics and the device that enabled modern electronics. It has been the basis component of modern digital electronics device since the late 20th century, paving the way for the digital age.

1.3 Construction of a Transistor

The internal construction and operational principles of transistors lead to different types, primarily categorized into Bipolar Junction Transistors (BJTs) and Field-Effect Transistors (FETs).

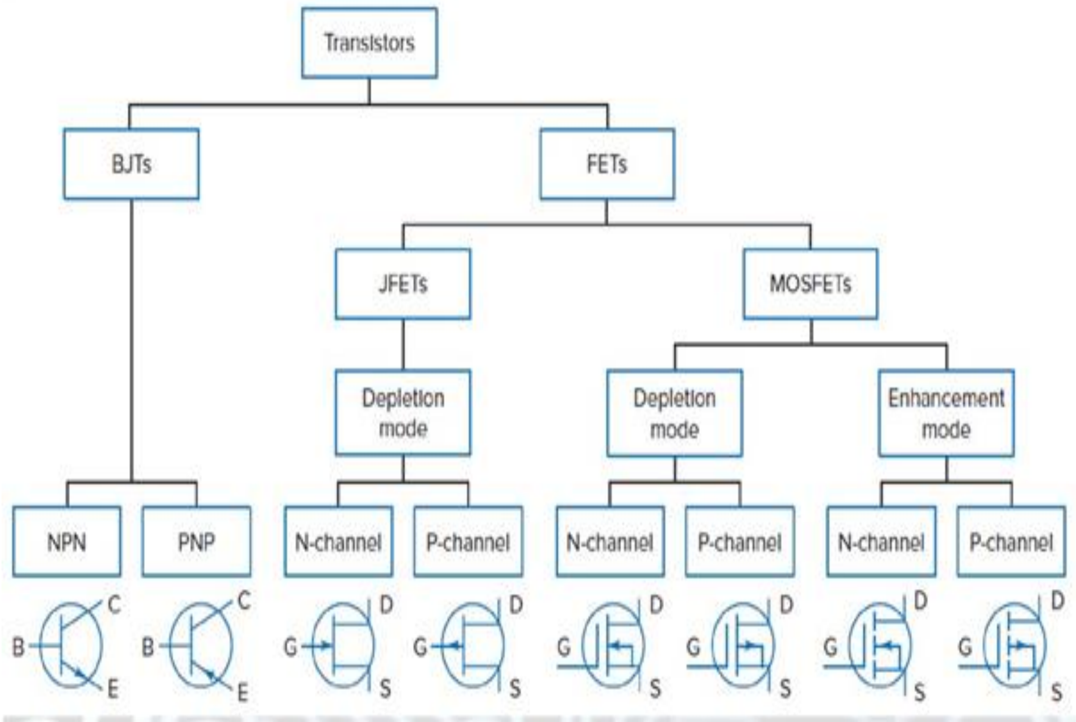


Figure 1.4: Transistor family tree

1.3.1 Bipolar Junction Transistors (BJT)

Transistor is constructed with two diodes that are connected in such a way that their backs get connected to one another. The name ‘Bipolar’ hence transistor use both electrons and holes as charge carriers in conductivity. It gets in TWO (2) type as **NPN** and **PNP**. It has three terminals drawn from the transistor indicate Emitter(E), Base(B) and Collector(C) terminals.

a). **NPN Transistors**

NPN transistors is formed when a P-type semiconductor material is fused between two N-type semiconductor materials They are commonly used because they offer better electron mobility and higher current gain compared to PNP transistors.

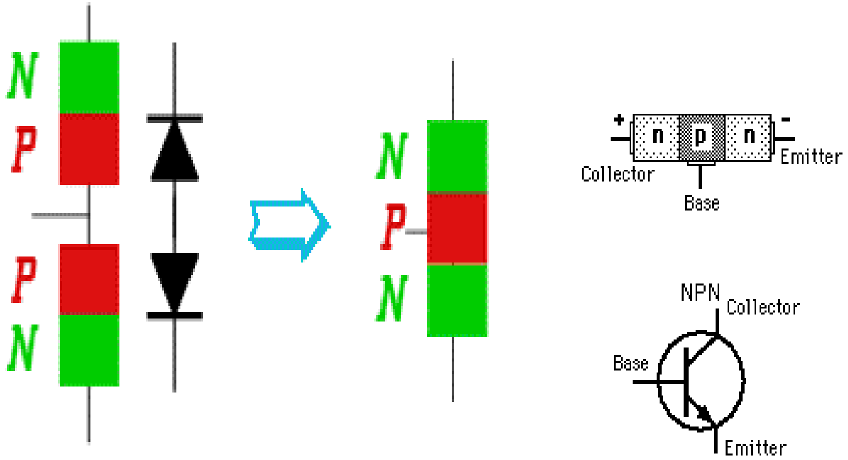


Figure 1.5: Construction of NPN and symbol

b). **PNP Transistors:**

PNP transistors is formed when a N-type semiconductor material is fused between two P-type semiconductor materials. They operate similarly to NPN transistors but with reversed polarity.

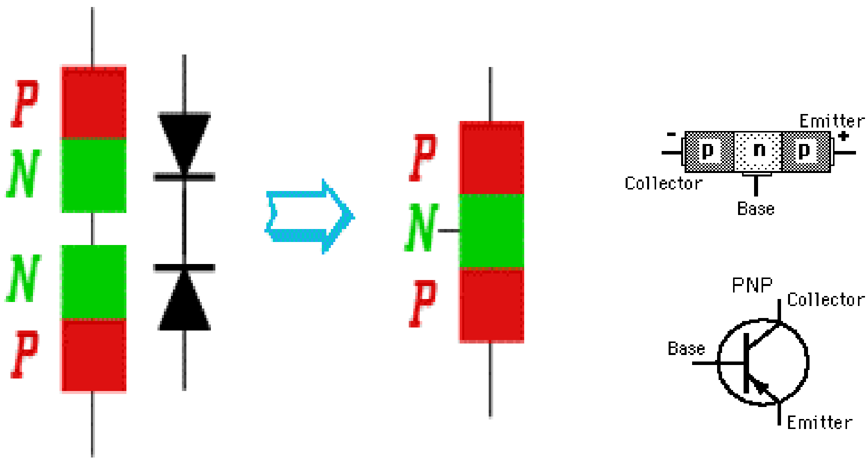


Figure 1.6: Construction of PNP and symbol

Construction and circuit symbol of **NPN** transistor and PNP transistor are shown in the above figures.1.5 and figure 1.6. In NPN transistor, electrons are the majority carriers and in PNP transistor, holes are the majority carriers.

1.3.2 Field-Effect Transistors (FET)

FETs control current via an electric field and are classified based on their gate structure and operation. A field-effect transistor (sometimes referred to as a unipolar transistor) is three-terminal active semiconductor. Regularly, it has 3 terminals as source(S), drain(D), and gate(G).

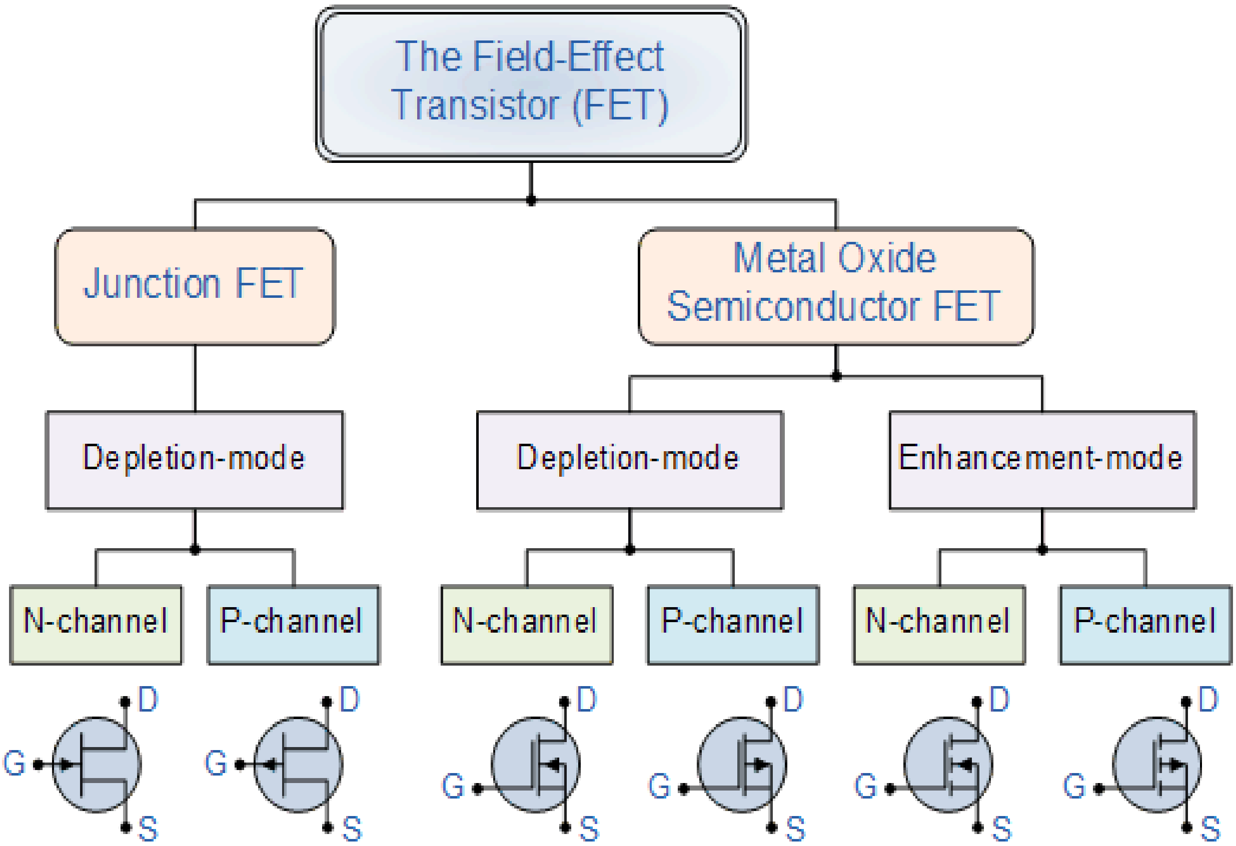


Figure 1.7: FET family tree

a). Junction Field-Effect Transistors (JFET)

Junction Field effect transistors (JFET) are one of the simplest types of Field-effect transistors. JFET is a voltage-controlled with three-terminal unipolar semiconductor device. There have 2 type of JFET as N-channel and P-channel.

N-channel JFET: The current flows through a channel of N-type material.

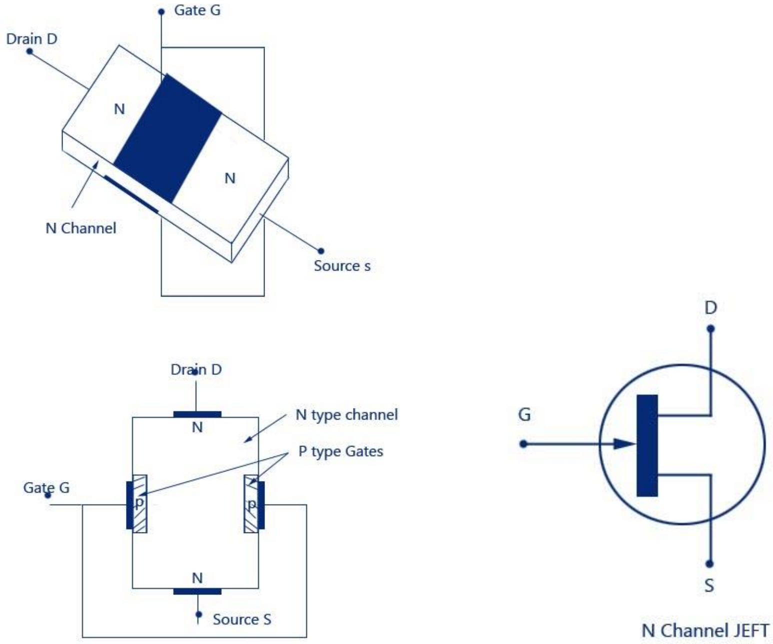


Figure 1.8: Construction of JFET N-channel and symbol

P-channel JFET: The current flows through a channel of P-type material.

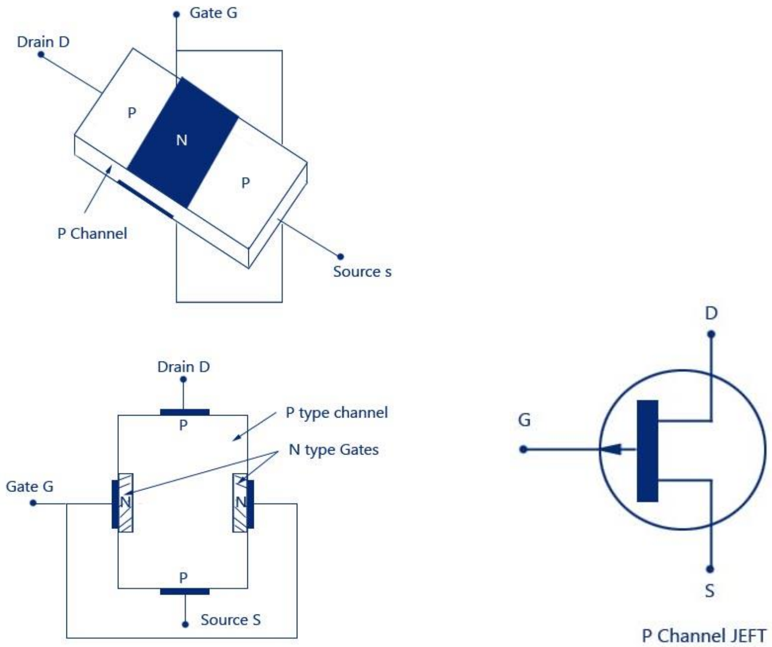


Figure 1.9: Construction of JFET P-channel and symbol

b). Metal-Oxide-Semiconductor Field-Effect Transistors (MOSFET)

MOSFETs have characteristics similar to JFETs and additional characteristics that make then very useful with terminal substrate, SS**.** MOSFETs are the most widely used hence to their high input impedance and efficient switching capabilities.

They are in forms:

- **N-channel MOSFET:** electrons as charge carriers.
- **P-channel MOSFET:** holes as charge carriers.
- **Depletion Mode MOSFET:** Conducts at zero gate-to-source voltage and requires a negative gate-to-source voltage to turn off.
- **Enhancement Mode MOSFET:** insulates/off at zero gate-to-source voltage and requires a positive gate-to-source voltage to conduct.

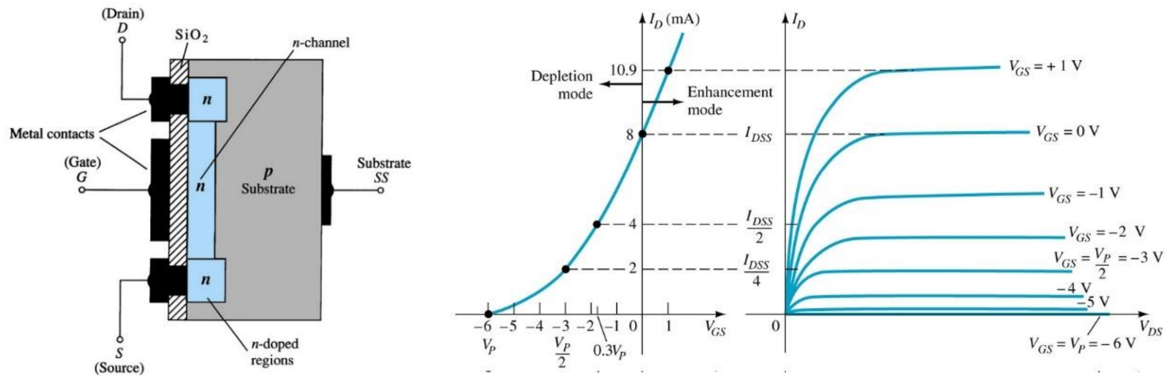


Figure 1.10: Construction of MOSFET N-channel and mode

The Drain (D) and Source (S) connect to the n-doped regions. These n-doped regions are connected via an n-channel. The n-channel is connected to the Gate (G) via a thin insulating layer of SiO_2. The n-doped material lies on a p-doped substrate that may have an additional terminal connection called substrate, SS.

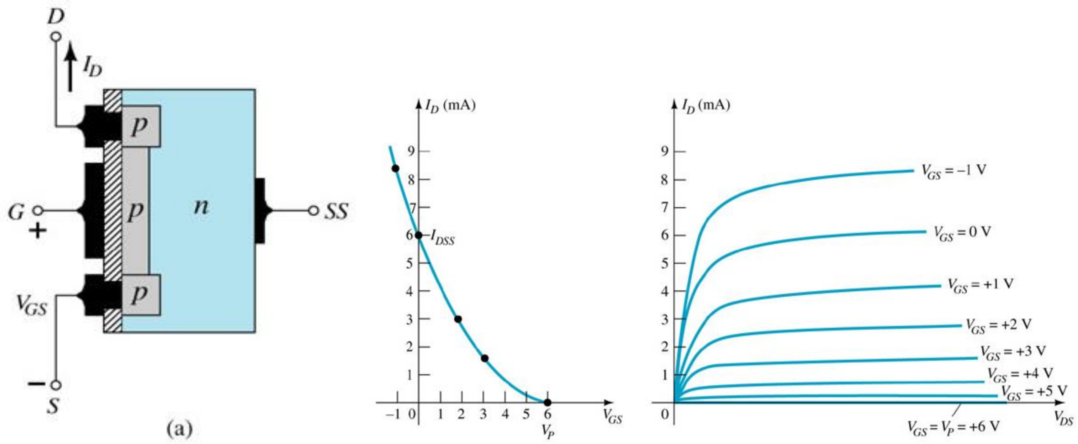


Figure 1.11: Construction of MOSFET P-channel and mode

The p-channel Depletion-type MOSFET is similar to the n-channel except that the voltage polarities and current directions are reversed.

MOSFETs are very static sensitive. Because of the very thin SiO_2 layer between the external terminals and the layers of the device, any small electrical discharge can stablish an unwanted conduction.

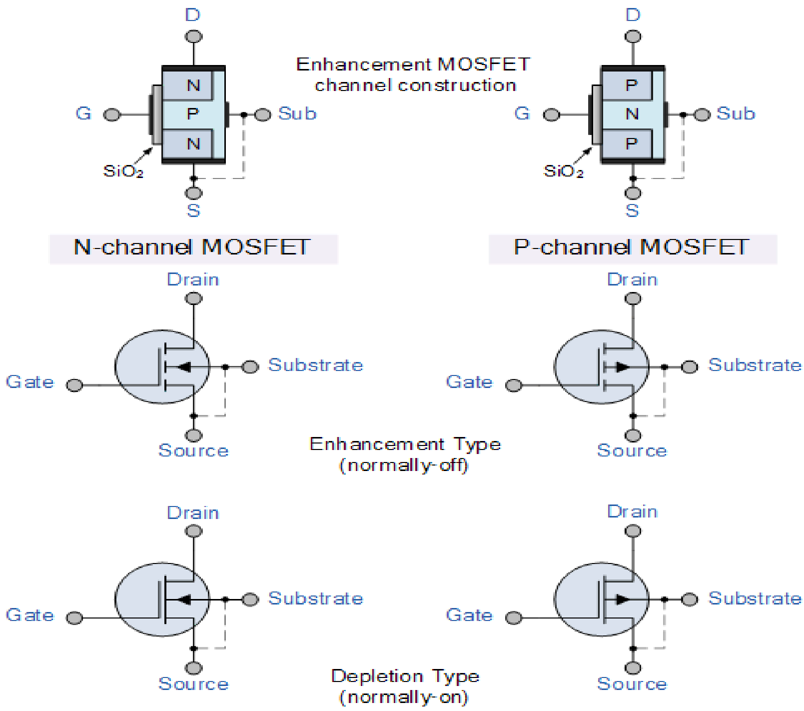


Figure 1.12: Symbol of MOSFET in depletion or enhancement mode

c). Others type of MOSFET

VMOS FET

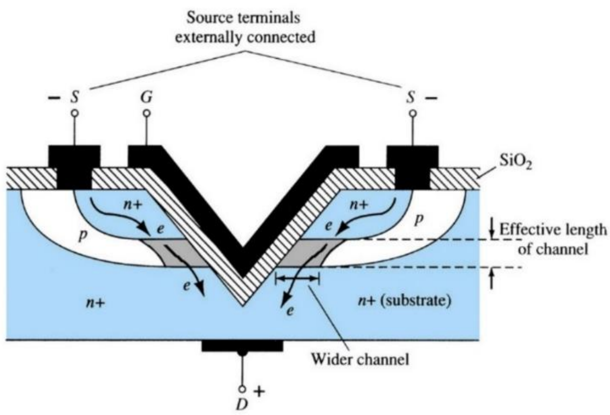


Figure 1.13: Construction of VMOSFET

VMOS FET is Vertical Metal Oxide Silicon FET. V shape of gate is cut vertical into the substrate part to increases the surface area of the device. The shape of the depletion region creates a wider channel, allowing more current to flow through VMOS. It allows the device to deliver high current from S(Source) terminal to D(Drain) terminal.

Advantage:

- This allows the device to handle higher currents by providing it more surface area to dissipate the heat.
- VMOSs also have faster switching times.

CMOS FET

CMOS is a complementary metal-oxide semiconductor (CMOS) p-channel and n-channel MOSFET on the same substrate which the semiconductor technology used in most of today's integrated circuits (ICs), also known as chips or microchips. CMOS transistors are based on metal-oxide semiconductor field-effect transistor (MOSFET) technology. MOSFETs serve as switches or amplifiers that control the amount of electricity flowing between source and drain terminals, based on the amount of applied voltage.

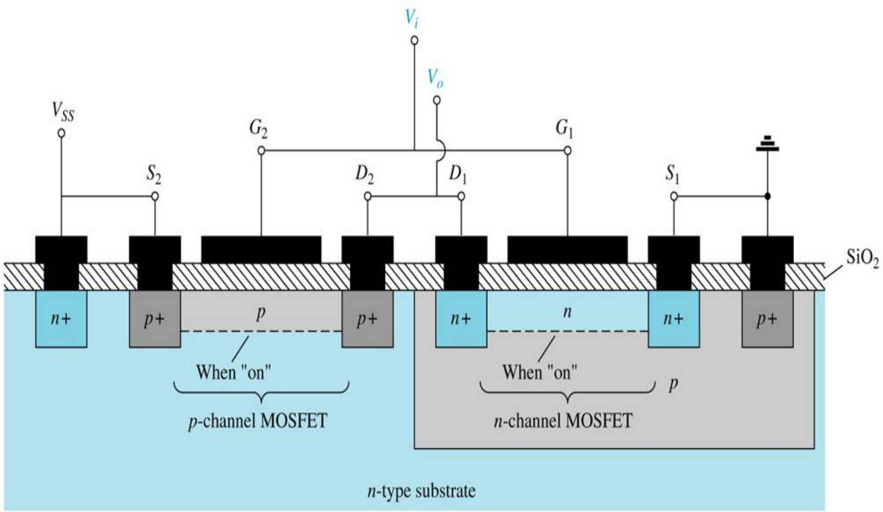


Figure 1.14: Construction of VMOSFET

1.4 Advantage & Similarities transistor

a) Advantage

- Useful in logic circuit designs
- Higher input impedance
- Faster switching speeds
- Lower operating power levels

a). Similarities:

- Amplifiers
- Switching devices
- Impedance matching circuits

1.5 Comparison among BJT, FET and MOSFET

Table 1.1: Comparison among BJT, FET and MOSFET

TERMS	BJT	FET	MOSFET
Device type	Current controlled	Voltage controlled	Voltage Controlled
Current flow	Bipolar	Unipolar	Unipolar
Terminals	emitter, collector and base	gate, source, drain	gate, source, drain, substrate
Operational modes	No modes	Depletion mode only	Both Enhancement and Depletion modes
Input impedance	Low.	High.	Very high
Output resistance	Moderate	Moderate	Low
Operational speed	Low	Moderate	High
Noise	High	Low	Low
Thermal stability	Low	Better	High
Size	BJTs are larger in size and therefore take up more physical space than FETs normally.	FETs can be manufactured much smaller than BJTs. This is especially important for integrated circuits that are composed up of many transistors.	smallest

Activity 1a

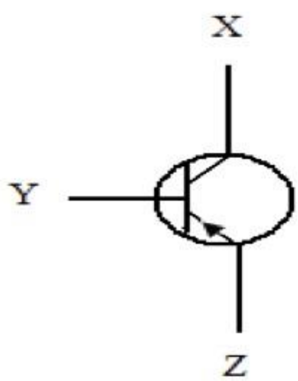
1. Who proposed the concept of a field-effect transistor (FET) in 1926?
    a. Walter Brattain
    b. Mohamed Atalla
    c. Julius Edgar Lilienfeld
    d. John Bardeen

2. What are the three terminals of the BJT?
    a. Anode, Cathode, Gate
    b. Source, Gate, and Drain.
    c. Emitter, base and collector
    d. anode1, anode 2, gate

3. What are the majority charge carriers in NPN transistors?
    a. Protons
    b. Electrons
    c. Neutrons
    d. holes

4. How does current flow in NPN transistor?
    a. the gate controls the amount of current passing through it while allowing current flow from the source to the drain.
    b. the base controls the amount of current passing through it while allowing current flow from the emitter to the collector.
    c. the base controls the amount of current passing through it while allowing current flow from the collector to the emitter.
    d. the collector controls the amount of current passing through it while allowing current flow from the emitter to the base.

5. What is the component symbol?



    a. Diode
    b. SCR
    c. NPN transistor
    d. PNP transistor

6. What are the three terminals of FET?
    a. Anode, Cathode, Gate
    b. Source, Gate, and Drain.
    c. Emitter, base and collector
    d. anode1, anode 2, gate

7. FET stands for?
    a. First electronic transistor
    b. Field effect transistor
    c. Firing effect transistor
    d. Field electromagnetic transistor

8. A BJT is a …………… operated device
    a. current
    b. voltage
    both voltage and current
    none of the above

9. The input impedance of a transistor is …………
    a. high
    b. low
    c. very high
    d. almost zero

10. What is the most widely used type of transistor?
    a. Field-effect transistor (FET)
    b. Photo-transistor
    c. Point-contact transistor
    d. Bipolar junction transistor (BJT)

Answer:
1c, 2c, 3b, 4b, 5d, 6b, 7b, 8a, 9b, 10a.

Chapter 2

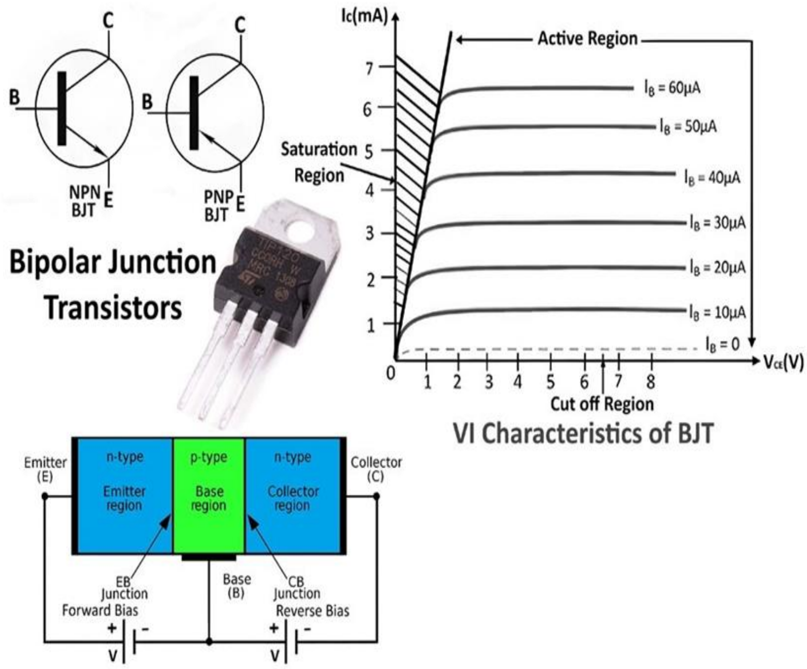
Transistor Working Principle

and

Characteristic

Upon completion this chapter, you should be able to:

- Understand the working principle of transistor
- Explain transistor characteristic



2.0 Introduction

To understand the working principle of transistor, we will look at how an NPN transistor works. The fluid flow analogy be referred to study the current flow between the three terminals and also Kirchhoff's Current Law be applied. PNP transistor works the same way as NPN but with voltage and currents reversed.

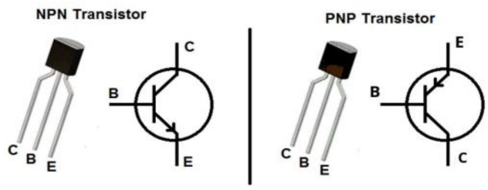


Figure 2.1: NPN and PNP

2.1 Basic parameters of transistor BJT in operation mode.

Transistor BJT operates in THREE (3) parameters of interest

1). Current gain Beta (β) & Current gain Alpha (α)

2). Voltage drop from base to emitter when $V_{BE}=V_{FB}$

3). Minimum voltage drops across the collector and emitter when transistor is saturated

2.1.1. Current gain Beta (β) & Current gain Alpha (α)

When a voltage positive voltage is high enough apply to forward bias the base-emitter junction, allowing current to flow from the base to the emitter, IB. Current will also flow from the VCC supply through the collector-to-emitter of the transistor, IC. Assume that IC is small enough to leave a relatively high voltage at the collector terminal as a voltage high enough, that is, to keep the base-to-collector junction reverse-biased. Therefore, a large current flow from the collector to the emitter, which is controlled by the smaller base current. The ratio of the collector current to the base current is known as the current gain (β) of the transistor. The current gain factor, β is a key parameter used to describe the amplification capability of a transistor. This means βdc= 100, the output current is 100 times the input current.

The Current gain Beta (β) factor is divided into DC and AC mode based on the transistor's operating conditions.

i). DC mode:

DC current gain or static current gain factor (βDC) - it describes the transistor's amplification capability which is expressed as the ratio of the constant collector current (I_C) to the constant base current (I_B) in a transistor by the formula

$$\beta_{DC} = I_C/I_B$$

where I_C is the collector current, and I_B is the base current.

ii). AC mode:

AC current gain or dynamic current gain factor (βAC), it describes the transistor's amplification capability which is expressed as the ratio of change the collector current (I_C) to change the base current (I_B) in a transistor by the formula

$$\beta_{AC} = \Delta I_C/\Delta I_B$$

where ΔI_C is the change in collector current, and ΔI_B is the change in base current.

The Current gain alpha (α) is defined as the ratio of the collector current (I_C) to the emitter current (I_E) in a transistor. It is divided into DC and AC mode based on the transistor's operating conditions.

i). DC mode:

It can be expressed as:

$$\alpha_{DC} = I_C/I_E$$

Note: Ideally: **α** = 1 and in reality: **α** is between 0.9 and 0.998.

ii). AC mode:

$$\alpha_{AC} = \Delta I_C/\Delta I_B$$

Calculation current gain.

Example 1: **Determining β**

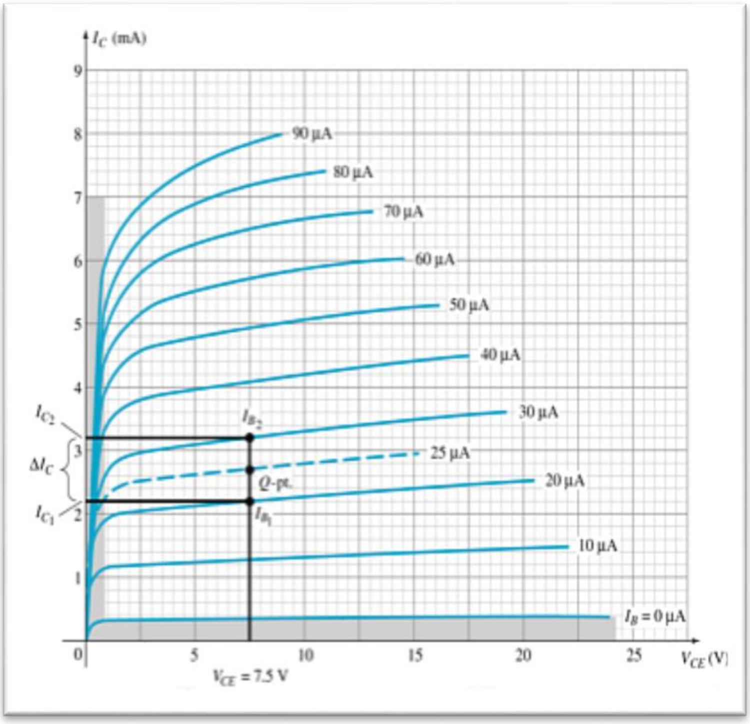


Figure 2.2: Operating of NPN

$$\beta_{AC} = \frac{(3.2\,\text{mA} - 2.2\,\text{mA})}{(30\,\mu\text{A} - 20\,\mu\text{A})}$$

$$= \frac{1\,\text{mA}}{10\,\mu\text{A}}\Bigg|_{V_{CE}=7.5}$$

$$= 100$$

$$\beta_{DC} = \frac{2.7\,\text{mA}}{25\,\mu\text{A}}\Bigg|_{V_{CE}=7.5}$$

$$= 108$$

Example 2: Determining β

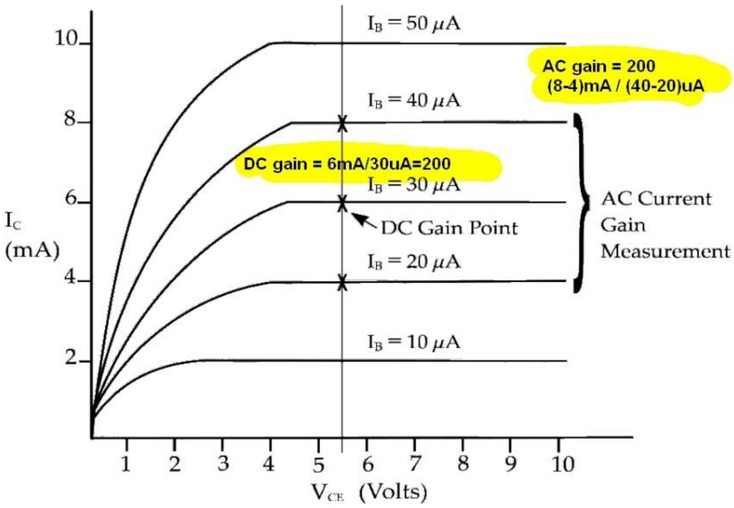


Figure 2.3: Operating of NPN

$$\beta_{AC} = \frac{(8\,\text{mA} - 4\,\text{mA})}{(40\,\mu\text{A} - 20\,\mu\text{A})} = \frac{4\,\text{mA}}{20\,\mu\text{A}} = 200$$

$$\beta_{DC} = \frac{6\,\text{mA}}{30\,\mu\text{A}} = 200$$

The relationship can be summarized as:

- Relationship between amplification factors β and α

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

- Relationship Between Currents

$$I_C = \beta I_B \qquad I_E = (\beta + 1) I_B$$

- Current Gain Alpha (α): $\alpha = I_C/I_E$
- Current Gain Beta (β): $\beta = I_C/I_B$
- Relationship: $\beta = \alpha/(1-\alpha)$

2.1.2. Voltage drop from base to emitter when $V_{BE}=V_{FB}$

V_{BE} is the potential voltage drops between the base terminal and the emitter terminal. The transistor is biased to operate in the active region, V_{BE} must be at least 0.7 V approximately for pure silicon to ensure that the depletion barrier is overcome by the forward bias. Then, the V_{BE} will be close to the forward voltage drop.

$$V_{BE}=V_{FB}$$

2.1.3. Minimum voltage drops across the collector and emitter when transistor is saturated

Collector to Emitter voltage be known as V_{CE}, is the voltage difference between the collector and emitter terminals of a BJT transistor. It is an important parameter in determining the operating point and characteristics of the transistor. The voltage drops across the collector and emitter must at less to make sure transistor in active region

2.2 Operation region of transistor

Transistor device operates in FOUR (4) different regions depending on the biasing conditions:

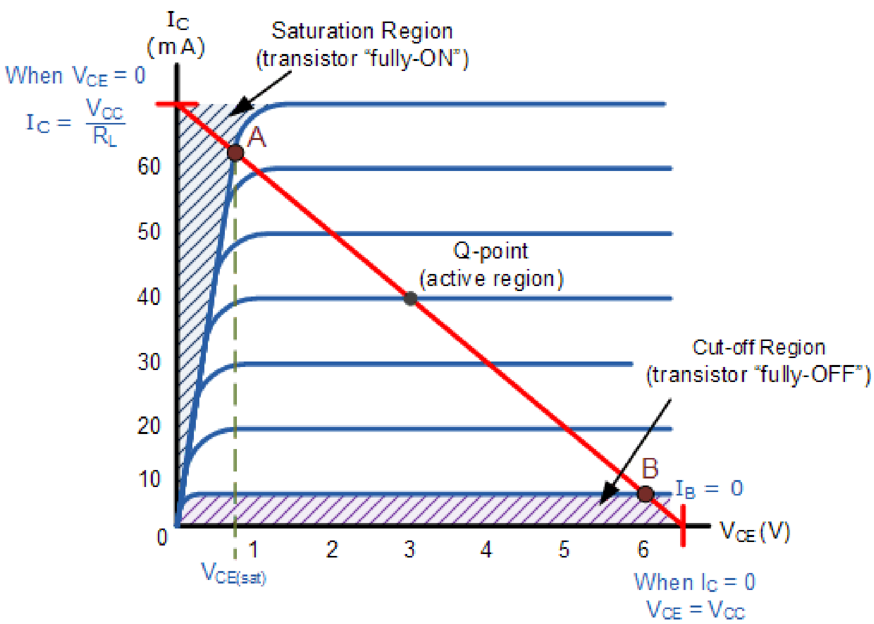


Figure 2.4: Operating Region of BJT

Let to discuss the operation region of the **NPN transistor as below: -**

i). Active region

In this region, the base-emitter junction is forward-biased and the base-collector junction is reverse-biased. The transistor operates as an amplifier, with the output current proportional to the input current.

$$\mathbf{V_{BE} = V_{FB},\ I_B \neq 0,\ I_C = \beta I_B}$$

ii). Cut off region

In this region, both the base-emitter and base-collector junctions are reverse-biased. The transistor is in the "off" state, and no current flows between the collector and emitter.

$$\mathbf{V_{BE} < V_{FB},\ I_B = 0}$$

iii). Saturation region

In this region, both the base-emitter and base-collector junctions are forward-biased. The transistor is in the "on" state, and the maximum current flows between the collector and emitter.

$$\mathbf{V_{BE} = V_{FB},\ I_B > I_{Cmax} / \beta}$$

iv). **Reverse Active**

In reverse active mode is the opposite of active mode. A transistor in reverse active mode conducts even amplifies but current flows in the opposite direction from emitter to collector. The downside to reverse active mode is the β (β_R in this case) is *much* smaller. A transistor in reverse active mode where the emitter voltage must be greater than the base voltage and also must be greater than the collector voltage (V_{BE}<0 and V_{BC}>0).

$$\mathbf{V_C < V_B < V_E}$$

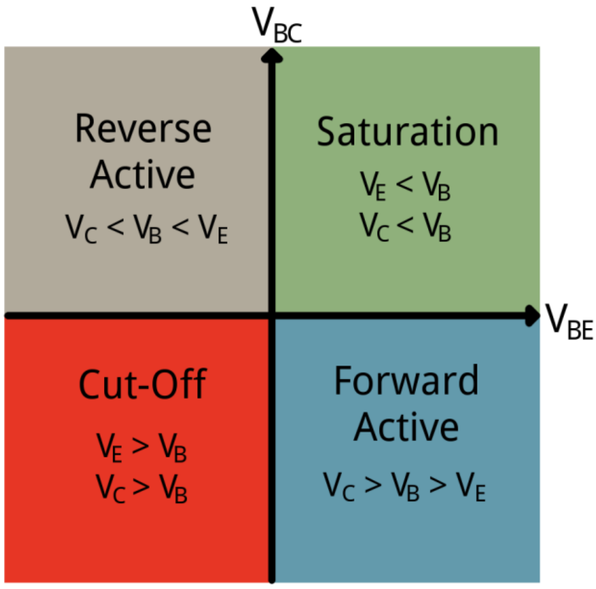


Figure 2.5: quadrant graph shows how positive and negative voltages at those terminals affect the mode.

Table 2.1: biasing condition: in operation region

Operation region	Emitter-Base junction	Collector-Base juntion
Active	**Forward bias**	**Reverse bias**
Cut-off	**Reverse bias**	**Reverse bias**
Saturation	**Forward bias**	**Forward bias**
Reverse active	**Reverse bias**	**Forward bias**

For PNP transistor, the operation region is same but simply flip the polarity of source or convert the signs ">" and "<".

2.3 Working Principle of Bipolar Junction Transistor (BJT)

A simple way to explain the working principle of transistor though fluid flow analogy. In the fluid flow analogy, fluid flowing through a tube controlled by a valve. fluid pressure represents Voltage, V and fluid flowing through a tube represents current, I as figure 2.5. The large tubes represent the Collector/Emitter junction with a valve in between which is actuated by current from a small tube representing the Base. The valve controls the fluid pressure from flowing from Collector to the Emitter. When fluid flows through the smaller tube represent the Base and make the valve between the Collector/Emitter junction be opened to allowing fluid to flow through to the Emitter and last to Ground represents the closed loop of voltage/current).

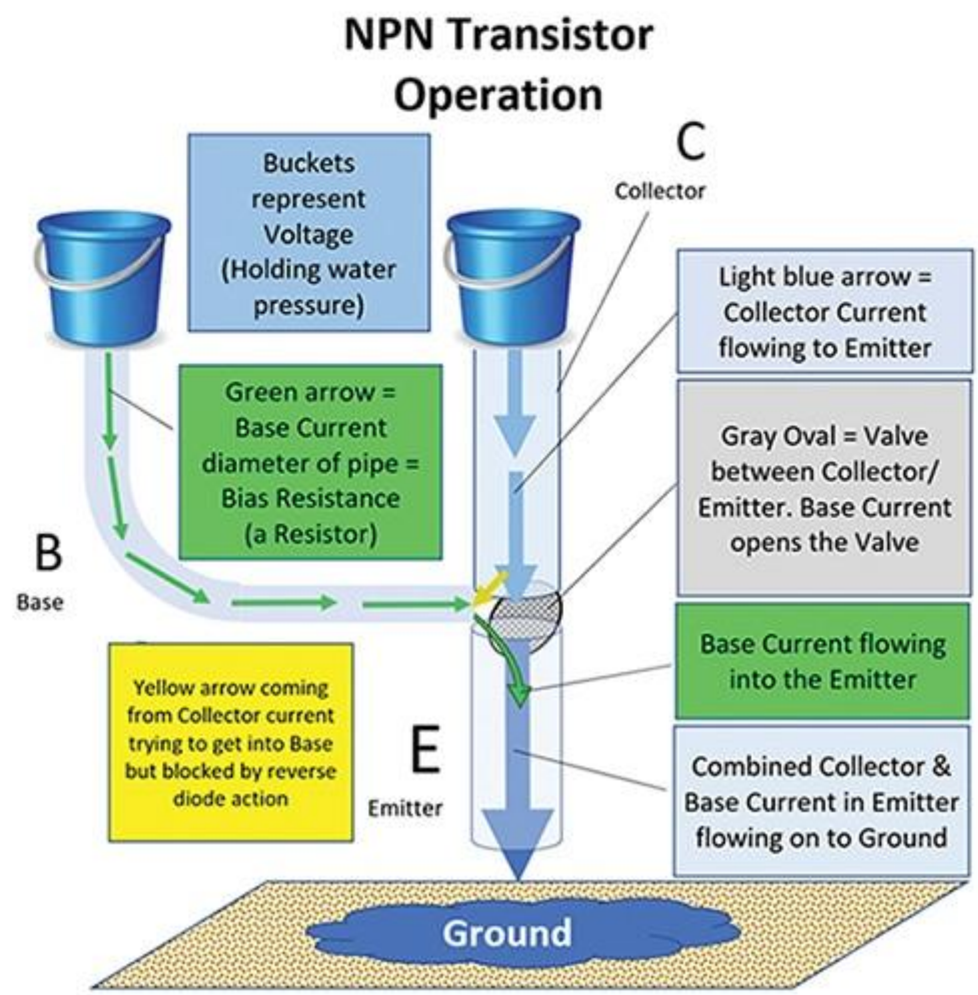


Figure 2.6: Fluid Flow Analogy

When fluid flows through the smaller tube (base), it opens the valve between the collector/emitter junction, allowing fluid to flow through the emitter to ground.

In working mode, the **NPN** transistors activate by a positive current biased at the base to control the current flow from collector (C) to emitter (E). The **PNP** transistors activate by a negative current biased at the base to control the flow from Emitter to Collector. The different NPN and PNP is that current flow polarity for PNP is reversed compared with NPN.

- ✓ NPN - Base is energized to allow current flow
- ✓ PNP - Base is connected to a lower potential to allow current flow

For NPN transistor, the voltage between the Base and Emitter, V_{BE} is positive at the base, B and negative at the emitter, E. The base, B terminal is always positive with respect to the emitter, E. The collector, C as supply voltage must also be more positive with respect to the emitter, V_{CE}.

The condition of biasing between terminals of NPN transistor,

- Base is a very thin region with less dopants
- Base collector junction reversed biased
- Base emitter junction forward biased

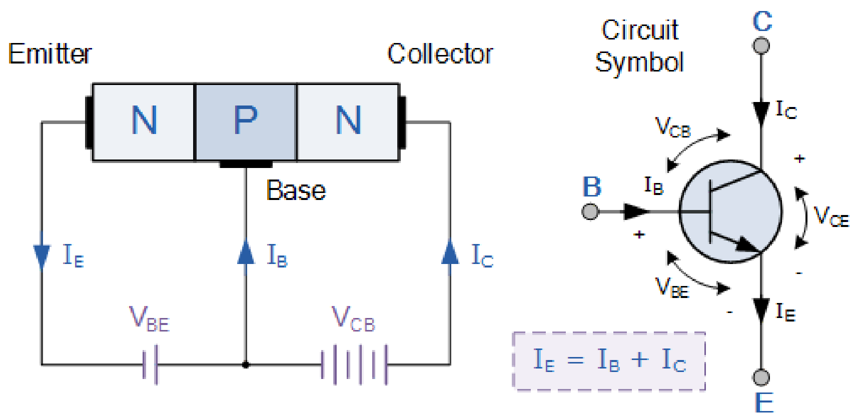


Figure 2.7: The Current Flow of NPN

The working principle of the PNP transistor like the NPN is based on the control of current flow between the emitter and collector regions by varying the base current. However, the PNP transistor operates with holes as the majority charge carriers, which is the opposite direction flow of the NPN transistor that operates with electrons as the majority charge carriers.

The condition of biasing between terminals of PNP transistor,

- Base is a very thin region with less dopants
- collector-base junction is reverse biased
- emitter-base junction is forward biased

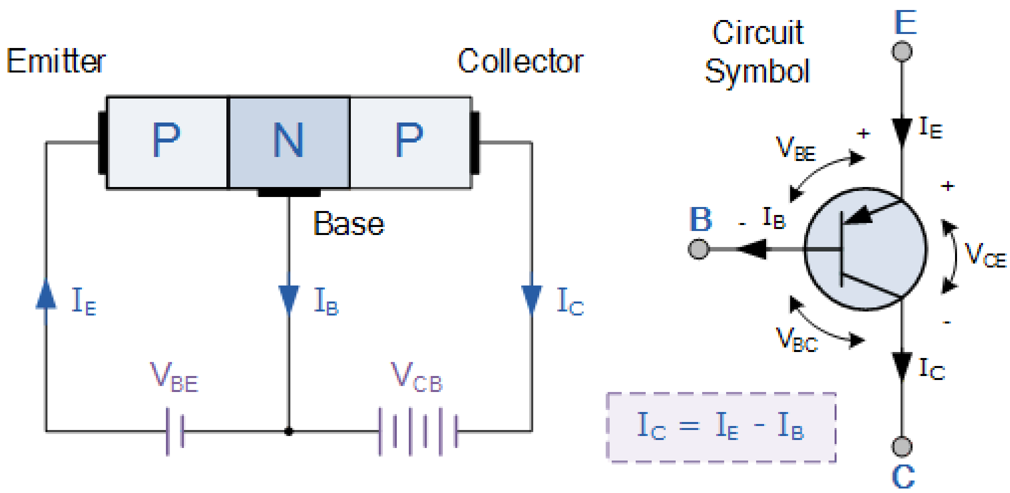


Figure 2.8: The Current Flow of PNP

2.4 The practical to identify transistor terminals

The terminals of PNP and NPN transistors can be determined using a Multimeter as below:

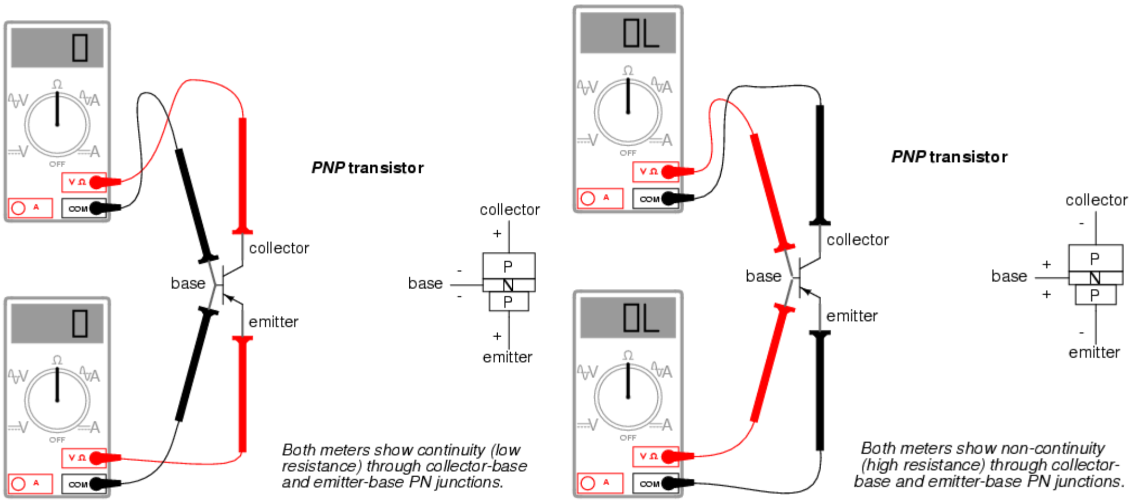


Figure 2.9: transistor terminals resistance measurement

An NPN transistor, with both PN junctions facing the other way. If a multimeter with a "diode check" function is used in this test, it will be found that the emitter-base junction possesses a slightly greater forward voltage drop than the collector-base junction. This forward voltage difference is due to the disparity in doping concentration between the emitter and collector regions of the transistor: the emitter is a much more heavily doped piece of semiconductor material than the collector, causing its junction with the base to produce a higher forward voltage drop.

All bipolar transistors have three terminals but the positions of the three terminals on the actual physical package are not arranged in any universal, standardized order. Suppose a technician finds a bipolar transistor and proceeds to measure continuity with a multimeter set in the "diode check" mode. Measuring between pairs of terminals and recording the values displayed by the multimeter in the table 2.

Figure 2.10: terminals of transistor view

- Meter touching wire 1 (+) and 2 (-): "OL"
- Meter touching wire 1 (-) and 2 (+): "OL"
- Meter touching wire 1 (+) and 3 (-): 0.655 ohm
- Meter touching wire 1 (-) and 3 (+): "OL"
- Meter touching wire 2 (+) and 3 (-): 0.621 ohm
- Meter touching wire 2 (-) and 3 (+): "OL"

The only combinations of test points giving conducting meter readings are wires 1 and 3 (red test lead on 1 and black test lead on 3), and wires 2 and 3 (red test lead on 2 and black test lead on 3). These two readings *must* indicate forward biasing of the emitter-to-base junction (0.655 ohm) and the collector-to-base junction (0.621 ohm).

Table 2.2: the terminal pair resistance value of transistor

Component	**Terminal pair/ Resistance**						**Terminal**
	1-2 (Ω)	**1-3 (Ω)**	**2-1 (Ω)**	**2-3 (Ω)**	**3-1 (Ω)**	**3-2 (Ω)**	
Transistor x	OL	0.655	OL	0.621	OL	OL	Base = 3 Collector = 2 Emitter = 1

The one terminal common to both sets of conductive readings. It must be the base connection of the transistor, because the base is the only layer of the three-layer device common to both sets of PN junctions (emitter-base and collector-base). In this example, that terminal is number 3, being common to both the 1-3 and the 2-3 test point combinations. In both those sets of meter readings, the *black* (-) meter test lead was touching terminal 3, which tells us that the base of this transistor is made of N-type semiconductor material (black = negative). Thus, the transistor is an PNP type with base on terminal 3, emitter on terminal 1 and collector on terminal 2.

2.5 Advantages of a transistor

- High voltage gain.
- Lower supply voltage is sufficient.
- Most suitable for low power applications.
- Smaller and lighter in weight.
- Mechanically stronger than vacuum tubes.
- No external heating required like vacuum tubes.
- Very suitable to integrate with resistors and diodes to produce ICs.

2.6 Disadvantages of a Transistor

- cannot be used for high power applications due to lower power dissipation
- have lower input impedance
- temperature dependent.

2.7 Working Principle of Field Effect Transistor (FET)

To explain the working principle of FET, the analogy of a water pipe and valve be applied.

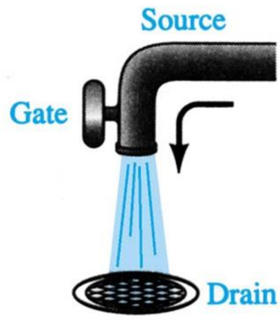


Figure 2.11: water flow analogy

The source of water pressure represents the accumulated electrons at the negative pole of the applied voltage from Drain to Source.
The drain of water represents electron deficiency (or holes) at the positive pole of the applied voltage from Drain to Source.

The valve of flow of water represents Gate voltage that controls the width of the n-channel, which in turn controls the flow of electrons in the n-channel from source to drain.

JFET has three basic operating conditions:

1. $V_{GS} = 0$, V_{DS} increasing to some positive value
2. $V_{GS} < 0$, V_{DS} at some positive value
3. Voltage-Controlled Resistor

2.7.1 Working Principle of N-Channel JFET

The JFET is a voltage control device where V_{GS} controls the drain-source resistance (rd).

a). $V_{GS} = 0$, V_{DS} increasing to some positive value

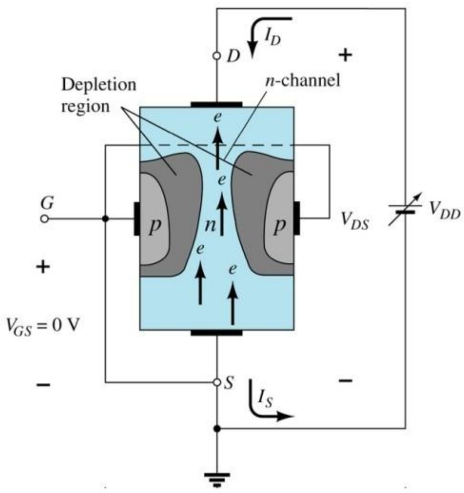


Figure 2.12: electron flow versa V_{GS} =0

If $V_{GS} = 0$ and V_{DS} is continuing in increase to a more positive voltage, the depletion zone gets so large that it ***pinches off*** the n-channel. Hence, the current in the n-channel (I_D) would drop to 0A, but it does just the opposite: as V_{DS} increases, so does I_D.

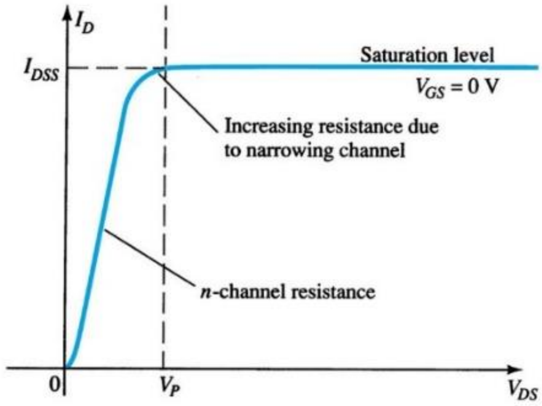


Figure 2.13: drain-source resistance (rd).

At the pinch-off point, increasing in V_{GS} does not produce any increase in I_D and V_{GS} at pinch-off is mentioned as Vp, I_D is at saturation or maximum which is referred to as I_{DSS}.

b). $V_{GS} < 0$, V_{DS} at some positive value

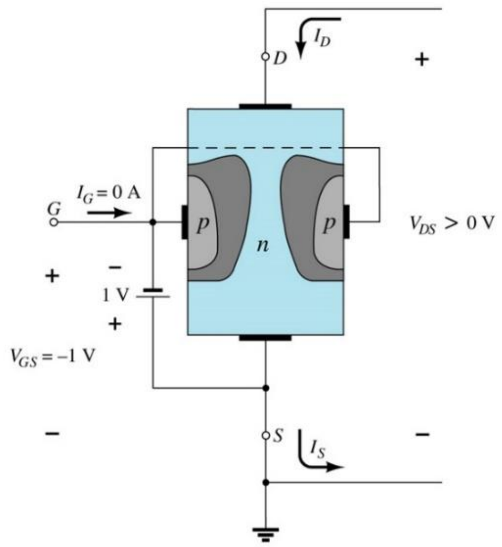


Figure 2.14: electron flow versa V_{GS} <0 in N-channel JFET

when V_{GS} becomes more negative, the depletion region increases.
when V_{GS} becomes more negative, the JFET will pinch-off at a lower voltage (Vp), I_D decreases ($I_D < I_{DSS}$) even though V_{DS} is increased and it will reach 0A. V_{GS} at this point is called Vp or $V_{GS\ (off)}$.

c). **Voltage-Controlled Resistor**

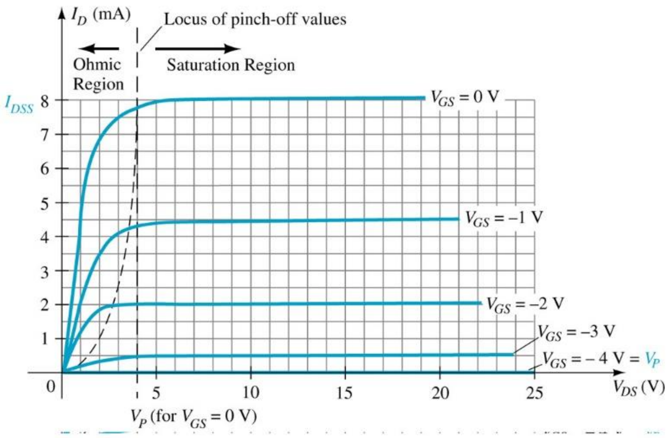


Figure 2.15: N-channel JFET in variable negative V_{GS}

The region at the left of the pinch-off point is called the ***ohmic region***. When V_{GS} becomes more negative, the resistance (rd) increases.

2.7.2 Working Principle of P-Channel JFET

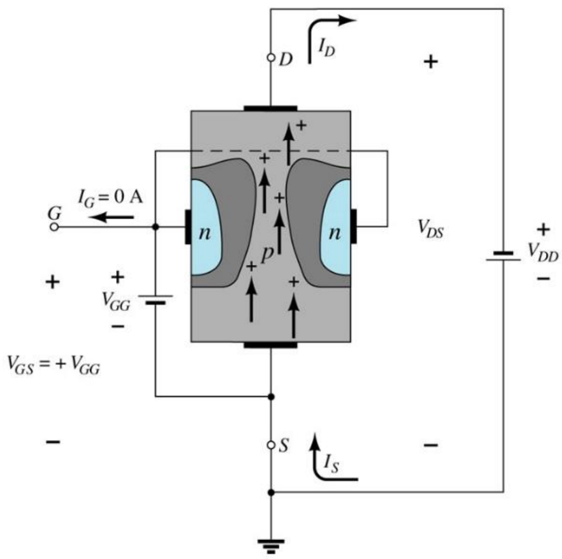


Figure 2.16: electron flow versa V_{GS} <0 in N-channel JFET

p-Channel JFET acts the same as the n-channel JFET, except the polarities and currents are reversed.

P-Channel JFET Characteristics

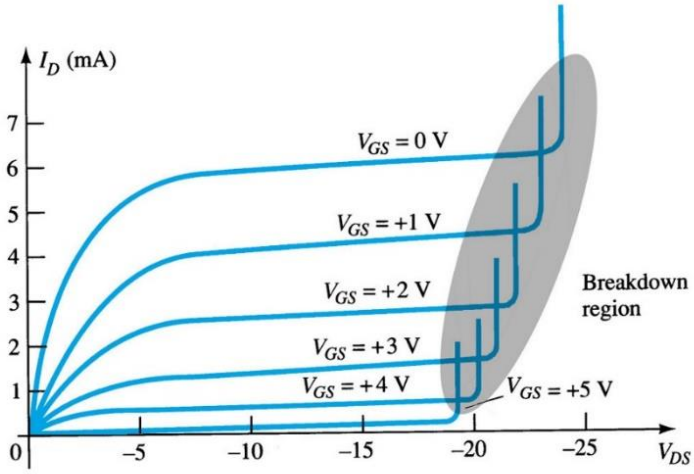


Figure 2.17: current flow versa V_{GS} in P-channel JFET

If V_{GS} increases more positively, the depletion zone increases

- I_D decreases ($I_D < I_{DSS}$), $I_D = 0A$

The JFET reaches a breakdown situation at high levels of VDS and I_D increases uncontrollably if $V_{DS} > V_{DSmax}$.

2.7.3 Working Principle of N-channel MOSFET

A Depletion MOSFET can operate in two modes: Depletion or Enhancement MODE

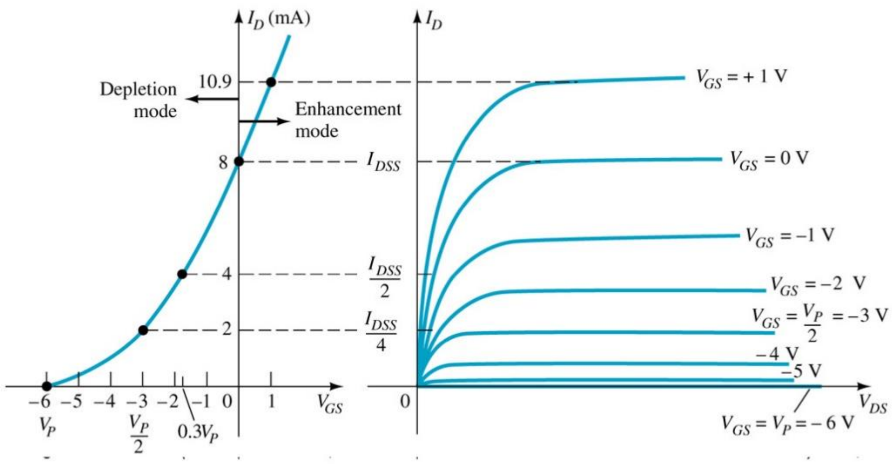


Figure 2.18: current flow versa V_{GS} in N-channel JFET

a. Depletion mode

The characteristics are similar to the JFET.

When $V_{GS} = 0V$, $I_D = I_{DSS}$

When $V_{GS} < 0V$, $I_D < I_{DSS}$

b. Enhancement mode

$V_{GS} > 0V$, I_D increases above I_{DSS}

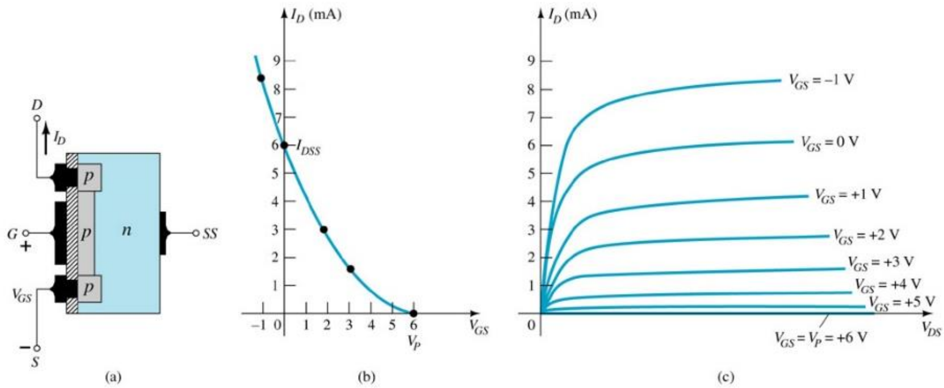


Figure 2.19: current flow versa V_{GS} in P-channel JFET

2.7.4 Working Principle of Operation of P-channel MOSFET

The p-channel Depletion-type MOSFET is similar to the N-channel except that the voltage polarities and current directions are reversed.

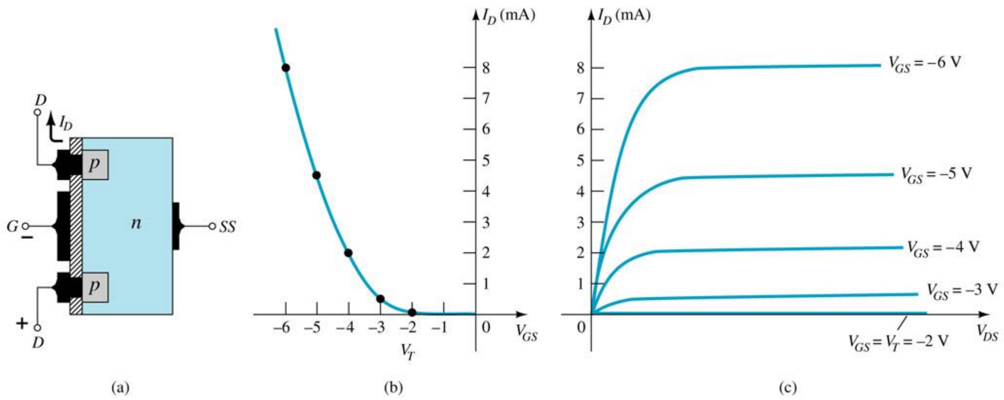
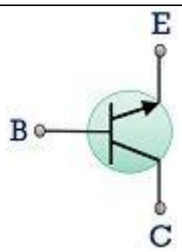
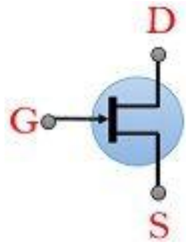


Figure 2.20: current flow versa V_{GS} in P-channel JFET

The p-channel Enhancement-type MOSFET is similar to the n-channel except that the voltage polarities and current directions are reversed.

2.8 Comparisons Between BJT and JFET

Table 2.3: Comparisons Between BJT and JFET

PARAMETER	BJT	JFET
Symbol		
Carrier	Bipolar (majority and minority)	Unipolar (majority)
Device type	Current controlled device.	Voltage controlled device.
Input impedance	Low	High
Gain	High gain	Low - medium gain
Power consumption	more power.	less power.
Noise level	High	Low
Thermal stability	Low	High
Size	Large	Small
Application	low current application.	low voltage application.

Activity 2a

1. What are the operative modes of a transistor?
   a. Cut-off mode c. Saturation mode
   b. Active mode d. Remote mode

2. What are the majority charge carriers in NPN transistors?
   a. Hole c. Electrons
   b. Neutron d. proton

3. How does current flow in NPN transistor?
   a. current flows from the base to the collector. The emitter terminal controls the flow of current through it.
   b. current flows from the base to the emitter. The collector terminal controls the flow of current through it.
   c. current flows from the collector to the emitter. The base terminal controls the flow of current through it.
   d. current flows from the emitter to the collector. The base terminal controls the flow of current through it.

4. PNP transistor has the following arrangement
   a. P type emitter, N type base, P type collector
   b. P type base, N type emitter, p type collector
   c. p type collector, N type base, N type emitter
   d. N type collector, N type emitter, p type base

5. What terminal essential for controlling the operation of both NPN and PNP transistors?
   a. Collector c. Gate
   b. Emitter d. Base

6. which transistors requires a positive base-emitter voltage to operate properly?
   a. NPN c. PNP
   b. Both PNP and NPN d. Neither

7. Which of the following conditions correctly describes the 'saturation' region of an NPN transistor?
   a. The base-emitter and base-collector junctions are forward biased.
   b. The base-emitter and base-collector junctions are reverse biased.
   c. The base-emitter is reverse biased and base-collector junctions is forward biased.
   d. The base-emitter is forward biased and base-collector junctions is reverse biased.

8. The PNP transistor be conducting when the emitter must be
    a. The same potential as the collector
    b. A lower potential than the base
    c. A higher potential than the base
    d. Grounded

9. What is the relationship between the polarity of the voltage applied to the PNP transistor and that applied to the NPN transistor?
    a. The polarity of voltage applied to the PNP transistor is the same of that applied to the NPN transistor
    b. The polarity of voltage applied to the PNP transistor is opposite of that applied to the NPN transistor
    c. Either a or b
    d. No relationship

10. What is the purpose of the lightly doped base region in an NPN transistor?
    a. To block the flow of current through the emitter-base and base-collector junctions
    b. To allow carriers to recombine or diffuse into the base region without significant resistance
    c. To provide a high resistance path for the base current
    d. To increase the current gain of the transistor

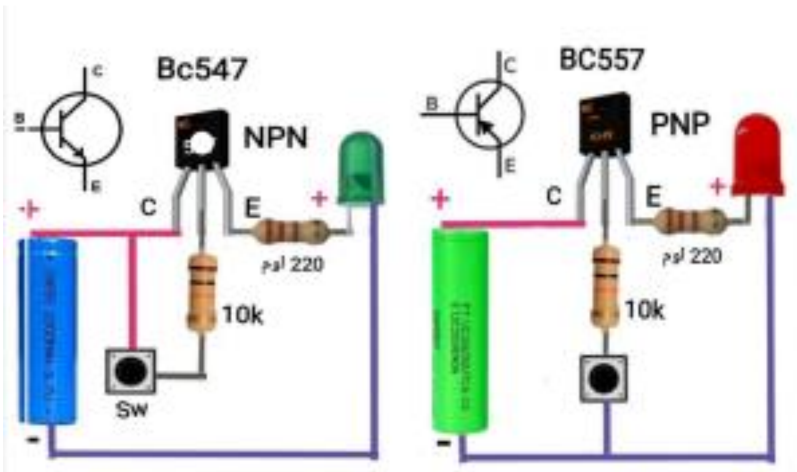
Answer:
1b, 2c, 3d, 4a, 5d, 6a, 7a, 8c, 9b, 10b.

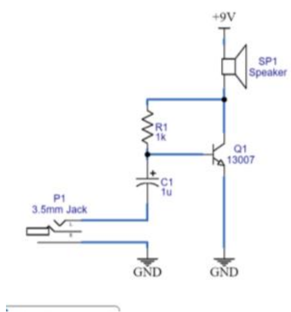
Chapter 3

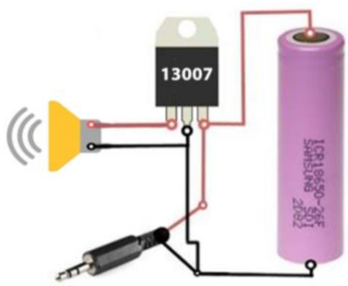
Transistor Applications

Upon completion this chapter, you should be able to:

- Define the applications of transistor
- Explain the application of transistor in electronic circuit.







3.0 Introduction

A transistor is a three terminal semiconductor device that it has many uses including switching, amplification, voltage regulation, and the modulation of signals. In the words, transistor acts as a switch or gate for signals to choose between available options, amplify the small or weak signal to large enough is needed wherever the signal strength has to be increased, regulates the incoming current and voltage of the signal, and also modulates the signal for transmission. All of that is done by a transistor.

3.1 Transistor as a Switch

Usually, the transistors are used as electronic switches which can be either in "ON" or "OFF" state. Transistor switches can be used to switch a low voltage DC device as like LED, buzzer, DC motor and etc. it also be used in low-power applications such a logic gates and high-power applications such as switched mode power supplies.

In a switching circuit, the ideal switch having the properties of an open circuit in “OFF”, the short circuit in “ON” state where the resistance of the transistor is too small to affect circuitry in the "ON" state, and too high enough in the “OFF” state. The areas of operation for a transistor switch are known as the **Saturation Region** and the **Cut-off Region**.

a). Cut-off Region.

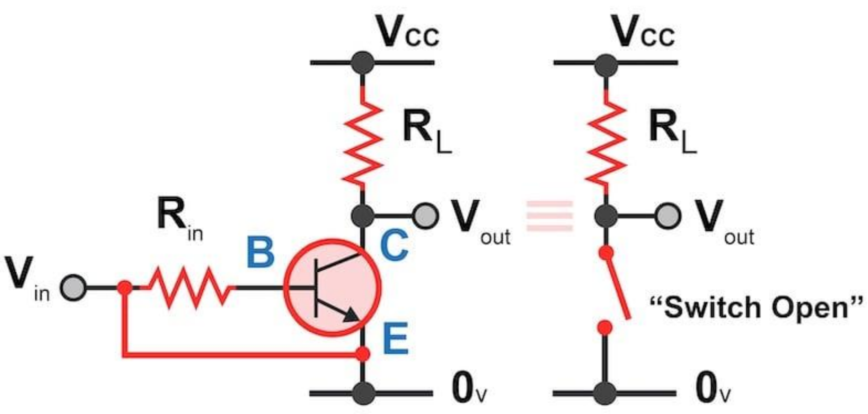


Figure 3.1: transistor as switch in “OFF” state

Cut-off characteristic

- Base-Emitter voltage $V_{BE} < 0.7v$
- Base-Emitter junction is reverse biased
- Base-Collector junction is reverse biased
- Transistor is "fully-OFF" (Cut-off region)
- No Collector current flows ($I_C = 0$)
- $V_{OUT} = V_{CE} = V_{CC}$
- Transistor operates as an "open switch"

The operating conditions of the transistor in figure 4.1 shown that when input base current (I_B) is zero which results in a large depletion layer and no current flowing through the device. Therefore, the transistor is switched "Fully-OFF".

b. Saturation Region

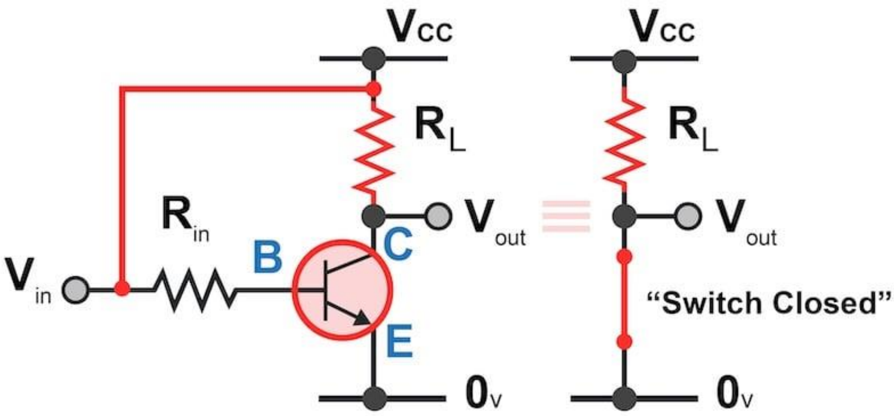


Figure 3.2: transistor as switch in "ON" state

Saturation characteristic

- Base-Emitter voltage $V_{BE} > 0.7v$
- Base-Emitter junction is forward biased
- Base-Collector junction is forward biased
- Transistor is "fully-ON" (saturation region)
- Max Collector current flows ($I_C = Vcc/R_L$)
- $V_{CE} = 0$ (ideal saturation)
- $V_{OUT} = V_{CE} =$ "0"
- Transistor operates as a "closed switch"

When the transistor be biased with the maximum amount of base current, I_B, resulting in maximum collector current resulting in the minimum collector emitter voltage, V_{CE} drop which results in the depletion layer being as small as possible and maximum current flowing through the transistor. Therefore, the transistor is switched "Fully-ON".

MOSFET is very good electronic switches in CMOS digital circuits operate between their cut-off and saturation regions for controlling loads. Enhancement-mode MOSFET (e-MOSFET) operates using a positive input voltage and has an extremely high input resistance to make it possible as a switch when interfaced with nearly any logic gate or driver capable of producing a positive output.

MOSFET Characteristics

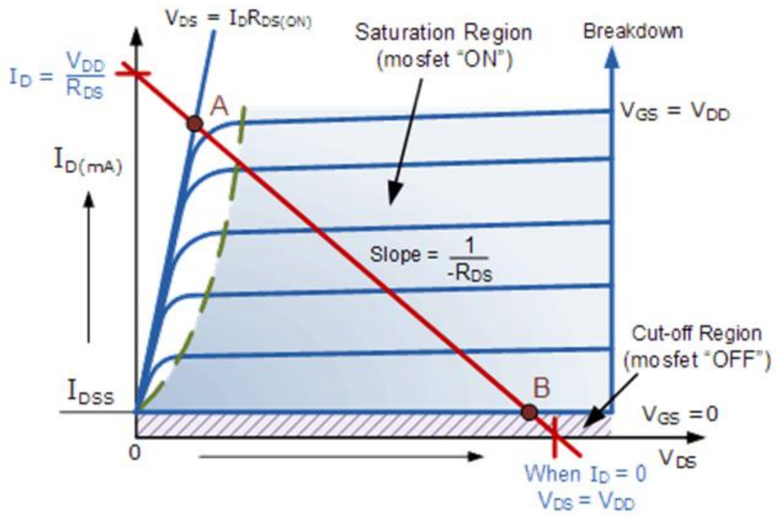


Figure 3.3: V-I transfer curve of MOSFET

In the V-I transfer curves in figure 3.4, when V_{IN} is high or equal to V_{DD}, the MOSFET Q-point moves to point A along the load line. The drain current ID increases to its maximum value due to a reduction in the channel resistance. ID becomes a constant value independent of VDD, and is dependent only on VGS. The transistor behaves like a closed switch but the channel ON-resistance does not reduce fully to zero due to its R_{DS} value, but gets very small.

When V_{IN} is low or reduced to zero, the MOSFET Q-point moves from point A to point B along the load line. The channel resistance is very high so the no current flows through the channel and transistor acts like an open circuit.

a. **Cut-off Region.**

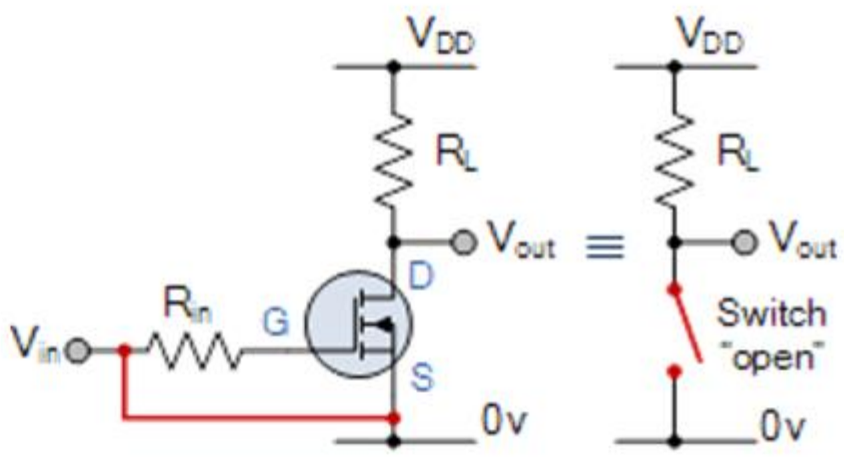


Figure 3.4: MOSFET as switch in "ON" state

Cut-off characteristic

- The input and Gate 0V
- Gate-source voltage, V_{GS} less than threshold voltage $V_{GS} < V_{TH}$
- MOSFET is "OFF" (Cut-off region)
- No Drain current flows (I_D = 0 Amps)
- $V_{OUT} = V_{DS} = V_{DD}$ = "1"
- MOSFET operates as an "open switch"

b. Saturation Region

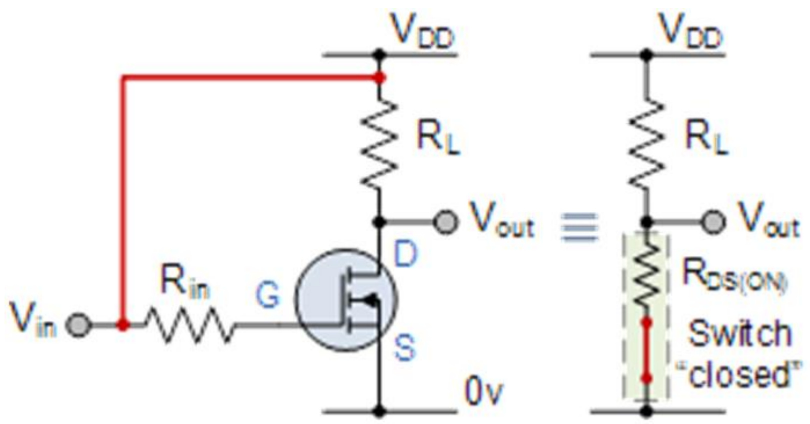


Figure 3.5: MOSFET as switch in "ON" state

Saturation characteristic

- Gate-source voltage is much greater than threshold voltage $V_{GS} > V_{TH}$
- MOSFET is “ON” (saturation region)
- Max Drain current flows ($I_D = V_{DD} / R_L$)
- $V_{DS} = 0V$ (ideal saturation)
- Min channel resistance $R_{DS(on)} < 0.1\Omega$
- $V_{OUT} = V_{DS} \cong 0.2V$ due to $R_{DS(on)}$
- MOSFET operates as a low resistance “closed switch”

This ability to turn the power MOSFET “ON” and “OFF” allows the device to be used as a very efficient switch with switching speeds much faster than standard bipolar junction transistors.

3.1.2 Applications transistor as switch.

a. solid state switch

A simple switch to turn ON an electronic circuit when the desired requirement be achieved. If the transistor is operated in the saturation region then it acts as closed switch and when it is operated in the cut off region then it behaves as an open switch. Example to turn on the LED and buzzer.

b. digital logic

The transistors particularly in complementary metal-oxide-semiconductor (CMOS) technology. In CMOS circuits, NPN and PNP transistors are used together to form logic gates such as inverters, NAND gates, flip-flops, and other digital circuits to perform binary operations. In other words, the transistor acts as a switch that turns on or off based on the input signals in performing the logic operation. These logic gates are the basis of control systems, proximity sensors, and industrial control.

c. Oscillator

An oscillator is a circuit that produces a periodic signal that swings between a high and low voltage. Oscillators are used in all sorts of circuits from simply blinking a LED to the producing a clock signal to drive a microcontroller. Transistor is one ways to create an oscillator circuit besides the quartz crystals.

3.2 Transistor as an Amplifier

Amplifiers are circuits that are meant to increase a signal's strength. Therefore, the transistor acts as an amplifier by raising the strength of a weak signal. The transistor amplifies a weak input signal to produce a larger output signal. The ability to amplify weak signals such as in audio amplifiers, radio frequency (RF) amplifiers, and operational amplifiers.

The transistor could be seen as an amplifier in the three combinations/configurations as below:

a. Common Base Configuration (CBC)

The input is applied between the emitter terminal and base terminal while output is taken the collector terminal and base terminal. This means that the base terminal is common terminal to both input side and output side of the transistor. This results in a relatively low output impedance with little amplification will have a meagre gain.

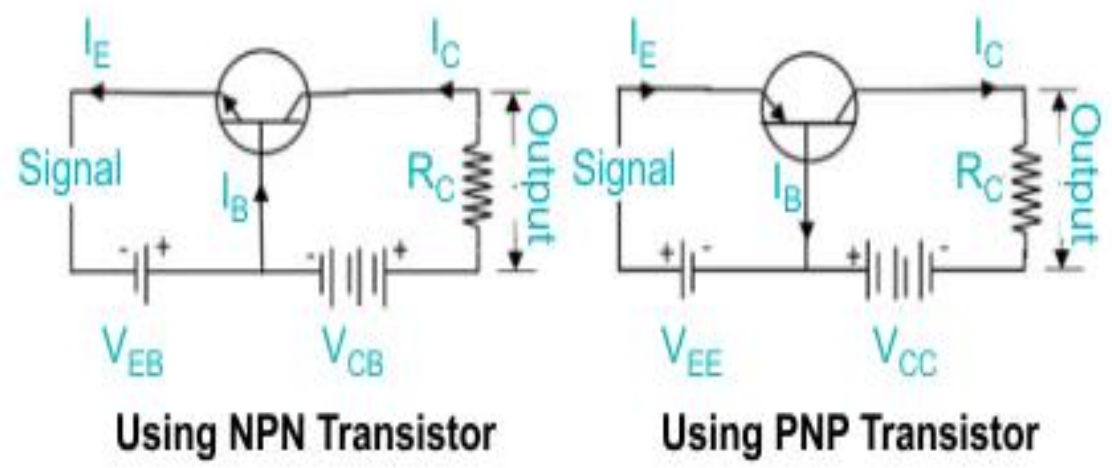


Figure 3.6: Common Base Configuration (CBC)

b. Common Collector Configuration (CCC)

In Common Collector Configuration**,** the input is applied between the base terminal and collector terminal while output is taken the emitter terminal and collector terminal. the output resistance is low for a high-power density, and the gain is superior when matched to the CB configuration.

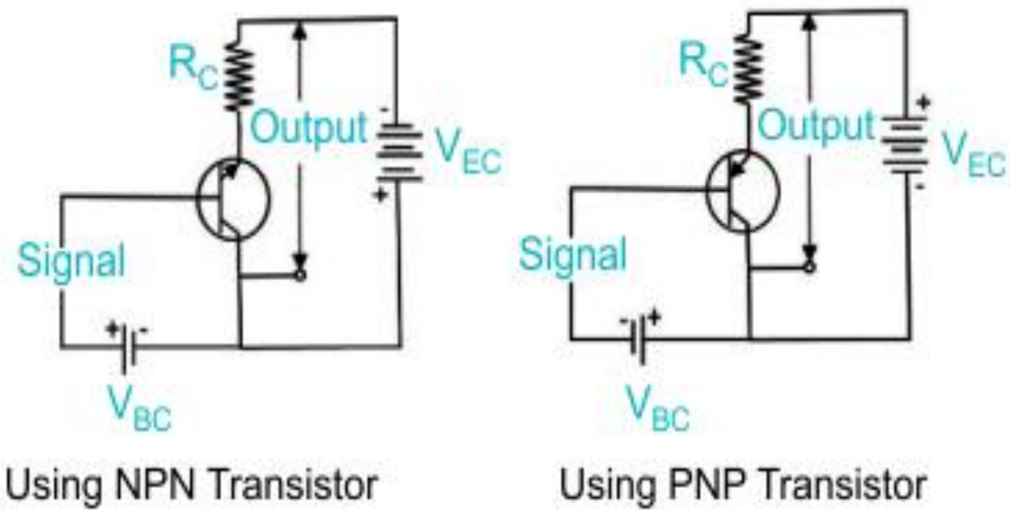


Figure 3.7: Common Collector Configuration (CCC)

c. Common Emitter Configuration (CEC)

In Common Emitter Configuration, the input is applied between the base and emitter, while output is taken the collector and emitter. Hence he input impedance shall become high, the output resistance shall be medium, and the gain shall become high.

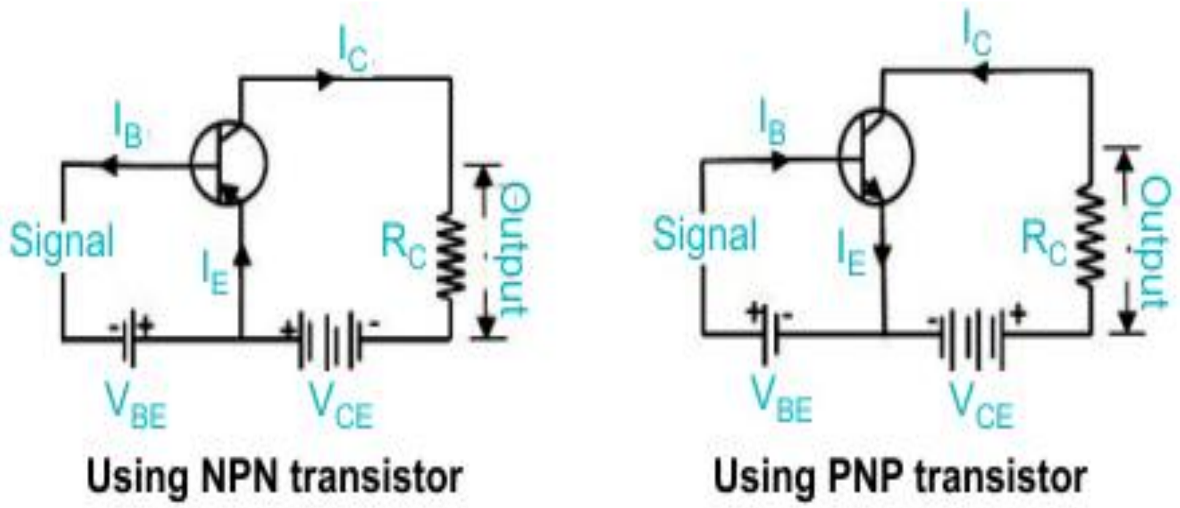


Figure 3.8: Common Emitter Configuration (CEC)

3.2.1 Advantage and Disadvantages of Amplifier

a. Advantages of Amplifier

- A low input impedance,
- high output impedance
- high voltage gain
- high current gain.

b. Disadvantages of Amplifier

- has a high output resistance
- poorly responds to high frequencies.
- has high thermal instabilities.
- voltage gain is very unstable.

3.2.2 Comparison the performance of Characteristics

Table 3: Comparison the performance of Characteristics (CBC, CCC & CEC)

NO	Parameter	CBC	CCC	CEC
1	Input Resistance	Very low	Very high	Moderately
2.	Output resistance	Very high	Low	Moderately
3	Input current	I_E	I_B	I_B
4	Output current	I_C	I_E	I_C
5	Input voltage applied between	Emitter and base	Bae and collector	Base and emitter
6	Output voltage is taken as base	Collector and emitter	Emitter and ground	Emitter and collector
7	Current gain	Less than unity	High (20 to few hundreds)	High (20 to few hundreds)
8	Voltage gain	High	Low $=\infty$	High

3.2.3 Applications among the three configurations.

a. Common emitter configuration: Offers high voltage gain and moderate current gain, commonly used for amplification applications.
b. Common base configuration: Provides high current gain and moderate voltage gain, suitable for impedance matching and RF amplifier circuits.
c. Common collector configuration: Offers high voltage gain and unity current gain, commonly used for impedance buffering and voltage amplification.

3.3 Transistor as a Voltage Regulation

The transistors as PNP are used in voltage regulators which particularly in linear voltage regulators. In these circuits, the PNP transistor is used as a pass element to control the output voltage by adjusts its resistance based on the input voltage and the desired output voltage, maintaining a stable output voltage even when the input voltage or load current changes. The transistor works as a variable resistor regulating its collector-emitter voltage in order to maintain the output voltage constant.

3.3.1 Zener Controlled Transistor Series Voltage Regulator

It also named an emitter follower voltage regulator because the transistor used is connected in an emitter follower configuration. The circuit consists of an N-P-N transistor and a zener diode. The collector and emitter terminals of the transistor are in series with the load. The transistor used is a series pass transistor.

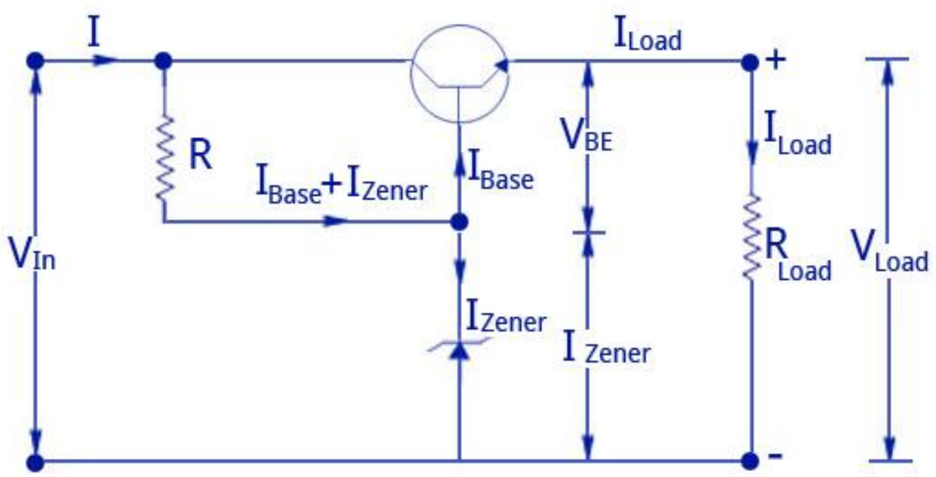


Figure 3.9: Zener Controlled Transistor Series Voltage Regulator

3.3.2 Zener Controlled Transistor Shunt Voltage Regulator

The circuit consists of an NPN transistor and a zener diode along with a series resistor R series that is connected in series with the input supply. The zener diode is connected across the base and the collector of the transistor which is connected across the output.

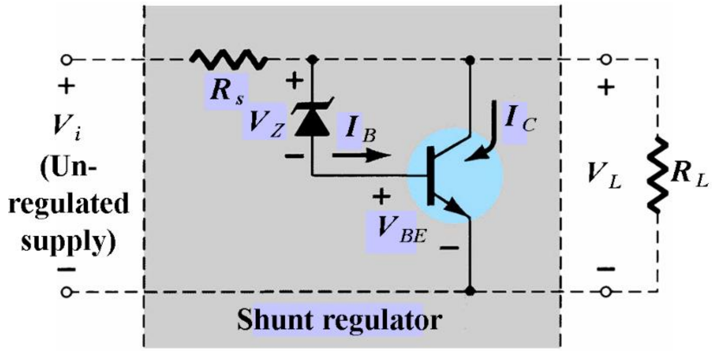


Figure 3.10: Zener Controlled Transistor Shunt Voltage Regulator

3.4 Applications of Junction Field Effect Transistor (JFET)

Some applications of JFET are listed below:

- JFET is used as a switch
- JFET is used as a chopper
- JFET is used as a buffer
- JFETs are used in oscillatory circuits
- JFETs are used in cascade amplifiers

3.5 Advantages and Disadvantages of JFET

a. Advantages of JFET

- JFET has a high impedance
- JFETs are low power consumption devices
- JFET can be fabricated in a smaller size, and as a result, they occupy less space in circuits due to their smaller size.

b. Disadvantages of JFET

- has a low gain-bandwidth product
- The performance of JFET is affected as frequency increases due to feedback by internal capacitance.
-

Activity 3a

1. Which is not the application of transistor?
    a. Amplification
    b. Filter
    c. Switching
    d. Voltage regulation

2. How many types of Configuration available in Transistor?
    a. 2
    b. 3
    c. 4
    d. 5

3. Which region transistor act as amplifier?
    a. Active region.
    b. Cut off region
    c. Saturation region
    d. Reverse bias region

4. What is not the JFET application?
    a. switch
    b. chopper
    c. filter
    d. oscillatory circuits.

5. Which type of device is JFET?
    a. current controlled device
    b. resistance controlled device
    c. voltage controlled device
    d. conductance controlled device

Answer:
1b, 2b, 3a, 4c, 5c

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