Dr APJ ABDUL KALAM SCHOOL OF ENGINEERING

Course Name: Basic Electronics Engineering

MODULE 1 – BASIC ELECTRONIC COMPONENTS HANDOUTS

TYPES OF ELECTRONIC COMPONENTS

Types of electronic components

The electronic components are generally classified into two types:

- Passive components
- Active components

Passive component

The electronic component, which consumes energy in the form of voltage from the source, but does not produce or supply energy is called passive electronic component.

1. Passive components cannot control the flow of electrons or electric current through a circuit, but they limit the flow of electrons or electric current.
2. Passive components cannot amplify or increase the power of an electrical signal.
3. Passive components temporarily store the electrical energy in the form of static electric field or magnetic field.
4. Passive components do not depend on the external source of energy or voltage to perform a specific operation.

Different types of passive components

The different types of passive components include resistors, capacitors, and inductors

1. RESISTOR

A resistor is an electrical component that limits or regulates the flow of electrical current in an electronic circuit. Resistors can also be used to provide a specific voltage for an active device. The symbol of the resistor is as follows

Resistor

OHM'S LAW

Ohm's law states that the voltage across a conductor is directly proportional to the current flowing through it, provided all physical conditions and temperatures remain constant.

$$V \propto I$$

$$V = IR$$

Where R is resistance measured in Ω

Electrical resistance is directly proportional to length (L) of the conductor and inversely proportional to the cross-sectional area (A). It is given by the following relation

$$R \propto \frac{L}{A}$$

$$R = \rho \frac{L}{A}$$

Where ρ is resistivity of the material and measured in Ωm

RESISTOR TYPES

Several different types of resistors exist. The most used resistors are fixed value resistors, but variable resistors are also very common. The most used variable resistors are the potentiometer and rheostat. On the other hand, there are also many types of resistors which have a variable resistance that is dependent on external factors such as temperature (thermistor), light (photoresistor), voltage (varistor) or magnetic fields (magneto resistor).

RESISTOR COLOUR CODE

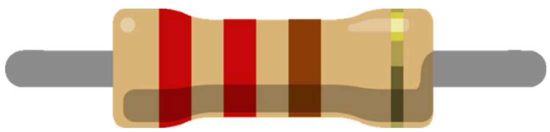
Color	1st Band	2nd Band	3rd Band (5-Band Only)	Multiplier (3rd or 4th Band)	Tolerance (Last Band)
Black	0	0	0	1	
Brown	1	1	1	10	± 1%
Red	2	2	2	100	± 2%
Orange	3	3	3	1000	
Yellow	4	4	4	10000	
Green	5	5	5	100000	± 0.5%
Blue	6	6	6	1000000	± 0.25%
Violet	7	7	7	10000000	± 0.1%
Grey	8	8	8		± 0.05%
White	9	9	9		
Gold				0.1	± 5%
Silver				0.01	± 10%
None					± 1%

3-BAND RESISTOR:

There are three colours in a group. These are the first, second are significant figures and last colour denotes the multiplier.

4-BAND RESISTOR:

There are three colours in a group. These are the first, second are significant figures and last colour denotes the multiplier. The final band is the resistor’s tolerance, a margin of error if you will. Most common tolerance value is Gold (5%)



5-BAND RESISTOR:

A five-band resistor has an additional band, a third significant figure, which affords a greater level of accuracy should a project require it. So, we have three significant figures, a multiplier and the tolerance.

RESISTOR IN SERIES:

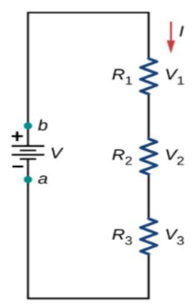
Resistors are said to be in series whenever the current flows through the resistors sequentially. The three resistors are connected in series with an applied voltage equal to Vab. Since there is only one path for the charges to flow through, the current is the same through each resistor. The equivalent resistance of a set of resistors in a series connection is equal to the algebraic sum of the individual resistances.

According to Ohm's law, the potential drop V across a resistor when a current flows through it is calculated using the equation V=IR, where I is the current in amps (A) and R is the resistance in ohms (Ω)

Since energy is conserved, the potential drops across the individual resistors around a loop should be equal to zero which is called Kirchoff's Voltage Law.

$$\sum V = 0$$

the sum of the potential drop of each resistor and the voltage supplied by the voltage source should equal zero:



$$\begin{aligned} V_{ab} &= V1 + V2 + V3 \\ &= IR1 + IR2 + IR3 \\ &= I\,(R1 + R2 + R3) \\ V &= I\,R_{eq} \\ R_{eq} &= R1 + R2 + R3 \end{aligned}$$

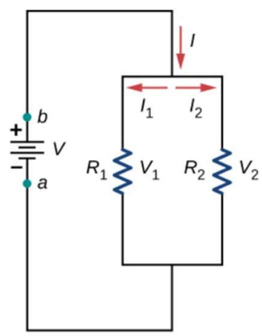
RESISTOR IN PARALLEL:

The potential drop across each resistor is the same. Current through each resistor can be found using Ohm's law I=V/R, where the voltage is constant across each resistor. For example, an automobile's headlights, radio, and other systems are wired in parallel, so that each subsystem utilizes the full voltage of the source and can operate completely independently. The same is true of the wiring in your house or any building.

The current flowing from the voltage source depends on the voltage supplied by the voltage source and the equivalent resistance of the circuit. In this case, the current flows from the voltage source and enters a junction, or node, where the circuit splits flowing through resistors R1 and R2. As the charges flow from the battery, some go through resistor R1 and some flow through resistor R2. The sum of the currents flowing into a junction must be equal to the sum of the currents flowing out of the junction which is called Kirchoff's Current Rule.

$$\sum I_{in} = \sum I_{out}$$

$$I = I_1 + I_2$$



$$= \frac{V}{R_1} + \frac{V}{R_2}$$

$$= V\left(\frac{1}{R_1} + \frac{1}{R_2}\right)$$

$$= \frac{V}{R_{eq}}$$

$$R_{eq} = \frac{1}{\left(\frac{1}{R_1} + \frac{1}{R_2}\right)}$$

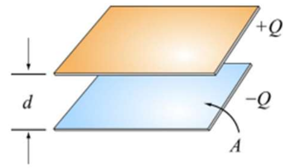
2. CAPACITOR:

The Capacitor consists of two conductors or electrodes separated by a dielectric material of uniform thickness. The conductors can be any material that will conduct electricity easily. The dielectric must be a poor conductor-an insulator.

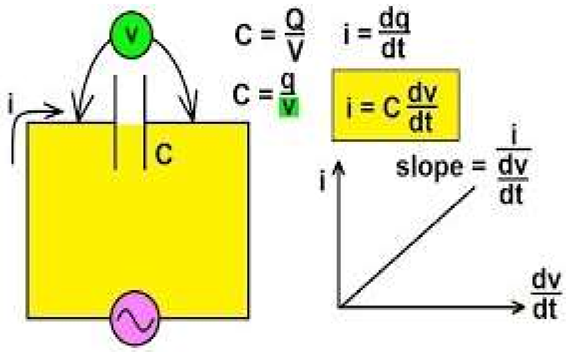
Capacitors vary in shape and size, but the basic configuration is two conductors carrying equal but opposite charges. Capacitors have many important applications in electronics. Some examples include storing electric potential energy, delaying voltage changes when coupled with resistors, filtering out unwanted frequency signals, forming resonant circuits and making frequency-dependent and independent voltage dividers when combined with resistors

In the uncharged state, the charge on either one of the conductors in the capacitor is zero. During the charging process, a charge Q is moved from one conductor to the other one, giving one conductor a charge +Q, and the other one -Q charge. A potential difference is created, with the positively charged conductor at a higher potential than the negatively charged conductor. Note that whether charged or uncharged, the net charge on the capacitor as a whole is zero

The simplest example of a capacitor consists of two conducting plates of area, which are parallel to each other, and separated by a distance d,



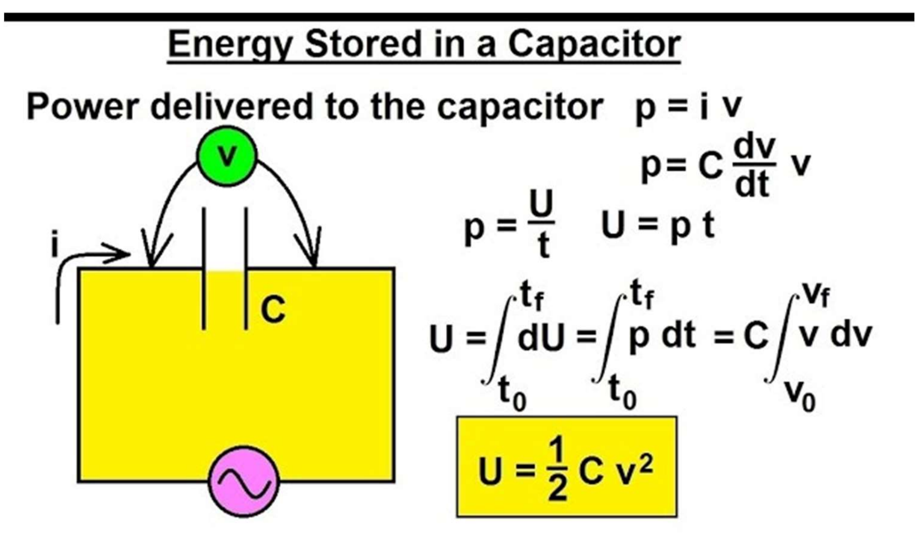
Experiments show that the amount of charge Q stored in a capacitor is linearly proportional to, the electric potential difference between the plates. Thus, we may write $Q = C\,|\,\Delta V\,|$



where C is a positive proportionality constant called capacitance. Physically, capacitance is a measure of the capacity of storing electric charge for a given potential difference ΔV. The SI unit of capacitance is the farad (F):

$$1\text{ F} = 1\text{ farad} = 1\text{ coulomb/volt} = 1\text{ C/V}$$

A capacitor stores electrical energy, blocks the flow of direct current, and permits the flow of alternating or pulsating current to a degree dependent on the capacitance and the frequency. The amount of energy stored is expressed as:



E = 1/2 CV

The capacitance of a parallel plate capacitor is given by the equation

$$\boldsymbol{C = \frac{\epsilon_0 A}{d}}$$

Where A is the area of the plates

d is the spacing between the plates

$\boldsymbol{\epsilon_0}$ is the permittivity on the medium

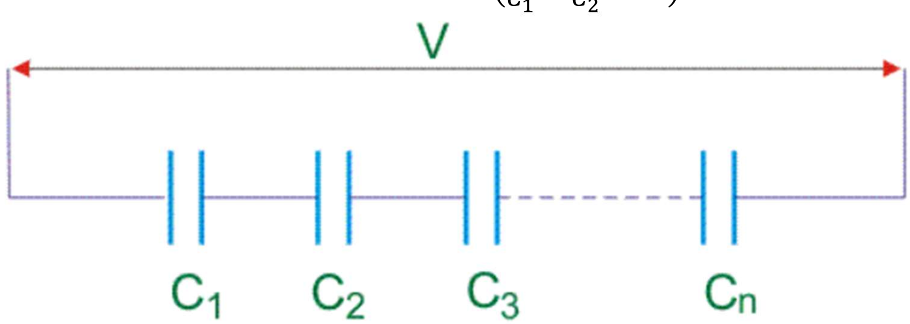
<u>CAPACITOR IN SERIES</u>:

Consider n number of **capacitors are connected in series**. V volt is applied across this series combination of capacitors. Let us consider capacitance of capacitors are C_1, C_2, C_3……. C_n respectively, and equivalent capacitance of series combination of the capacitors is C. The voltage drops across capacitors are considered to be V_1, V_2, V_3……. V_n respectively.

By Kirchoff's Voltage Law, the sum of the potential drop of each resistor and the voltage supplied by the voltage source should equal zero

$V = V_1 + V_2 + \ldots + V_n$
We know V = Q/C

$$\frac{Q}{C_1} + \frac{Q}{C_2} + \cdots$$
$$= Q\left(\frac{1}{C_1} + \frac{1}{C_2} + ..\right)$$
$$= \frac{Q}{C_{eq}}$$
$$C_{eq} = \frac{1}{\left(\frac{1}{C_1} + \frac{1}{C_2} + \cdots\right)}$$



<u>CAPACITOR IN PARALLEL</u>:

Let us consider the capacitance of the capacitors are C_1, C_2, C_3…..C_n, respectively and equivalent capacitance of the combination of the capacitor is C. As the **capacitors are connected in parallel**, like current charge in each capacitor will be same. Total charge of the parallel combination, will be divided in each capacitor according to its capacitance value but voltage across each capacitor will be same and at steady state condition it is exactly equal to the applied voltage.

$$Q = Q_1 + Q_2 + Q_3 + \ldots\ldots Q_n$$

Where Q_1, Q_2, Q_3, ……. Q_n are the charge of capacitor C_1, C_2, C_3….. C_n respectively.

$$Now, \quad Q = CV \; and \; Q_1 = C_1V, Q_2 = C_2V, Q_3 = C_3V \; and \ldots\ldots Q_n = C_nV$$

Now equation (2) can be written as,

$$CV = C_1V + C_2V + C_3V + \ldots\ldots + C_nV$$

$$\Rightarrow C = C_1 + C_2 + C_3 + \ldots\ldots + C_n$$

3. INDUCTOR

An inductor is a two terminal passive electrical component **that store energy in a magnetic field**. This magnetic field is produced due to the current flow through it.

It is basically made up of a coil surrounding a core. Every coil is an inductor essentially. The change of current through the coil produces a magnetic field around it. This magnetic field, according to **Lenz's law**, induces an EMF across the coil that is opposite in direction to the input current. Thus, an inductor opposes any change in supply current.

Chokes.

Another name used for an inductor is a "Choke". Inductors, being just coils of copper wire, will allow DC to pass easily, but when AC is applied, inductors create an opposition to current flow that increases, as the frequency of the alternating current increases. Therefore, AC is prevented from flowing or is "Choked off" while DC is allowed to pass. This effect is used in power supply circuits where the public AC mains (line) supply has to be converted to a DC supply suitable for powering electronic circuits.

Inductance:

Inductance is the ability or property of inductor to produce an electromotive force (EMF or voltage) due to change in the electric current.

It is the ratio of the voltage to the rate of change of current through the inductor.

$$\mathbf{L = V / (di/dt)}$$

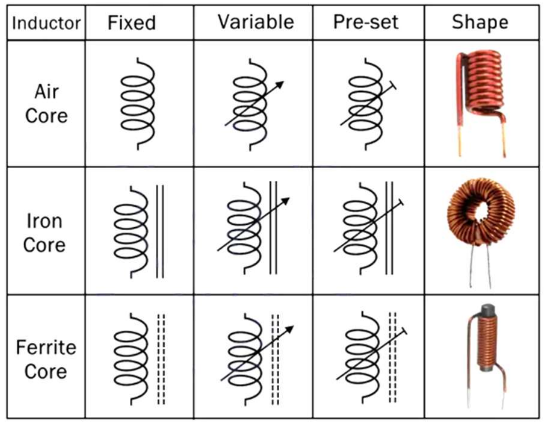
The **SI unit of inductance is Henry** named after American scientist Joseph Henry.

It is denoted by H.

The inductance of an inductor depends on many factors like number of turns, core material etc.

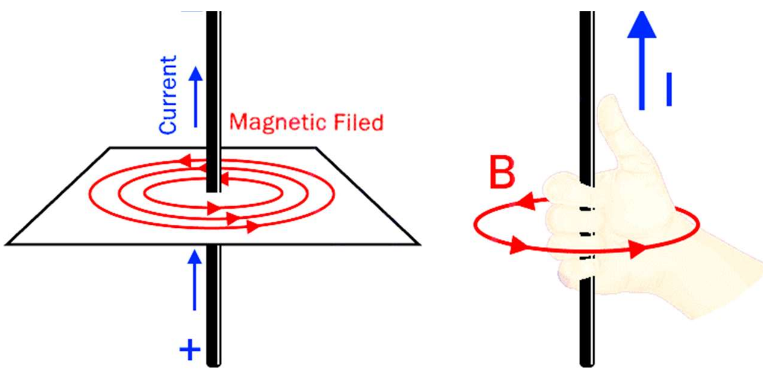
Inductors have inductance typically ranging from 1μH up to 20H.

Symbol of Inductor



Working of Inductor:

According to the electromagnetism rule, **Oersted's law**, when a steady current is passing through a straight conductor, it produces a magnetic field around it. The strength of the magnetic field depends on the supply current. If the current through the conductor is changed, the resulting magnetic field will also change. This magnetic field produced is perpendicular to the conductor.



FLEMING'S RIGHT HAND RULE:

The direction of the magnetic field produced can be found using the Fleming's right hand rule or the right-hand grip rule. Curl your finger as if you are holding the conductor & point your thumb in the direction of the current. The thumb shows the direction of the current whereas the curly fingers show the direction of the magnetic field around the conductor.

As we know that an inductor is a conductor wrapped in the form of a coil. A varying magnetic field is produced by varying the current passing through it. The changing magnetic field causes the magnetic lines to cut across some of the conductor, which induces an EMF in the wires. This phenomenon is known as Self-Induction.

LEN’S LAW:

According to Lenz’s law, this EMF induced in the coil is opposite in direction to the supply current & opposes any change in the supply current. The higher the rate of change of supply current, higher the rate of change of magnetic field & stronger the opposing induced current.
In simple words, the reactance (resistance) of the inductor increases with an increase in the supply frequency. It increases to the point where it completely blocks the input current. So, an inductor blocks AC current while it behaves as a shorts circuit for DC current.

Applications of Inductor

- Frequency Selective Circuits (Filters)

Inductor together with resistor & capacitor can be used in different frequency filter such as high pass, low pass, band pass & band reject filter.
They frequency filters are used in separating unnecessary frequency component from the signal.

- Tuning Circuit:

Inductor combined with the capacitor is used in the tuning circuit in radio & television etc. for selecting the desired frequency.

- Sensor:

An inductor is used in sensors for detecting an object in proximity without any physical contact. The inductor as we know creates a magnetic field around it when current flow through it or any change in the magnetic field causes an induced current in the inductor.

- Transformers

A transformer is essentially two separate inductors in close proximity with a common core that uses the magnetic flux created by one coil and induces EMF in the other coil through mutual induction. Transformers are used for stepping up or stepping down of voltage in power transmission.

- Electromagnetic Relay:

An electromagnetic relay is an electronic switch that has an inductive coil that creates a magnetic field when the coil is energized. This magnetic field pulls the terminal’s contact together allowing the current to flow.

- Induction Motors

In the induction motor, the rotor rotates due to the rotating magnetic field produced by the winding across the stator. Its rotor speed depends on rotating magnetic field which depends on the supply frequency. So, the only way to vary the speed is through the use of inductor.

Active component

The electronic component, which consumes energy in the form of voltage or current and produces or supplies energy in the form of electric current or voltage is called active component.

1. An active component not only controls the flow of electrons or electric current, but also amplifies or increases the power of electronic signal.
2. Active components depend on the external source of energy or voltage to perform a specific operation.
3. When the active components consume enough voltage, they start operating.

Different types of active components
The different types of active components include diodes, transistors, and integrated circuits (IC).

2 JUNCTION DIODE CHARACTERISTICS AND SPECIAL SEMICONDUCTOR DEVICES

2.1 INTRODUCTION

The *PN* junction diode is a semiconductor device with two semiconductor materials in physical contact, one with excess of holes (*P*-type) and other with excess of electrons (*N*-type). A *PN* junction diode may be formed from a single-crystal intrinsic semiconductor by doping part of it with acceptor impurities and the remaining with donors. Such junctions can form the basis of very efficient rectifiers. The most important characteristic of a *PN* junction is its ability to allow the flow of current in only one direction. In the opposite direction, it offers very high resistance. The high vacuum diode has largely been replaced by silicon and selenium rectifiers. Semiconductor diodes find wide applications in all phases of electronics, viz. radio and TV, optoelectronics, power supplies, industrial electronics, instrumentation, computers, etc. The chapter deals with the working of a *PN* junction diode and its characteristics.

In addition to the *PN* junction diode, other types of diodes like zener diode, varactor diode and tunnel diode are also discussed in this chapter and they are manufactured for specific applications. These special diodes are two-terminal devices with their doping levels carefully selected to give the desired characteristics.

Thyristor, in general, is a semiconductor device having three or more junctions. Such a device acts as a switch without any bias and can be fabricated to have voltage ratings of several hundred volts and current ratings from a few amperes to almost thousand amperes. The family of thyristors consists of *PNPN* diode (Shockley diode), SCR, TRIAC, DIAC, etc. which are discussed here. This chapter also discusses the operation and characteristics of special semiconductor devices like LED, LCD, photodiode and UJT.

2.2 THEORY OF *PN* JUNCTION DIODE

2.2.1 *PN* Junction Diode in Equilibrium with no Applied Voltage

In a piece of semiconductor material, if one half is doped by *P*-type impurity and the other half is doped by *N*-type impurity, a *PN* junction is formed. The plane dividing the two halves or zones is called *PN* junction. As shown in Fig. 2.1, the *N*-type material has high concentration of free electrons, while *P*-type material has high concentration of holes. Therefore, at the junction there is a tendency for the free electrons to diffuse over to the *P*-side and holes to the *N*-side. This process is called *diffusion.* As the free electrons move across the junction from *N*-type to *P*-type, the donor ions become positively charged. Hence a positive charge is built on the *N*-side of the junction. The free electrons that cross the junction uncover the negative acceptor ions by filling in the holes. Therefore, a net negative charge is established on the *P*-side of the junction. This net negative charge on the *P*-side prevents further diffusion of electrons into the *P*-side. Similarly, the net positive charge on the *N*-side repels the hole crossing from *P*-side to *N*-side. Thus a barrier is set-up near the junction which prevents further movement of charge carriers. i.e. electrons and holes. As a consequence of the induced electric field across the depletion layer, an electrostatic potential difference is established between *P*-and *N*-regions, which is called the potential barrier, junction barrier, diffusion potential, or contact potential, V_o. The magnitude of the contact potential V_o varies with doping levels and temperature. V_o is 0.3 V for germanium and 0.72 V for silicon.

The electrostatic field across the junction caused by the positively charged *N*-type region tends to drive the holes away from the junction and negatively charged *P*-type region tends to drive the electrons away from the junction. The majority holes diffusing out of the *P*-region leave behind negatively charged acceptor atoms bound to the lattice, thus exposing negative space charge in a previously neutral region. Similarly, electrons diffusing from the *N*-region expose positively ionised donor atoms, and a double space charge layer builds up at the junction as shown in Figs. 2.1(a) and (c).

It is noticed that the space-charge layers are of opposite sign to the majority carriers diffusing into them, which tends to reduce the diffusion rate. Thus, the double space of the layer causes an electric field to be set up across the junction directed from *N*- to *P*-regions, which is in such a direction to inhibit diffusion of majority electrons and holes, as illustrated in Figs. 2.1(a) and (d). The shape of the charge density, ρ, depends upon how the diode is doped, Thus, the junction region is depleted of mobile charge carriers. Hence, it is called the depletion region (layer), the space charge region, or the transition region. The depletion region is of order 0.5 μm thick. There are no mobile carriers in this very narrow depletion layer. Hence no current flows across the junction and the system is in equilibrium. To the left of this depletion layer, the carrier concentration is $p \approx N_A$, and to its right it is $n \approx N_D$.

Calculation of depletion width Let us now consider the width of the depletion region in the junction of Fig. 2.1. The region contains space charge due to the fact that, donors on the *N*-side and acceptors on the P-side have lost their accompanying electrons and holes. Hence, an electric field is established which, in turn, causes a difference in potential energy, qV_o, between the two parts of the specimen. Thus, a potential is built up across the junction and Fig. 2.1(e) represents the

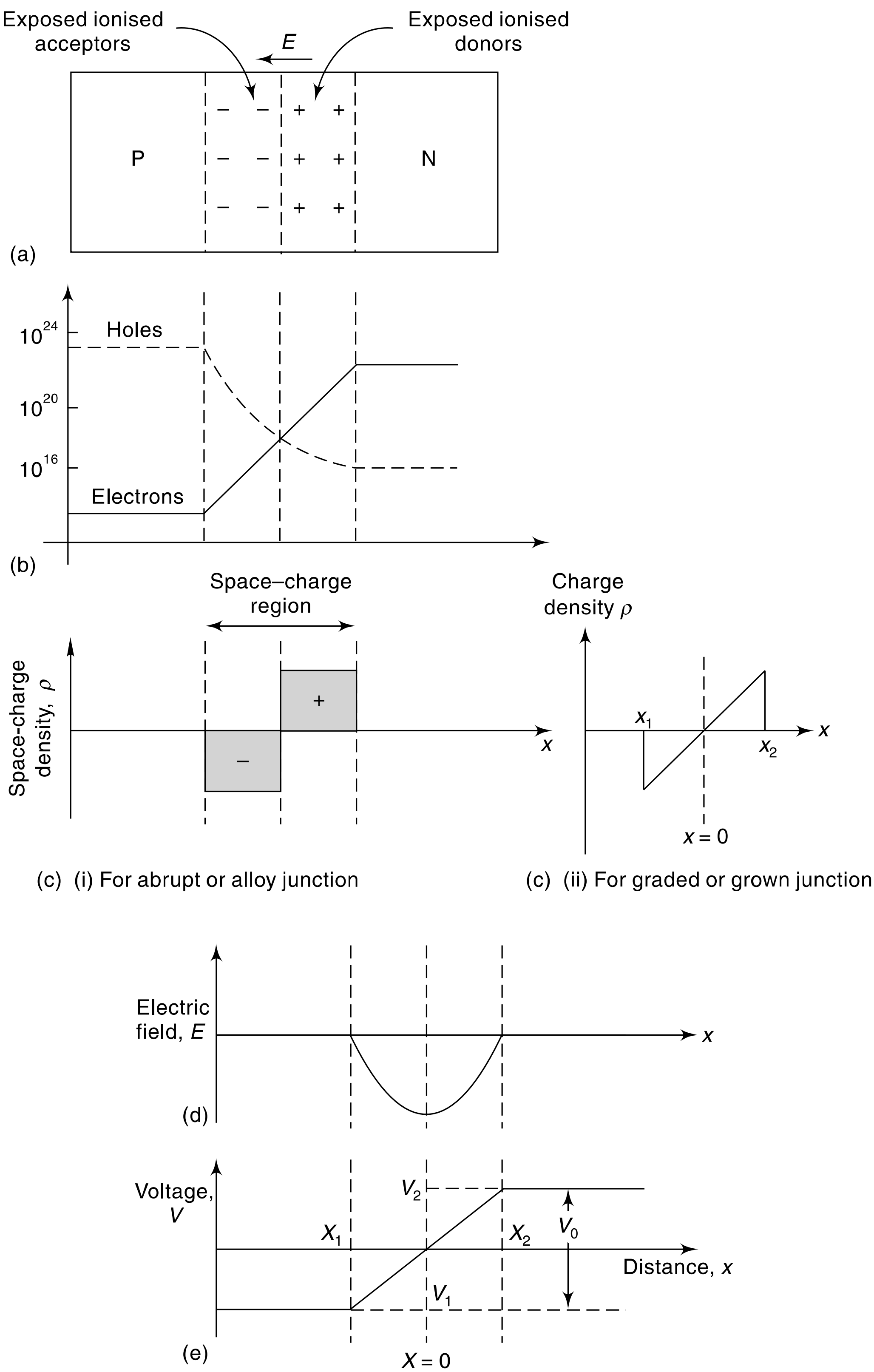


Fig. 2.1 *Formation of PN junction*

Dividing Eq. (2) by Eq. (1), we get

$$\frac{20 \times 10^{-3}}{0.6 \times 10^{-3}} = \frac{I_o \cdot e^{\frac{20}{\eta}}}{I_o \cdot e^{\frac{16}{\eta}}}$$

Therefore, $$\frac{100}{3} = e^{\frac{4}{\eta}}$$

Taking natural logarithms on both sides, we get

$$\log_e \frac{100}{3} = \frac{4}{\eta}$$

$$3.507 = \frac{4}{\eta}$$

Therefore, $$\eta = \frac{4}{3.507} = 1.14$$

EXAMPLE 2.4

Find the voltage at which the reverse current in a germanium *PN* junction diode attains a value of 90% of its saturation value at room temperature.

Solution We know that the current of a *PN* junction diode is

$$I = I_o \left(e^{\frac{V}{V_T}} - 1\right)$$

Therefore, $$-0.90\, I_o = I_o \left(e^{\frac{V}{V_T}} - 1\right)$$

where $$V_T = \frac{T}{11,600} = 26 \text{ mV}$$

$$-0.9 = \left(e^{\frac{V}{0.026}} - 1\right)$$

$$0.1 = e^{\frac{V}{0.026}}$$

Therefore, $$V = -0.06 \text{ V}$$

2.5 V–I CHARACTERISTICS

2.5.1 Under Forward Bias Condition

When positive terminal of the battery is connected to the *P*-type and negative terminal to the *N*-type of the *PN* junction diode, the bias applied is known as forward bias.

Operation As shown in Fig. 2.2, the applied potential with external battery acts in opposition to the internal potential barrier and disturbs the equilibrium. As soon as equilibrium is disturbed by the application of an external voltage, the Fermi level is no longer continuous across the junction. Under the forward bias condition, the applied positive potential repels the holes in *P*-type region so that the holes move towards the

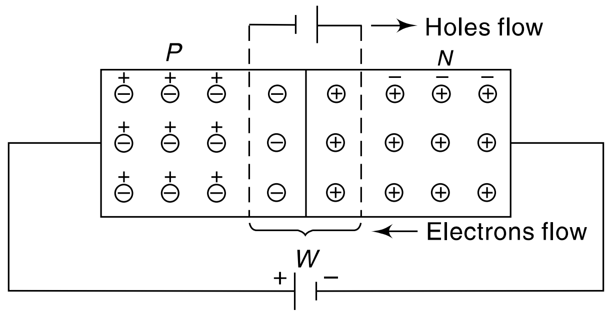


Fig. 2.2 *PN junction under forward bias*

junction and the applied negative potential repels the electrons in the *N*-type region and the electrons move towards the junction. Eventually, when the applied potential is more than the internal barrier potential, the depletion region and internal potential barrier disappear.

V–I Characteristics of a diode under forward bias Under forward bias condition, the *V–I* characteristics of a *PN* unction diode are shown in Fig. 2.3. As the forward voltage (V_F) is increased, for $V_F < V_O$, the forward current I_F is almost zero (region *OA*) because the potential barrier prevents the holes from *P*-region and electrons from N-region to flow across the depletion region in the opposite direction.

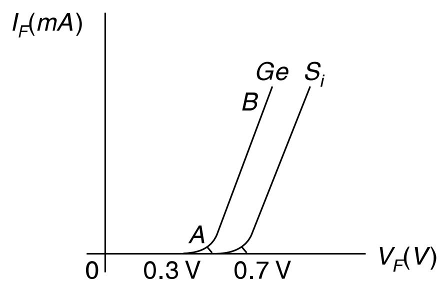


Fig. 2.3 *V–I characteristics of a diode under forward bias condition*

For $V_F > V_O$, the potential barrier at the junction completely disappears and hence, the holes cross the junction from *P*-type to *N*-type and the electrons cross the junction in the opposite direction, resulting in relatively large current flow in the external circuit.

A feature worth to be noted in the forward characteristics shown in Fig. 2.3 is the cut in or threshold voltage (V_r) below which the current is very small. It is 0.3 V and 0.7 V for germanium and silicon, respectively. At the cut in voltage, the potential barrier is overcome and the current through the junction starts to increase rapidly.

2.5.2 Under Reverse Bias Condition

When the negative terminal of the battery is connected to the *P*-type and positive terminal of the battery is connected to the *N*-type of the *PN* junction, the bias applied is known as reverse bias.

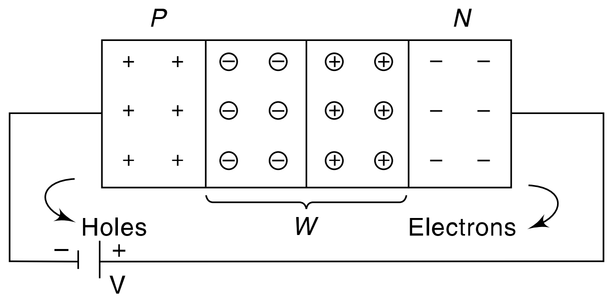


Fig. 2.4 *PN junction under reverse bias*

Operation Under applied reverse bias as shown in Fig. 2.4, holes which form the majority carriers of the *P*-side move towards the negative terminal of the battery and electrons which form the majority carrier of the *N*-side are attracted towards the positive terminal of the battery. Hence, the width of the depletion region which is depleted of mobile charge carriers increases. Thus, the electric field produced by applied reverse bias, is in the same direction as the electric field of the potential barrier. Hence, the resultant potential barrier is increased which prevents the flow of majority carriers in both directions; the depletion width, W, is proportional to $\sqrt{V_o}$ under reverse bias. Therefore, theoretically no current should flow in the external circuit. But in practice, a very small current of the order of a few microamperes flows under reverse bias as shown in Fig. 2.5. Electrons forming covalent bonds of the semiconductor atoms in the *P*- and *N*-type regions may absorb sufficient energy from heat and light to cause breaking of some covalent bonds. Hence electron–hole pairs are continually produced in both the regions. Under the reverse bias condition, the thermally generated holes in the *P*-region are attracted towards the negative terminal of the battery and the electrons in the *N*-region are attracted towards the positive terminal of the battery. Consequently, the minority carriers, electrons in the *P*-region and holes in the *N*-region, wander over to the junction and flow towards their majority carrier side giving rise to a small reverse current. This current is known as *reverse saturation current, I_o*. The magnitude of

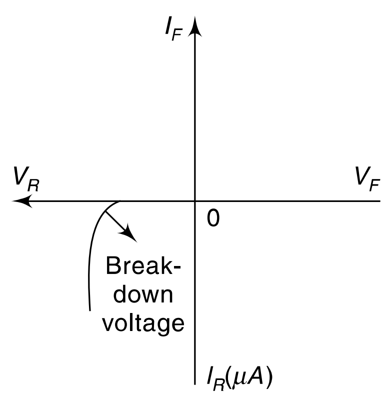


Fig. 2.5 *V-I characteristics under reverse bias*

reverse saturation current mainly depends upon junction temperature because the major source of minority carriers is thermally broken covalent bonds.

For large applied reverse bias, the free electrons from the *N*-type moving towards the positive terminal of the battery acquire sufficient energy to move with high velocity to dislodge valence electrons from semiconductor atoms in the crystal. These newly liberated electrons, in turn, acquire sufficient energy to dislodge other parent electrons. Thus, a large number of free electrons are formed which is commonly called as an avalanche of free electrons. This leads to the breakdown of the junction leading to very large reverse current. The reverse voltage at which the junction breakdown occurs is known as *Breakdown Voltage*, V_{BD}.

2.5.3 *PN* Junction as a Diode

Figure 2.6 shows the current-voltage characteristics of *PN* junction. The characteristics of the *PN* junction vary enormously depending upon the polarity of the applied voltage. For a forward-bias voltage, the current increases exponentially with the increase of voltage. A small change in the forward-bias voltage increases the corresponding forward-bias current by orders of magnitude and hence the forward-bias *PN* junction will have a very small resistance. The level of current flowing across a forward-biased *PN* junction largely depends upon the junction area. In the reverse-bias direction, the current remains small, i.e., almost zero, irrespective of the magnitude of the applied voltage and hence the reverse-bias *PN* junction will have a high resitance. The reverse bias current depends on the area, temperature and type of semiconductor material.

The semiconductor device that displays these *I-V* characteristics is called a *PN* junction diode. Figure 2.7 shows the *PN* junction diode with forward-bias and reverse-bias and their circuit symbols. The metal contacts are indicated with which the homogeneous *P*-type and *N*-type materials are provided. Thus two metal-semiconductor junctions, one at each end of the diode, are introduced. The contact potential across these junctions is approximately independent of the direction and magnitude of the current. A contact of this type is called an *ohmic contact*, which has low resistance. In the forward-bias, a relatively large current

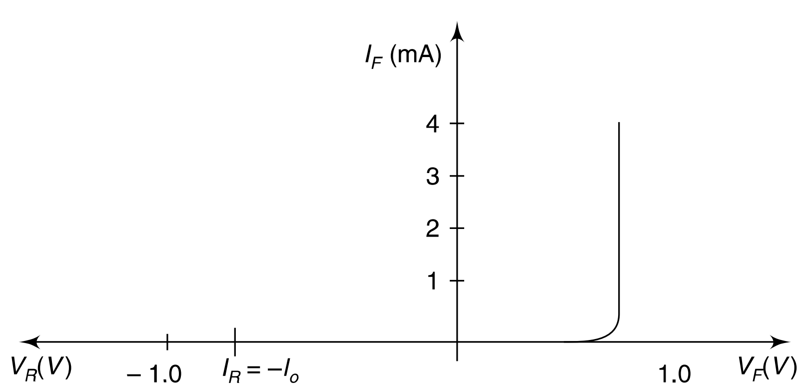


Fig. 2.6 *Ideal I-V characteristics of a PN junction diode*

is produced by a fairly small applied voltage. In the reverse-bias, only a very small current, ranging from nanoamps to microamps is produced. The diode can be used as a voltage controlled switch, i.e., OFF for a reverse-bias voltage and ON for a forward-bias voltage.

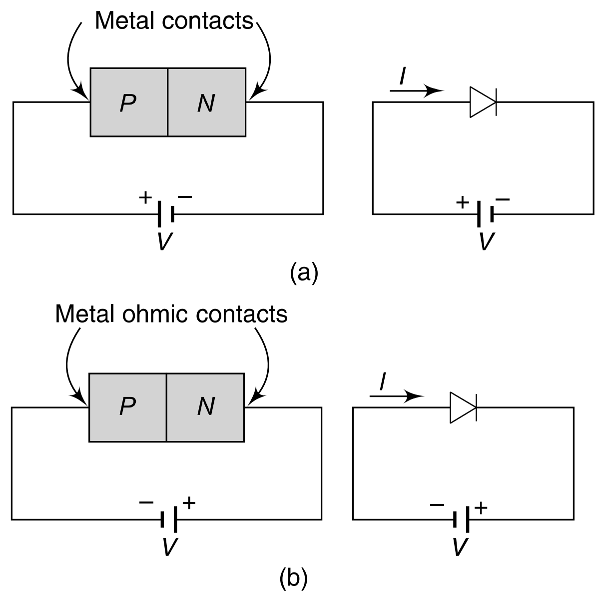


Fig. 2.7 *(a) Forward-biased PN junction diode and its circuit symbol (b) Reverse-biased PN junction diode and its circuit symbol*

When a diode is reverse-biased by atleast 0.1V, the diode current is $I_R = -I_o$. As the current is in the reverse direction and is a constant, it is called the diode *reverse saturation current.* Real diodes exhibit reverse-bias current that are considerably larger than I_o. This additional current is called a *generation current* which is due to electrons and holes being generated within the space-charge region. A typical value of I_0 may be 10^{-14} A and a typical value of reverse-bias current may be 10^{-9} A.

2.6 TEMPERATURE DEPENDENCE OF *V-I* CHARACTERISTICS OF DIODES

The reverse saturation current I_o is temperature dependent while voltage equivalent of temperature V_T is also temperature dependent. Hence, the diode current involving I_o and V_T is temperature dependent. The overall diode characteristics depends on the temperature.

The dependence of I_o on temperature T is given by

$$I_o = KT^m e^{-V_{Go}/\eta V_T} \tag{2.7}$$

where K = constant independent of temperature (not the Boltzmann's constant) causes transfer of electrons and energy until the Fermi levels on the two sides get equalised. However, such a shift does not disturb the relative position of the conduction band, valence band and Fermi level in any region. Equalisation of Fermi levels in the *P* and *N* materials of a *PN* junction is similar to equalisation of levels of water in two containers on being joined together.

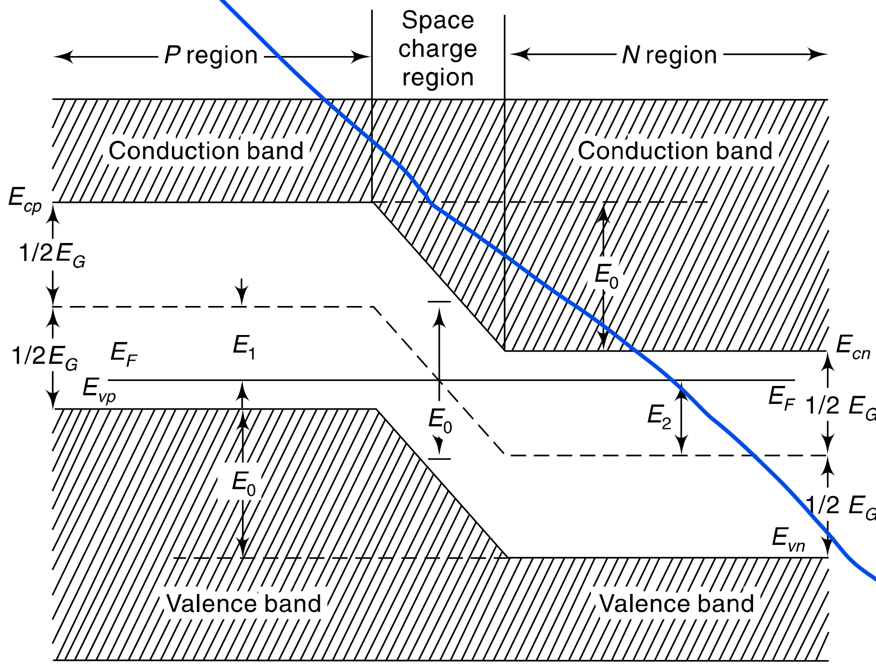


Fig. 2.14 *Energy-band structure*

2.10 ZENER DIODE

When the reverse voltage reaches breakdown voltage in normal *PN* junction diode, the current through the junction and the power dissipated at the junction will be high. Such an operation is destructive and the diode gets damaged. Whereas diodes can be designed with adequate power dissipation capabilities to operate in the breakdown region. One such diode is known as Zener diode. Zener diode is heavily doped than the ordinary diode.

From the *V–I* characteristics of the Zener diode, shown in Fig. 2.15, it is found that the operation of Zener diode is same as that of ordinary *PN* diode under forward-biased condition. Whereas under reverse-baised condition, breakdown of the junction occurs. The breakdown voltage depends upon the amount of doping. If the diode is heavily doped, depletion layer will be thin and, consequently, breakdown occurs at

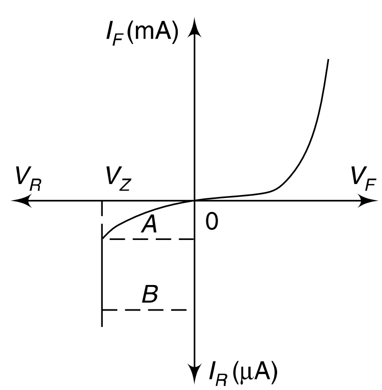


Fig. 2.15 *V–I characteristics of a Zener diode*

lower reverse voltage and further, the breakdown voltage is sharp. Whereas a lightly doped diode has a higher breakdown voltage. Thus, breakdown voltage can be selected with the amount of doping.

The sharp increasing current under breakdown conditions are due to the following two mechanisms.

(1) Avalanche breakdown
(2) Zener breakdown.

2.11 BREAKDOWN MECHANISMS

2.11.1 Avalanche Breakdown

As the applied reverse bias increases, the field across the junction increases correspondingly. Thermally generated carriers while traversing the junction acquire a large amount of kinetic energy from this field. As a result the velocity of these carriers increases. These electrons disrupt covalent bond by colliding with immobile ions and create new electron-hole pairs. These new carriers again acquire sufficient energy from the field and collide with other immobile ions thereby generating further electron–hole pairs. This process is cumulative in nature and results in generation of avalanche of charge carriers within a short time. This mechanism of carrier generation is known as Avalanche multiplication. This process results in flow of large amount of current at the same value of reverse bias.

2.11.2 Zener Breakdown

When the P and N regions are heavily doped, direct rupture of covalent bonds takes place because of the strong electric fields, at the junction of *PN* diode. The new electron–hole pairs so created increase the reverse current in a reverse biased *PN* diode. The increase in current takes place at a constant value of reverse bias typically below 6 V for heavily doped diodes. As a result of heavy doping of *P* and *N* regions, the depletion region width becomes very small and for an applied voltage of 6 V or less, the field across the depletion region becomes very high, of the order of 10^7 V/m, making conditions suitable for Zener breakdown. For lightly doped diodes, Zener breakdown voltage becomes high and breakdown is then predominantly by Avalanche multiplication. Though Zener breakdown occurs for lower breakdown voltage and Avalanche breakdown occurs for higher breakdown voltage, such diodes are normally called Zener diodes.

2.11.3 Zener Resistances and Zener Diode Ratings

Zener resistances Let us consider two resistances of the Zener diode (i) d.c. or static resistance, and (ii) a.c. or dynamic resistance.

(a) Zener Static or d.c. Resistance R_Z It is the ratio of total Zener diode voltage to total diode current measured at the given operating point, i.e.

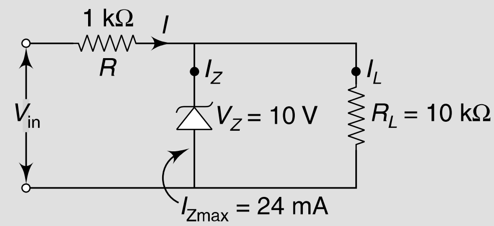


Fig. 2.23

Solution As $V_o = 10$ V constant and $R_L = 10$ kΩ constant, we have

$$I_L = \frac{V_o}{R_L} = \frac{10}{10 \times 10^3} = 1 \text{ mA}$$

When $V_{\text{in}} = V_{\text{in (max)}}$, $I_Z = I_{Z\text{(max)}}$

Now $I = I_Z + I_L$

Therefore, $I_{\text{max}} = I_{Z\text{(max)}} + I_L = 24 \text{ mA} + 1 \text{ mA} = 2 \text{ mA}.$

$$\frac{V_{\text{in(max)}} - V_Z}{R} = 25 \text{ mA}$$

Therefore, $V_{\text{in(max)}} - 10 = 1 \times 10^3 (25 \times 10^{-3})$

$$V_{\text{in(max)}} = 35 \text{ V}.$$

When $V_{\text{in}} = V_{\text{in(min)}}$, $I_Z = I_{Z\text{(min)}} = 5$ mA

Therefore, $I_{\text{min}} = I_{Z\text{(min)}} + I_L = 5 \text{ mA} + 1 \text{ mA} = 6 \text{ mA}$

$$\frac{V_{\text{in (min)}} - V_z}{R} = 6 \times 10^{-3}$$

$$V_{\text{in(min)}} - 10 = 1 \times 10^3 (6 \times 10^{-3})$$

$$V_{\text{in(min)}} = 16 \text{ V}$$

2.13 LIGHT EMITTING DIODE (LED)

The Light Emitting Diode (LED) is a *PN* junction device which emits light when forward biased, by a phenomenon called electroluminescence. In all semiconductor *PN* junctions, some of the energy will be radiated as heat and some in the form of photons. In silicon and germanium, greater percentage of energy is given out in the form of heat and the emitted light is insignificant. In other materials such as gallium phosphide (GaP) or gallium arsenide phosphide (GaAsP), the number of photons of light energy emitted is sufficient to create a visible light source. Here, the charge carrier recombination takes place when electrons from the N-side cross the junction and recombine with the holes on the P-side.

LED under forward bias and its symbol are shown in Figs. 2.24(a) and (b), respectively. When an LED is forward biased, the electrons and holes move towards the junction and recombination takes place. As a result of recombination, the electrons lying in the conduction bands of *N*-region fall into the holes lying in the valence band of a *P*-region. The difference of energy between the conduction band and the valence band is radiated in the form of light energy. Each recombination causes radiation of light energy. Light is generated by recombination of electrons and holes whereby their excess energy is transferred to an emitted photon. The brightness of the emitted light is directly proportional to the forward bias current.

Figure 2.24(c) shows the basic structure of an LED showing recombination of carriers and emission of light. Here, an N-type layer is grown on a substrate and a *P*-type is deposited on it by diffusion. Since carrier recombination takes place in the *P*-layer, it is kept uppermost. The metal anode connections are made at the outer edges of the *P*-layer so as to allow more central surface area for the light to escape. LEDs are manufactured with domed lenses in order to reduce the reabsorption problem. A metal (gold) film is applied to the bottom of the substrate for reflecting as much light as possible to the surface of the device and also to provide cathode connection. LEDs are always encased to protect their delicate wires.

The efficiency of generation of light increases with the increases in injected current and with a decrease in temperature. The light is concentrated near the junction as the carriers are available within a diffusion length of the junction.

LEDs radiate different colours such as red, green, yellow, orange, blue and white. Some of the LEDs emit infrared (invisible) light also. The wavelength of emitted light depends on the energy gap of the material. Hence, the colour of the emitted light depends on the type of material used is given as follows.

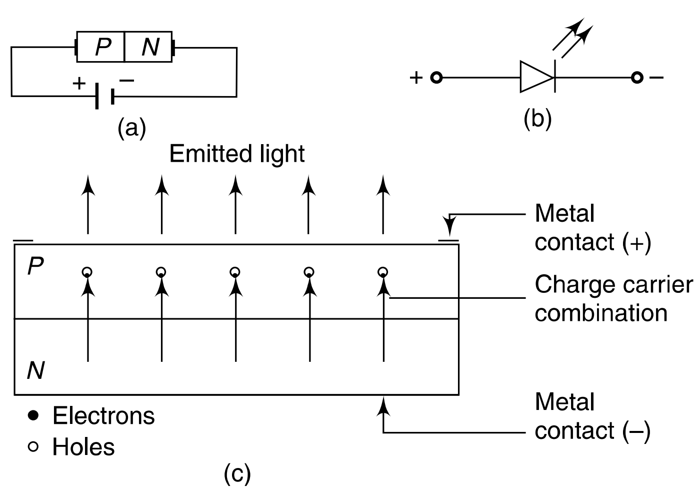


Fig. 2.24 *(a) LED under forward bias (b) Symbol (c) Recombinations and emission of light*

Gallium arsenide (GaAs) – infrared radiation (invisible)

Gallium phosphide (GaP) – red or green

Gallium arsenide phosphide (GaAsP) – red or yellow

In order to protect LEDs, resistance of 1 kΩ or 1.5 kΩ must be connected in series with the LED. LEDs emit no light when reverse biased. LEDs operate at voltage levels from 1.5 to 3.3 V, with the current of some tens of milliamperes. The power requirement is typically from 10 to 150 mW with a life time of 1,00,000 + hours. LEDs can be switched ON and OFF at a very fast speed of 1 ns.

They are used in burglar alarm systems, picture phones, multimeters, calculators, digital meters, microprocessors, digital computers, electronic telephone exchange, intercoms, electronic panels, digital watches, solid state video displays and optical communication systems. Also, there are two-lead LED lamps which contain two LEDs, so that a reversal in biasing will change the colour from green to red, or vice-versa.

When the emitted light is coherent, i.e. essentially monocromatic, then such a diode is referred to as an Injection Laser Diode (ILD). The LED and ILD are the two main types used as optical sources. ILD has a shorter rise time than LED, which makes the ILD more suitable for wide-bandwidth and high-data-rate applications. In addition, more optical power can be coupled into a fiber with an ILD, which is important for long distance transmission. A disadvantage of the ILD is the strong temperature dependence of the output characteristic curve.

2.14 LIQUID CRYSTAL DISPLAY (LCD)

Liquid Crystal Displays (LCDs) are used for display of numeric and alphanumeric character in dot matrix and segmental displays. The two liquid crystal materials which are commonly used in display technology are nematic and cholesteric whose schematic arrangement of molecules is shown in Fig. 2.25(a). The most popular liquid crystal structure is the Nematic Liquid Crystal (NLC). In this type, all the molecules align themselves approximately parallel to a unique axis (director), while retaining the complete translational freedom. The liquid is normally transparent, but if subjected to a strong electric field, disruption of the well ordered crystal structure takes place causing the liquid to polarise and turn opaque. The removal of the applied electric field allows the crystal structure to regain its original form and the material becomes transparent.

Based on the construction, LCDs are classified into two types. They are (i) Dynamic scattering type, and (ii) Field effect type.

Dynamic scattering type The construction of a dynamic scattering liquid crystal cell is shown in Fig. 2.25(b). The display consists of two glass plates, each coated with tin oxide (SnO_2) on the inside with transparent electrodes separated by a liquid crystal layer, 5 to 50 μm thick. The oxide coating on the front sheet

2.18 PNPN DIODE (SHOCKLEY DIODE)

As shown in Fig. 2.36, it is a four layer *PNPN* silicon device with two terminals. When an external voltage is applied to the device in such a way that anode is positive with respect to cathode, junctions J_1 and J_3 are forward biased and J_2 is reverse biased. Then the applied voltage appears across the reverse biased junction J_2. Now the current flowing through the device is only reverse saturation current.

However, as this applied voltage is increased, the current increases slowly until the so called firing or breakover voltage (V_{BO}) is reached. Once firing takes place, the current increases abruptly and the voltage drop across the device decreases sharply. At this point, the diode switches over from 'OFF' to 'ON'state. Once the device is fired into conduction, a minimum amount of current known a *holding current*, I_H, is required to flow to keep the device in ON state. To turn the device OFF from ON state, the current has to be reduced below I_H by reducing the applied voltage close to zero, i.e. below *holding voltage*, V_H. Thus the diode acts as a switch during forward bias condition. The characteristic curve of a *PNPN* diode is shown in Fig. 2.37.

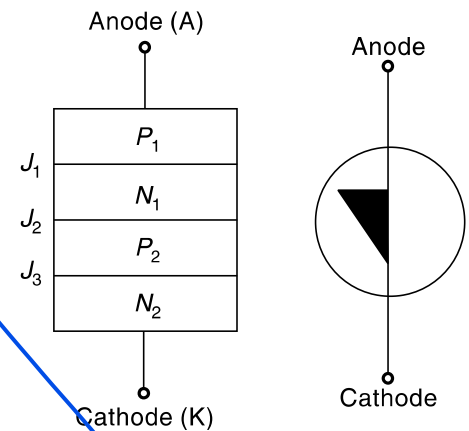


Fig. 2.36 *PNPN diode: (a) Basic structure and (b) Circuit symbol*

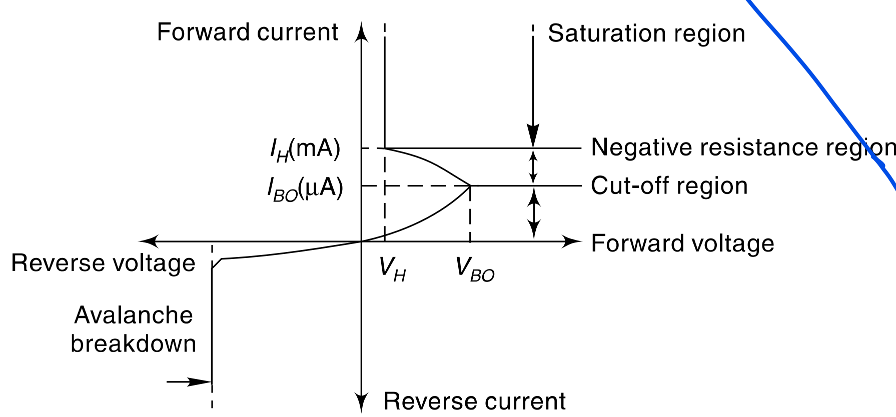


Fig. 2.37 *Characteristic curve of PNPN diode*

2.19 SCR (SILICON CONTROLLED RECTIFIER)

The basic structure and circuit symbol of SCR is shown in Fig. 2.38. It is a four layer three terminal device in which the end *P*-layer acts as anode, the end N-layer acts as cathode and P-layer nearer to cathode acts as gate. As leak-

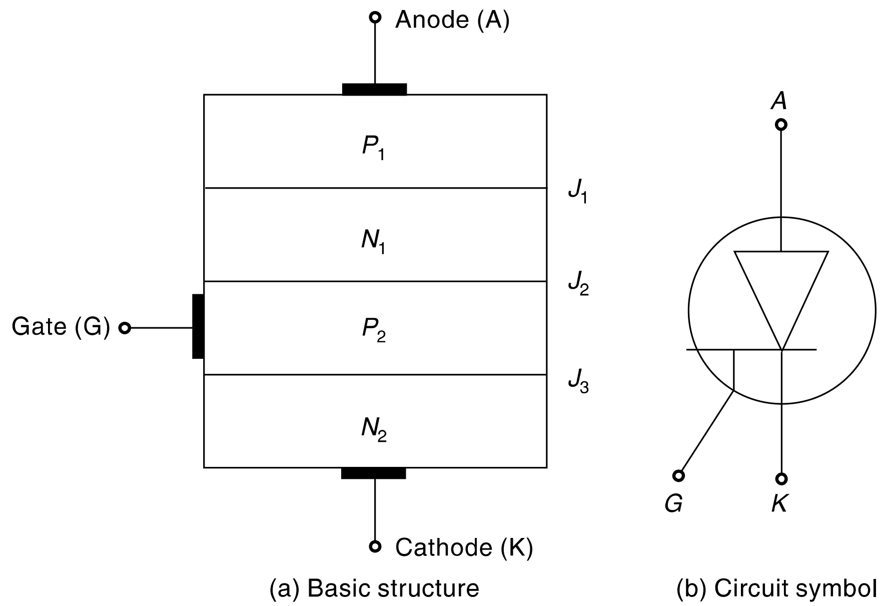


Fig. 2.38 *Basic structure and circuit symbol of SCR*

age current in silicon is very small compared to germanium, SCRs are made of silicon and not germanium.

Characteristics of SCR The characteristics of SCR are shown in Fig. 2.39. SCR acts as a switch when it is forward biased. When the gate is kept open, i.e. gate current $I_G = 0$, operation of SCR is similar to PNPN diode. When $I_G < 0$, the amount of reverse bias applied to J_2 is increased. So the breakover voltage V_{BO} is increased. When $I_G > 0$, the amount of reverse bias applied to J_2 is decreased thereby decreasing the breakover voltage. With very large positive gate current, breakover may occur at a very low voltage such that the characteristics of SCR is similar to that of ordinary PN diode. As the voltage at which SCR is switched 'ON' can be controlled by varying the gate current I_G, it is commonly called as

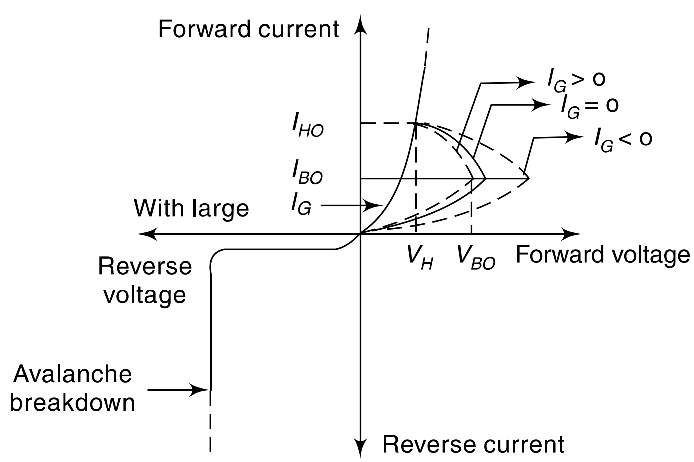


Fig. 2.39 *Characteristics of SCR*

controlled switch. Once SCR is turned ON, the gate loses control, i.e. the gate cannot be used to switch the device OFF. One way to turn the device OFF is by lowering the anode current below the holding current I_H by reducing the supply voltage below holding voltage V_H, keeping the gate open.

SCR is used in relay control, motor control, phase control, heater control, battery chargers, inverters, regulated power supplies and as static switches.

Two transistor version of SCR The operation of SCR can be explained in a very simple way by considering it in terms of two transistors, called as the two transistor version of SCR. As shown in Fig. 2.40, an SCR can be split into two parts and displaced mechanically from one another but connected electrically. Thus the device may be considered to be constituted by two transistors T_1 (PNP) and T_2 (NPN) connected back to back.

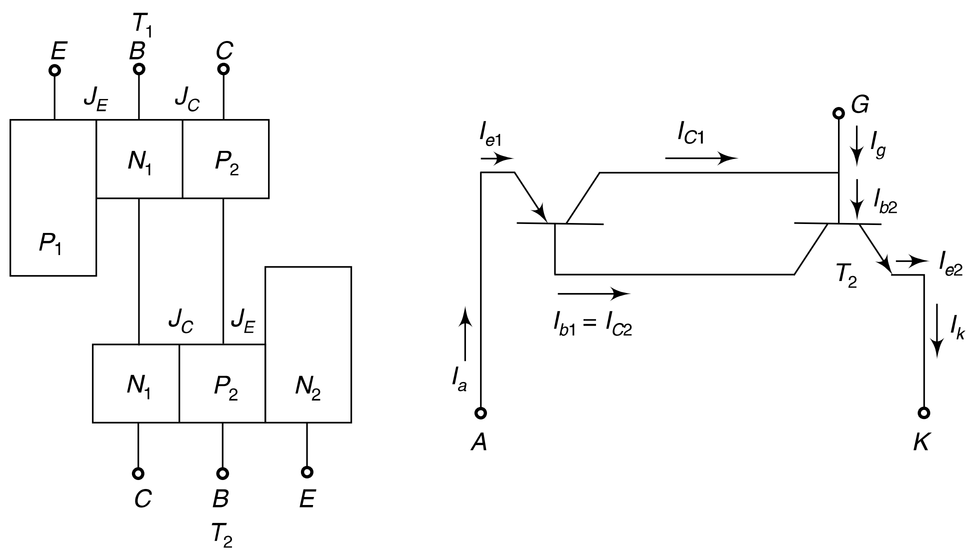


Fig. 2.40 *Two transistor version of SCR*

Assuming the leakage current of T_1 to be negligibly small, we obtain

$$I_{b1} = I_A - I_{e1} = I_A - \alpha_1 I_A = (1 - \alpha_1)\, I_A \qquad (2.23)$$

Also, from the Fig. 2.40, it is clear that

$$I_{b1} = I_{C2} \qquad (2.24)$$

and

$$I_{C2} = \alpha_2 I_K \qquad (2.25)$$

Substituting the values given in Eqs (2.24) and (2.25) in Eq. (2.23), we get

$$(1 - \alpha_1)\, I_A = \alpha_2 I_K \qquad (2.26)$$

We know that

$$I_K = I_A + I_g \qquad (2.27)$$

Substituting Eq. (2.27) in Eq. (2.26), we obtain

$$(1 - \alpha_1)\, I_A = \alpha_2 (I_A + I_g)$$

i.e.

$$(1 - \alpha_1 - \alpha_2) I_A = \alpha_2 I_g$$

4 TRANSISTOR CHARACTERISTICS (BJT AND FET)

4.1 INTRODUCTION

A Bipolar Junction Transistor (BJT) is a three-terminal semiconductor device in which the operation depends on the interaction of both majority and minority carriers and hence, the name *bipolar*. The BJT is analogous to a vacuum triode and is comparatively smaller in size. It is used in amplifier and oscillator circuits, and as a switch in digital circuits. It has wide applications in computers, satellites and other modern communication systems. The FET is a device in which the flow of current through the conducting region is controlled by an electric field. Hence, the name *Field Effect Transistor (FET)*. As current conduction is only by majority carriers, the FET is said to be a unipolar device. The construction, operation, characteristics and applications of both BJTs and FETs are discussed in this chapter.

4.2 BIPOLAR JUNCTION TRANSISTOR

The BJT consists of a silicon (or germanium) crystal in which a thin layer of *N*-type Silicon is sandwiched between two layers of *P*-type silicon. This transistor is referred to as *PNP*. Alternatively, in an *NPN* transistor, a layer of *P*-type material is sandwiched between two layers of *N*-type material. The two types of the BJT are represented in Fig. 4.1.

The symbolic representation of the two types of the BJT is shown in Fig. 4.2. The three portions of the transistor are Emitter, Base and Collector, shown as

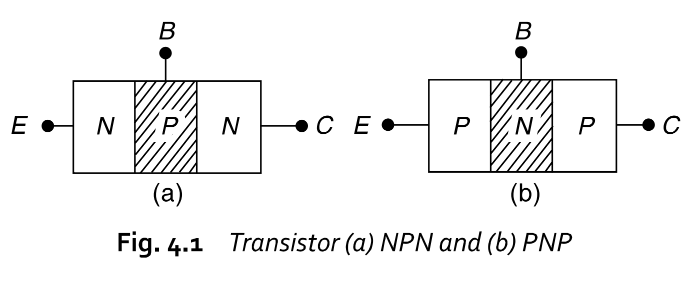


Fig. 4.1 *Transistor (a) NPN and (b) PNP*

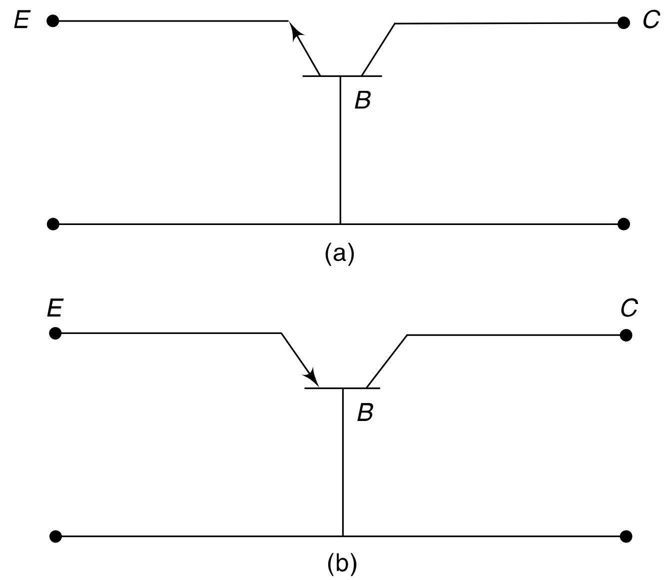


Fig. 4.2 *Circuit symbol (a) NPN transistor and (b) PNP transistor*

E, *B* and *C*, respectively. The arrow on the emitter specifies the direction of current flow when the *EB* junction is forward biased.

Emitter is heavily doped so that it can inject a large number of charge carriers into the base. Base is lightly doped and very thin. It passes most of the injected charge carriers from the emitter into the collector. Collector is moderately doped.

4.3 TRANSISTOR CURRENT COMPONENTS

As shown in Fig. 4.3, usually the emitter-base junction is forward biased and collector-base junction is reverse biased. Due to the forward bias on the emitter-base junction an emitter current flows through the base into the collector. Though the, collector-base junction is reverse biased, almost the entire emitter current flows through the collector circuit.

4.4 OPERATION OF *NPN* TRANSISTOR

As shown in Fig. 4.4, the forward bias applied to the emitter base junction of an *NPN* transistor causes a lot of electrons from the emitter region to crossover to the base region. As the base is lightly doped with *P*-type impurity, the number of holes in the base region is very small and hence the number of electrons that combine with holes in the *P*-type base region is also very small. Hence a few electrons combine with holes to constitute a base current I_B. The remaining electrons (more than 95%) crossover into the collector region to constitute a collector current I_C. Thus the base and collector current summed up gives the emitter current, i.e. $I_E = -(I_C + I_B)$.

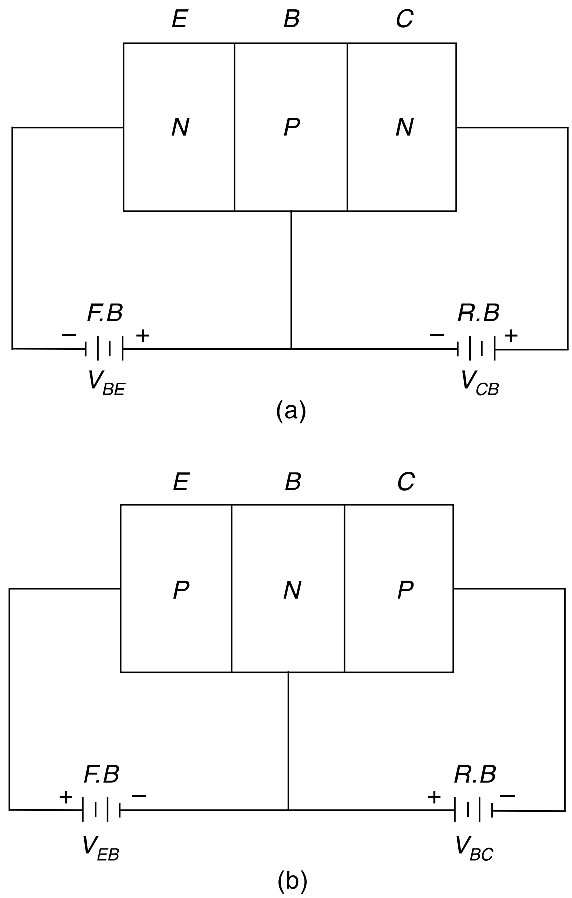


Fig. 4.3 *Transistor biasing (a) NPN transistor and (b) PNP transistor*

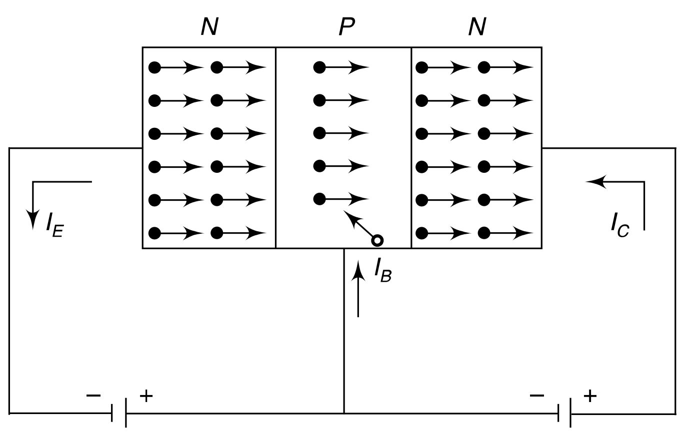


Fig. 4.4 *Current in NPN transistor*

In the external circuit of the *NPN* bipolar junction transistor, the magnitudes of the emitter current I_E, the base current I_B and the collector current I_C are related by $I_E = I_C + I_B$.

4.5 OPERATION OF A *PNP* TRANSISTOR

As shown in Fig. 4.5, the forward bias applied to the emitter-base junction of a *PNP* transistor causes a lot of holes from the emitter region to crossover to the base region as the base is lightly doped with *N*-types impurity. The number of electrons in the base region is very small and hence the number of holes combined with electrons in the *N*-type base region is also very small. Hence a few holes combined with electrons to constitute a base current I_B. The remaining holes (more than 95%) crossover into the collector region to constitute a collector current I_C. Thus the collector and base current when summed up gives the emitter current, i.e. $I_E = -(I_C + I_B)$.

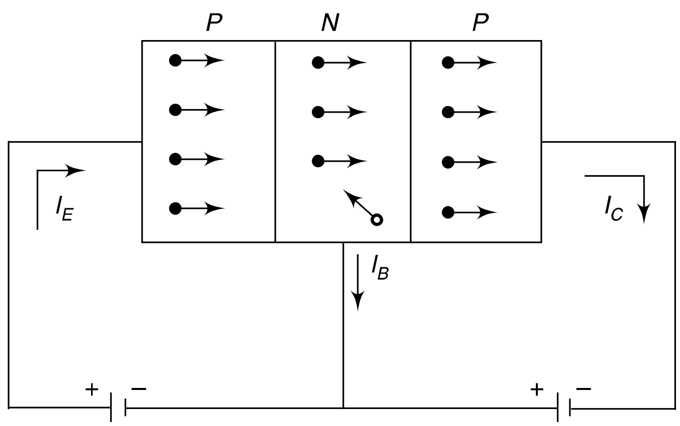


Fig. 4.5 *Current in PNP transistor*

In the external circuit of the PNP bipolar junction transistor, the magnitudes of the emitter current I_E, the base current I_B and the collector current I_C are related by

$$I_E = I_C + I_B \tag{4.1}$$

This equation gives the fundamental relationship between the currents in a bipolar transistor circuit. Also, this fundamental equation shows that there are current amplification factors α and β in common base transistor configuration and common emitter transistor configuration respectively for the static (d.c.) currents, and for small changes in the currents.

Large-signal current gain (α) The large signal current gain of a common base transistor is defined as the ratio of the negative of the collector-current increment to the emitter-current change from cut-off ($I_E = 0$) to I_E, i.e.

$$\alpha = -\frac{(I_C - I_{CBO})}{I_E - 0} \tag{4.2}$$

where I_{CBO} (or I_{CO}) is the reverse saturation current flowing through the reverse biased collector-base junction, i.e. the collector to base leakage current with emitter open. As the magnitude of I_{CBO} is negligible when compared to I_E, the above expression can be written as

$$\alpha = \frac{I_C}{I_E} \tag{4.3}$$

Since I_C and I_E are flowing in opposite directions, α is always positive. Typical value of α ranges from 0.90 to 0.995. Also, α is not a constant but varies with emitter current I_E, collector voltage V_{CB} and temperature.

General transistor equation In the active region of the transistor, the emitter is forward biased and the collector is reverse biased. The generalised expression for collector current I_C for collector junction voltage V_C and emitter current I_E is given by

$$I_C = -\alpha I_E + I_{CBO}(1 - e^{V_C/V_T}) \tag{4.4}$$

If V_C is negative and $|V_c|$ is very large compared with V_T, then the above equation reduces to

$$I_C = -\alpha I_E + I_{CBO} \tag{4.5}$$

If V_C, i.e. V_{CB}, is few volts, I_C is independent of V_C. Hence the collector current I_C is determined only by the fraction α of the current I_E flowing in the emitter.

Relation among I_C, I_B and I_{CBO} From Eqn. (4.5), We have

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

Since I_C and I_E are flowing in opposite directions,

$$I_E = -(I_C + I_B)$$

Therefore,

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

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

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

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

Since

$$\beta = \frac{\alpha}{1-\alpha}, \tag{4.6}$$

the above expression becomes

$$I_C = (1 + \beta) I_{CBO} + \beta I_B \tag{4.7}$$

Relation among I_C, I_B and I_{CEO} In the common-emitter (CE) transistor circuit, I_B is the input current and I_C is the output current. If the base circuit is open, i.e, $I_B = 0$, then a small collector current flows from the collector to emitter. This is denoted as I_{CEO}, the collector-emitter current with base open. This current I_{CEO} is also called the collector to emitter leakage current.

In this CE configuration of the transistor, the emitter-base junction is forward-biased and collector-base junction is reverse-biased and hence the collector current I_C is the sum of the part of the emitter current I_E that reaches the collector, and the collector-emitter leakage current I_{CEO}. Therefore, the part of I_E, which reaches collector is equal to $(I_C - I_{CEO})$.

Hence, the *large-signal current gain* (β) is defined as,

$$\beta = \frac{(I_C - I_{CEO})}{I_B} \tag{4.8}$$

From the equation, we have

$$I_C = \beta I_B + I_{CEO} \tag{4.9}$$

Relation between I_{CBO} and I_{CEO}

Comparing Eqs. (4.7) and (4.9), we get the relationship between the leakage currents of transistor common-base (CB) and common-emitter (CE) configurations as

$$I_{CEO} = (1 + \beta)\, I_{CBO} \tag{4.10}$$

From this equation, it is evident that the collector-emitter leakage current (I_{CEO}) in CE configuration is $(1 + \beta)$ times larger than that in CB configuration. As I_{CBO} is temperature-dependent, I_{CEO} varies by large amount when temperature of the junctions changes.

Expression for emitter current The magnitude of emitter-current is

$$I_E = I_C + I_B$$

Substituting Eqn. (4.7) in the above equation, we get

$$I_E = (1 + \beta)\, I_{CBO} + (1 + \beta)\, I_B \tag{4.11}$$

Substituting Eqn. (4.6) into Eqn. (4.11), we have

$$I_E = \frac{1}{1-\alpha} I_{CBO} + \frac{1}{1-\alpha} I_B \tag{4.12}$$

DC current gain ($\beta_{d.c.}$ or h_{FE}) The d.c. current gain is defined as the ratio of the collector current I_C to the base current I_B. That is,

$$\beta_{\text{d.c.}} = h_{FE} = \frac{I_C}{I_B} \tag{4.13}$$

As I_C is large compared with I_{CEO}, the large signal current gain (β) and the d.c. current gain (h_{FE}) are approximately equal.

4.6 TRANSISTOR CONFIGURATION

When a transistor is to be connected in a circuit, one terminal is used as an input terminal, the other terminal is used as an output terminal and the third terminal is common to the input and output. Depending upon the input, output and common terminal, a transistor can be connected in three configurations. They are: (i) Common base (CB) configuration, (ii) Common emitter (CE) configuration, and (iii) Common collector (CC) configuration.

(i) CB configuration This is also called grounded base configuration. In this configuration, emitter is the input terminal, collector is the output terminal and base is the common terminal.

(ii) CE configuration This is also called grounded emitter configuration. In this configuration, base is the input terminal, collector is the output terminal and emitter is the common terminal.

(iii) CC configuration This is also called grounded collector configuration. In this configuration, base is the input terminal, emitter is the output terminal and collector is the common terminal.

The supply voltage connections for normal operation of an *NPN* transistor in the three configurations are shown in Fig. 4.6.

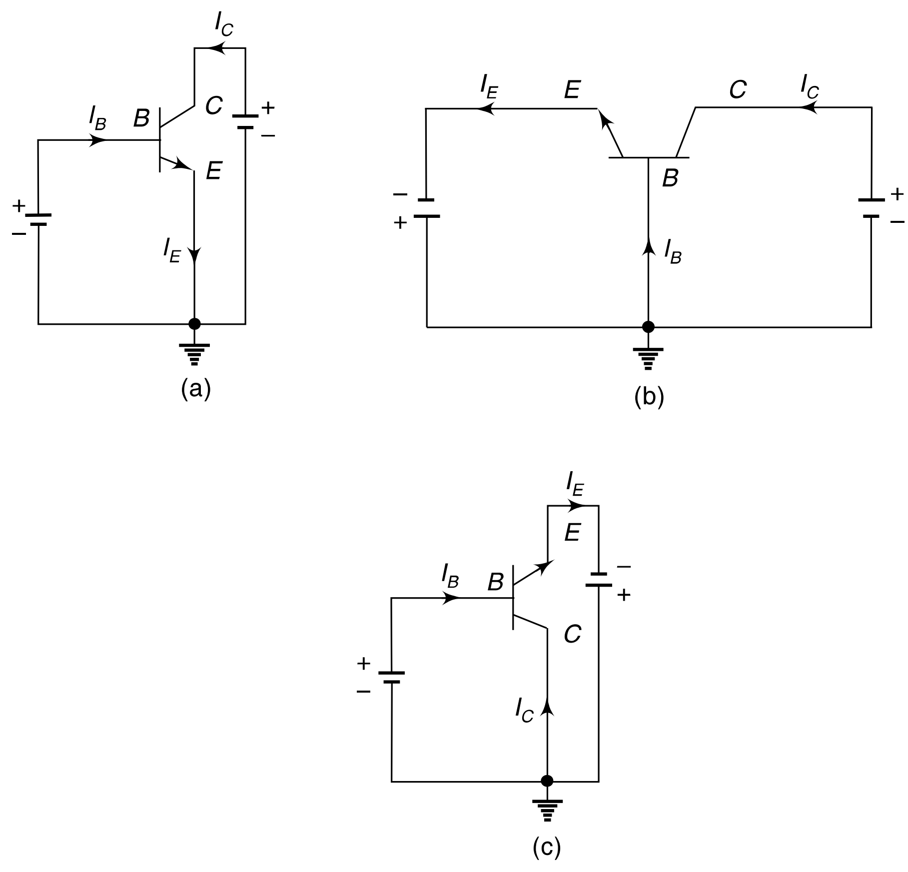


Fig. 4.6 *Transistor configuration: (a) Common base (b) Common emitter and (c) Common collector*

4.6.1 CB Configuration

The circuit diagram for determining the static characteristics curves of an *NPN* transistor in the common base configuration is shown in Fig. 4.7.

Input characteristics To determine the input characteristics, the collector-base voltage V_{CB} is kept constant at zero volt and the emitter current I_E is increased from zero in suitable equal steps by increasing V_{EB}. This is repeated

When the light is turned ON, additional minority carriers are photogenerated and the total collector current is

$$I_C = (\beta + 1)(I_{CO} + I_L)$$

where I_L is the reverse saturation current due to the light.

Current in a phototransistor is dependent mainly on the intensity of light entering the lens and is less affected by the voltage applied to the external circuit. Figure 4.25 shows a graph of collector current I_C as a function of collector-emitter voltage V_{CE} and as a function of illumination H.

The phototransistors find extensive applications in high-speed reading of computer punched cards and tapes, light detection systems, light operated switches, reading of film sound track, production line counting of objects which interrupt a light beam, etc.

4.12 TYPICAL TRANSISTOR JUNCTION VOLTAGE VALUES

The specifications of some of the commonly used BJT-*NPN* small-signal transistor and BJT-*PNP* small-signal transistor are given in Table 4.2(a) and (b) respectively.

4.13 TYPES OF FET

Based on the construction, the FET can be classified into two types as *Junction FET (JFET)* and *Metal Oxide Semiconductor FET (MOSFET)* or *Insulated Gate FET (IGFET)* or *Metal Oxide Silicon Transistor (MOST)*.

Depending upon the majority carriers, JFET has been classified into two types, namely (i) *N-channel JFET* with electrons as the majority carriers, and (iii) *P-channel JFET* with holes as the majority carriers.

4.14 CONSTRUCTION OF *N*-CHANNEL JFET

It consists of a *N*-type bar which is made of silicon. Ohmic contacts (terminals), made at the two ends of the bar, are called Source and Drain.

Source (S) This terminal is connected to the negative pole of the battery. Electrons which are the majority carriers in the *N*-type bar enter the bar through this terminal.

Drain (D) This terminal is connected to the positive pole of the battery. The majority carriers leave the bar through this terminal.

Gate (G) Heavily doped *P*-type silicon is diffused on both sides of the *N*-type silicon bar by which *PN* junctions are formed. These layers are joined together and called Gate *G*.

Table 4.2 (a) BJT-*NPN* Small-Signal Transistor

Parameter Type	I_C *(max) (mA)*	P_D *(max) (mW)*	V_{CEO} *(max) (Volts)*	V_{CBO} *(max) (Volts)*	h_{fe} *(min-max) @* I_C *(mA)*	V_{ce} *(Volts)*	f_T *@ MHz*	*Complement*	*Applications*
BC107	100	300	45	50	110-450@2	5	300	BC177	Audio driver
BC108	100	300	20	30	110-800@2	5	300	BC178	General purpose
BC109	100	300	20	30	200-800@2	5	300	BC179	Low noise audio
BC547	100	625	45	50	110-800@2	5	300	BC557	Amplifier
BC548	100	625	30	30	110-800@2	5	300	BC558	Amplifier
BC549	100	625	30	30	110-800@2	5	250	BC559	Low noise audio
2N2369A	200	360	15	40	20 (min)@100	1	500 (min)	-	High-speed switch
2N3904	200	350	40	60	100-300@10	1	300 (min)	2N3906	Low level amplifier
2N4401	600	350	40	60	100-300@150	2	250 (max)	2N4403	General purpose
2N3053	700	5.0 W	40	60	50-250@ 150	10	100	-	General purpose
2N2222A	800	500	40	75	100-300 @ 150	10	300	-	High speed switch
BFY50	1000	2800	35	80	30(min)@150	10	60 (min)	-	General purpose
BUY82	10000	30 W	60	150	40 (min) @ 1.5A	5	60	-	High power switch
2N3055	15 A	115 W	60	70	20-70 @ 4A	1.1	0.8	BDY20	O/P – SW
2N916		360	25	45	50-200 @ 10	0.5	300	2N2222A	-
2N2369		360		40	40-120 @ 10	0.35	500	-	-
2N3040		360	30	40	40-160 @ 150	0.20	50	2N3040	-
BF184	30	145	20	30	75 to 750	10	300	-	For IF amplifier
BF185	30	145	20	30	67	10	220	-	Low noise AN and FM applications
BF195	30	250	20	30	67	10	200	-	
SL100	500	800	50	60	50-280	7	-	SK100	AM for receivers class B push pull stage
PT4	2 Amps	4 W	20	32	80-320	10	3	PT6	Amplifier and Radio receiver
AC176	1 Amp	155 mW	32	32	83	-	Mc/S	AC128	Radio receivers, Tape recording
BF115	30	145 mW	30	50	45-165	-	230	-	General Broadcast and television

Table 4.2 (b) BJT-PNP Small-Signal Transistor

Parameter Type	V_{CE} (Volts)	V_{CB} (Volts)	I_C (mA)	V_{ce} @ I_C (Volts)		h_{fe} @ I_C		f_T @ I_C (MHz)		P_{tot} (mW)	Use	Comparable Types
BC157	–45	–50	–100	–0.25	10 mA	75-260	2 mA	150	10 mA	300	S.S. Amplifier	BC177, BC212, BC307
BC158	–25	–30	–100	–0.25	10 mA	75-500	2 mA	150	10 mA	300	S.S. Amplifier	BC175, BC308
BC159	–20	–25	–100	–0.25	10 mA	125-500	2 mA	150	10 mA	300	S.S. Amplifier	BC179, BC309
BC557	–45	–50	–100	-		110-300	2 mA	150	-	500	4p. small sig.	BC157, DS557
BC558	–30	–30	–100	-	75	75	2 mA	150	-	500	4p. small sig.	BC158, DS558
AF115	–32	–32	–10	-	-	150	-	75	-	75	RF. Amplifier mixer oscil-lator in SW receiver	AF125. AF200
2N2904	–40	–60	–0.6 A	-	-	20-40	-	200	-	0.6 W	Switching & driving applications	-
AD162	–20	–32	–2 A	–1	50-300	50-300		1.5	6 W	.6W	Audio matched pair	-
BC177	–45	–50	–100	–5	-	175-500	-	200	-	300	Audio driver	BC107

Channel The region BC of the N-type bar between the depletion region is called the channel. Majority carriers move from the source to drain when a potential difference V_{DS} is applied between the source and drain.

4.15 OPERATION OF *N*-CHANNEL JFET

When $V_{GS} = 0$ and $V_{DS} = 0$ When no voltage is applied between drain and source, and gate and source, the thickness of the depletion regions around the PN junction is uniform as shown in Fig. 4.26.

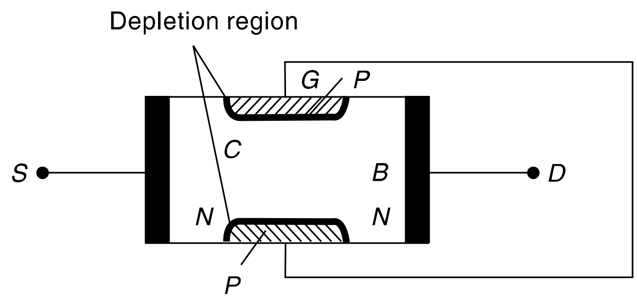


Fig. 4.26 *JFET construction*

When $V_{DS} = 0$ and V_{GS} is decreased from zero In this case, the PN junctions are reverse biased and hence the thickness of the depletion region increases. As V_{GS} is decreased from zero, the reverse bias voltage across the PN junction is increased and hence, the thickness of the depletion region in the channel also increases until the two depletion regions make contact with each other. In this condition, the channel is said to be cut-off. The value of V_{GS} which is required to cut-off the channel is called the cut-off voltage V_C.

When $V_{GS} = 0$ and V_{DS} is increased from zero Drain is positive with respect to the source with $V_{GS} = 0$. Now the majority carriers (electrons) flow through the N-channel from source to drain. Therefore the conventional current I_D flows from drain to source. The magnitude of the current will depend upon the following factors:

1. The number of majority carriers (electrons) available in the channel, i.e. the conductivity of the channel.
2. The length L of the channel.
3. The cross-sectional area A of the channel at B.
4. The magnitude of the applied voltage V_{DS}. Thus the channel acts as a resistor of resistance R given by

$$R = \frac{\rho L}{A} \tag{4.33}$$

$$I_D = \frac{V_{DS}}{R} = \frac{A V_{DS}}{\rho L} \tag{4.34}$$

where ρ is the resistivity of the channel. Because of the resistance of the channel and the applied voltage V_{DS}, there is a gradual increase of positive potential along the channel from source to drain. Thus the reverse voltage across the *PN* junctions increases and hence the thickness of the depletion regions also increases. Therefore, the channel is wedge shaped as shown in Fig. 4.27.

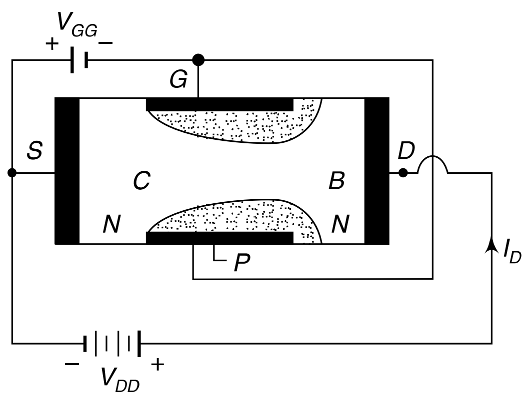


Fig. 4.27 *JFET under applied bias*

As V_{DS} is increased, the cross-sectional area of the channel will be reduced. At a certain value V_P of V_{DS}, the cross-sectional area at B becomes minimum. At this voltage, the channel is said to be pinched off and the drain voltage V_P is called the pinch-off voltage.

As a result of the decreasing cross-section of the channel with the increase of V_{DS}, the following results are obtained.

(i) As V_{DS} is increased from zero, I_D increases along OP, and the rate of increase of I_D with V_{DS} decreases as shown in Fig. 4.28. The region from V_{DS} = 0V to $V_{DS} = V_P$ is called the ohmic region. In the ohmic region,

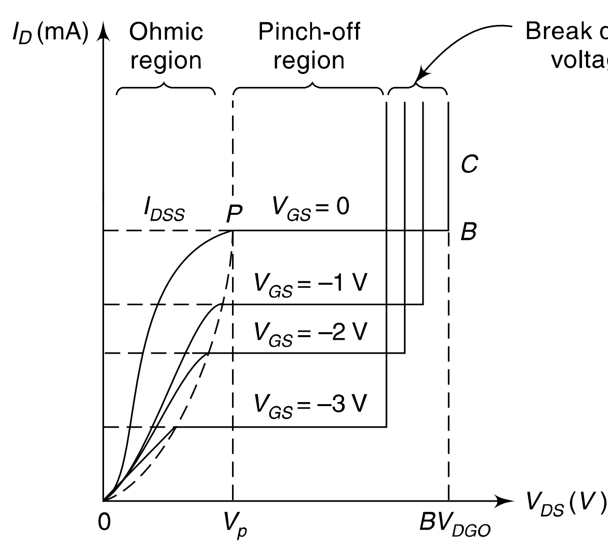


Fig. 4.28 *Drain characteristics*

the drain to source resistance $\dfrac{V_{DS}}{I_D}$ is related to the gate voltage V_{GS}, in an almost linear manner. This is useful as a voltage variable resistor (VVR) or voltage dependent resistor (VDR).

(ii) When $V_{DS} = V_P$, I_D becomes maximum. When V_{DS} is increased beyond V_P, the length of the pinch-off or saturation region increases. Hence, there is no further increase of I_D.

(iii) At a certain voltage corresponding to the point B, I_D suddenly increases. This effect is due to the Avalanche multiplication of electrons caused by breaking of covalent bonds of silicon atoms in the depletion region between the gate and the drain. The drain voltage at which the breakdown occurs is denoted by BV_{DGO}. The variation of I_D with V_{DS} when $V_{GS} = 0$ is shown in Fig. 4.27 by the curve *OPBC*.

When V_{GS} is negative and V_{DS} is increased When the gate is maintained at a negative voltage less than the negative cut-off voltage, the reverse voltage across the junction is further increased. Hence for a negative value of V_{GS}, the curve of I_D versus V_{DS} is similar to that for $V_{GS} = 0$, but the values of V_P and BV_{DGO} are lower, as shown in Fig. 4.29.

From the curves, it is seen that above the pinch-off voltage, at a constant value of V_{DS}, I_D increases with an increase of V_{GS}. Hence, a JFET is suitable for use as a voltage amplifier, similar to a transistor amplifier.

It can be seen from the curve that for voltage $V_{DS} = V_P$, the drain current is not reduced to zero. If the drain current is to be reduced to zero, the ohmic voltage drop along the channel should also be reduced to zero. Further, the reverse biasing to the gate-source *PN* junction essential for pinching off the channel would also be absent.

The drain current I_D is controlled by the electric field that extends into the channel due to reverse biased voltage applied to the gate; hence, this device has been given the name *Field Effect Transistor*.

In a bar of *P*-type semiconductor, the gate is formed due to N-type semiconductor. The working of the *P*-channel JFET will be similar to that of *N*-channel JFET with proper alterations in the biasing circuits; in this case holes will be the current carriers instead of electrons. The circuit symbols for *N*-channel and *P*-channel JFETs are shown in Fig. 4.28. It should be noted that the direction of

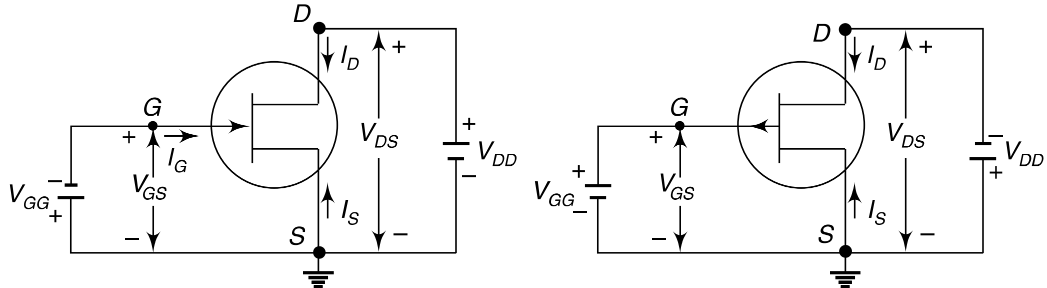


Fig. 4.29 *Circuit symbols for N- and P-channel JFET*

Therefore, $$V_P = \frac{qN_A}{2\varepsilon} \times a^2 = \frac{1 \times 10^{-4}}{2 \times 12 \times 8.854 \times 10^{-12}} \times (2 \times 10^{-4})^2 = 1.89 \text{ V}$$

4.19 COMPARISON OF JFET AND BJT

1. FET operation depends only on the flow of majority carriers-holes for *P*-channel FETs and electrons for *N*-channel FETs. Therefore, they are called Unipolar devices. Bipolar transistor (BJT) operation depends on both minority and majority current carriers.
2. As FET has no junctions and the conduction is through an *N*-type or *P*-type semiconductor material, FET is less noisy than BJT.
3. As the input circuit of FET is reverse biased, FET exhibits a much higher input impedance (in the order of 100 M Ω) and lower output impedance and there will be a high degree of isolation between input and output. So, FET can act as an excellent buffer amplifier but the BJT has low input impedance because its input circuit is forward biased.
4. FET is a voltage controlled device, i.e. voltage at the input terminal controls the output current, whereas BJT is a current controlled device, i.e. the input current controls the output current.
5. FETs are much easier to fabricate and are particularly suitable for ICs because they occupy less space than BJTs.
6. The performance of BJT is degraded by neutron radiation because of the reduction in minority-carrier lifetime, whereas FET can tolerate a much higher level of radiation since they do not rely on minority carriers for their operation.
7. The performance of FET is relatively unaffected by ambient temperature changes. As it has a negative temperature coefficient at high current levels, it prevents the FET from thermal breakdown. The BJT has a positive temperature co-efficient at high current levels which leads to thermal breakdown.
8. Since FET does not suffer from minority carrier storage effects, it has higher switching speeds and cut-off frequencies. BJT suffers from minority carrier storage effects and therefore has lower switching speed and cut-off frequencies.
9. FET amplifiers have low gain bandwidth product due to the junction capacitive effects and produce more signal distortion except for small signal operation.
10. BJTs are cheaper to produce than FETs.

4.20 APPLICATIONS OF JFET

1. FET is used as a buffer in measuring instruments, receivers since it has high input impedance and low output impedance.

2. FETs are used in RF amplifiers in FM tuners and in communication equipment for its low noise level.
3. Since the input capacitance is low, FETs are used in cascade amplifiers in measuring and test equipments.
4. Since the device is voltage controlled, it is used as a voltage variable resistor in operational amplifiers and tone controls.
5. FETs are used in mixer circuits in FM and TV receivers, and in communication equipment because inter modulation distortion is low.
6. It is used in oscillator circuits because frequency drift is low.
7. As the coupling capacitor is small, FETs are used in low frequency amplifiers in hearing aids and in inductive transducers.
8. FETs are used in digital circuits in computers, LSD and memory circuits because of its small size.

4.21 METAL OXIDE SEMICONDUCTOR FIELD EFFECT TRANSISTOR (MOSFET)

MOSFET is the common term for the Insulated Gate Field Effect Transistor (IGFET). There are two basic forms of MOSFET: (i) Enhancement MOSFET and (ii) Depletion MOSFET.

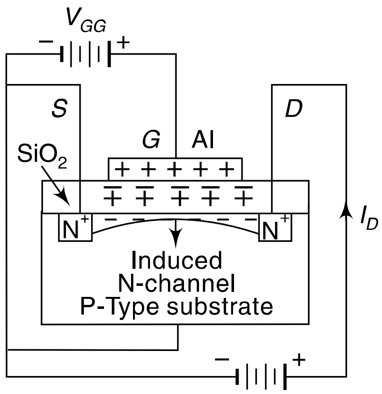
Principle By applying a transverse electric field across an insulator deposited on the semiconducting material, the thickness and hence the resistance of a conducting channel of a semiconducting material can be controlled.

In a depletion MOSFET, the controlling electric field reduces the number of majority carriers available for conduction, whereas in the enhancement MOSFET, application of electric field causes an increase in the majority carrier density in the conducting regions of the transistor.

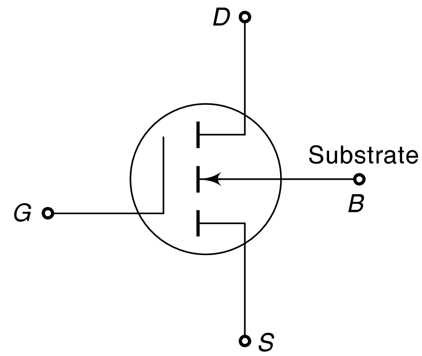
4.22 ENHANCEMENT MOSFET

Construction The construction of an *N*-channel enhancement MOSFET is shown in Fig. 4.33(a) and the circuit symbols for an *N*-channel and a *P*-channel enhancement MOSFET are shown in Fig. 4.33(b) and (c), respectively. As there is no continuous channel in an enhancement MOSFET, this condition is represented by the broken line in the symbols.

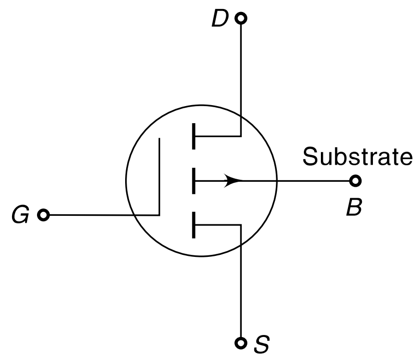
Two highly doped N^+ regions are diffused in a lightly doped substrate of *P*-type silicon substrate. One N^+ region is called the source *S* and the other one is called the drain *D*. They are separated by 1 mil (10^{-3} inch). A thin insulating layer of SiO_2 is grown over the surface of the structure and holes are cut into the oxide layer, allowing contact with source and drain. Then a thin layer of metal aluminium is formed over the layer of SiO_2. This metal layer covers the entire channel region and it forms the gate *G*.



(a)



(b) *N*-Channel



(c) *P*-Channel

Fig. 4.33 *(a) N-channel enhancement MOSFET, (b) and (c) Circuit symbols for enhancement MOSFET*

The metal area of the gate, in conjunction with the insulating oxide layer of SiO_2 and the semiconductor channel forms a parallel plate capacitor. This device is called the insulated gate FET because of the insulating layer of SiO_2. This layer gives an extremely high input impedance for the MOSFET.

Operation If the substrate is grounded and a positive voltage is applied at the gate, the positive charge on *G* induces an equal negative charge on the substrate side between the source and drain regions. Thus, an electric field is produced between the source and drain regions. The direction of the electric field is perpendicular to the plates of the capacitor through the oxide. The negative charge of electrons which are minority carriers in the *P*-type substrate forms an inversion layer. As the positive voltage on the gate increases, the induced negative charge in the semiconductor increases. Hence, the conductivity increases and current flows from source to drain through the induced channel. Thus the drain current is enhanced by the positive gate voltage as shown in Fig. 4.34.

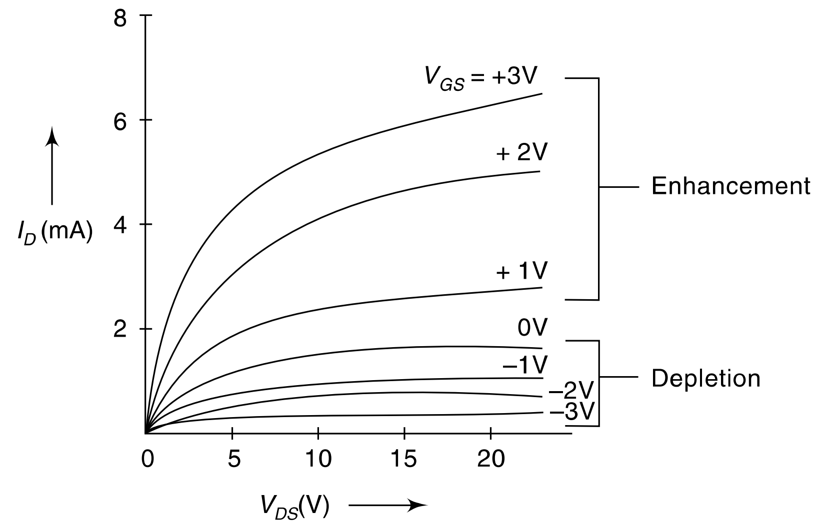


Fig. 4.34 *Volt-ampere characteristics of MOSFET*

4.23 DEPLETION MOSFET

The construction of an *N*-channel depletion MOSFET is shown in Fig. 4.35(a) where an *N*-channel is diffused between the source and drain to the basic structure of MOSFET. The circuit symbols for an *N*-channel and a *P*-channel depletion MOSFET are shown in Figs. 4.35(b) and (c), respectively.

With $V_{GS} = 0$ and the drain *D* at a positive potential with respect to the source, the electrons (majority carriers) flow through the *N*-channel from *S* to *D*. Therefore, the conventional current I_D flows through the channel *D* to *S*. If the gate voltage is made negative, positive charge consisting of holes is induced in the channel through SiO_2 of the gate-channel capacitor. The introduction of the positive charge causes depletion of mobile electrons in the channel. Thus a depletion

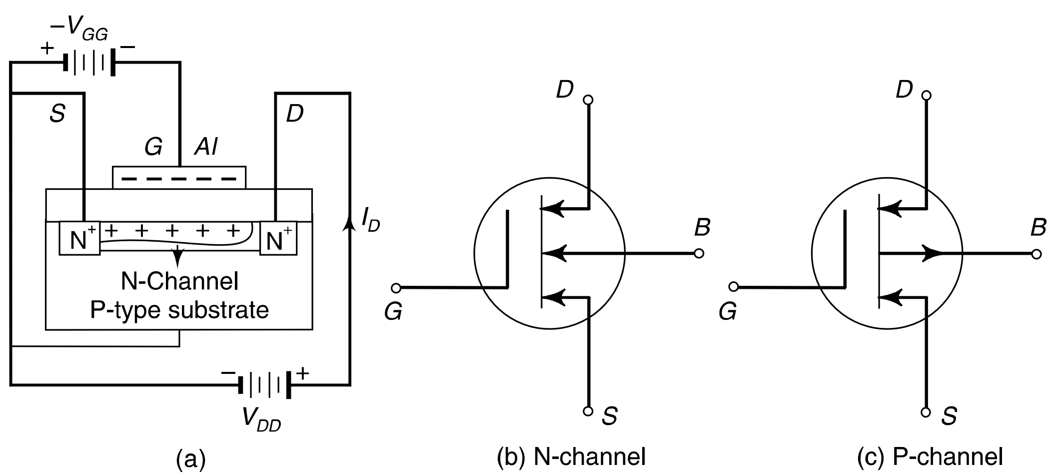


Fig. 4.35 (a) *N-channel depletion MOSFET, (b) and (c) Circuit symbols for depletion MOSFETs.*

region is produced in the channel. The shape of the depletion region depends on V_{GS} and V_{DS}. Hence the channel will be wedge shaped as shown in Fig. 4.35. When V_{DS} is increased, I_D increases and it becomes practically constant at a certain value of V_{DS}, called the pinch-off voltage. The drain current I_D almost gets saturated beyond the pinch-off voltage.

Since the current in an FET is due to majority carriers (electrons for an N-type material), the induced positive charges make the channel less conductive, and I_D drops as V_{GS} is made negative.

The depletion MOSFET may also be operated in an enhancement mode. It is only necessary to apply a positive gate voltage so that negative charges are induced into the N-type channel. Hence, the conductivity of the channel increases and I_D increases. As the depletion MOSFET can be operated with bipolar input signals irrespective of doping of the channel, it is also called as *dual mode MOSFET*. The volt-ampere characteristics are indicated in Fig. 4.36.

The curve of I_D versus V_{GS} for constant V_{DS} is called the transfer characteristics of MOSFET and is shown in Fig. 4.36.

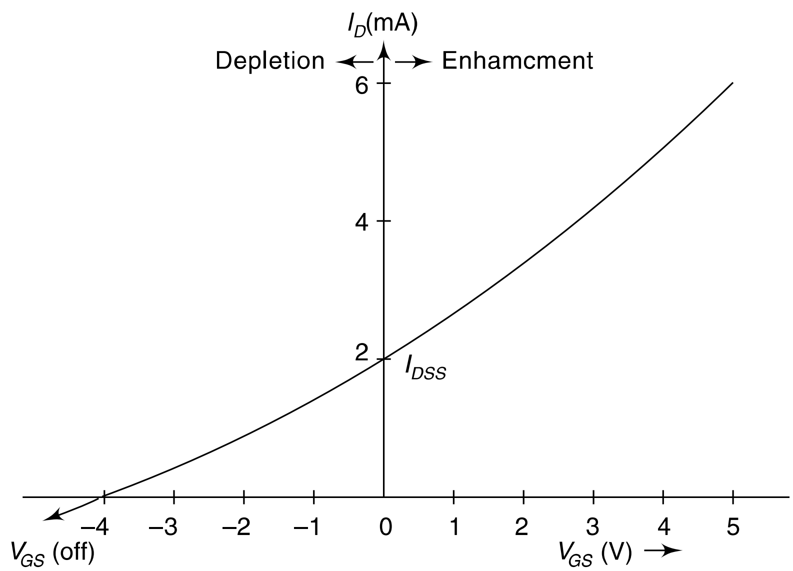


Fig. 4.36 *Transfer characteristics of MOSFET*

4.23.1 Effect of Channel Length Modulation

In actual MOSFET characteristic as shown in Fig. 4.37, a non-zero slope exists beyond the saturation point. For the saturation region, i.e., ($V_{DS} > V_{DS}$ (sat)), the effective channel length decreases and this phenomenon is called channel length modulation. For an N-channel device, the slope of the curve in the saturation region can be expressed by using the drain current I_D given by

$$I_D = K_N(V_{GS} - V_{TN})^2 (1 + \lambda V_{DS})$$