MANJARA CHARITABLE TRUST
RAJIV GANDHI INSTITUTE OF TECHNOLOGY, MUMBAI
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NOTES ON

SEMICONDUCTOR PHYSICS

(Course code: BSC 2022)

(As per revised syllabus NEP-2020, University of Mumbai)

By

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Syllabus

Sr. No.	Name of Module	Detailed Content	Hours	CO Mapping
	Prerequisite	Band theory of solids Fermi Dirac Distribution function Density of states and	-	-
1	**Basics of Semiconductors**	Types of semiconductors, Carrier Concentration in Intrinsic Semiconductors, Fermi level of Intrinsic Semiconductors, Variation of Fermi level of Intrinsic Semiconductors, w r to temperature. Extrinsic Semiconductors, Fermi level of Extrinsic Semiconductors, Variation of Fermi level of Extrinsic Semiconductors, w r to temperature and Impurity Concentration, Equation of conductivity with current flow, Hall Effect, Calculation of Hall Voltage**.**	**4**	**CO1**
2	**Junction diode**	Formation of p-n junction, calculation of barrier potential Diode equation, p-n junction in forward Bias, p-n junction in Reverse bias, Current- voltage curve for p-n junction diode, LED and its working	**4**	**CO2**
3	**Important Diodes**	Working of: Photo diode, solar cell, Zener diode ,Varactor diode , Gunn diode and their applications.	**4**	**CO3**
4	**Bipolar Junction Transistors**	BJT Structure and Operation - BJT structure, Modes of operation, CB, CE I-V characteristics BJT Amplification and Switching - Current gain, BJT as a switch,	**4**	**CO4**
5	**Field Effect Transistors**	Field-Effect Transistors (FETs) - FET types: JFET, MOSFET, Structure and operation MOSFETs	**6**	**CO5**

		in Detail - MOSFET structure, Enhancement and depletion modes, Threshold voltage MOSFET Applications - MOSFET as a switch,		
6	**Nano Technology**	Introduction to Nanotechnology , Properties (optical, Electrical, Structural, Mechanical) Importance of surface to Volume ratio, Bonding in solids (Vander walls interactions) , Application: Lithography, Single Electron Transfer (SET), Spin Valves.	**4**	**CO6**

Course Objectives:

1. to provide students with a basic understanding of semiconductors in the field of basic engineering.
2. to explain basic importance of p-n junction diodes.
3. to learn about few special diode important for semiconductor industry.
4. to understand the basics of transistors and their applications in the field of electronics.
5. to build foundation of field effect transistors and their applications.
6. to give exposure to the upcoming field of nano technology in the field of solid state physics.

Course Outcomes:

1. learners will be able to **use** and **demonstrate** his/ her ability earned here to **apply it to calculate hall voltage**
2. learners will be able to **calculate** barrier potential and **plot i-v** characteristics of p-n junction diode.
3. learners will be able to **plot** i - v characteristics and understand their applications of some special diodes
4. learners will be able to **calculate** current gain and **plot i-v** characteristics for cb-ce configurations.
5. learner will be able to **plot** i-v characteristics and understand applications of fets
6. learner will be able to **apply** the knowledge of nano technology to certain emerging areas of technology.

Module 1

BASICS OF SEMICONDUCTORS

BASICS OF SEMICONDUCTORS

Types of semiconductors, Carrier Concentration in Intrinsic Semiconductors, Fermi level of Intrinsic Semiconductors, Variation of Fermi level of Intrinsic Semiconductors, w r t temperature. Extrinsic Semiconductors, Fermi level of Extrinsic Semiconductors, Variation of Fermi level of Extrinsic Semiconductors, w r t temperature and Impurity Concentration, Equation of conductivity with current flow, Hall Effect, Calculation of Hall Voltage.

Types of semiconductors:

Semiconductors are materials that have electrical conductivity between that of a conductor and an insulator. There are several types of semiconductors, classified based on their properties and applications:

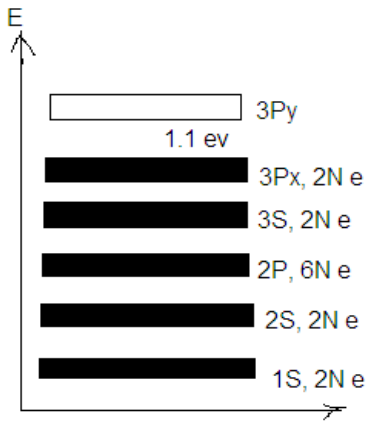
Intrinsic Semiconductors

1. Silicon (Si):

Formation of energy band in silicon.

Si (14):- electronic configuration -$1s^2$ $2s^2$ $2p^6$ $3s^2$ $3p^2$

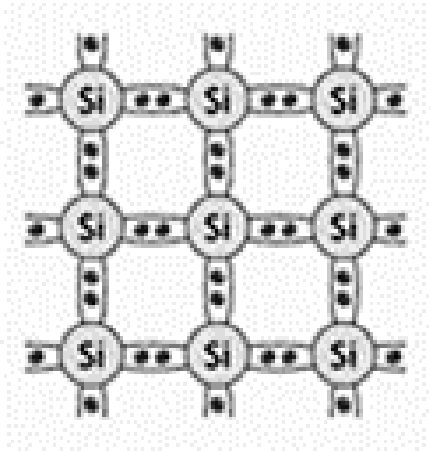
If the silicon crystal contains N no of atoms, the total no. of electrons are 14N. The 1s, 2s and 3s bands are formed by energy levels of 2N electrons; 2p band is formed by energy levels of 6N electrons. The 3p band is divided in to $3p_x$, $3p_y$ and $3p_z$ bands. The $3p_x$ band is completely filled by 2N electrons and $3p_y$ band is formed above the $3p_x$ band with energy gap of 1.1 ev.

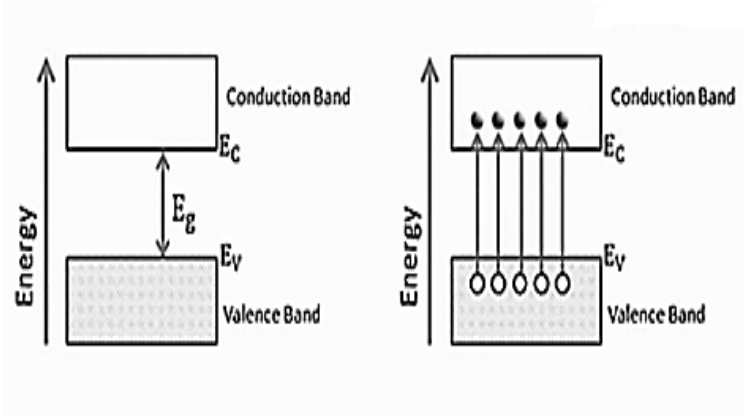


Energy band diagram of Si

The most widely used semiconductor material, used in a variety of applications, including computers, smartphones, and solar panels.

2. Germanium (Ge): Used in high-speed electronic devices, such as amplifiers and switches.



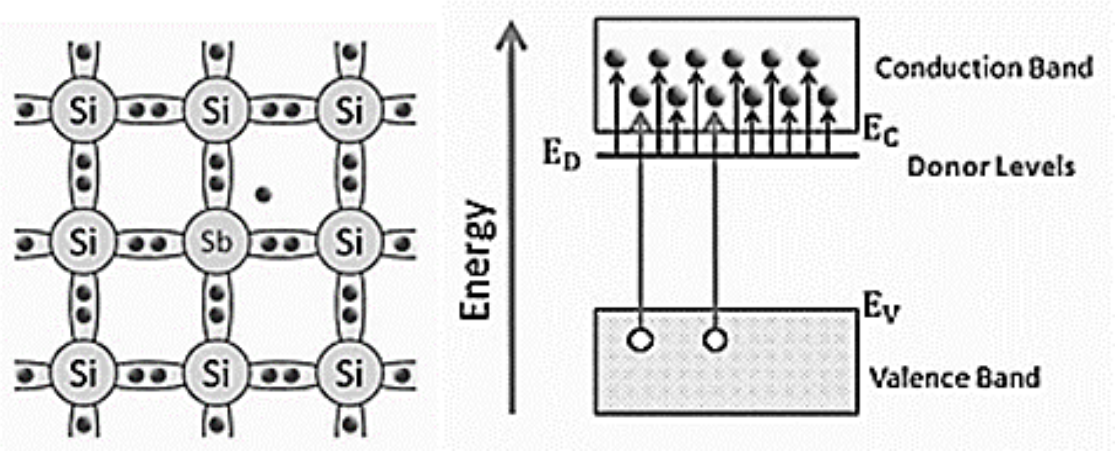


Extrinsic Semiconductors

1. N-Type Semiconductors: Doped with donor impurities, such as phosphorus or arsenic, to create an excess of electrons.

2. P-Type Semiconductors: Doped with acceptor impurities, such as boron or gallium, to create a deficiency of electrons.

N-type semiconductor:



Compound Semiconductors

Direct and Indirect Band Gap Semiconductor:

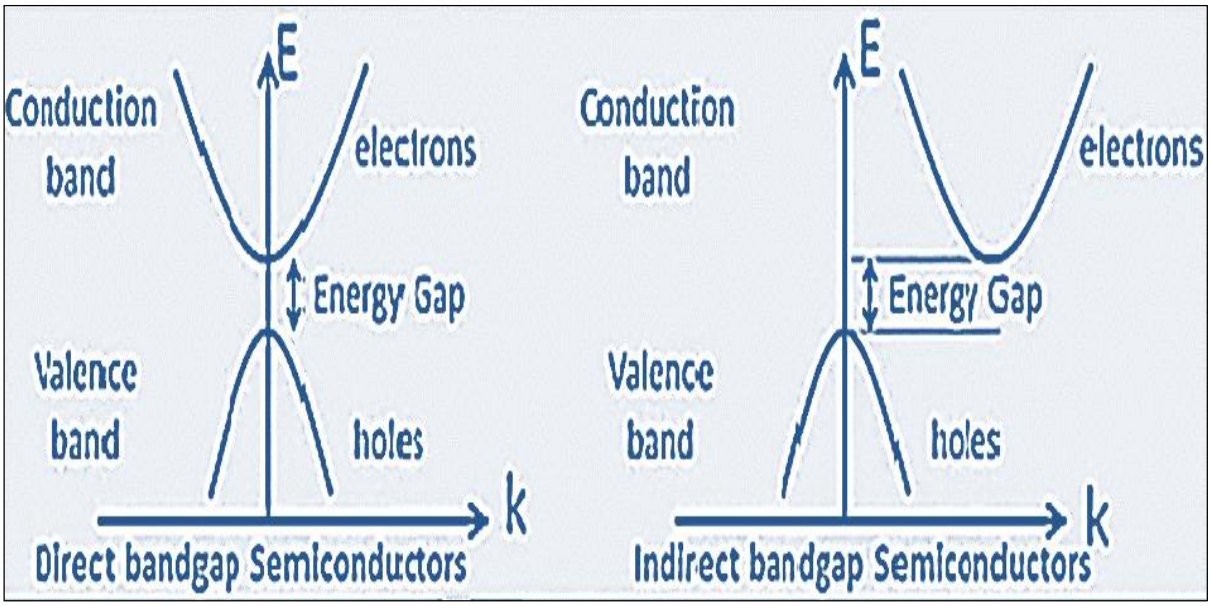
1) The solid crystals are formed when the isolated atoms are brought together. However,

when two atoms are brought close to each other, it leads to intermixing of electrons in the valence shell. As a result, the number of permissible energy levels is formed, which is called an energy band.

2) Each band is formed due to the splitting of one or more atomic energy levels. Therefore, the minimum number of states in a band equals twice the number of atoms in the material. The reason for the factor of two is that every energy level can contain two electrons with opposite spin.
3) Band gap is the difference in energy between the valence band and the conduction band of a solid material that consists of the range of energy values forbidden to electrons in the material.
4) In semiconductor physics, the band gap of a semiconductor can be of two basic types, a direct band gap or an indirect band gap. Therefore another way of classifying semiconductors based on their band structure is

   a) Direct band gap semiconductor b) Indirect band gap semiconductor

5) The difference between direct and indirect band gap semiconductors is related to their band structure. Electrons in solids have a wave like character. An electron wave is characterized by a wave vector k. Thus, for crystalline materials it possible to plot E vs. vector k diagrams. These are related to the simple band diagrams that show the valence and conduction band.
6) The band gap is called "direct" if the crystal momentum (Vector k) of electrons and holes is the same in both the conduction band and the valence band. In direct band-gap (DBG) semiconductor the maximum energy level of the valence band aligns with the minimum energy level of the conduction band with respect to momentum.
7) The band gap is called "indirect" if the crystal momentum (Vector k) of electrons and holes is not same in both the conduction band and the valence band. In indirect band-gap (IBG) semiconductor the maximum energy level of the valence band misaligned with the minimum energy level of the conduction band with respect to momentum.



8) Electrons from the valence band can be excited to the conduction band by either thermal excitation or by optical absorption. When the electron returns to the valence band the energy is released either as heat or as photons.

9) An electron can directly emit a photon. In an "indirect" gap, a photon cannot be emitted because the electron must pass through an intermediate state and transfer momentum to the crystal lattice.

10) An example of direct band gap material includes some III-V materials such as GaAs, InP, SiC are also known as compound semiconductor. Indirect band gap materials include Si, Ge are also known as elemental semiconductor.

1. Gallium Arsenide (GaAs): Used in high-frequency electronic devices, such as microwave amplifiers and switches.

2. Indium Phosphide (InP): Used in high-speed electronic devices, such as fiber optic communications and radar systems.

3. Silicon Carbide (SiC): Used in high-power electronic devices, such as power supplies and motor control systems

Wide Band gap Semiconductors:

1. Silicon Nitride (Si3N4): Used in high-temperature electronic devices, such as sensors and actuators.

2. Diamond: Used in high-power electronic devices, such as power supplies and radiation detectors.

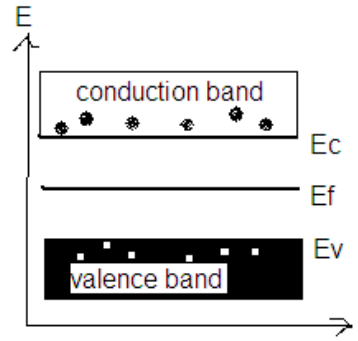
Organic Semiconductors

1. Polymer Semiconductors: Used in flexible electronic devices, such as displays and sensors.

2. Small-Molecule Semiconductors: Used in organic light-emitting diodes (OLEDs) and organic photovoltaic (OPVs).

Each type of semiconductor has its unique properties and applications

Carrier Concentration in Intrinsic Semiconductor:



Fermi level in intrinsic semiconductor

In an intrinsic semiconductor, the carrier concentration is the number of charge carriers (electrons and holes) per unit volume of the material. Since intrinsic semiconductors are pure materials without any doping, the number of electrons and holes is equal.

The intrinsic carrier concentration (ni) is a fundamental property of the semiconductor material. It depends on the material's band gap energy (Eg) and temperature (T).

Typical values of ni for silicon (Si) at room temperature (T = 300 K) are around 1.45×10^{10} cm^{-3}.

Consider at temp. T^0K,

n – Concentration of free electrons in conduction band.

P – Concentration of holes in the valence band.

N_c– Effective density of states in the conduction band.

N_v – Effective density of states in the valence band.

$$n = Nc\ e^{-(Ec - Ef)/KT}$$

$$p = Nv\ e^{-(Ef - Ev)/KT}$$

Product of n & p is

$$n.p = Nc\, e^{-(Ec - Ef)/KT} . Nv\, e^{-(Ef - Ev)/KT}$$

$$n,p = Nc.Nv\, e^{-(Ec - Ev)/KT} \text{ ----------(1)}$$

For intrinsic semiconductor n=ni, p=pi and Ef = Ei

$$ni.pi = Nc\, e^{-(Ec - Ei)/KT} . Nv\, e^{-(Ei - Ev)/KT}$$

$$ni,pi = Nc.Nv\, e^{-(Ec - Ev)/KT}$$

For intrinsic semiconductor ni =pi

$$ni^2 = Nc.Nv\, e^{-(Ec - Ev)/KT} \text{----------(2)}$$

From equation (1) and (2)

$$\mathbf{ni^2 = ni.pi}$$

Fermi-Dirac distribution function:

The distribution of electrons of energy E in various energy levels is given by Fermi-Dirac distribution function,

$$f(E) = \frac{1}{1+e^{\left(\frac{E-E_F}{kT}\right)}}$$

f(E) is the probability of occupancy for energy level E

E_F is Fermi energy

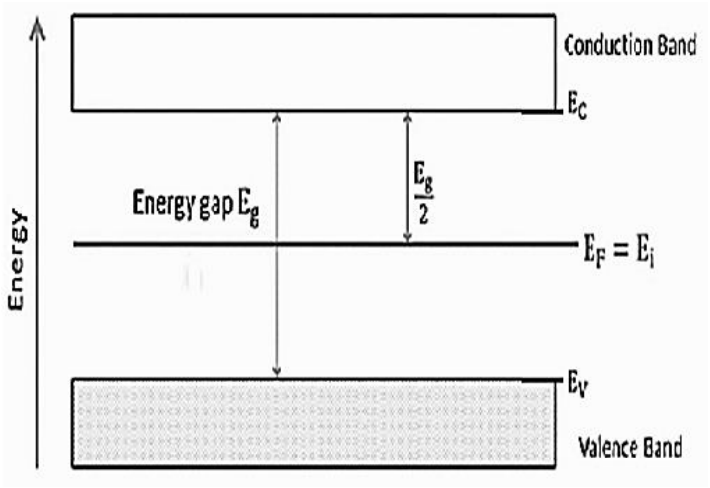
T is temperature in ^{0}K and

$k = 1.38 \times 10^{-23}$ J/K $= 8.625 \times 10^{-5}$ eV/K

Fermi function F(E) gives the probability that an electrons of energy E occupying particular energy level.

Q. Show that in intrinsic semiconductor, Fermi level always lies at the middle between the valence and conduction band?

FERMI LEVEL IN INTRINSIC SEMICONDUCTOR:-



1) In an intrinsic semiconductor, the Fermi level (Ef) is the energy level at which the probability of finding an electron is 50%. It is a critical concept in understanding the behavior of semiconductors.
2) In semiconductors at temp. T = O^0K, the valance band is completely filled by the electrons and conduction band is empty. At temp. T^0K, some electrons from the valence band can jump in to the conduction band, leaving behind equal number of holes in the valence band. Thus in semiconductors the charged carriers are electrons and holes.
3) At temp. T^0K, the density of free electrons in the conduction band and density of holes in the valence band is equal. Therefore Fermi level always at the middle between the valence band and conduction band.
4) Thus in semiconductor Fermi level is not an allowed energy level for electrons in the semiconductor, but it is reference level between the valence band and conduction band.

If E_v – energy of upper level of valence band.

E_c – energy of bottom level of conduction band.

E_f – Fermi energy level.

E_g– energy gap between valence band and conduction band.

Therefore, $Ef = \frac{Ec+Ev}{2} = \frac{Eg}{2}$

Consider at temp. T^0K,

n_c – Concentration of free electrons in conduction band.

n_v– Concentration of holes in the valence band.

N_c– Effective density of states in the conduction band.

N_v – Effective density of states in the valence band.

$$n_c = Nc\ e^{-(Ec - Ef)/KT}$$

$$n_v = Nv\ e^{-(Ef - Ev)/KT}$$

$$\text{but } n_c = n_v$$

$$Nc\ e^{-(Ec - Ef)/KT} = Nv\ e^{-(Ef - Ev)/KT}$$

$$e^{-(Ec - Ef)/KT} = \frac{Nv}{Nc}\ e^{-(Ef - Ev)/KT}$$

But Nv = Nc, therefore Nv / Nc =1

$$e^{-(Ec - Ef)/KT} = e^{-(Ef - Ev)/KT}$$

Take logarithm on both sides,

$$\frac{-(Ec - Ef)}{KT} = \frac{-(Ef - Ev)}{KT}$$

$$-Ec + Ef + Ef - Ev = 0$$

Therefore, $\boldsymbol{Ef = \frac{Ec+Ev}{2} = \frac{Eg}{2}}$

Thus in intrinsic semiconductor, Fermi level always at the middle between the valence band and conduction band.

As the temperature increases:

1. The Fermi level shifts upward, toward the conduction band edge (Ec).
2. The shift is proportional to the temperature (T).
3. The Fermi level remains approximately at the middle of the bandgap energy (Eg).

Consequences of Fermi Level Shift:

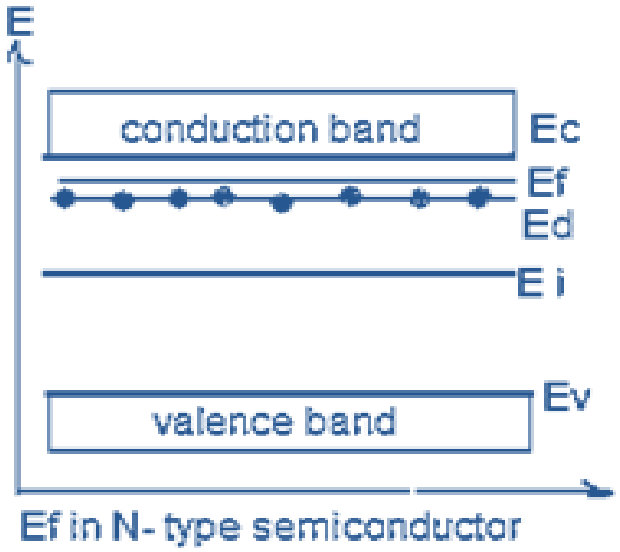
The shift in Fermi level with temperature affects the electrical properties of the intrinsic semiconductor:

1. Carrier concentration: Increases with temperature.
2. Conductivity: Increases with temperature.
3. Bandgap energy: Decreases with temperature

FERMI LEVEL IN EXTRINSIC SEMICONDUCTOR:-

Explain Fermi level in extrinsic semiconductor?

Fermi level in N-type semiconductor:



Ef in N- type semiconductor

In N – type semiconductor, donor impurity is just below the conduction band, therefore the density of free electrons in the conduction band is greater than density of holes in the valence band. The Fermi level lies at the middle between the bottom level of conduction band Ec and donor level of impurity atoms Ed.

$$\text{Therefore, } Ef = \frac{Ec + Ed}{2}$$

Consider at temp. T^0K,

n_c – Concentration of free electrons in conduction band.

$$n_c = Nc\ e^{-(Ec - Ef)/KT}$$

but $n_c = N_D$

Therefore, $N_D = Nc\ e^{-(Ec - Ef)/KT}$

$$N_D/N_C = e^{-(Ec - Ef)/KT}$$

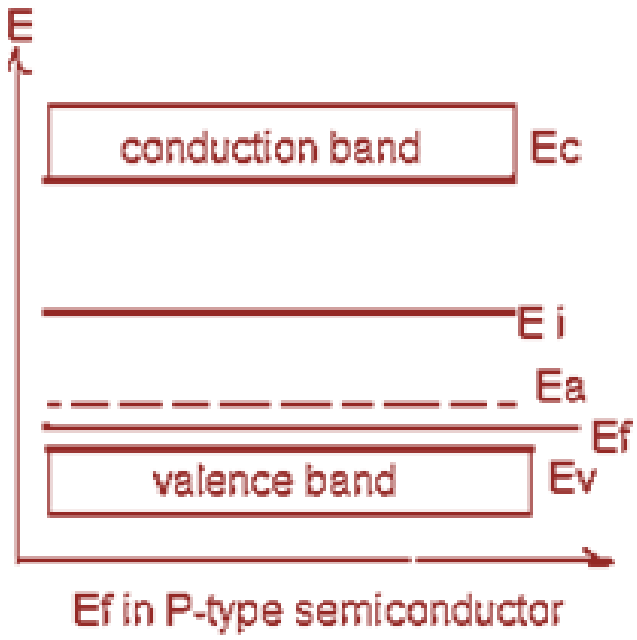
Take logarithm on both side

$$\text{Log } N_D/N_C = -(Ec - Ef)/KT$$

$$KT \log N_D/N_C = -E_C + E_F$$

$Ef = E_C + KT \log N_D / N_C$

Fermi level in P-type semiconductor:



Ef in P-type semiconductor

In P – type semiconductor, the Fermi level lies at the middle between the top level of valence band Ev and acceptor level of impurity atoms E_A.

$$\text{Therefore, } Ef = \frac{Ec + EA}{2}$$

Consider at temp. T^0K,

n_v – Concentration of holes in valence band.

$$n_v = Nv\, e^{-(Ef - Ev)/KT}$$

but $n_v = N_A$

Therefore, $N_A = Nv\, e^{-(Ef - Ev)/KT}$

$$N_A/N_V = e^{-(Ef - Ev)/KT}$$

Take logarithm on both side

$$\text{Log } N_A/N_v = -(Ef - Ev)/KT$$

$$KT \log N_A/N_v = -E_f + E_v$$

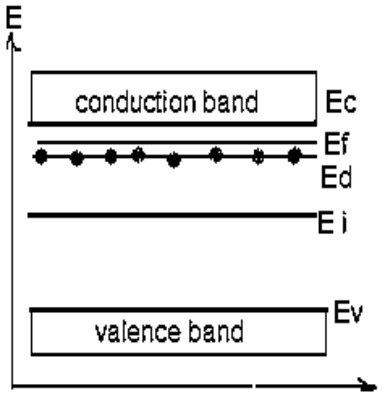
$$\mathbf{Ef = E_v - KT \log N_A / N_v}$$

Q. Explain the variation of Fermi level with temperature & impurity concentration in N-type semiconductor?

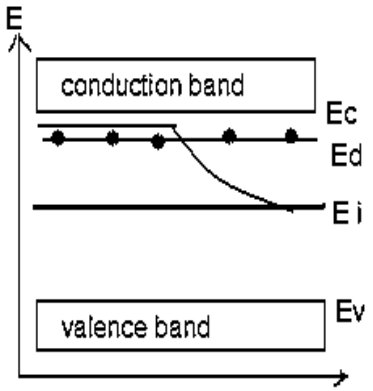
In extrinsic semiconductor, density of free charge carriers (electrons or holes) in the conduction band and valence band increases with temperature and impurity concentration, hence Fermi level depends upon the temp. and impurity concentration.

1) **Variation of Ef with temperature**:-

In extrinsic semiconductor the Fermi level lies in upper half or lower half of the energy gap depending upon the concentration of majority charge carriers.



Ef in N- type semiconductor



variation of Ef with temp.

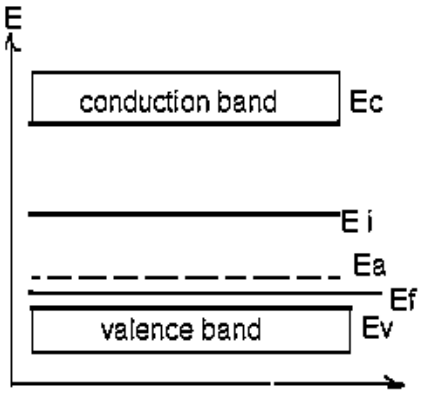
In N – type semiconductor, the density of free electrons in the conduction band is greater than density of holes in the valence band. The Fermi level lies at the middle between the bottom level of conduction band Ec and donor level of impurity atoms Ed.

$$\text{Therefore, } Ef = \frac{Ec + Ed}{\text{----------}}$$

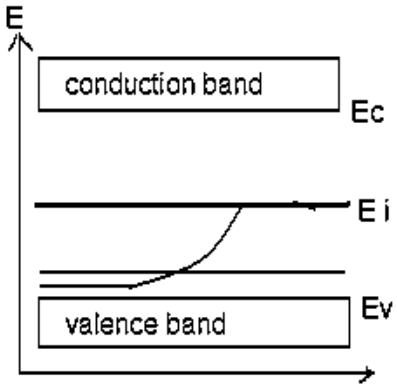
2

As the temp. Increases, the donor level are depleted by the electrons from the valence band and density of holes in the valence band increases. Therefore Fermi level Ef go on decreasing. At particular temp. The density of free electrons in the conduction band becomes equal to the density of holes in the valence band and Fermi level reaches to intrinsic level Ei. The material loses its extrinsic nature and become intrinsic semiconductor. The Fermi level Ef becomes independent of temp.

In P – type semiconductor, the Fermi level lies at the middle between the top level of valence band Ev and acceptor level of impurity atoms E_A.



Ef in P-type semiconductor

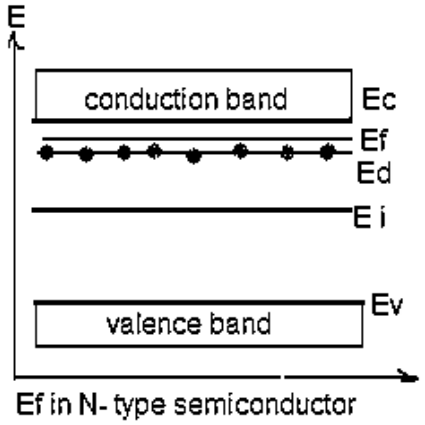


variation of Ef with temp.

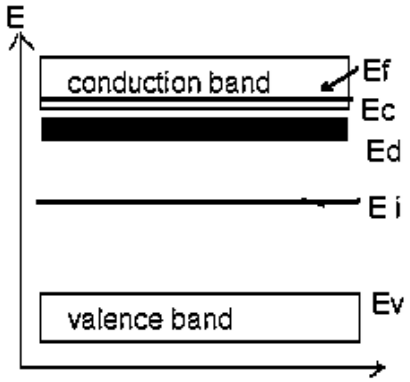
$$\text{Therefore, } Ef = \frac{Ec + E_A}{2}$$

As the temp. Increases, the Fermi level go on increasing. At particular temp., the Fermi level Ef reaches to intrinsic level Ei and material loses its extrinsic nature and become intrinsic semiconductor.

2) **Variation of Ef with impurity concentration**:



Ef in N- type semiconductor



variation of Ef with impurity concentration

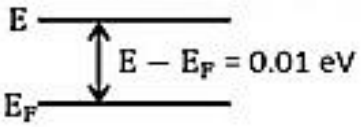
In N – type semiconductor at low impurity concentration, the donor atoms are isolated from each other and therefore single donor energy level Ed is formed below the conduction band. The Fermi level lies at the middle between the bottom level of conduction band Ec and donor level of impurity atoms Ed.

$$\text{Therefore, } Ef = \frac{Ec + Ed}{2}$$

As the impurity concentration increases, the number of donor atoms in the donor level increases. These atoms are interacting with each other, therefore donor level splits in to no. of discrete energy levels and donor energy band is formed. The width of donor energy band increases with increase in impurity concentration. The Fermi level Ef shift close to conduction band and at higher concentration Ef may enter in to the conduction band.

Calculate probability of non-occupancy for the energy level which lies 0.01 eV above the Fermi energy level at 27 °C.

Given : T = 27 °C = 300 °K, $k = 8.625 \times 10^{-5} \frac{eV}{°K}$



$$\text{Probability of occupancy } f(E) = \frac{1}{1+e^{\left(\frac{E-E_F}{kT}\right)}}$$

$$\therefore \text{Probability of non} - \text{occupancy} = 1 - f(E) = 1 - \frac{1}{1+e^{\left(\frac{E-E_F}{kT}\right)}}$$

$$= 1 - \frac{1}{1+e^{\left(\frac{0.01}{8.625\times10^{-5}\times300}\right)}}$$

$$= 0.595$$

Fermi level for silver is 5.5 eV. Find out the energy for which the probability of occupancy at 300 K is 0.9.

Given : T = 27 °C = 300°K, $k = 8.625 \times 10^{-5} \frac{eV}{°K}$, $E_F = 5.5$ eV

when $f(E) = 0.9, E = ?$

$$\text{Probability of occupancy } f(E) = \frac{1}{1+e^{\left(\frac{E-E_F}{kT}\right)}}$$

$$\therefore 1 + e^{\left(\frac{E-E_F}{kT}\right)} = \frac{1}{f(E)}$$

$$\therefore e^{\left(\frac{E-E_F}{kT}\right)} = \frac{1}{f(E)} - 1$$

$$\therefore \frac{E-E_F}{kT} = \ln\left(\frac{1}{f(E)} - 1\right)$$

$$\therefore E - E_F = kT \ln\left(\frac{1}{f(E)} - 1\right)$$

$$\therefore E = E_F + kT \ln\left(\frac{1}{f(E)} - 1\right)$$

For $f(E) = 0.9$

$$E = 5.5 + 8.625 \times 10^{-5} \times 300 \ln\left(\frac{1}{0.9} - 1\right)$$

$$= 5.443 \text{ eV}$$

Fermi level in potassium is 2.1 eV. What are the energies for which the probability of occupancy at 300 K are 0.99 and 0.01.

Given :$T = 27\,^{\circ}C = 300^{0}K$, $k = 8.625 \times 10^{-5}\frac{eV}{^{\circ}K}$, $E_F = 2.1\ eV$

when $f(E) = 0.99$ and $f(E) = 0.01$, $E = ?$

$$\text{Probability of occupancy } f(E) = \frac{1}{1+e^{\left(\frac{E-E_F}{kT}\right)}}$$

$$\therefore E = E_F + kT\ln\left(\frac{1}{f(E)} - 1\right)$$

$$\therefore 1 + e^{\left(\frac{E-E_F}{kT}\right)} = \frac{1}{f(E)}$$

$$\therefore e^{\left(\frac{E-E_F}{kT}\right)} = \frac{1}{f(E)} - 1$$

$$\therefore \frac{E - E_F}{kT} = \ln\left(\frac{1}{f(E)} - 1\right)$$

For $f(E) = 0.99$

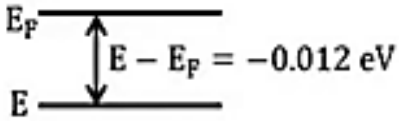
$$E = 2.1 + 8.625 \times 10^{-5} \times 300 \ln\left(\frac{1}{0.99} - 1\right) = 1.981\ eV$$

For $f(E) = 0.01$

$$E = 2.1 + 8.625 \times 10^{-5} \times 300 \ln\left(\frac{1}{0.01} - 1\right) = 2.218\ eV$$

In a solid, consider the energy level lying 0.012 eV below the Fermi energy level at 27 ^{0}C. What is the probability of this level being occupied by an electron?

Given : $T = 27\,^{0}C = 300\,^{0}K$, $k = 8.625 \times 10^{-5}\frac{eV}{^{\circ}K}$



$$\text{Probability of occupancy } f(E) = \frac{1}{1+e^{\left(\frac{E-E_F}{kT}\right)}}$$

$$\therefore \text{Probability of occupancy } f(E) = \frac{1}{1+e^{\left(\frac{E-E_F}{kT}\right)}} = \frac{1}{1+e^{\left(\frac{-0.012}{8.625\times10^{-5}\times300}\right)}}$$

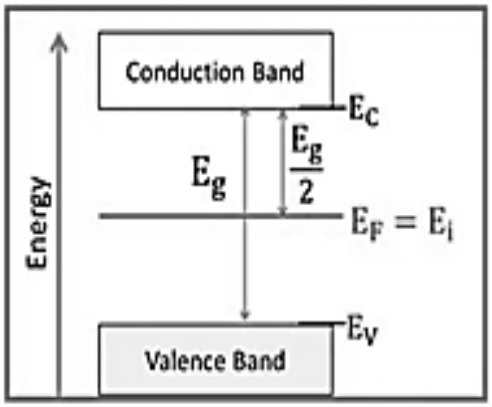
$$= 0.614$$

What is the probability of an electron being thermally excited to conduction band in intrinsic Si at 27 ^{0}C. The band gap energy of Si is 1.12 eV.

Given : T = 27 ^{0}C = 300 ^{0}K, $k = 8.625 \times 10^{-5} \frac{eV}{^0K}$, $E_g = 1.12$ eV

For intrinsic semiconductor $E_F = \frac{E_C + E_V}{2}$

$$\therefore E_C - E_F = \frac{E_g}{2} = \frac{1.12}{2} = 0.56 \text{ eV}$$



$$\therefore \text{Probability of occupancy} = f(E_C) = \frac{1}{1+e^{\left(\frac{E_C - E_F}{kT}\right)}}$$

$$= \frac{1}{1+e^{\left(\frac{0.56}{8.625\times10^{-5}\times300}\right)}}$$

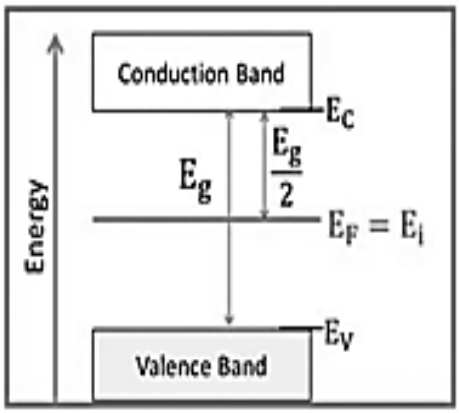
$$= 3.99 \times 10^{-10}$$

What is the probability of an electron being thermally promoted to conduction band in diamond at 27^{0}C if band gap is 5.6 eV wide.

Given . T = 27 ^{0}C = 300 ^{0}K, $k = 8.625 \times 10^{-5} \frac{eV}{^0K}$, $E_g = 5.6$ eV

For diamond, $E_F = \frac{E_C + E_V}{2}$

$$\therefore E_C - E_F = \frac{E_g}{2} = \frac{5.6}{2} = 2.8 \text{ eV}$$



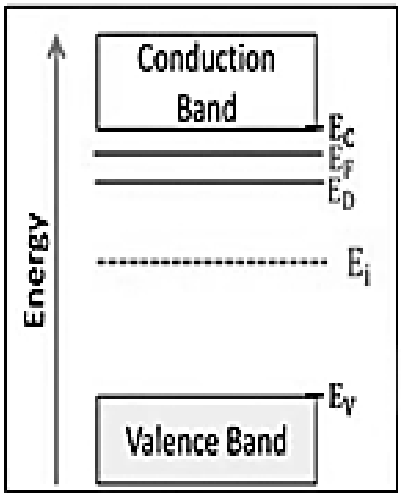
$$\therefore \text{Probability of occupancy} = f(E_C) = \frac{1}{1+e^{\left(\frac{E_C - E_F}{kT}\right)}}$$

$$= \frac{1}{1+e^{\left(\frac{2.8}{8.625\times10^{-5}\times300}\right)}}$$

$$= 1.09 \times 10^{-47}$$

In an n-type semiconductor, the Fermi level lies 0.4 eV below the conduction band. If the concentration of donor atoms is doubled, find the new position of the Fermi level w.r.t. conduction band.

Given : $E_C - E_F = 0.4$ eV



Temperature is not mentioned.
Let us assume T = 300 K

Electron concentration is given by

$$n = N_C e^{-(E_C - E_F)/kT} \quad (1)$$

When donor concentration is doubled, electron concentration will also get doubled and fermi level will be shifted to E_{F2}

$$2n = N_C e^{-(E_C - E_{F2})/kT} \quad (2)$$

Divide (2) by (1)

$$\frac{e^{-(E_C - E_{F2})/kT}}{e^{-(E_C - E_F)/kT}} = 2$$

$$\therefore e^{\frac{-(E_C - E_{F2}) + (E_C - E_F)}{kT}} = 2$$

$$\therefore -(E_C - E_{F2}) + (E_C - E_F) = kT \ln(2)$$

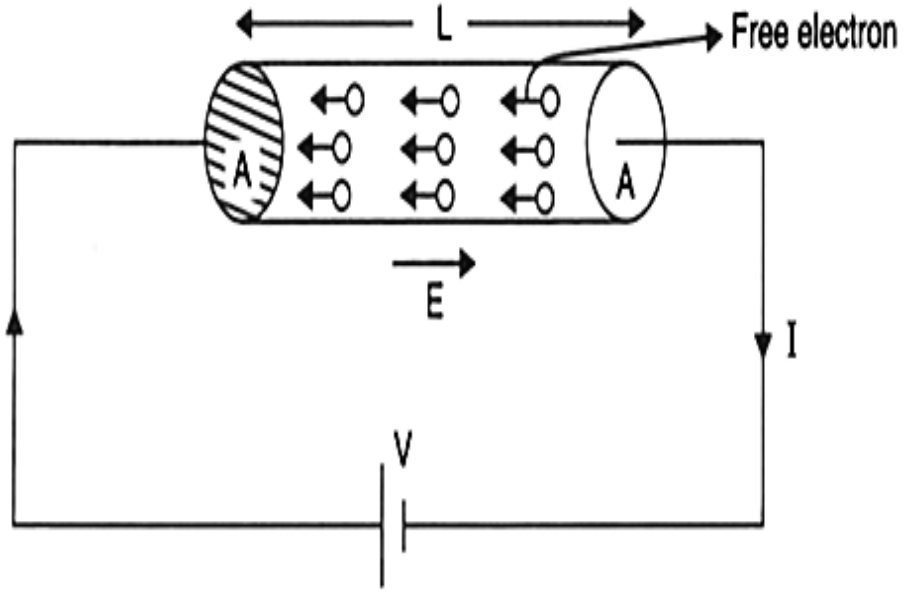
$$\therefore (E_C - E_{F2}) = (E_C - E_F) - kT \ln(2)$$

$$\therefore (E_C - E_{F2}) = 0.4 - 8.625 \times 10^{-5} \times 300 \ln(2)$$

$$\therefore (E_C - E_{F2}) = 0.382 \text{ eV}$$

So, The Fermi level shifts towards the Conduction band as donor concentration increases.

DRIFT CURRENT:-



In metals large numbers of free electrons are present. There is force of repulsion between these electrons. These free electrons are colliding with each other and with the atoms of the material and rebound in various directions. The motion of electrons is equivalent to Brownian motion.

When external field E is applied, the electrons are accelerated in the direction of applied field and acquire certain velocity known as driftvelocity. The applied electric field does not stop the collision of electrons with the atoms and renounce in various directions, but the electrons are drifted in the direction of applied field and constitute an electric current. This current is known as drift current. The drift velocity per unit electric field is known as mobility of charge carriers. The SI unit of mobility is m^2 / volt.Second. The mobility of electrons is greater than holes.

If n – density of free electrons

e - electron charge.

Ve – drift velocity of electrons.

A – area of cross section

Therefore drift current, $I = n\ e\ V_e\ A$

If E is applied electric field, the mobility of electrons $\mu_e = V_e / E$

$$V_e = \mu_e E$$

$$I = n\ e\ \mu_e E\ A$$

Drift current density, $\mathbf{J_{n(drift)} = I / A = n\ e\ \mu_e E}$

The equation of conductivity with current flow:

Conductivity Equation:

The conductivity (σ) of a material is related to the current flow (I) by the following equation:

$$\sigma = I / (E * A)$$

Where:

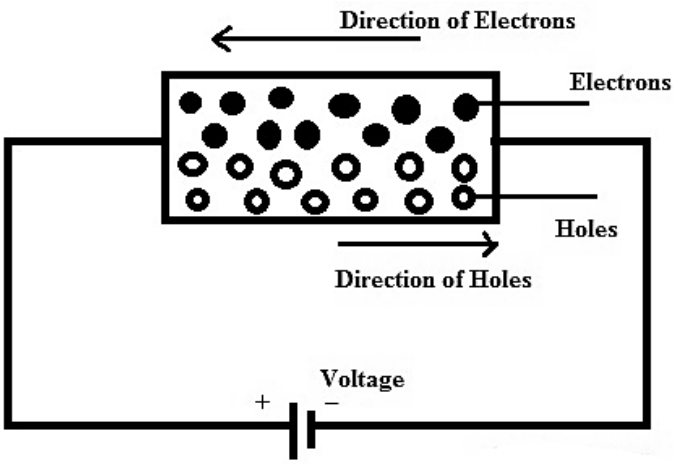
σ is the conductivity of the material

I is the current flowing through the material

E is the electric field strength

A is the cross-sectional area of the material

CURRENT CONDUCTION IN SEMICONDUCTOR:-



Consider a piece of intrinsic semiconductor of length l and area of cross section A. If V is the P.D. applied across the semiconductor, then current flows through the semiconductor is due to motion of electrons and holes in opposite direction.

The current flows though the external circuit is due to electrons only. Therefore total current flowing through the semiconductor is

$I = I_e + I_h$ ---------- (1)

If n – density of free electrons

e - electron charge.

Ve – drift velocity of electrons.

A – area of cross section

Therefore drift current, $I = n e V_e A$

If E is applied electric field, **the mobility of electrons** $\boxed{\mu_e = V_e / E}$

$V_e = \mu_e E$

$I_e = n e \mu_e E A$

Similarly, $I_h = p e \mu_h E A$

Therefore, eqn.(1)=> $I = n e \mu_e E A + p e \mu_h E A$

But in intrinsic semiconductor n = p = ni intrinsic carrier density

$I = n_i e(\mu_e + \mu_h) E A$

Current density $\boxed{J = I / A = n_i e(\mu_e + \mu_h) E}$

But $E = V / l$

$I = n_i e(\mu_e + \mu_h) (V / l) A$

$$V / I = (1 / ni e(\mu e + \mu h) \ l / A$$

$$R = \rho (l / A)$$

$\boxed{\rho = 1 / nie(\mu_e + \mu_h)}$ resistivity of semiconductor.

Reciprocal of resistivity is conductivity, $\boxed{\sigma = 1 / \rho = nie(\mu_e + \mu_h)}$

Find resistivity of Ge at 300 ^{0}K. Given density of carriers is 2.5 x 10^{19} / m^3. Mobility of electrons is 0.39 m^2/V-sec, mobility of holes = 0.19 m^2/V-sec.

Given : $n_i = 2.5 \times 10^{19} / m^3$,

$\mu_e = 0.39\ m^2/V\text{-sec}$, $\mu_h = 0.19\ m^2/V\text{-sec}$

For intrinsic semiconductor, conductivity is given by –

$$\sigma_i = n_i\, e\, (\mu_e + \mu_h)$$

$$= 2.5 \times 10^{19} \times 1.6 \times 10^{-19} (0.39 + 0.19)$$

$$= 2.32\ (\Omega - m)^{-1}$$

$$\text{Resistivity } = \rho = \frac{1}{\sigma} = \frac{1}{2.32} = 0.43\ \Omega - m$$

The resistivity of intrinsic InSb at room temperature is 2×10^{-4} ohm-cm. If the mobility of electron is 6 m^2/V-s and mobility of hole is 0.2 m^2/V-s, calculate its intrinsic carrier density.

Given : Resistivity $\rho = 2 \times 10^{-4}$ ohm $-$ cm $= 2 \times 10^{-6}$ ohm $-$ m

$\mu_e = 6 \frac{m^2}{Vsec}$, $\mu_h = 0.2 \frac{m^2}{Vsec}$, $n_i = ?$

For intrinsic semiconductor, conductivity is given by – $\sigma = \frac{1}{\rho} = n_i e(\mu_e + \mu_h)$

$$\therefore n_i = \frac{1}{\rho\, e\, (\mu_e + \mu_h)}$$

$$\therefore n_i = \frac{1}{2 \times 10^{-6} \times 1.6 \times 10^{-19} \times (6 + 0.2)} = 5.04 \times 10^{23}\ /m^3$$

The resistivity of intrinsic InSb at room temperature is 2×10^{-4} ohm-cm. If the mobility of electron is 6 m^2/V-s and mobility of hole is 0.2 m^2/V-s, calculate its intrinsic carrier density.

Given : Resistivity $\rho = 2 \times 10^{-4}$ ohm $-$ cm $= 2 \times 10^{-6}$ ohm $-$ m

$\mu_e = 6 \frac{m^2}{Vsec}$, $\mu_h = 0.2 \frac{m^2}{Vsec}$, $n_i = ?$

For intrinsic semiconductor, conductivity is given by – $\sigma = \frac{1}{\rho} = n_i e(\mu_e + \mu_h)$

$$\therefore n_i = \frac{1}{\rho\, e\, (\mu_e + \mu_h)}$$

$$\therefore n_i = \frac{1}{2 \times 10^{-6} \times 1.6 \times 10^{-19} \times (6 + 0.2)} = 5.04 \times 10^{23}\ /m^3$$

Calculate the number of donor atoms which must be added to an intrinsic semiconductor to obtain the resistivity as 10^{-6} ohm-cm. Use mobility of electron = 1000 cm^2/V-sec.

Given : $\mu_e = 1000\ cm^2/V\text{-}sec$, Resistivity $\rho = 10^{-6}\ \Omega - cm$

$N_d = ?$

For n-type semiconductor, conductivity is given by – $\sigma = n\, e\, \mu_e = N_d\, e\, \mu_e$

$$\therefore N_d = \frac{\sigma}{e\, \mu_e} = \frac{1}{\rho\, e\, \mu_e} = \frac{1}{10^{-6} \times 1.6 \times 10^{-19} \times 1000} = 6.25 \times 10^{21}\ /cm^3$$

6.25×10^{21} donor atoms must be added per cm^3

Find resistivity of Copper assuming that each atom contributes one free electron for conduction. Given density of Cu = 8.96 gm / cm^3, atomic weight = 63.5, Avogadro's Number = 6.023×10^{23} / gm-mol, Mobility of electron = 43.3 cm^2/V-sec.

Given : μ_e = 43.3 cm^2/V-sec, density ρ = 8.96 gm/cm^3, Atomic weight =63.5

Resistivity = ?

In 63.5 gm there are 6.023×10^{23} atoms

Number of atoms per unit volume (i.e. in 8.96 gm) will be –

$$\text{Atomic density} = \frac{8.96 \times 6.023 \times 10^{23}}{63.5} = 8.4985 \times 10^{22} \text{ /cm}^3$$

each atom contributes one free electron

$$\therefore \text{ electron concentration} = n = 1 \times \text{Atomic density} = 8.4985 \times 10^{22} \text{ /cm}^3$$

Resistivity is given by –

$$\rho = \frac{1}{\sigma} = \frac{1}{n\, e\, \mu_e} = \frac{1}{8.4985 \times 10^{22} \times 1.6 \times 10^{-19} \times 43.3} = 1.698 \times 10^{-6} \Omega - \text{cm}$$

Calculate conductivity of a germanium sample if donor impurity atoms are added to the extent of one part in 10^8 germanium atoms at room temperature. Assume that only one electron of each atom takes part in conduction process. Avogadro's number = 6.023×10^{23} / gm-mol, Density of Ge = 5.32 gm / cm^3 Atomic weight of Ge =72.6, mobility of electrons = 3800 cm^2/volt-sec

72.6 gm Ge contains 6.023×10^{23} atoms

$\therefore$ 5.32 gm i.e. 1 cm^3 will have $\frac{6.023 \times 10^{23}}{72.6} \times 5.32 = 4.41 \times 10^{22}$ atoms

As donor impurity is 1 part in 10^8, donor concentration, $Nd = \frac{4.41 \times 10^{22}}{10^8}$

$= 4.41 \times 10^{14} / cm^3$

As only one electron of each donor atom takes part in conduction,

electron concentration $= n = 4.41 \times 10^{14} / cm^3$

Now, conductivity, $\sigma = n\, e\, \mu_e = 4.41 \times 10^{14} \times 1.6 \times 10^{-19} \times 3800 = 0.268 \text{ /}\Omega\text{cm}$

❖ **The intrinsic carrier density of a semiconductor is 2.1×10^{19} m^{-3}. The electron and hole mobilities are 0.4 and 0.2 $m^2 V^{-1} s^{-1}$ respectively. Calculate the conductivity.**

Solution:

Given data:

Intrinsic carrier concentration $n_i = 2.1 \times 10^{19}\ m^{-3}$

Mobility of electron $\mu_e = 0.4\ m^2 V^{-1} s^{-1}$

Mobility of hole $\mu_h = 0.2\ m^2 V^{-1} s^{-1}$

Conductivity $\sigma = n_i e (\mu_e + \mu_h)$

$= 2.1 \times 10^{19} \times 1.6 \times 10^{-19} \times (0.4 + 0.2)$

Conductivity $\sigma = 2.016\ \Omega^{-1} m^{-1}$

13. The electron mobility and hole mobility in Si are 0.135 $m^2 V^{-1} s^{-1}$ and 0.048 $m^2 V^{-1} s^{-1}$ respectively at room temperature. If the carrier concentration is 1.5×10^{16} m^{-3}. Calculate the resistivity of Si at room temperature.

Solution:

Given data:

Carrier concentration $n_i = 1.5 \times 10^{16}\ m^{-3}$

Mobility of electron $\mu_e = 0.135\ m^2 V^{-1} s^{-1}$

Mobility of hole $\mu_h = 0.048\ m^2 V^{-1} s^{-1}$

i) Electrical Conductivity σ

$\sigma = n_i e (\mu_e + \mu_h)$

$= 1.5 \times 10^{16} \times 1.6 \times 10^{-19} \times (0.135 + 0.048)$

$\sigma = 0.4392 \times 10^{-3}\ \Omega^{-1} m^{-1}$

ii) Resistivity pf silicon

$$\rho = \frac{1}{\sigma}$$

$$= \frac{1}{0.4392 \times 10^{-3}}$$

$\rho = 2.2768\ \Omega\ m$

10. Find the resistance of an intrinsic Ge rod 1 mm long, 1 mm wide and 1 mm thick at 300 K. the intrinsic carrier density 2.5 ×1019 m^{-3} is at 300 K and the mobility of electron and hole are 0.39 and 0.19 $m^2 v^{-1} s^{-1}$.

Solution:

Given:

Length of Ge rod $l = 1mm = 1 \times 10^{-3}$ m

Breath $b = 1mm = 1 \times 10^{-3}$ m

Thickness $t = 1mm = 1 \times 10^{-3}$ m

Intrinsic carrier concentration $n_i = 2.5 \times 10^{19}\ m^{-3}$

Mobility of electron $\mu_e = 0.39\ m^2\ v^{-1}\ s^{-1}$

Mobility of hole $\mu_h = 0.19\ m^2\ v^{-1}\ s^{-1}$

a) Conductivity

$$\sigma = n_i e(\mu_e + \mu_h)$$

$$= 2.5 \times 10^{19} \times 1.6 \times 10^{-19}(0.39 + 0.19)$$

$$\sigma = 2.32\ \Omega^{-1}\ m^{-1}$$

b) Resistance

$$R = \frac{\ell}{\sigma A}$$

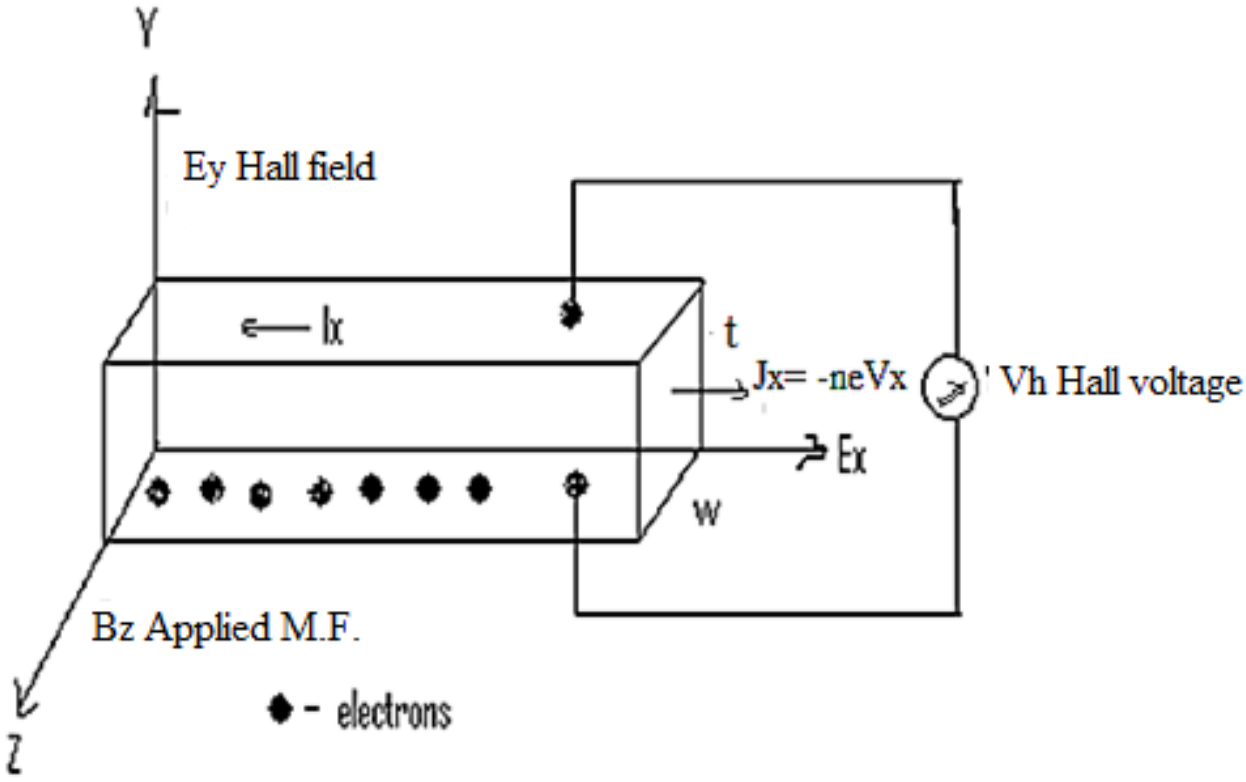
$$= \frac{1 \times 10^{-3}}{2.32 \times \left(1 \times 10^{-3}\ 1 \times 10^{-3}\right)} \qquad \therefore\ (A = b \times t)$$

$$R = 431\ \Omega$$

HALL EFFECT:-

Q. What is Hall Effect? Give its applications?

Q. Explain the Hall Effect? How it is used to measure the concentration (density) & mobility of the charge carriers?



"If a conductors (metal or semiconductor) carrying an electric current is kept in magnetic field, then an electric field is produced in the conductor which is perpendicular to both the direction of electric current and applied magnetic field".

Consider a piece of metal carrying an electric current kept in a magnetic field.

If t – thickness and w – width of metal piece.

Ex – applied electric field along X-axis.

Jx – current density along + ve X direction.

Ix - current flowing along X- axis.

Bz – apllied magnetic field along Z – axis.

Vx – drift velocity of electrons along – ve X- axis.

The force acting on the electrons due to magnetic field Bz is

$$F = Bz\ e\ Vx$$

This force is known as Lorentz force. The direction of this force is along – ve Y- axis.

Due to this force, the free electrons in the metal are collected on the bottom surface of the metal and equal deficiency of electrons will produce on the top surface of the metal piece. Thus an electric field Ey is produced along Y-axis. This field is known as Hall field.

The force acting on the electrons due to Hall field Ey is`

$$F = e\,Ey$$

The direction of this force is along + ve Y- axis.

At equilibrium, force due to E.F. = force due to M.F.

$$eEy = Bz\,e\,Vx$$

$$Ey = VxBz \quad \text{---------- (1)}$$

The current density along X- axis is $Jx = - n\,e\,Vx$

$$Vx = - Jx / n\,e$$

Keep this value in equation (1)

$$Ey = (-Jx/ne)\,Bz$$

But $\boxed{R_H = - 1/ne}$ known as Hall coefficient. The measurement of Hall coefficient gives the sign of the charge carriers and density of charge carriers in the material.

$$Ey = R_H JxBz \quad \text{---------- (2)}$$

If V_h is Hall voltage across the thickness t, then Hall field $Ey = V_h / t$.

If w is width of sample $J_x = I_x / A = I_x / w \times t$

Equation (2) $\Rightarrow V_h / t = R_H\,(I_x / w \times t)\,Bz$

$$\mathbf{V_h = R_H \left(\frac{Ix}{W}\right) Bz)}$$

$$= \frac{\boldsymbol{Rh\ Ix\ Bz}}{\boldsymbol{W}}$$

$$= \frac{\boldsymbol{Ix\ Bz}}{\boldsymbol{neW}}$$

The drift velocity per unit electric field is known as mobility of charge carriers.

Therefore $\mu_e = Vx / Ex$

$$Vx = \mu_e\,Ex$$

Keep this value in equation (1)

$$Ey = \mu e\ Ex\ Bz \text{----------(3)}$$

Equating equations (2) and (3)

`

$$R_H JxBz = \mu e\ Ex\ Bz$$

$$\mu_e = R_H J_x / E_x$$

$$J_x / E_x = \sigma \text{ conductivity of material.}$$

$$\boxed{\mu_e = R_H \sigma}$$

This equation is used to determine the mobility of charge carriers.

Applications of Hall Effect:-

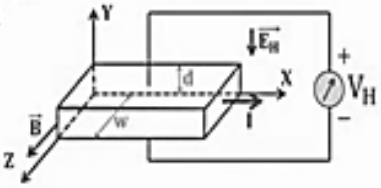
1) To determine the sign of the charge carriers.
2) To determine the electronic structure of the material, whether the material is conductor, insulator or semiconductor.
3) To determine the concentration of the charge carriers.
4) To determine the mobility of the charge carriers.

n-type Ge sample has donor concentration $10^{21}/m^3$ and thickness = 3 mm is used in a Hall effect experiment set up. If B = 0.5 T, J = 500 A/m^2, Find Hall voltage.

Given : $n = N_d = 10^{21}\ /m^3$ $\quad d = 3 \times 10^{-3}$ m

$B = 0.5\ Wb/m^2$ $\quad J = 500\ A/m^2$

$V_H = ?$



$$V_H = \frac{BI}{new} = \frac{BId}{ne\,wd} = \frac{BId}{neA} = \frac{BJd}{ne}$$

$$= \frac{0.5 \times 500 \times 3\times10^{-3}}{10^{21} \times 1.6 \times 10^{-19}} = 4.688\times10^{-3} \text{ volts}$$

The mobility of hole is $\mu_h = 0.025 \frac{m^2}{V-sec}$. What would be the resistivity of p-type silicon if the Hall coefficient of the sample is $2.25 \times 10^{-5}\ m^3/C$?

Given : $R_H = \frac{1}{pe} = 2.25 \times 10^{-5}\ m^3/C$ $\mu_h = 0.025 \frac{m^2}{V-sec}$

Resistivity = ρ =?

For p-type semiconductor, conductivity is given by – $\sigma = p\, e\, \mu_h$

$$\therefore \text{Resistivity} = \rho = \frac{1}{\sigma} = \frac{1}{p\, e\, \mu_h} = R_H \frac{1}{\mu_h}$$

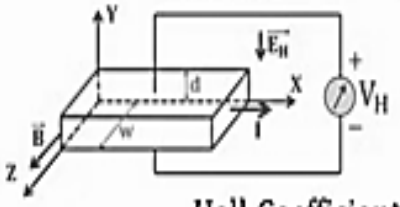
$$= 2.25 \times 10^{-5} \times \frac{1}{0.025}$$

$$= 9 \times 10^{-4}\ \Omega - m$$

In a Hall effect experiment, a potential difference of 4.5 μV is developed across a foil of zinc of thickness 0.02 mm, while carrying a current of 1.5 A in a direction perpendicular to applied magnetic field of 2 tesla. Calculate a) Hall coefficient for zinc b) concentration of electrons.

Given : $V_H = 4.5\ \mu V = 4.5 \times 10^{-6} V$ $I = 1.5\ A$ $B = 2\ T$

thickness = $w = 0.02mm = 0.02 \times 10^{-3} m$ R_H =? n =?



As $V_H = \frac{B\, I}{n\, e\, w}$

$$\text{Hall Coefficient} = R_H = \frac{1}{n\, e} = \frac{V_H\, w}{B I} = \frac{4.5 \times 10^{-6} \times 0.02 \times 10^{-3}}{2 \times 1.5} = 3 \times 10^{-11} \frac{m^3}{C}$$

$$\text{Concentration of electrons} = n = \frac{B\, I}{V_H\, e\, w}$$

$$= \frac{2 \times 1.5}{4.5 \times 10^{-6} \times 1.6 \times 10^{-19} \times 0.02 \times 10^{-3}} = 2.083 \times 10^{29}\ /m^3$$

- Semiconducting crystal with 12 mm long, 5 mm wide and 1 mm thick has a magnetic density of 0.5 Wbm^{-2} applied from front to back perpendicular to largest faces. When a current of 20 mA flows length wise through the specimen, the voltage measured across its width is found to be $37\mu V$. What is the Hall coefficient of this semiconductor?

Solution:

Given:

$$\text{Hall voltage} \quad V_H = 37\ \mu V = 37 \times 10^{-6}\ V$$

$$\text{Breath of the material} \quad t = 1\ mm = 1 \times 10^{-3}\ m$$

$$\text{Current} \quad I_H = 20\ mA = 20 \times 10^{-3}\ A$$

Magnetic flow density

$$B = 0.5\ Wbm^{-2}$$

$$\text{Hall coefficient} \quad R_H = \frac{V_H t}{I_H B}$$

$$= \frac{37 \times 10^{-6} \times 1 \times 10^{-3}}{20 \times 10^{-3} \times 0.5}$$

$$R_H = 3.7 \times 10^{-6}\ C^{-1}\ m^3$$

$$\therefore \quad \text{Hall coefficient } R_H = 3.7 \times 10^{-6}\ C^{-1}\ m^3$$

❖ Hall coefficient of a specimen of depend silicon found to be 3.66×10^{-4} m^3 C^{-1}. The resistivity of the specimen is 8.93×10^{-3} m. Find the mobility and density of the charge carriers.

Solution:

Hall coefficient $R_H = 3.66 \times 10^{-4}\ m^3\ C^{-1}$

Resistivity $\rho = 8.93 \times 10^{-3}\ \Omega m$

i) Density of holes

$$n_h = \frac{1}{R_H e}$$

$$= \frac{1}{3.66 \times 10^{-4} \times 1.6 \times 10^{-19}}$$

$$n_h = 1.7076 \times 10^{22}\ m^{-3}$$

ii) Mobility of holes $\mu_n = \frac{1}{\rho ne}$

$$= \frac{1}{8.93 \times 10^{-3} \times 1.7076 \times 10^{22} \times 1.6 \times 10^{-19}}$$

$$\mu_n = 0.041\ m^2\ V^{-1}\ s^{-1}$$

What are the basic steps used to derive the Fermi-Dirac distribution?

What is the physical significance of the Fermi energy?

How does the position of Fermi level with respect to band structure?

Describe the two types of semiconductors and contrast their conduction mechanism.

Why Does the Resistivity of Semiconductors Go Down with Temperature?

With neat sketches, explain how Fermi level varies with impurity concentration and temperature in both p-type and n-type semiconductors.

What is Hall Effect? Describe an experimental arrangement to measure the Hall coefficient.

Assuming the Fermi-Dirac distribution, derive or State an expression for the concentration of electrons per unit volume in conduction band of an intrinsic semiconductor.

State Limitations of intrinsic semiconductor.

Give its importance of Fermi energy. Write down expression for Fermi Distribution function.

Give the expression for the carrier concentration in semiconductor.

Why? Silicon is widely used to manufacture the elemental device Compared with Germanium.

Draw the graph for variation of Fermi level with temperature in p -type semiconductor.

Define Fermi level in case of semiconductors. Mention its position in intrinsic and extrinsic semiconductors at 0 k.

What is Fermi level? Prove that the Fermi level is lies exactly in between conduction band and valance band of intrinsic semiconductor.

What are the properties of semiconductor?

What is intrinsic semiconductor and explain formation of extrinsic semiconductors through doping?

Derive expression for current generated due to drifting of charge carriers in semiconductors in the presence of electric field.

Obtain the conductivity of intrinsic semiconductor with relevant expressions?

Distinguish between intrinsic and extrinsic semiconductors?

Explain effect of temperature on Fermi energy level of an extrinsic semiconductor?

Explain the role of density states.

What do you understand by extrinsic semiconductor.

Draw the energy level diagram to show effect of temperature and effect of impurity concentration in P and N-type semiconductors.

Explain How to calculate Hall voltage?

State at least any four applications of the Hall Effect?

Why is Silicon preferred over germanium in the manufacture of semiconductor devices?

Explain application of Hall voltage?

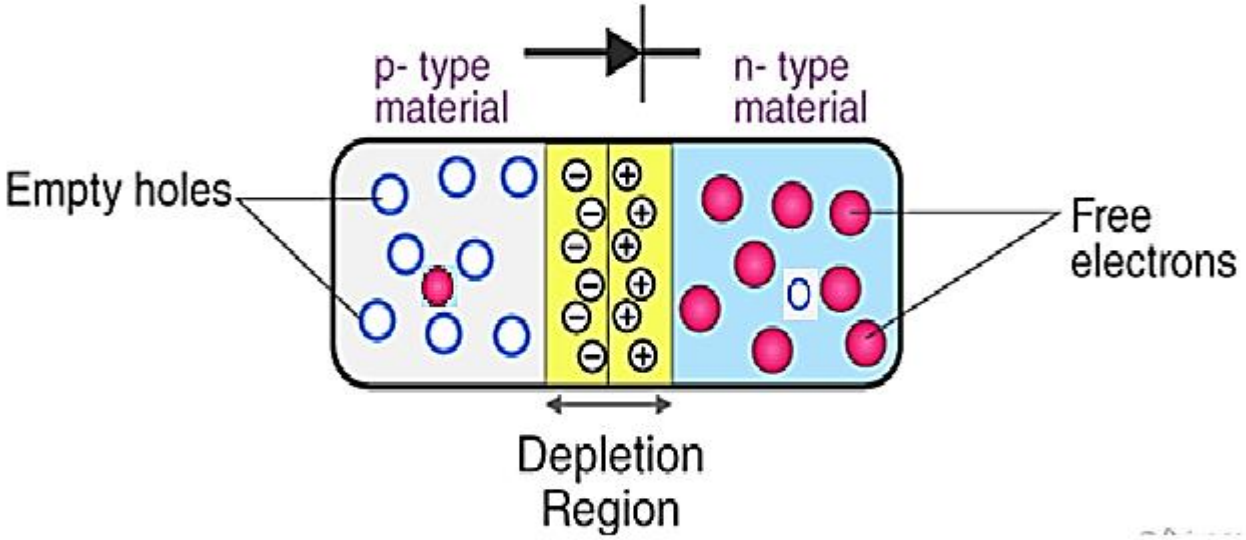
Module 2

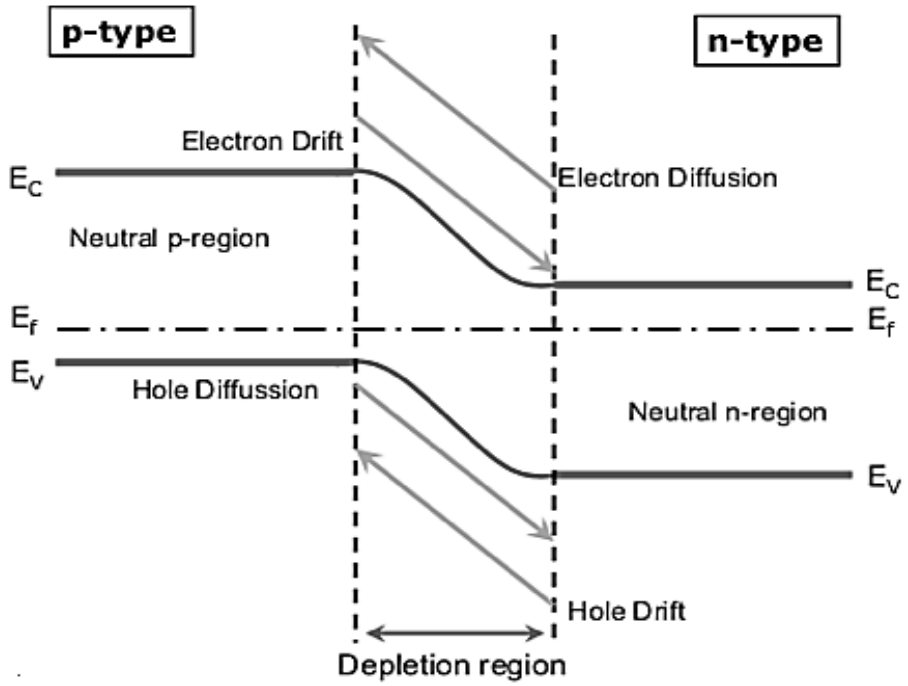
JUNCTION DIODE

JUNCTION DIODE

Formation of p-n junction, calculation of barrier potential, Diode equation, p-n junction in forward Bias, p-n junction in Reverse bias, Current- voltage curve for p-n junction diode, LED and its working.

Formation of PN junction:





1) When P- type and N-type semiconductors are joined together by diffusion method, then it is called P-N junction.
2) In P-type semiconductor majority charge carriers are holes and in N-type semiconductor majority charge carriers are electrons. Due to thermal excitation during formation of P-N junction some minority charge carriers are produced in the P-type and N-type region.
3) During formation of P-N junction, the electrons and holes crossover the junction and recombine with each other to become neutral.
4) The pentavalent impurity atoms donates it valence electron and become + vely charged ions in N-type region, while trivalent atoms gains an extra nuclear electrons and become – vely charged ions in P-type region. These ions are immobile and bounded to the crystal lattice.
5) A layer of +vely charged ions is formed towards N-type region and layer of –vely charged ions is formed towards P-type region. This region is known as depletion region.
6) Due to charge separation, a small P.D. is developed at the junction, known as barrier potential. The height of the barrier potential continuously increased by the recombination of electrons and holes and after some time further recombination of electrons and holes is not possible. The resultant device is known as diode.
7) The barrier potential for Ge diode is 0.3 V, while for Si diode it is 0.6 V.
8) The width of the depletion region depends on the voltage applied to the diode.
9) The width of depletion region is given by

$$W = 2\,\varepsilon\,(V_b + V_a)\,e\,Na\,Nd$$

Where:

- W is the width of the depletion region in meters
- ε is the permittivity of the semiconductor material in farads per meter
- V_b is the barrier potential of the PN junction in volts
- V_a is the applied voltage in volts
- e is the electron charge in coulombs
- N_a is the doping concentration of the P-type material in atoms per cubic meter
- N_d is the doping concentration of the N-type material in atoms per cubic meter

The PN junction formula can be used to design PN junctions with specific properties. For example, the doping concentrations can be adjusted to control the width of the depletion region, and the applied voltage can be used to control the current flow through the PN junction

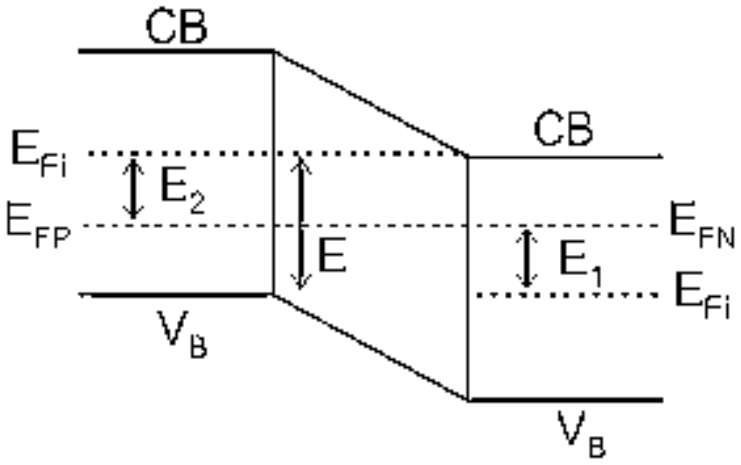
10) The diode conducts an electric current only in one direction during forward bias condition. PN junction diodes are versatile and important semiconductor devices that are used in a wide variety of applications.

Applications of P-N Junction Diode

- P-N junction diode can be used as a photodiode as the diode is sensitive to the light when the configuration of the diode is reverse-biased.
- It can be used as a solar cell.
- When the diode is forward-biased, it can be used in LED lighting applications.
- It is used as rectifier in many electric circuits and as a voltage-controlled oscillator in varactors.

Calculation of barrier potential:

The electric field established in the depletion region creates a potential barrier that opposes further diffusion of charge carriers. This potential difference is known as the **built-in potential or barrier potential (Vbi).**



$$Vbi = \frac{E1+E2}{e} \text{ -------- (1)}$$

ni – Intrinsic carrier concentration in cm^3

NA - doping concentration of P side in cm^3

ND – doping concentrations of N side in cm^3

E_{Fi} = intrinsic Fermi level

E_{FP} = Fermi level of P-type

E_{FN} = fermi level of n-types

$$E_1 = E_{FN} - E_{Fi} = KT \ln\left(\frac{N_D}{n_i}\right)$$

$$E_2 = E_{Fi} - E_{FP} = KT \ln\left(\frac{N_A}{n_i}\right)$$

Substitute the calculated values of E1 and E2 in equation (1)

$$\text{Vbi} = \frac{\text{KT X} \log \frac{\text{NA}}{\text{ni}} + \text{KT X} \log \frac{\text{ND}}{\text{ni}}}{\text{e}}$$

$$V_{bi} = \frac{KT}{\text{e}} \ln\left(\frac{N_A N_D}{n_i^2}\right)$$

Diode Equation:

The diode equation is a mathematical model that describes the behavior of a diode. It relates the voltage across the diode (Vd) to the current flowing through it (Id). The ideal diode equation is

$$\mathbf{Id = Io\ e^{\left(\frac{Vd}{ήVt} - 1\right)}}$$

Where:

Id is the diode current

Io is the reverse saturation current (a very small value)

Vd is the voltage across the diode

Vt = KT/q is the thermal voltage (approximately equal to 25.85 mV at room temperature 300 K)

ή is the ideality factor, also known as the quality factor, emission coefficient, or the material constant. (ή =1 for Ge & ή = 2 for SI)

Thermal voltage $\text{Vt} = \frac{\text{KT}}{\text{q}} = \frac{\text{T}}{11600}$ volt

For most practical purposes, the diode equation can be simplified to:

$$\mathbf{Id = Is\ e^{\left(\frac{Vd}{\eta Vt}\right)}}$$

This simplified equation assumes that the reverse saturation current (Is) is very small.

Important Points:

1. The diode equation is a non-linear equation, meaning that the current through the diode does not increase linearly with the voltage across it.
2. The thermal voltage (Vt) is a critical parameter in the diode equation, as it affects the shape of the current-voltage curve.
3. The diode equation is widely used in electronic circuit design and analysis, particularly in the study of diode circuits, rectifiers, and power supplies.

Biasing Conditions of PN Junction Diode

A PN junction diode is a semiconductor device that allows current to flow in one direction only. This is due to the different types of materials used in the construction of the diode. The P-type material has a majority of holes, while the N-type material has a majority of electrons. When these two materials are brought into contact, the electrons from the N-type material diffuse into the P-type material, and the holes from the P-type material diffuse into the N-type material. This creates a region of depletion, or space charge, around the junction.

The width of the depletion region depends on the voltage applied to the diode. When no voltage is applied, the depletion region is very narrow. As the voltage is increased, the depletion region widens. This is because the electric field created by the voltage pushes the electrons and holes away from the junction.

The biasing conditions of a PN junction diode refer to the different ways in which a voltage can be applied to the diode. There are three main biasing conditions:

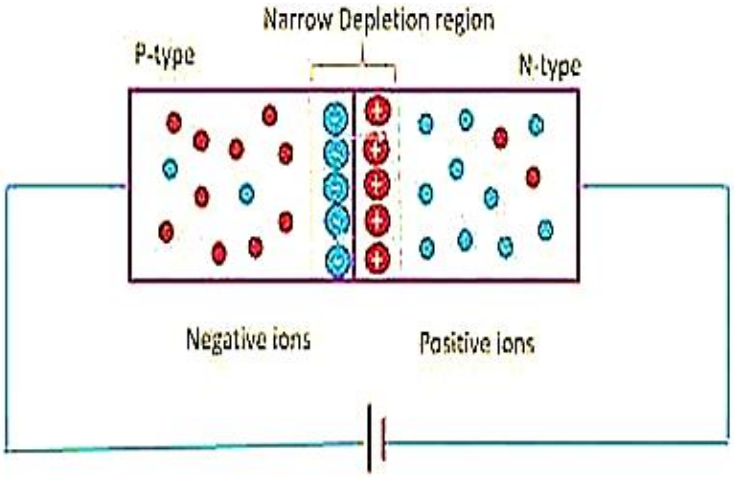
- **Forward bias:** In forward bias, the positive terminal of the voltage source is connected to the P-type material, and the negative terminal is connected to the N-type material. This causes the depletion region to narrow, and current flows easily through the diode.
- **Reverse bias:** In reverse bias, the positive terminal of the voltage source is connected to the N-type material, and the negative terminal is connected to the P-type material. This causes the depletion region to widen, and current does not flow through the diode.

- **Zero bias:** In zero bias, no voltage is applied to the diode. The depletion region is very narrow, and a small amount of current flows through the diode.

The biasing conditions of a PN junction diode have a significant impact on its operation. In forward bias, the diode acts as a conductor, while in reverse bias, it acts as an insulator. This makes the PN junction diode a very versatile device that can be used in a variety of applications.

The behavior of PN junction when it is (I) Forward Biased (II) Reverse Biased

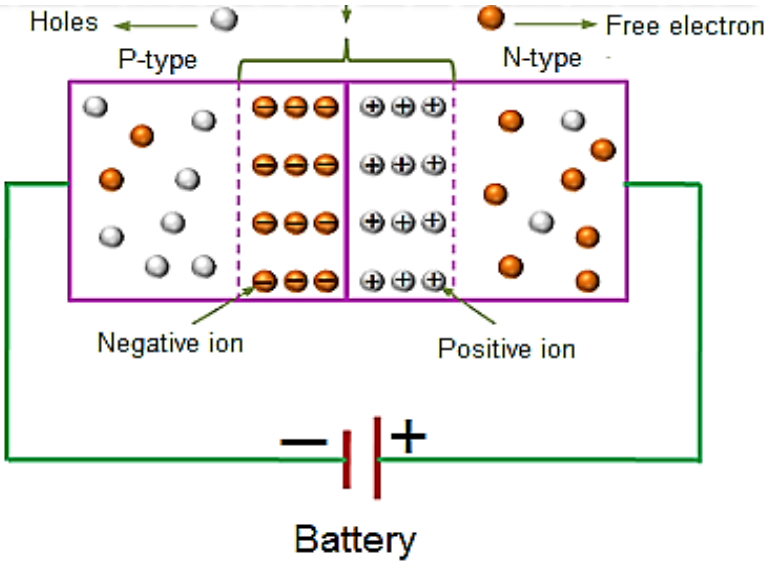
Forward Bias:



In forward bias, the p-type is connected with the positive terminal and the n-type is connected with the negative terminal. ith a battery connected this way, the holes in the P-type region and the electrons in the N-type region are pushed toward the junction. This reduces the width of the depletion zone.

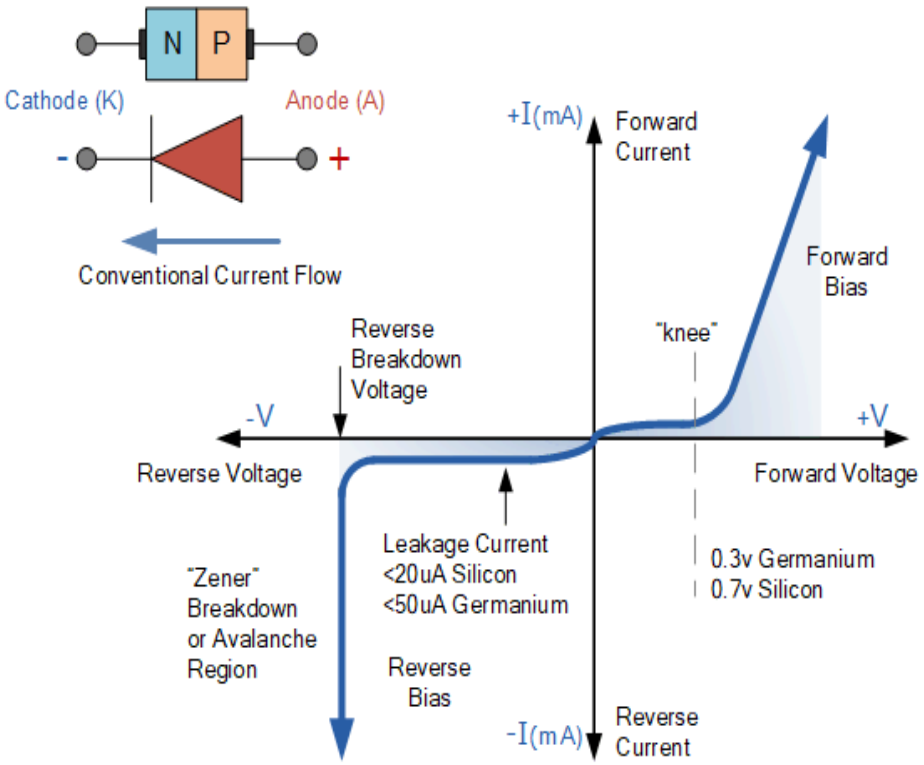
The positive potential applied to the P-type material repels the holes, while the negative potential applied to the N-type material repels the electrons. As electrons and holes are pushed toward the junction, the distance between them decreases. This lowers the barrier in potential. With increasing forward-bias voltage, the depletion zone eventually becomes thin enough that the zone's electric field cannot counteract charge carrier motion across the p–n junction, as a consequence reducing electrical resistance. The electrons that cross the p–n junction into the P-type material (or holes that cross into the N-type material) will diffuse in the near-neutral region. Therefore, the amount of minority diffusion in the near-neutral zones determines the amount of current that may flow through the diode.

Reverse Bias:



Connecting the P-type region to the negative terminal of the battery and the N-type region to the positive terminal corresponds to reverse bias. If a diode is reverse-biased, the voltage at the cathode is comparatively higher than the anode. Therefore, no current will flow until the diode breaks down. Because the p-type material is now connected to the negative terminal of the power supply, the 'holes' in the P-type material are pulled away from the junction, causing the width of the depletion zone to increase. Likewise, because the N-type region is connected to the positive terminal, the electrons will also be pulled away from the junction. Therefore, the depletion region widens, and does so increasingly with increasing reverse-bias voltage. This increases the voltage barrier causing a high resistance to the flow of charge carriers, thus allowing minimal electric current to cross the p–n junction. The increase in resistance of the p–n junction results in the junction behaving as an insulator.

I-V Characteristics of PN junction diode:



The operation of diodes (as with other semiconductor devices) is often described by a special graph called a "characteristic curve". These graphs show the relationship between the currents and voltages associated with the different terminals of the device.

The axes of the graph show both positive and negative values and so intersect at the center. The intersection has a value of zero for both current (the Y axis) and voltage (the X axis). The axes +I and +V (top right) show the current rising steeply after an initial zero current area. This is the forward conduction of the diode when the anode is positive and cathode negative. Initially no current flows until the applied voltage is at about the forward junction potential, after which current rises steeply showing that the forward resistance (I/V) of the diode is very low; a small increase in voltage giving a large increase in current.

The -V and -I axes show the reverse biased condition (bottom left). Here we see that although the voltage increases hardly any current flows. This small current is called the leakage current of the diode and is typically only a few micro-amps with germanium diodes and even less in silicon. If a high enough reverse voltage is applied however there is a point (called the reverse breakdown

voltage) where the insulation of the depletion layer breaks down and a very high current suddenly flows. In most diodes this breakdown is permanent and a diode subjected to this high reverse voltage will be destroyed.

Applications of PN Junction Diode

A PN junction diode is a semiconductor device that allows current to flow in only one direction. This property makes it useful for a variety of applications, including:

1. Rectification

The most common application of a PN junction diode is rectification, which is the process of converting alternating current (AC) to direct current (DC). This is done by allowing current to flow through the diode in one direction only, blocking the flow of current in the opposite direction.

2. Voltage regulation

PN junction diodes can also be used to regulate voltage. This is done by using a diode to limit the voltage that can be applied to a circuit. When the voltage exceeds a certain level, the diode will start to conduct, shunting the excess voltage to ground.

3. Logic gates

PN junction diodes can be used to create logic gates, which are electronic circuits that perform logical operations. Logic gates are used in computers and other digital devices to perform a variety of tasks, such as addition, subtraction, and multiplication.

4. Optoelectronics

PN junction diodes can also be used in optoelectronic devices, which are devices that convert light into electricity or electricity into light. Optoelectronic devices include solar cells, light-emitting diodes (LEDs), and photodiodes.

5. Sensors

PN junction diodes can also be used as sensors. For example, a diode can be used to sense the presence of light, heat, or magnetic fields.

6. Power electronics

PN junction diodes are also used in power electronics, which is the field of electronics that deals with the control and conversion of electrical power. Power electronics devices include rectifiers, inverters, and voltage regulators.

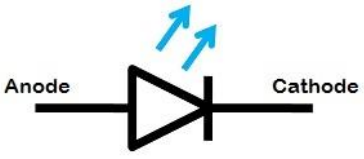
7. Other applications

In addition to the applications listed above, PN junction diodes are also used in a variety of other applications, including:

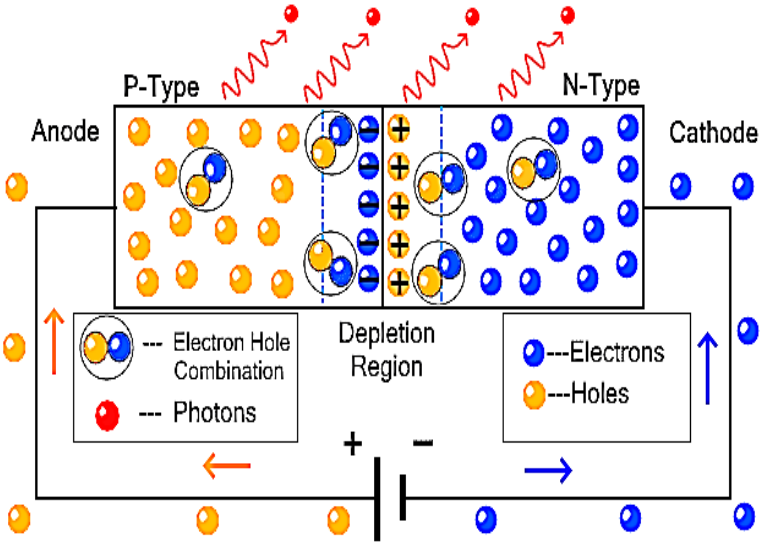
- **Circuit protection:** Diodes can be used to protect circuits from damage caused by overvoltage or overcurrent.
- **Signal processing:** Diodes can be used to process signals, such as clipping, clamping, and filtering.
- **Frequency mixing:** Diodes can be used to mix two or more signals to create a new signal.
- **Voltage multiplication:** Diodes can be used to multiply the voltage of a signal.

Light Emitting Diode:

Light Emitting Diode



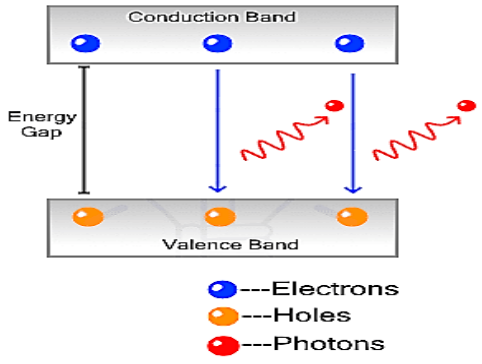
LED Symbol



Working of LED

It is a p-n junction diode which emits light when it is forward biased.

Principle:



Light Emission in LED

The injection of electrons into the p - region from n- region makes a direct transition from the conduction band to valence band. Then, the electrons recombine with holes and emits photons of energy E_g

The forbidden energy gap is given by

$$E_g = h\,v$$

Hence, the wavelength of the emitted photon is given by the relation

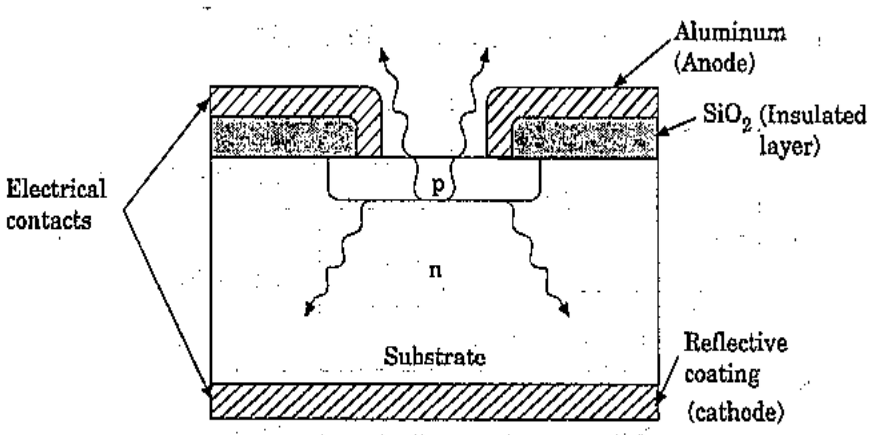
$$\lambda = \frac{hc}{E_g}$$

The wave length of the light emitted purely depends on the band gap energy.

Note: Bandgap energy E_g (generally in eV) should be converted into joule unit. [1 eV $= 1.6 \times 10^{-19}$ J]

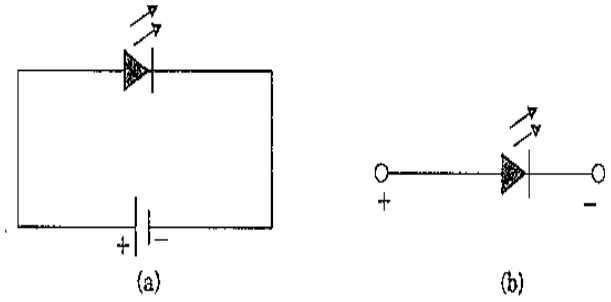
Construction:

A n-type layer is grown on a substrate and a p-type layer is deposited on it by diffusion. Since carrier recombination takes place in the player, it is deposited on the top.



Cross sectional view of LED

For maximum light emission, a metal film anode is deposited at the outer edges of the p-type layer. The bottom of the substrate is coated with a metal (gold) film. It reflects most of the light to the surface of the device and also provides cathode connection.



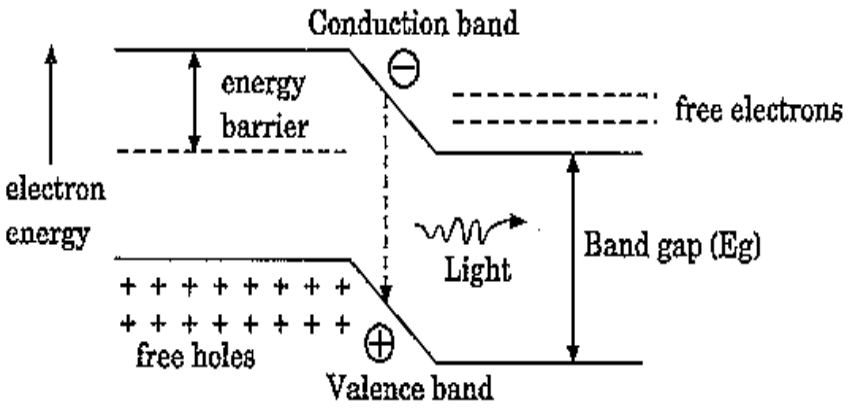
Circuit and symbol of LED

Working

Just like any normal diode, LED or light Emitting Diode only operates in forward bias i.e. the anode is kept at a higher voltage as compared to the cathode, or the anode is connected with the positive terminal and the cathode is connected with the negative terminal of the battery. The n region has electrons in the majority while the p region has holes in the majority. Apart from that, the n-type layer is heavily doped as compared to p-type layer

When LED is forward biased, the applied potential starts pushing on the P-layer and the N-layer. As a result, the depletion region or the active layer starts to shrink. Therefore electrons from n region and holes from p region start passing through the junction. It starts to recombine in the active region or depletion region. During its recombination, the electrons from the higher band (conduction band) fall into the lower energy band (valance band) by recombining with the holes (absence of an electron in the valance band) and release the energy in the form of light. After a few recombination, the width of the depletion region further decreases and the intensity of the light is increased

The property of conversion of electricity into light energy is called Electro-Luminance. Certain semiconductors exhibit such property such as the GaAs, GaAsP, GaP etc.



Energy band for LED

Advantages of LEDs

i. LEDs are smaller in size. A number of LEDs can be stacked together in a small space to form numerical display.

ii. LED's can be turned ON and OFF in less than 1 nanosecond (10^{-9} second). So, they are known as fast devices.

iii. Variety of LEDs are available which emit light in different colours like red, green, yellow etc.

iv. Light modulation can be achieved with pulse supply.

v. It has long life time.

vi. It has low drive voltage and low noise.

vii. It is easily interfaced to digital logic circuits.

viii. It can be operated over a wide range of temperatures.

Disadvantages of LEDs

i. They require high power.

ii. Their preparation cost is high when compared to LCD.

Applications and uses of LEDs

i. Because of their miniature size, they are widely used in numeric and alphanumeric display devices.

ii. They are used as indicator lamps.

. Calculate the reverse saturation current of a diode if the current at 0.2V forward bias is 0.1mA at a temperature of 25°C and the ideality factor is 1.5.

Explanation: Equation for diode current

$I = I_0 \times (e^{(V/\eta V_T)} - 1)$ where I_0 = reverse saturation current

η = ideality factor

V_T = thermal voltage

V = applied voltage

Here, I = 0.1mA, η = 1.5, V= 0.2V, $V_T = T_K/11600$

Therefore, V_T at T= 25+273=298 is 298/11600 = 0.0256V.

$$I_0 = 0.1 \times \frac{10^{-2}}{e^{\frac{0.2}{1.5 \times 0.0256}} - 1}$$

Therefore, reverse saturation current

I_O=0.00055mA = 5.5×10^{-7}A.

Find the applied voltage on a forward biased diode if the current is 1mA and reverse saturation current is 10^{-10}. Temperature is 25°C and take ideality factor as 1.5.

V_T at T= 25+273=298 is 298/11600 = 0.0256V, η = 1.5, I = 1mA, $I_0 = 10^{-10}$A

$$V = \eta V_T \ln\left(\left(\frac{I}{I_0}\right) + 1\right)$$

$$V = 1.5 \times 0.0256 \times \ln\left(\frac{10^{-2}}{10^{-10}} + 1\right) = 0.618V$$

❖ A germanium diode has a reverse saturation current of 0.19μA. Find the current in the diode when it is forward biased with 0.3V at 27°C.

Given:

$I_o = 0.19\mu A,\ V_D = 0.3V,\ T = 27°C,\ \eta = 1\ for\ Germanium\ Diode,\ and\ I_D = ?$

$$I_D = I_o\left(e^{V_D/\eta V_T} - 1\right)$$

$$=> I_D = 0.19 \times 10^{-6} \times \left(e^{0.3V/1\times 25.862\times 10^{-3}} - 1\right)$$

$$=> I_D = 20.72\ mA$$

$$V_T = \frac{T}{11{,}600}$$

$$= \frac{273^o + 27^o}{11{,}600}$$

$$= 25.862mV$$

❖ The forward current in a Silicon Diode is 15mA at 27°C. If reverse saturation current is 0.24nA, what is the forward bias voltage?

Given:

$I_D = 15mA,\ I_o = 0.24nA,\ T = 27°C,\ \eta = 2\ for\ Si\ Diode,\ and\ V_D = ?$

$$I_D = I_o\left(e^{V_D/\eta V_T} - 1\right)$$

$$=> V_D = \eta V_T \ln\left(\frac{I_D}{I_o} + 1\right)$$

$$=> V_D = 2 \times 25.862mV \times \ln\left(\frac{15m}{0.24n} + 1\right)$$

$$V_D = 0.928V$$

$$V_T = \frac{T}{11{,}600}$$

$$= \frac{273^o + 27^o}{11{,}600}$$

$$= 25.862mV$$

A germanium diode carries a current of 10mA when it is forward biased with 0.2V at 27°C. (a) Find reverse saturation current. (b) Find the bias voltage required to get a current of 100mA.

Given, $I_D = 10mA,\ V_D = 0.2V,\ t = 27°C,\ \eta = 1\ for\ Ge\ Diode$

$$V_T = \frac{T}{11{,}600}$$

$$= \frac{273^o + 27^o}{11{,}600}$$

$$= 25.862mV$$

(a) I_o =?

$$I_o = \frac{I_D}{\left(e^{V_D/\eta V_T} - 1\right)}$$

$$I_o = \frac{10m}{\left(e^{0.2/1\times 25.862m} - 1\right)} \quad \Rightarrow I_o = 4.3816\mu A$$

(b) $I_D = 100mA,\ V_D$ =?

$$\Rightarrow V_D = \eta V_T \ln\left(\frac{I_D}{I_o} + 1\right)$$

$$\Rightarrow V_D = 1 \times 25.862mV \times \ln\left(\frac{100m}{4.3816\mu} + 1\right)$$

$$V_D = 0.2595\ V$$

❖ .Calculate the static and dynamic resistance of a P-N Junction diode, when the applied voltage is 0.25V for Germanium Diode. I_0 =1μA and T=300K.

Given, $I_o = 1\mu A,\ V_D = 0.25V,\ T = 300K,\ \eta = 1\ for\ Ge\ Diode$

$$V_T = \frac{T}{11{,}600}$$

$$= \frac{273^o + 27^o}{11{,}600}$$

$$= 25.862mV$$

$$I_D = I_o\left(e^{V_D/\eta V_T} - 1\right)$$

$$\Rightarrow I_D = 1\mu A \times \left(e^{0.25/1\times 25.862m} - 1\right)$$

$$\Rightarrow I_D = 15.782\ mA$$

For Static Resistance,

$$(a)\ R_D = \frac{V_D}{I_D} = \frac{0.25}{15.782m} = 15.84\Omega$$

For Dynamic Resistance,

$$(b)\ r_d = \frac{\eta V_T}{I_D} = \frac{1\times 25.862m}{15.782m} = 1.638\Omega$$

- Using a direct band gap semiconductor, a green LED was fabricated. if the wavelength of the emitted light is 520 nm. Find the energy gap of the semiconductor?

Energy gap, λ = 520 nm = 520× 10^{-9}m

The bandgap is given by

$$E_g = \frac{hc}{\lambda} = \frac{6.625 * 10^{-34} \times 3 \times 10^8}{520 \times 10^{-9} \times 1.6 \times 10^{-19}} eV = 2.39\text{eV}$$

- Find the wavelength of an LED whose energy gap is 3 eV.

Enrgy gap: E_g = 3 eV = 3×1.6×10^{-19}

Wavelength

$$\lambda = \frac{hc}{E_g} = \frac{6.625 \times 10^{-34} \times 3 \times 10^8}{3 \times 1.6 \times 10^{-19}} = 4.14 \times 10^{-7} m$$

- A germanium diode at room temperature (25°C) has a forward current of 2 mA when the forward voltage across it is 0.3V. Assuming the ideality factor (*n*) is 1, calculate the reverse saturation current (*IS*) of the diode.

Solution:

- First, recall the diode current equation:

$$I = I_s\left(e^{V/nV_T} - 1\right)$$

- Rearrange the equation to solve for I_s

$$I_s = \frac{I}{e^{V/nV_T} - 1}$$

- Plug in the values (I=2mA, V=0.3V, n=1, and V_T≈26mV) to find I_S:

$$I_s = \frac{2mA}{e^{0.3/1\times 26mV} - 1}$$

- A diode with a reverse saturation current of 20 nA sees a forward voltage of 0.5V. Calculate the forward current through the diode for ideality factors of 1 and 2 at room temperature.

Solution:

Use the diode current equation:

$$I = I_s\left(e^{V/nV_T} - 1\right)$$

$$I = 20nA\left(e^{0,5/nV_T} - 1\right)$$

Calculate the forward current for n=1 and n=2, remembering $V_T \approx 26mV$:

for n=1

$$I = 20nA\left(e^{0,5/1\times 26mV} - 1\right)$$

for n=2

$$I = 20nA\left(e^{0,5/2\times 26mV} - 1\right)$$

- A silicon diode with a reverse saturation current (I_S) of 5 nA at 25°C is subjected to a forward bias of 0.7V. If the temperature increases to 35°C, calculate the new forward current (I). Assume the ideality factor (n) is 1. Remember, the thermal voltage (VT) varies with temperature, and $VT=kT/q$.

1. Calculate V_T at 25°C and 35°C (use 300K and 308K for simplicity):
   - V_T at 25°C $\approx 26mV$
   - V_T at 35°C can be calculated by the formula, taking into account the increased temperature.
2. Calculate the forward current (I) at 25°C using the diode current equation.
3. Recalculate I at 35°C using the new V_T for 35°C.

1. Explain the formation of a diode?
2. What is meant by an unbiased PN junction?
3. What is meant by depletion layer in an unbiased PN junction?
4. Define forward static and dynamic resistances of a diode.
5. State the principle of LED and explain its working.
6. Draw V-I characteristics of PN junction Diode.
7. Write Diode Current equation and explain each term in it.
8. What is meant by LED? What materials are used to construct an LED?
9. Explain IV characteristics of LED.
10. What is a PN junction diode?
11. Why is silicon preferred over Germanium in the manufacture of semiconductor devices?
12. Define forward and reverse recovery time of a diodes.
13. Define knee voltage and breakdown voltage with respect to diode.
14. What is meant by the mean life time of a carrier in semiconductor?
15. Explain the operation of forward biased and reverse biased PN junction diodes.
16. Explain the current components in a PN junction diodes.
17. Derive the diode current equation.

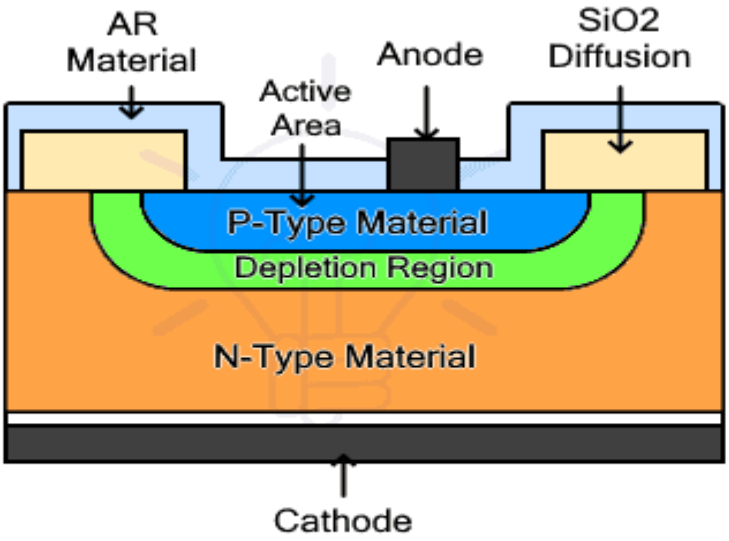
Module 3

IMPORTANT DIODES

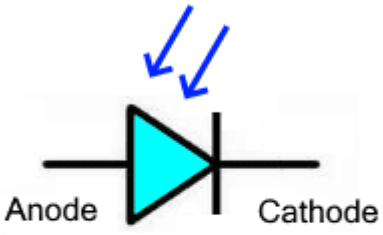
IMPORTANT DIODES

Working of: Photo diode, solar cell, Zener diode ,Varactor diode , Gunn diode and their applications.

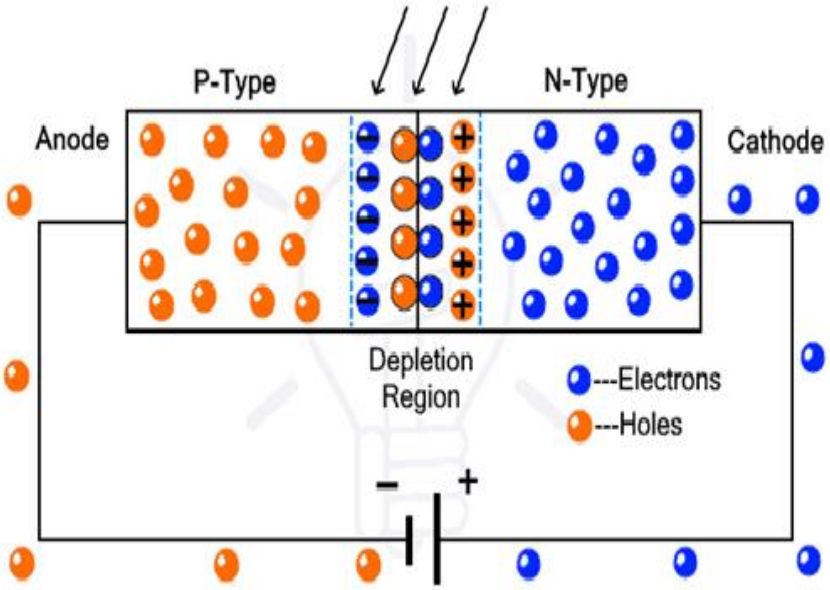
Photodiode:



PN Photodiode Structure



Photodiode



Working of a Photodiode:

A PN photodiode is similar to a conventional PN junction diode. When a PN junction diode is reverse biased, the depletion region widens. Minority charge carriers are generated that constitute the reverse current of the diode. This reverse current is directly proportional to the applied reverse voltage.

Similarly, in the photodiode, there is a built-in-potential difference across the depletion region. When a light ray or photon of enough energy (hv) greater than the energy gap (Eg) falls on the junction of the photodiode, it dislodges or removes an electron from its valance band into the conduction band. The electron lefts an empty space called a hole, thus electron-hole pair is generated. This phenomenon is also called the inner photovoltaic effect. Under the influence of an inbuilt electric field, the electron and hole moves in opposite directions i.e. the electron moves toward the cathode and the hole moves toward the anode. This current is called photocurrent and it is directly proportional to the intensity of the falling light.

In photodiodes, there is still a flow of current even when there is no light source or photons falling onto its junction. This current is known as dark current. It is extremely small in microampere. It resembles the leakage current of any conventional PN junction diode. It is the unwanted current in reverse bias that varies directly with temperature and it must be reduced to have increased sensitivity of the photodiode. The total current of any photodiode is the sum of the photocurrent and the dark current.

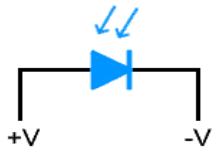
Modes of Photodiode

A photodiode can operate in the following three modes.

- Photovoltaic Mode
- Photoconductive Mode
- Avalanche Diode Mode

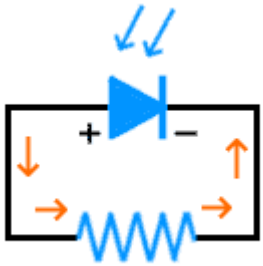
Photovoltaic Mode

This mode is also known as Zero Bias Mode as there is no biasing or external voltage source connected to the photodiode. When light or photon hits the depletion region, electron-hole pair is generated that moves in opposite direction away from the junction under the influence of the inbuilt electric field. As a result, a current is generated if it is connected in a closed circuit or a potential difference is generated between the cathode and anode if it is an open circuit.



Photovoltaic Mode

In the case of an open circuit, a forward voltage proportional to the light intensity falling on the active region is generated across its anode and cathode. This voltage is in forward bias mode as the potential at the anode is greater than the cathode.

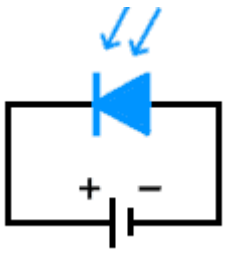


In the case of a closed circuit, a forward current flows through the circuit. This forward current is equal to the sum of photocurrent and dark current. This phenomenon is known as the photovoltaic effect and it is mainly responsible for the operation of solar cells.

Photovoltaic mode provides low-level current variation (low dynamic range) with nonlinear voltage. It is used in low-level frequency applications and low-level light. This mode has low electronic noise. But it has a slow response time due to maximum junction capacitance due to an unbiased system.

Photoconductive Mode

In photoconductive mode, the photodiode is reverse biased i.e. its anode is connected with the negative terminal and the cathode is connected with the positive terminal of the battery or the cathode is at higher potential with respect to the anode. Therefore this mode is also known as a reverse-biased mode.



Due to reverse bias, the depletion region expands and varies directly with the increase in reverse voltage. Due to the large area, more charge carriers are collected more quickly from the junction. It also reduces the capacitance of the junction resulting in a much quicker response time.

In photoconductive mode, apart from the photocurrent, there is another current called dark current in the reverse direction. Dark current is due to the reverse bias in the absence of light. It greatly depends on the temperature and varies directly with it. It also depends on the type of material and the active region of the photodiode. It is an unwanted current that generates electrical noise.

Avalanche Mode

In avalanche mode, the photodiode is connected with high reverse bias voltage. The high reverse voltage increases the depletion width and the potential across it. Due to high potential, the electron-hole pair flows with maximum speed hitting more atoms in its path resulting in more photocurrent. Therefore, avalanche mode has high internal gain and responsivity.

Quantum Efficiency of Photodiode

Quantum efficiency is the fraction of incident photons that are absorbed by the photodiode and generate electrons. In other words, the quantum efficiency is defined as the fraction of incident photon that contributes to the photocurrent. It is directly proportional to the responsivity.

The quantum efficiency can be maximized by reducing the reflection using anti-reflection coating. It highly depends on the wavelength of the incident light. The quantum efficiency can be very high up to 95%.

Performance Parameters

The performance of photodiode depends mainly on the following parameters.

Response Time

Response time for a photodiode can be defined as the time a charge carrier takes to cross the junction. It greatly depends on the capacitance of the junction. Whereas the junction capacitance depends on the width of the junction. Larger the junction's width, the smaller the capacitance and lower the response time. To provide a better performance, response time is kept minimum.

Responsivity

Responsivity is the ratio of the photocurrent generated from the incident light to the actual power of the incident light. The unit of responsivity is A/W (current/power). Responsivity is kept higher to offer better performance.

Dark Current

Dark current is the current in the photodiode in reverse bias when there is no light. It is similar to the reverse leakage current in a conventional PN junction diode. It is very small often measured in

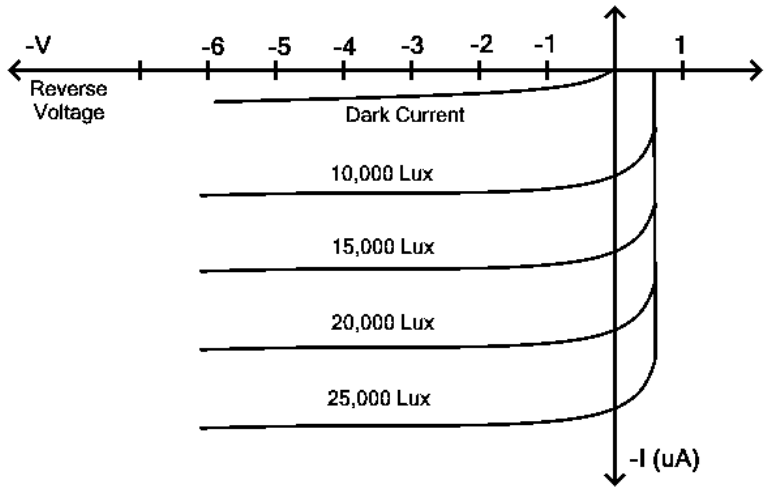
microamperes. However, it is minimum in unbiased or zero bias mode. It varies directly with the change in temperature. Dark current causes electronic noise in the system. Therefore it is kept minimum to offer better performance.

Breakdown Voltage

The breakdown voltage is the maximum reverse voltage a photodiode can tolerate. If the applied voltage crosses the breakdown voltage, the reverse leakage current or dark current will increase exponentially and the diode will get permanently damaged. Photodiodes must be operated below this level. The breakdown voltage decreases with an increase in temperature.

VI Characteristics of Photodiode

The VI characteristics curve shows the relationship between the voltage and current of a device. The horizontal axis or x-axis represents the voltage while the vertical axis or y-axis represents the current through the device. Given below is the characteristic curve for the photodiode.



VI Characteristics of Photodiode

As we know that photodiode operates in reverse bias, therefore the graph is between the reverse voltage and the reverse current. The reverse voltage is represented on the negative x-axis while the reverse current is represented in microamperes on the negative y-axis.

The reverse current does not vary with a change in the reverse voltage. However the reverse current increases with an increase in the intensity of the incident light. At zero light intensity or no light, there is no significant reverse current except for a very small constant current called the dark current. By increasing the intensity of light the reverse current increases linearly

Advantages and Disadvantages of Photodiode

Advantages

Here are some advantages of Photodiode

- It operates on light energy.
- It facilitates fast communication through an optical fiber.
- It creates very low noise.
- It generates a low dark current as compared to the phototransistor.
- It has high quantum efficiency.
- It has very low resistance.
- It is rugged and has a longer lifespan
- It operates on low voltage.
- It has a linear response
- It is cost-effective.

Disadvantages

Here are some disadvantages of Photodiode

- The active area is relatively small.
- It has lower sensitivity than other components.
- It requires an external power source to supply sufficient current to a load.
- It requires amplification when operated under low light intensity.
- The simple PN photodiode has a high response time.
- Thermal noise greatly affects its performance.
- It has poor temperature stability.
- It uses offset voltage.

Applications of Photodiode

Photodiodes are basically used to detect and measure light intensity, therefore it has numerous applications in almost every field. Here are some applications of Photodiode

Electrical Isolation:

Photodiodes are used in opt couplers to electrically isolate two circuits. It isolates any low voltage sensitive circuit from a high voltage circuit. The circuits are optically coupled and electrically isolated.

Renewable Energy:

Photodiodes are extensively used to convert solar energy into electrical energy to power our daily use equipment. They are used at the domestic as well as industrial level. Hundreds of panels each containing arrays of photodiodes are used in a single solar plant to produce electrical energy.

Optical Communication:

High-speed photodiodes such as PIN photodiodes are used for high-speed optical communication using fiber optic cables.

Building Safety:

It is also used in fire and smoke alarms to prevent any kind of fire hazard in a building. Its light sensor can detect smoke.

Medical Instruments:

Photodiodes also find multiple applications in medical Instruments such as CT scans, PET scanners, sample analyzers, etc.

Burglar alarm

In a burglar alarm, there is a light source fixated in such a way that it constantly strikes the photodiode and generates a constant current. If something or someone passes through and causes obstruction to the light, the diode current falls and triggers the alarm.

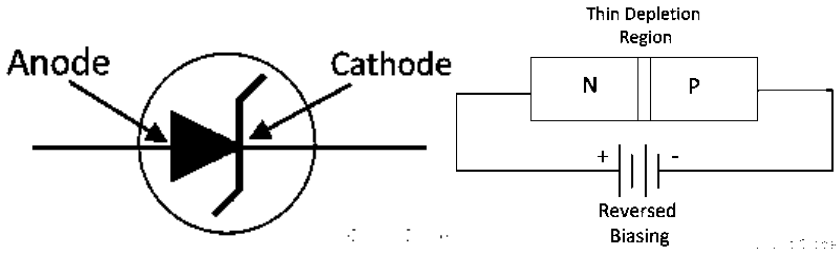
Counter

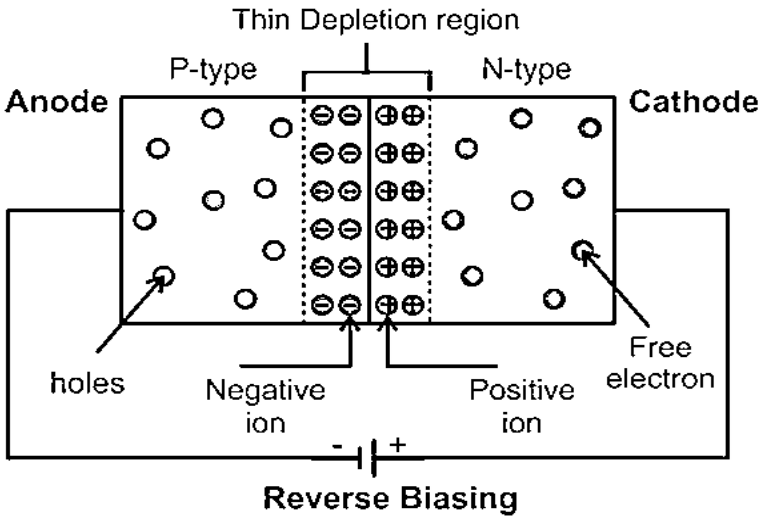
The photodiode can be used to count objects that pass between it and a continuous source of light.

- It is used as a photo sensor to measure different levels of light intensity in a digital camera.
- It is used to detect visible as well as invisible (IR) light.
- It is used as an optical encoder and decoder.
- It is used as a position sensor, proximity sensor and bar code reader.
- It is used in automatic street light that switches according to the light falling on it.
- It is used in infrared remote to control any device remotely such as a TV, air conditioner, etc.
- It is used in a compact disc CD player, scanner,
- It is used in printers to detect and count pages.
- It is used as a variable resistance device whose resistance varies with light intensity.
- It is used in digital logic circuits due to its high speed and low voltage requirement.
- They are used in character recognition techniques.

Zener Diode

Definition: A heavily doped semiconductor diode which is designed to operate in reverse direction is known as the Zener diode.





The Zener diode is made up of heavily doped semiconductor material. The heavily doped means the high-level impurities is added to the material for making it more conductive. The depletion region of the Zener diode is very thin because of the impurities. The heavily doping material increases the intensity of the electric field across the depletion region of the Zener diode even for the small reverse voltage.

Working of zener diode:

When no biasing is applied across the Zener diode, the electrons remain in the valence band of the p-type material and no current flow through the diode. The band in which the valence electrons

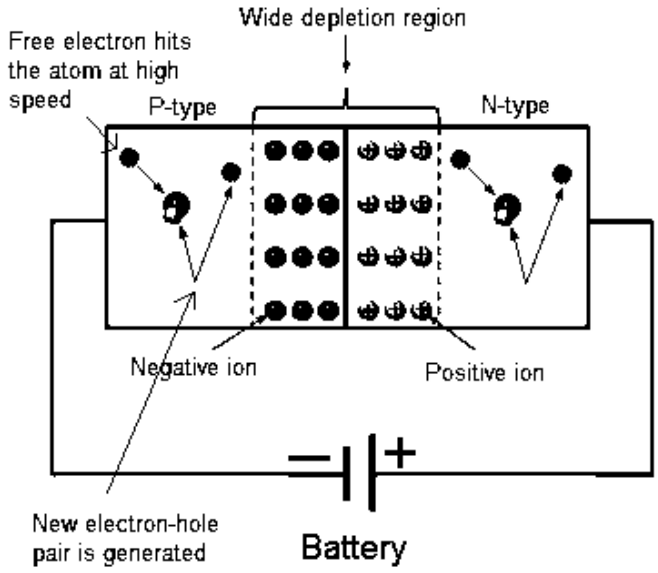
(outermost orbit electron) place is known as the valence band electron. The electrons of the valence band easily move from one band to another when the external energy is applied across it.

When the reverse bias applies across the diode and the supply voltage is equal to the Zener voltage then it starts conducting in the reverse bias direction. The Zener voltage is the voltage at which the depletion region completely vanishes. The reverse bias applies across the diode increases the intensity of electric field across the depletion region. Thus, it allows the electrons to move from the valence band of P-type material to the conduction band of N-type material. This transferring of valence band electrons to the conduction band reduces the barrier between the p and n-type material. When the depletion region become completely vanishes the diode starts conducting in the reverse biased.

Types of a Breakdown of Zener Diode

There are two types of breakdown that can be observed for a Zener diode

Avalanche Breakdown

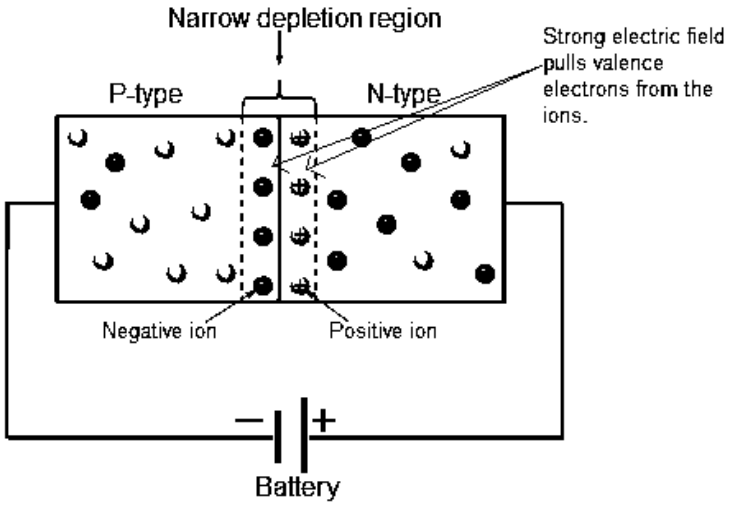


Avalanche breakdown

1) Avalanche breakdown occurs in lightly doped diodes having wide depletion region. If reverse voltage is increased, at a particular value, velocity of minority carriers increases.
2) Due to kinetic energy associated with the minority carriers, more minority carriers are generated when there is collision of minority carriers with the atoms.

3) The collision makes the electrons to break the covalent bonds.
4) These electrons are available as minority carriers and get accelerated due to high reverse voltage.
5) They again collide with another atoms to generate more minority carriers. This is called carrier multiplication.
6) Finally large number of minority carriers move across the junction, breaking the p-n junction.
7) These large number of minority carriers give rise to a very high reverse current.
8) This effect is called avalanche effect and the mechanism of destroying the junction is called reverse breakdown of a p-n junction.
9) The voltage at which breakdown of a p-n junction occurs is called reverse breakdown voltage.

Zener Breakdown



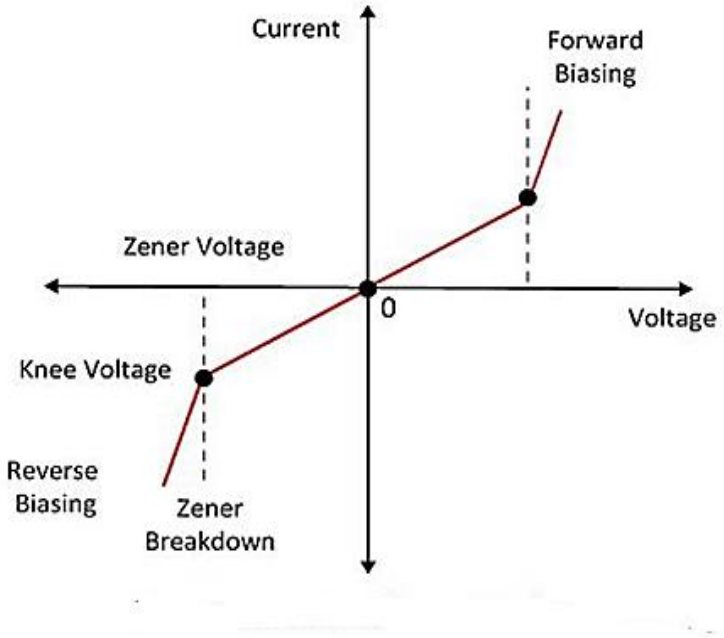
Zener breakdown

1) Zener breakdown occurs in highly doped p-n junction. When a p-n junction is heavily doped the depletion region is very narrow. So under reverse bias conditions, the electric field across the depletion layer is very intense.
2) Such an intense field is enough to pull the electrons out of the valance bands of the stable atoms.
3) So this is not due to the collision of carriers with atoms.
4) Such a creation of free electrons is called zener effect.

5) These minority carriers constitute very large current and mechanism is called zener breakdown. The voltage across the diode drops to a constant value known as the breakdown voltage.

Zener Breakdown	Avalanche Breakdown
Zener breakdown refers to the process where electrons move from the valence band of p-type material across the barrier to the conduction band of n-type material.	Avalanche breakdown is the process where a high voltage application increases the number of free electrons or electric current in semiconductors and insulating materials.
Zener breakdown is observed in Zener diodes with a Zener breakdown voltage V_z ranging from 5 to 8 volts.	Avalanche breakdown is observed in Zener diodes with a Zener breakdown voltage V_z above 8 volts.
In Zener breakdown, the valence electrons move to conduction due to the high electric field in the narrow depletion region.	In avalanche breakdown, the valence electrons are forced into conduction due to the energy gained by accelerated electrons, which gain their velocity due to their collision with other atoms.
The increase in temperature decreases the breakdown voltage in Zener breakdown.	The increase in temperature increases the breakdown voltage in avalanche breakdown.
The VI characteristics of a Zener breakdown show a sharp curve.	The VI characteristic curve of avalanche breakdown is not as sharp as that of Zener breakdown.
Zener breakdown occurs in highly doped diodes.	Avalanche breakdown occurs in lightly doped diodes.

V-I Characteristics of Zener Diode



The VI characteristics of the Zener diode is described through the graph, mentioned in the figure below. This shows that the Zener diode behaves like an ordinary diode when it is connected in forward bias. But when the reverse voltage is applied across the Zener diode, such that the reverse voltage rises beyond the predetermined rating, breakdown occurs on the Zener diode.

The electric current starts to flow in the reverse direction at the breakdown voltage of the Zener diode. The graph represents that the Zener diode has resistance. Further, it is shown that the graph of Zener breakdown is not exactly vertical. The voltage across the Zener diode is represented by the equation given below:

$$V = V_Z + I_Z R_Z$$

Zener Diodes Specifications

Some characteristics of Zener diodes are mentioned as follows:

- Zener or Breakdown Voltage – The Zener or the breakdown voltage in zener diode varies from 2.4 V to 200 V, sometimes it can go up to 1 kV while its maximum value for the surface-mounted device is only 47 V.
- Power Rating – It indicates the maximum power that a diode can disperse, which is given by the product of the voltage of the diode and the current flowing through it.
- Current Iz (maximum) – It is the maximum current reading at the rated Zener Voltage, which is Vz – 200μA to 200 A
- Voltage Tolerance – It's typically ±5%
- Current IzIz (minimum) – It is the minimum value of the current reading required for the diode to break down.
- Temperature Stability – it has the best stability of around 5 V.
- Zener Resistance Rz – It is the resistance that the Zener diode shows.

Difference between PN Junction and Zener Diode

Zener Diode	PN Junction Diode
It allows the current to flow in both directions which means that its current can flow forward as well as in the reverse direction.	A PN junction diode allows current to pass only in one direction which is a forward direction.
Zener diode has high doping.	PN junction diode has low doping.
A reverse current has no effect on a Zener diode.	A reverse current effect on a PN junction diode by damaging its junctions.
A breakdown occurs at a lower voltage in a Zener diode.	A breakdown occurs at a higher voltage in a PN junction diode.
A Zener diode does not follow Ohm's law.	A PN junction diode does follow Ohm's law.

Applications of Zener Diode

The uses of a Zener diode are mentioned as follows:

Zener Diode as Voltage Regulator

Zener diodes are employed as shunt voltage regulators to stabilize voltage across low-power loads. They are connected in parallel with the load, subjecting them to reverse bias. Once the Zener diode's knee voltage is surpassed, the load voltage stabilizes. Notably, the breakdown voltage of a Zener diodes remains constant across a wide range of currents.

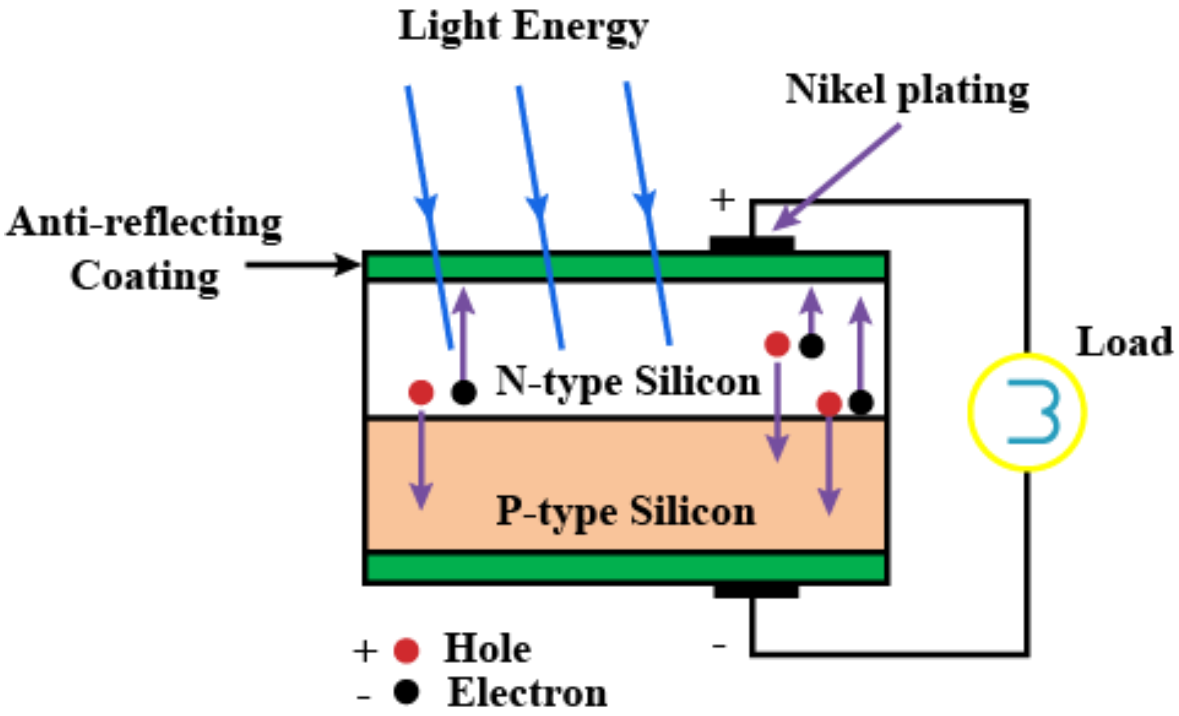
Zener Diode in Over-Voltage Protection

In situations where the input voltage exceeds the breakdown voltage of a Zener diode, the voltage across the resistor plummets, potentially leading to a short circuit. By employing a Zener diode, this issue can be effectively circumvented.

Zener Diode in Clipping Circuits

Zener diodes play a crucial role in shaping AC waveforms by selectively limiting portions of one or both half-cycles of the AC waveform. This process, known as clipping, is achieved by employing Zener diodes in specific circuit configurations.

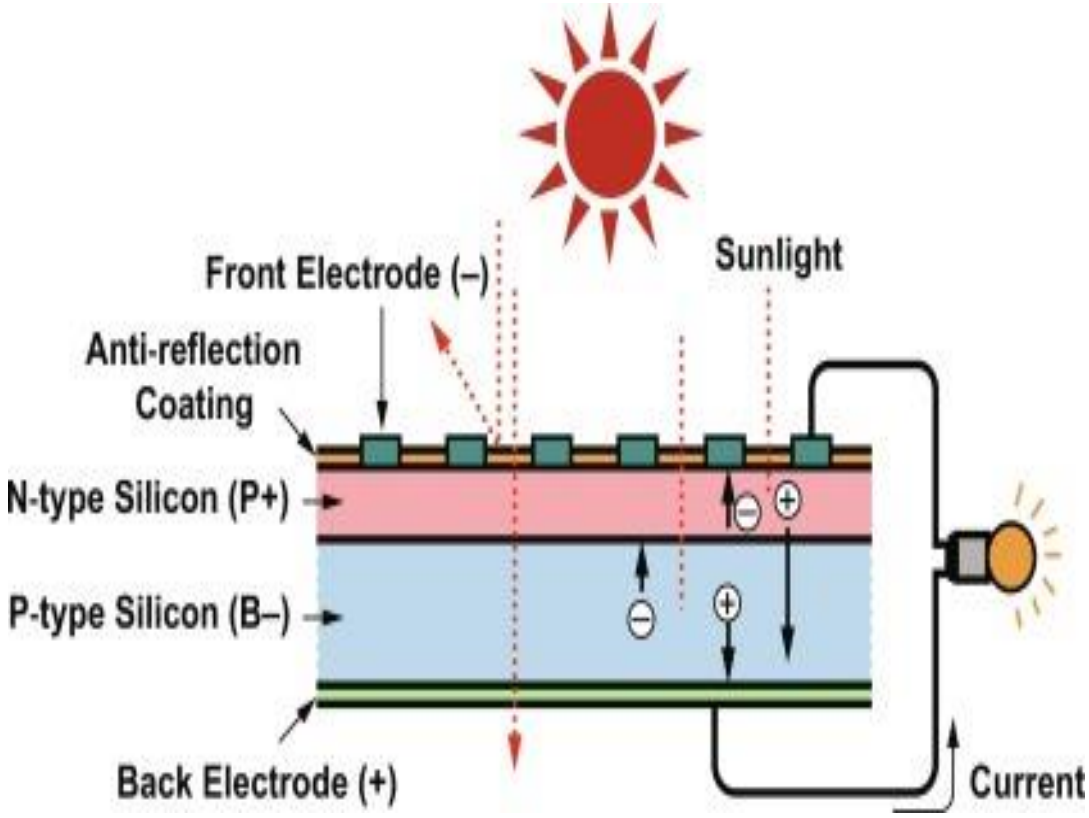
Solar cell:



Construction:

1) It consist of P-N junction having flat surface. P type region is made thick while N-type region is made thin.
2) The N side of the junction faces the solar radiation and P side is at the back side of solar cell.
3) Both P-side and N-side are coated with a conducting material to provide electrical contact.
4) The N side is coated with an antireflection coating which avoid reflection and allows visible light to pass through it and fall on N side. This coating also reflect the IR radiation and protect solar cell from heat.
5) The N side of solar cell is thin so that the light incident on it reaches the depletion region where the electron-hole pairs are generated.

Working:



1) When light of photon energy E = hv greater than the band gap energy Eg of semiconductor material is incident on a solar cell, due to thin N type region, electron-hole pairs are created in the depletion region of the diode. Due to electric field at the junction, photo generated electron move towards n side and holes move towards P side.
2) The intrinsic electric field of the depletion region separate the charge carriers and small potential difference is develop at the junction.
3) When solar cell is connected to an external circuit, the light generated carriers flow through the external circuit.

Criteria for Materials to be used in Solar Cell

1. Must have band gap from 1ev to 1.8ev.
2. It must have high optical absorption.
3. It must have high electrical conductivity.
1. The raw material must be available in abundance and the cost of the material must be low.

Advantages of Solar Cell

1. No pollution associated with it.

2. It must last for a long time.
3. No maintenance cost.

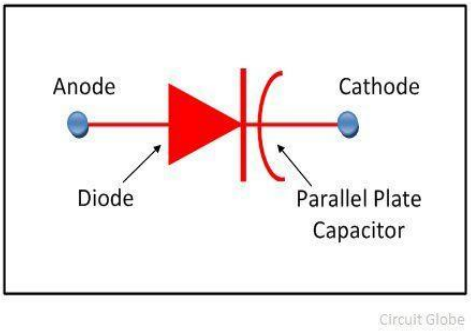
Disadvantages of Solar Cell

1. It has high cost of installation.
2. It has low efficiency.
3. During cloudy day, the energy cannot be produced and also at night we will not get solar energy.

Uses of Solar Generation Systems

1. It may be used to charge batteries.
2. Used in light meters.
3. It is used to power calculators and wrist watches.
4. It can be used in spacecraft to provide electrical energy.

Varactor Diode:

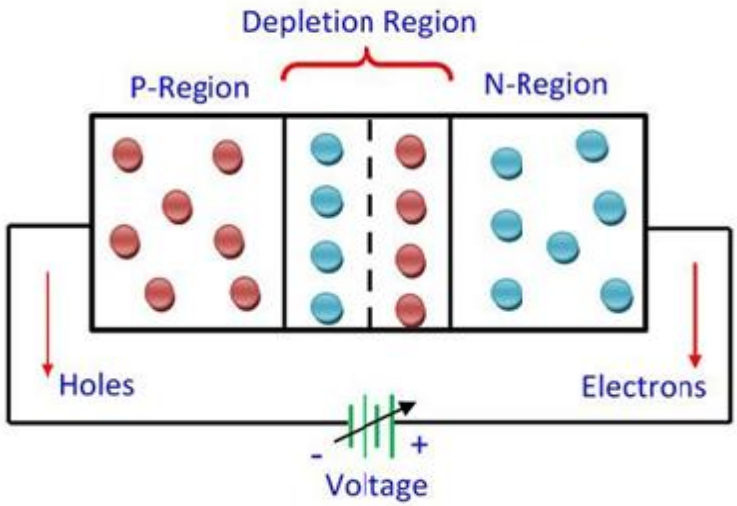


Definition: The diode whose internal capacitance varies with the variation of the reverse voltage such type of diode is known as the Varactor diode. It is used for storing the charge. The varactor diode always works in reverse bias, and it is a voltage-dependent semiconductor device

The voltage-dependent device means the output of the diode depends on their input voltage. The varactor diode is used in a place where the variable capacitance is required, and that capacitance is controlled with the help of the voltage. The Varactor diode is also known as the Varicap, Voltcap, Voltage variable capacitance or Tunning diode.

Working of Varactor Diode:

The Varactor diode is made up of n-type and p-type semiconductor material. In an n-type semiconductor material, the electrons are the majority charge carrier and in the p-type material, the holes are the majority carriers. When the p-type and n-type semiconductor material are joined together, the p-n junction is formed, and the depletion region is created at the PN-junction. The positive and negative ions make the depletion region. This region blocks the current to enter from the PN-region.



- The varactor diode operates only in reverse bias. Because of reverse bias, the current does not flow. The Varactor diode is used for storing the charge not for flowing the charge. Thus, the Varactor diode always operates in the reverse bias.

- A varactor diode is constructed similarly to a standard p-n junction diode, consisting of a p-type and an n-type semiconductor region separated by a depletion region. However, it's operated in reverse bias mode.

- When a reverse bias voltage is applied to the varactor diode (the p-side is connected to the negative terminal, and the n-side to the positive terminal of a power supply), it creates a depletion region around the p-n junction. This region is essentially a non-conductive area.

- The width of the depletion region in the varactor diode varies with the magnitude of the applied reverse voltage.

- As the reverse voltage increases, the depletion region widens, reducing the effective capacitance of the diode. Conversely, as the voltage decreases, the depletion region narrows, increasing the capacitance.

The formula gives the capacitance of varactor diode,

$$C_T = \frac{\in A}{W}$$

Where, ε – Permittivity of the semiconductor material.

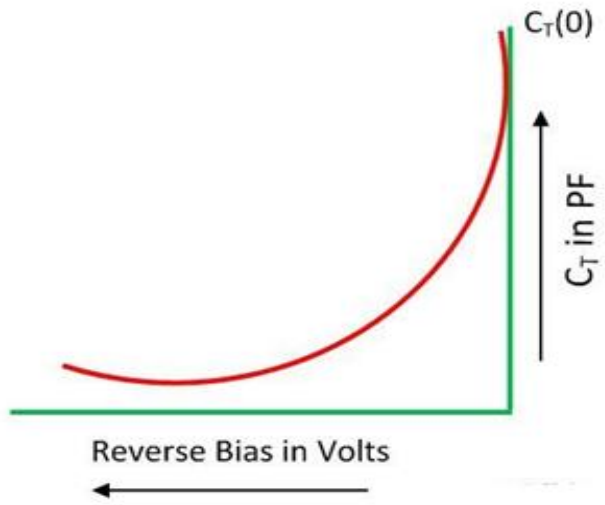
A – area of PN-junction

W – width of depletion region

The capacitance of the varactor diode increases with decrease of width of the depletion region. The increase in capacitance means the more charges are stored in the diode. For increasing the storage capacity of charge the depletion region (which acts as a dielectric of the capacitor) of the diode should be kept small.

Characteristic of Varactor Diode:

The characteristic curve of the varactor diode is shown in the figure below. The graph shows that when the reverse bias voltage increases the depletion region increases, and the capacitance of the diode reduces.



Advantages of Varactor Diode

The following are the advantages of the varactor diode.

1. The varactor diode produces less noise as less compared to the other diode.
2. It is less costly and more reliable.
3. The varactor diode is small in size and less in weight.

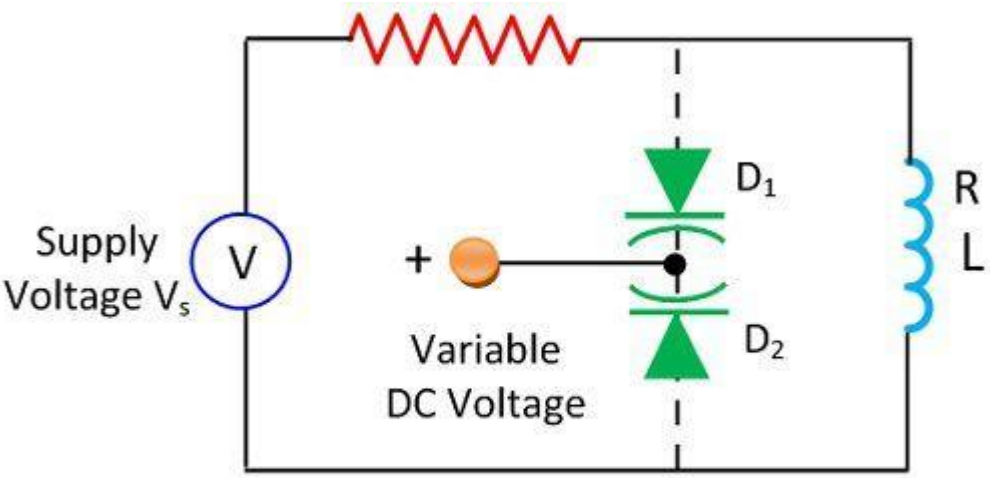
Varactor diode in tunning Circuit

Varactor diodes are commonly used in tuning circuits, especially in radio frequency (RF) and microwave applications, to achieve variable capacitance and thus frequency tuning.
In a tuning circuit, the varactor diode is connected in parallel with a fixed capacitor, often in an LC (inductor-capacitor) resonant circuit. By changing the reverse bias voltage across the varactor diode, its capacitance changes, which, in turn, alters the resonant frequency of the circuit.

- The ability to vary capacitance with voltage allows for precise and rapid frequency tuning. This makes varactor diodes valuable components in applications like voltage-controlled oscillators (VCOs), frequency synthesizers, and agile radio systems.

In summary, a varactor diode's ability to change its capacitance with applied voltage makes it a key component in tuning circuits.

The figure below shows that D_1 and D_2 are the two Varactor diode. These diodes provide the variable resistance in the parallel resonance circuit. The V_c is the DC voltage used for controlling the reverse voltage of the diode.



Varactor Diode in Tunning Circuit

Circuit Globe

$$f_0 = \frac{1}{2\pi\sqrt{LC_T}}$$

Where,

$$C_T = \frac{C_1 C_2}{C_1 + C_2}$$

The L is the inductance of the circuit, and it is measured in Henry. The resonant frequency of the circuit is expressed as C_1 and C_2 is the maximum voltage capacitance of the diode

Applications of Varactor Diode:

- FM radio and TV receivers
- Self-adjusting bridge circuits
- Adjustable band pass filters
- Very low noise microwave parametric amplifiers
- Tuning of LC resonant circuits in microwave frequency multipliers
- Voltage control oscillators
- Frequency and phase modulators

How do varactor diodes contribute to frequency tuning in electronic circuits?

Varactor Diodes have a frequency-dependent capacitance, slight change in voltage change their capacitance. In electronic circuits, varactor diodes play a important role by electronically setting the frequency of the oscillators, filters and resonant circuits by changing the bias voltage.

What role do varactor diodes play in radar and sensing systems?

Radar and sensing systems use varactor diodes for frequency modulation and phase shifting through varactor diodes for pulse generation and signal processing. In sensing systems, the varactor diodes will trigger the frequency-modulated continuous-wave (FMCW) radars for distance measurement and object detection.

How are varactor diodes used in satellite communication and navigation?

Varactor diodes are used in satellite communication and navigation systems for synthesizing frequencies, phase locking, and frequency modulation. In satellite navigation systems like GPS, varactor diodes enable precise frequency generation and modulation which are used in navigation process e.g. positioning or timing.

What advantages do varactor diodes offer in medical imaging and diagnostic equipment?

With the help of varactor diodes, frequency agility and modulation skills are presented in the medical imaging and diagnostic equipment, which is essential for simultaneous pulse excitation and signal reception of radio frequency.

How do varactor diodes contribute to energy-efficient wireless communication in IoT devices?

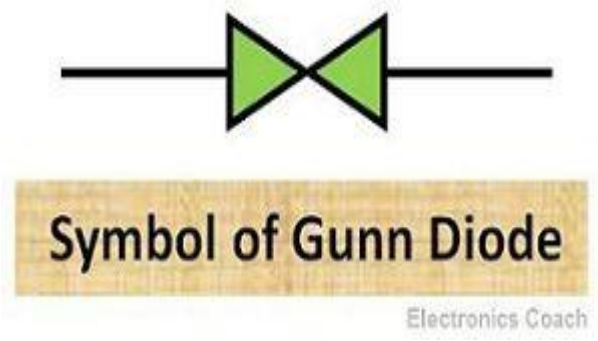
Varactor diodes helps in frequency agility as well as adaptive modulation at the wireless sensor networks and IoT devices and hence the RF usage is done efficiently and at the same time the data transmission happen which is based on environmental conditions and constraints of energy.

What applications do varactor diodes have in aerospace and defense systems?

Varactor diodes plays a very important role in aerospace and defense system in communication, and electronic warfare applications. In radar systems, frequency agility, waveform tracking, and target surveillance functions are ensured by varactor diodes that enable waveform generation.

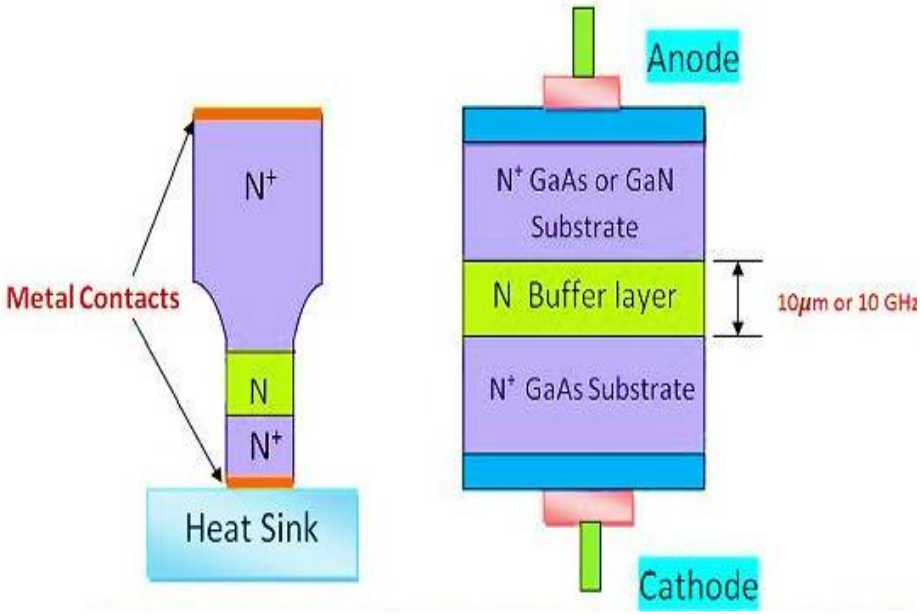
Gunn Diode

Definition: Gunn diode is a transferred electronic device, which is composed of only one type of semiconductor i.e. N-type and utilizes the **negative resistance** characteristics to generate current at high frequencies. It is used to generate RF and microwave frequencies. It is composed of only N-type semiconductor because N-type semiconductor has electrons as majority carriers. And transferred electronic devices use such materials which have electrons as majority charge carrier.



Construction of Gunn Diode

It is made up of three layers of N-type semiconductor. The semiconductors used in Gunn diodes are Gallium Arsenide (GaAs), Gallium Nitride (GaN), Cadmium Telluride (CdTe), Cadmium Sulphide (CdS), Indium Phosphide (InP), Indium Arsenide (InAs), Indium Antimonide (InSb) and Zinc Selenide (ZnSe).



Among these three layers the **top** most and the **bottom** most are **heavily doped** while the **middle layer** is **lightly doped**. The middle layer is an epitaxial layer grown on the N-type substrate and the top most layer is formed by ion implantation technique. The metallic contacts are provided on extreme layers to facilitate biasing. The heat sink is there so that the diode can withstand excessive heat and can be prevented from damage.

Working of Gunn Diode

1. The Gunn diode is not actually a P-N junction diode because there is no P-region and no junction. But still, it is called diode because of involvement of two electrodes.

2. When biasing is applied to Gunn diode, the entire voltage appears across the active region. The active region is the middle layer of the device.

3. The active region is **6-18 μm** long. Due to which the current pulses start traversing the active region. The **potential gradient** will fall when current pulse traverses in the active region which blocks another pulse to form.

4. The next current pulse will form only when the previous current pulse has traversed the entire active region or it will be on the end of the active region.

5. In this way, the thickness of active region modifies the frequency at which the device is working.

6. This is a transferred electronic device so it deals with the movement of electrons only. In Gunn diode, there is valence band, conduction band and one more band near conduction band.

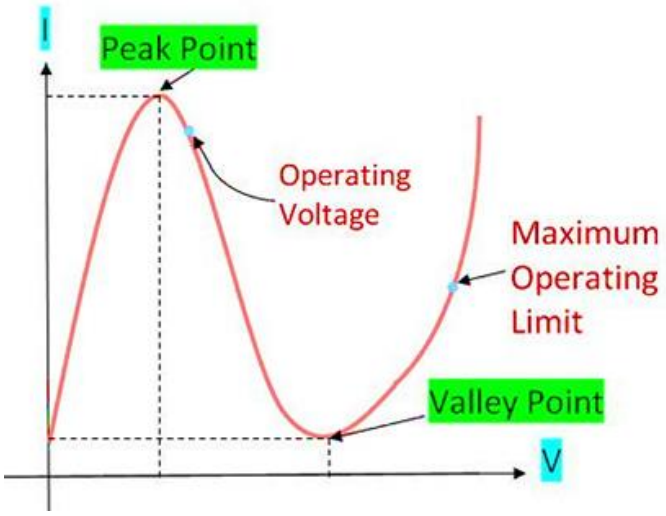
7. Thus, on initial DC bias the current through the device increases because electrons move from valence band to conduction band. After moving in conduction band the current through the device starts decreasing because the electrons in conduction band move to band above the conduction band Due to this the **effective mass** of electrons starts increasing and thus **mobility** starts decreasing due to which the current starts decreasing, And this creates the negative resistance region in the diode.

8. In this negative resistance region, the current starts increasing with the fall in voltage and will starts decreasing with increase in voltage.

9. Thus, it generates pulses with phase reversal and thus this device is appropriate for the fabrication of amplifier and oscillator circuits. It generates frequency ranging from **10 GHz to THz.**

V-I Characteristics of Gunn Diode

The Current in Gunn diode starts increasing initially with the applied DC voltage. At a particular point, the current starts decreasing this point is called threshold point or peak point.



After crossing threshold point the current starts decreasing and this creates negative resistance region in the diode. Due to this negative resistance region, the diode acts as

amplifier and oscillator. In this negative resistance region, the Gunn diode is able to amplify the signals.

Advantages of Gunn diode

1. Portable and Small Size device.
2. The cost of manufacturing of Gunn diode is low.
3. It possesses better noise to signal ratio as it is immune from noise disturbance.
4. The Gunn diode is reliable and stable at higher frequencies.
5. It has a high bandwidth of operation.

Disadvantages of Gunn Diode

1. The Gunn diode has poor temperature stability.
2. The device operating current is higher and therefore power dissipation is more.
3. The efficiency of Gunn Diode is low below 10GHz.

Applications of Gunn Diode

1. Gunn Diodes are used as oscillators and Amplifiers.
2. They are used in radio communication, military and commercial radar sources.
3. Gunn diodes are used as fast controlling equipment in microelectronics for modulation of laser beams.
4. It is used in tachometers.
5. Gunn diode is used in sensors for detection in trespass detecting system, in-door opening system, pedestrian safety systems etc.
6. It is also used extensively in microwave relay data link transmitters.
7. These are extensively used in sensors in the detection system.

1. Explain the working of a Photodiodes.
2. State applications of Photodiodes.
3. Explain VI Characteristics of Photodiodes.
4. Explain the working of a solar cell Range.
5. Explain VI Characteristics of Solar Cells.
6. Draw V-I characteristics of a Zener Diode.
7. List the applications of Zener Diodes.
8. Explain the working of a Zener diode and state its applications.
9. Explain the characteristics of a Varactor diode.
10. Explain the working of a Gunn diode and state its applications.

Module 4

BIPOLAR JUNCTION TRANSISTOR

BIPOLAR JUNCTION TRANSISTOR

BJT Structure and Operation - BJT structure, Modes of operation, CE I-V characteristics BJT Amplification and Switching - Current gain, BJT as a switch,

Introduction

Bipolar junction transistor definition

A bipolar junction transistor or BJT is a three terminal electronic device that amplifies the flow of current. It is a current controlled device. In bipolar junction transistor, electric current is conducted by both free electrons and holes. Unlike a normal pn junction diode, the transistor has two p-n junctions.

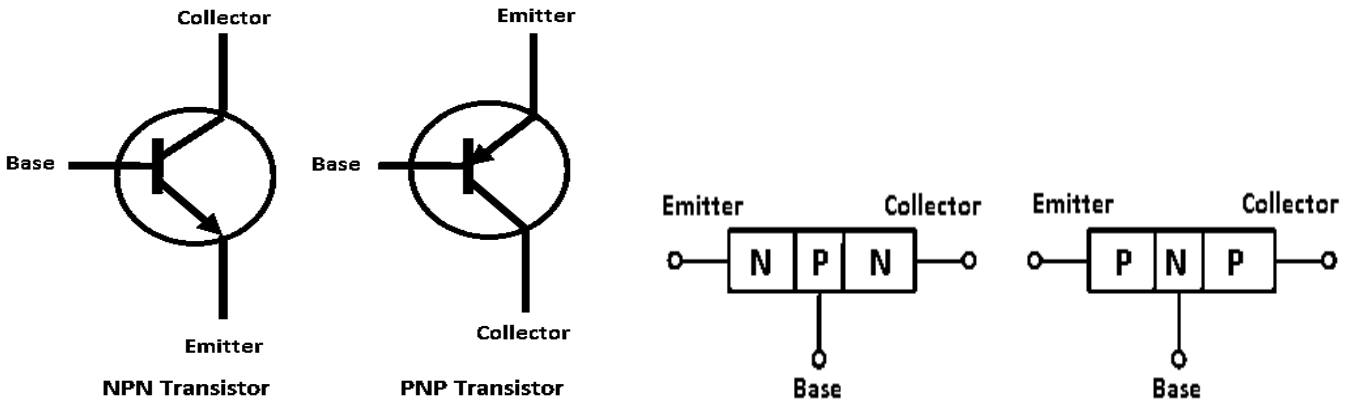
Types of Bipolar Junction Transistors (BJTs)

The bipolar junction transistors are formed by sandwiching either n-type or p-type semiconductor layer between pairs of opposite polarity semiconductor layers. Bipolar junction transistors are classified into two types based on their construction: They are

- NPN transistor
- PNP transistor

NPN transistor

When a single p-type semiconductor layer is sandwiched between two n-type semiconductor layers, the transistor is said to be an npn transistor



PNP transistor

When a single n-type semiconductor layer is sandwiched between two p-type semiconductor layers, the transistor is said to be a pnp transistor. Both PNP and NPN transistors consist of three terminals: they are emitter, base, and collector.

Terminals of BJT

Emitter:

As the name suggests, the emitter section supplies the charge carriers. The emitter section is heavily doped so that it can inject a large number of charge carriers into the base. The size of the emitter is always greater than the base.

Base:

The middle layer is called base. The base of the transistor is very thin as compared to emitter and collector. It is very lightly doped.

Collector:

The function of the collector is to collect charge carriers. It is moderately doped. That is the doping level of the collector section is in between emitter and base. The size of the collector is always greater than emitter and base. The collector area in the transistor is considerably larger than the emitter area. This is because the collector region has to handle more power than the emitter does and more surface area is required for heat dissipation.

In transistor, the amplification is achieved by passing input current from a region of low resistance to a region of high resistance. Therefore, it is known as transfer of resistor.

Applications of bipolar junction transistor

The various applications of bipolar junction transistors are:

- Televisions
- Mobile phones
- Computers
- Radio transmitters

- Audio amplifiers

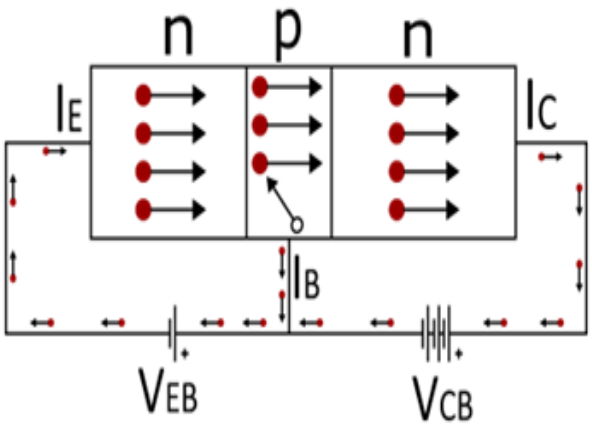
Important Facts about BJT

- There are two pn-junctions, hence a transistor may be regarded as a combination of two back-to-back connected diodes.
- The collector region is wider than both emitter and base. The base is much thinner than both emitter and collector. During the transistor operation, a lot of heat is generated at the collector, hence the collector is made larger to dissipate the heat.
- A transistor has three sections of doped semiconductors. The one section is called the Emitter, the other is called the Collector, and the middle section is called the Base and forms two pn-junctions between emitter and collector.
- In general, the emitter-base junction of the BJT is made forward-biased, whereas the collector-base junction is reverse-biased.
- The resistance of forward-biased junction is very small as compared to that of the reverse-biased junction.
- The emitter is heavily doped so that it can supply a greater number of charge carriers (electrons or holes) to the base. The base is lightly doped and very thin, hence it passes most of the charge carriers injected by the emitter to the collector. The doping concentration of the collector region is moderate.

Working Principle of BJT

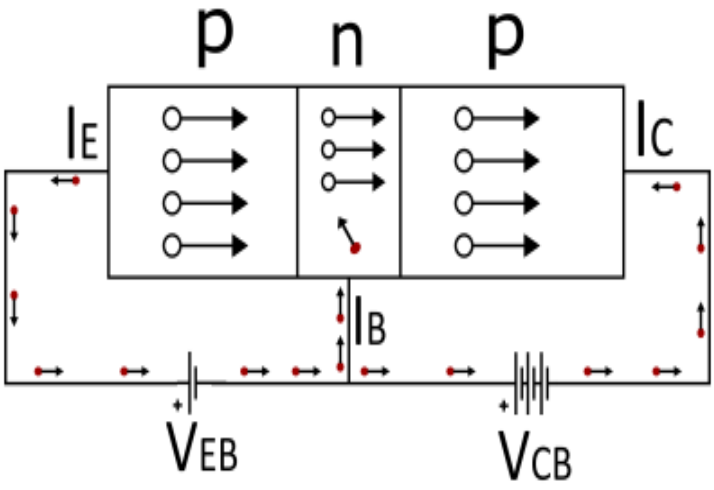
The emitter-base junction of BJT is forward-biased, whereas the collector-base junction is reverse biased. The forward bias of the emitter-base junction causes the emitter current to flow and this emitter current entirely flows in the collector circuit. Therefore, the collector current depends upon the emitter current and nearly equal to the emitter current.

Working of NPN Transistor:



With the forward-biased emitter-base junction and reverse-biased collector-base junction, it can be seen that the forward bias causes the flow of electrons from the n-type emitter into the p-type base. This constitutes the emitter current (I_E). As these electrons flow through the p-type base, they tend to combine with the holes. Since the base is lightly doped and very thin, hence, only a small number electrons (less than 5%) combine with the holes to constitute the base current (). The remaining (more than 95%) electrons cross over the base region and reach to the collector region to constitute the collector current (). In this manner, the entire emitter current flows in the collector circuit. The emitter current is the sum of base and collector currents. $\mathbf{I_E=I_B+I_C}$

Working of PNP Transistor:

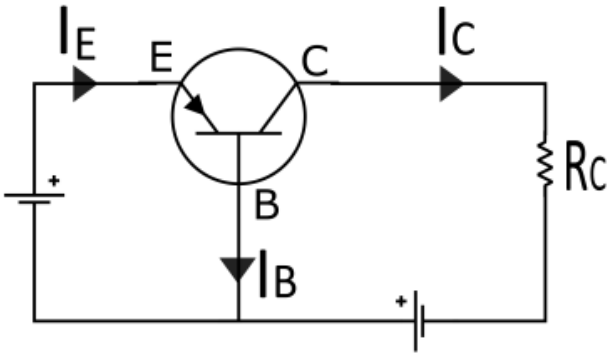


For the pnp-transistor, the forward bias of emitter-base junction causes the flow of holes in the p-type emitter region towards the n-type base and constitutes the emitter current (I_E). As these holes

cross into the n-type base region, they tend to combine with the electrons. Since the base is lightly doped and very thin, hence only a small number of holes (less than 5%) combine with the electrons. The remaining (more than 95%) cross the base and reach into the collector region to constitute the collector current (I_C). In this manner, the entire emitter current flows into the collector circuit. It may be noted that the current conduction inside the pnp-transistor is due to the movement of holes. However, in the external connecting wires, the current is still due to the flow of electrons. Again, the emitter current is the sum of collector current and base current. $\mathbf{I_E=I_B+I_C}$

BJT Biasing:

A BJT has two pn-junctions *viz*. emitter-base junction and collector-base junction. Application of proper DC voltage at the two junctions of the BJT is known as BJT or Transistor Biasing.



When a transistor used as an amplifier, the emitter-base junction is forward biased and collector-base junction is reverse biased. If the transistor is operated under this bias condition, then it is said to be operating in the **active region**.

When both the junctions are forward biased then the transistor is said to be operating in the **saturation region**. The transistor operated in saturation region acts like a closed switch and the collector current becomes maximum.

When both the junctions are reverse biased, the transistor is said to be operating in the **cut off region**. The BJT operated in cut off region acts as an open switch and a very small collector current (in **μA**) flows from emitter to collector. This current is called reverse leakage current and is due to minority charge carriers (electrons in p-region and holes in n-region).

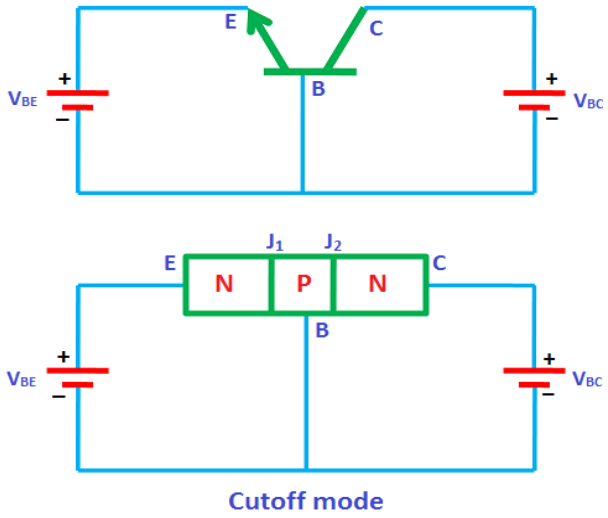
BJT operation modes

The transistor can be operated in three modes:

- Cut-off mode
- Saturation mode
- Active mode

In order to operate transistor in one of these regions, we have to supply dc voltage to the npn or pnp transistor. Based on the polarity of the applied dc voltage, the transistor operates in any one of these regions. Applying dc voltage to the transistor is nothing but the biasing of transistor.

Cutoff mode:

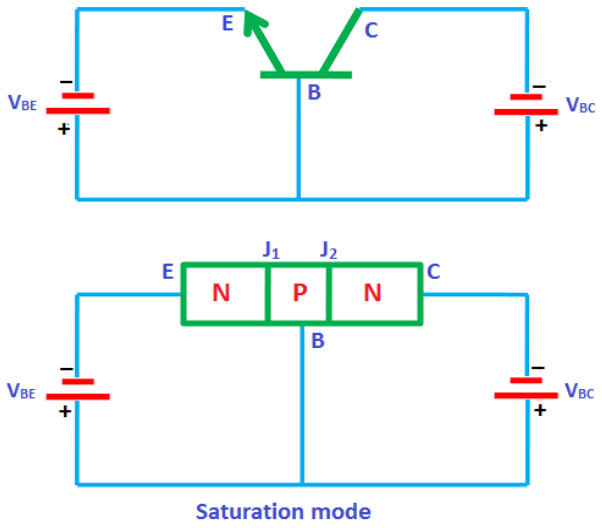


Cutoff mode

In the cutoff mode, both the junctions of the transistor (emitter to base and collector to base) are reverse biased. In other words, if we assume two p-n junctions as two p-n junction diodes, both the diodes are reverse biased in cutoff mode. We know that in reverse bias condition, no current flows through the device. Hence, no current flows through the transistor. Therefore, the transistor is in OFF state and acts like an open switch. The cutoff mode of the transistor is used in switching operation for switch OFF application.

Saturation mode:

In the saturation mode, both the junctions of the transistor (emitter to base and collector to base) are forward biased. In other words, if we assume two p-n junctions as two p-n junction diodes, both the diodes are forward biased in saturation mode. We know that in forward bias condition, current flows through the device. Hence, electric current flows through the transistor.

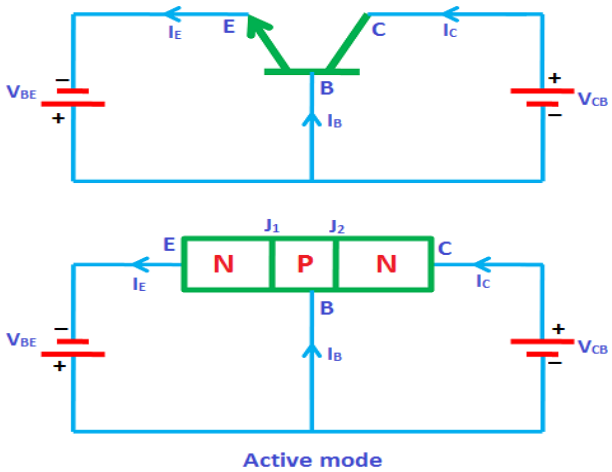


Saturation mode

In saturation mode, free electrons (charge carriers) flows from emitter to base as well as from collector to base. As a result, a huge current will flow to the base of transistor. Therefore, the transistor in saturation mode will be in ON state and acts like a closed switch. The saturation mode of the transistor is used in switching operation for switch ON application. From the above discussion, we can say that by operating the transistor in saturation and cutoff region, we can use the transistor as an ON/OFF switch.

Active mode:

In the active mode, one junction (emitter to base) is forward biased and another junction (collector to base) is reverse biased. In other words, if we assume two p-n junctions as two p-n junction diodes, one diode will be forward biased and another diode will be reverse biased.



Active mode

The active mode of operation is used for the amplification of current.

Types of Transistor Configuration:

Transistor is an electronic device which is primarily used to amplify the electric current. We know that transistor has three terminals namely emitter (E), base (B), and collector (C). But to connect a

transistor in the circuit, we need four terminals: two terminals for input and other two terminals for output. But the transistor does not have four terminals, then how do we connect transistor in a circuit. It is not as difficult as you think. One of the three terminals is used as common to both input and output. When a transistor is to be connected in a circuit, one terminal is used as the input terminal, the other terminal is used as the output terminal and the third terminal is common to the input and output. That means here input is applied between the input terminal and common terminal, and the corresponding output is taken between the output terminal and common terminal. Depending upon the terminal which is used as a common terminal to the input and output terminals, the transistor can be connected in the following three configurations. They are:

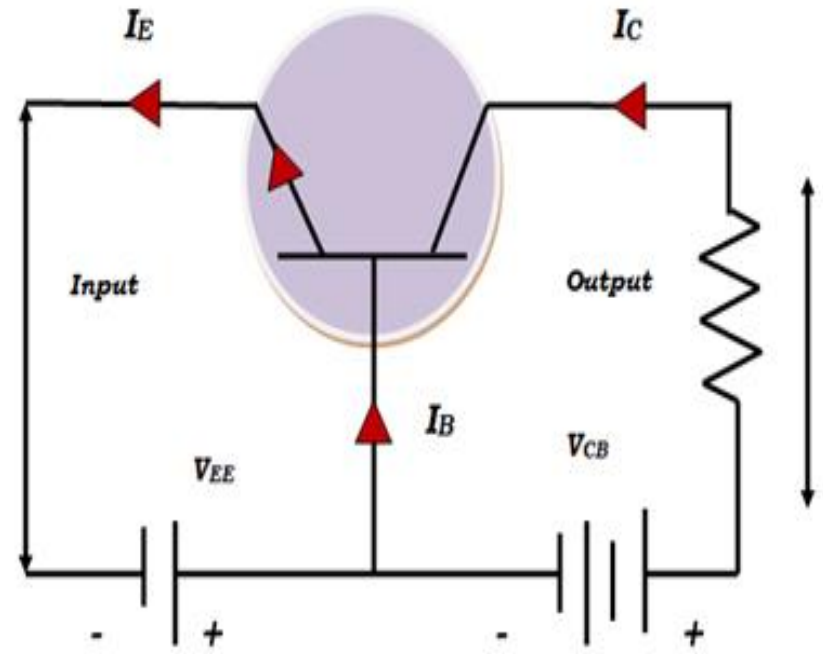
- Common base (CB) configuration
- Common emitter (CE) configuration
- Common collector (CC) configuration

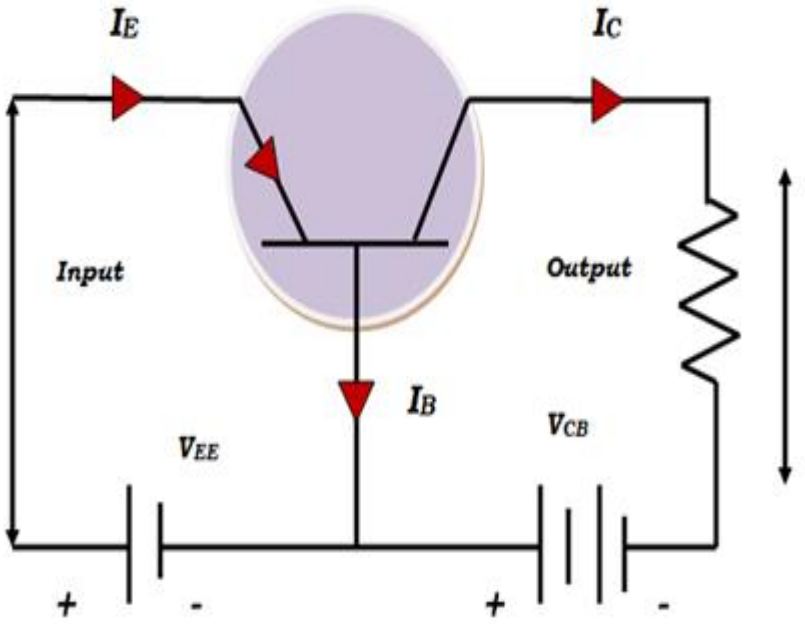
In every configuration, the base-emitter junction J_E is always forward biased and the collector-base junction J_C is always reverse biased to operate the transistor as a current amplifier.

Common Base Configuration:

The input signal is applied between the emitter and base terminals while the corresponding output signal is taken across the collector and base terminals. Thus, the base terminal of a transistor is common for both input and output terminals and hence it is named as common base configuration. The supply voltage between base and emitter is denoted by V_{BE} while the supply voltage between collector and base is denoted by V_{CB}. Therefore, in common base configuration, the base-emitter junction J_E is forward biased and collector-base junction J_C is reverse biased.

The common base configuration for both NPN and PNP transistors is shown in the below figure.





The free electrons which are flowing from emitter to base will combine with the holes in the base region similarly the holes which are flowing from base to emitter will combine with the electrons in the emitter region. The width of the base region is very thin. Therefore, only a small percentage of free electrons from emitter region will combine with the holes in the base region and the remaining large number of free electrons cross the base region and enters into the collector region. A large number of free electrons which entered into the collector region will experience an attractive force from the positive terminal of the battery. Therefore, the free electrons in the collector region will

flow towards the positive terminal of the battery. Thus, electric current is produced in the collector region. The electric current produced at the collector region is primarily due to the free electrons from the emitter region similarly the electric current produced at the base region is also primarily due to the free electrons from emitter region. Therefore, the emitter current is greater than the base current and collector current. The emitter current is the sum of base current and collector current.

$$I_E = I_B + I_C$$

Current Amplification Factor α

The ratio of change in collector current ΔI_C to the change in emitter current ΔI_E when collector voltage V_{CB} is kept constant, is called as **Current amplification factor**. It is denoted by α.

$$\alpha = \frac{\Delta I_C}{\Delta I_E} \; at\, constant\, V_{CB}$$

Expression for Collector current

With the idea above, let us try to draw some expression for collector current. Along with the emitter current flowing, there is some amount of base current I_B which flows through the base terminal due to electron hole recombination. As collector-base junction is reverse biased, there is another current which is flown due to minority charge carriers. This is the leakage current which can be understood as $I_{leakage}$. This is due to minority charge carriers and hence very small.

The emitter current that reaches the collector terminal is αI_E

Total collector current

$$I_C = \alpha I_E + I_{leakage}$$

If the emitter-base voltage $V_{EB} = 0$, even then, there flows a small leakage current, which can be termed as I_{CBO} collector−base current with output open.

The collector current therefore can be expressed as

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

$$I_E = I_C + I_B$$

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

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

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

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

Hence the above derived is the expression for collector current. The value of collector current depends on base current and leakage current along with the current amplification factor of that transistor in use.

Characteristics of CB configuration:

- This configuration provides voltage gain but no current gain. The output collector current is less than the input emitter current, so the current gain of this amplifier is actually less than 1. In other words, the common base amplifier attenuates the electric current rather than amplifying it.
- The input resistance ri is the ratio of change in emitter-base voltage ΔVEB to the change in emitter current ΔIE at constant collector base voltage $\mathbf{V_{CB}}$.

$$\eta = \frac{\Delta V_{EB}}{\Delta I_E} \; at\; constant\; V_{CB}$$

- As the input resistance is of very low value, a small value of V_{EB} is enough to produce a large current flow of emitter current $\mathbf{I_E}$.
- The output resistance r_o is the ratio of change in the collector base voltage ΔVCB to the change in collector current ΔIC at constant emitter current $\mathbf{I_E}$.
- $$r_o = \frac{\Delta V_{CB}}{\Delta I_C} \; at\; constant\; l_E$$

- As the output resistance is of very high value, a large change in $\mathbf{V_{CB}}$ produces a very little change in collector current $\mathbf{I_C}$. Therefore, the common base amplifier provides a low input impedance and high output impedance.
- This Configuration provides good stability against increase in temperature.
- The CB configuration is used for high frequency applications.
- The common base amplifier is mainly used as a voltage amplifier or current buffer.

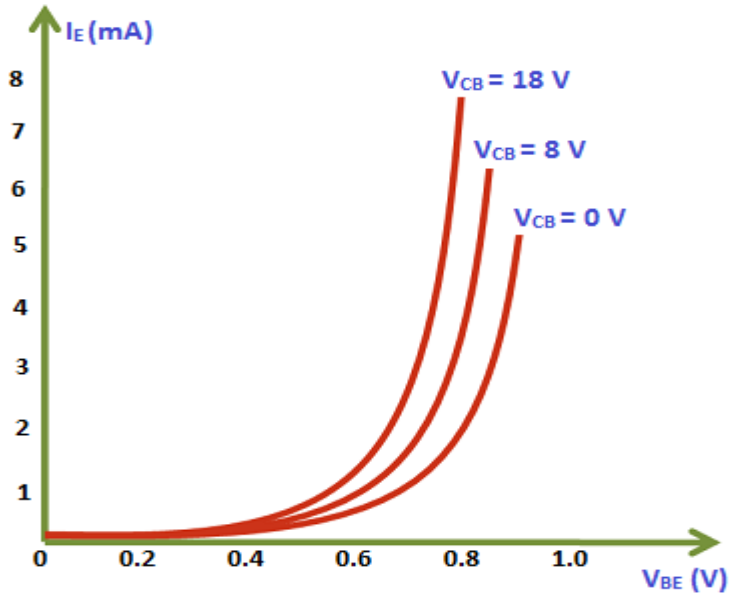
The working principle of pnp transistor with CB configuration is same as the npn transistor with CB configuration. The only difference is in npn transistor free electrons conduct most of the current whereas in pnp transistor the holes conduct most of the current.

To fully describe the behaviour of a transistor with CB configuration, we need two set of characteristics: they are

- Input characteristics
- Output characteristics.

Input characteristics:

- The input characteristics is the relationship between input current (I_E) and the input voltage (V_{BE}) at constant output voltage V_{CB} (collector-base voltage) . A curve is then drawn between input current I_E and input voltage V_{BE} at constant output voltage V_{CB} .

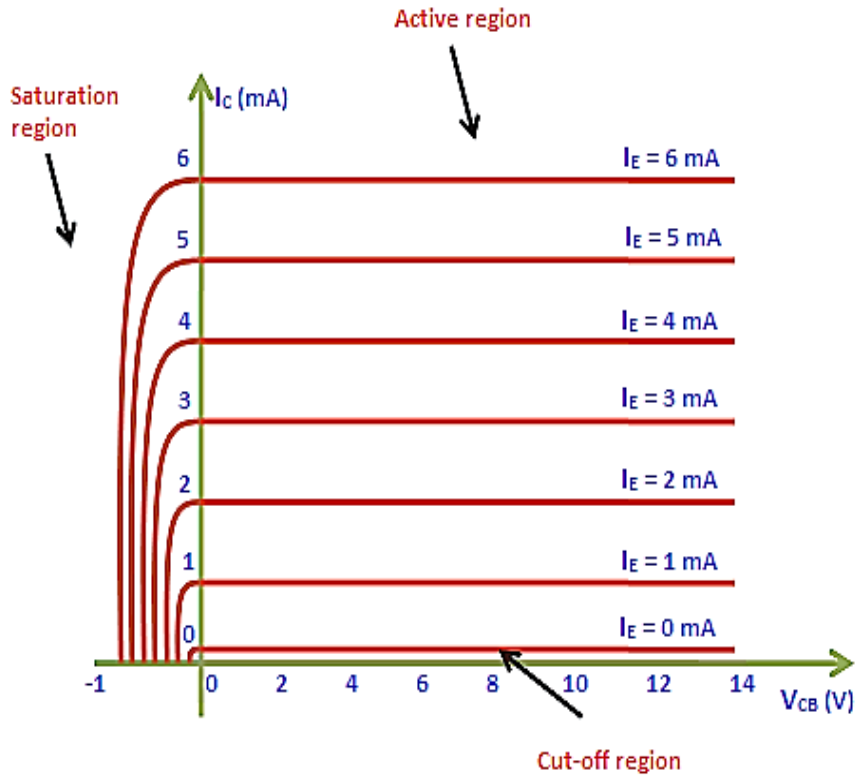


I/p characteristics CB configuration

- When output voltage (V_{CB}) is at zero volts and emitter-base junction J_E is forward biased by the input voltage (V_{BE}), the emitter-base junction acts like a normal p-n junction diode. So the input characteristics are same as the forward characteristics of a normal pn junction diode.
- When the output voltage (V_{CB}) is increased from zero volts to a certain voltage level (8 volts), the emitter current flow will be increased which in turn reduces the depletion region width at emitter-base junction. As a result, the cut in voltage will be reduced. Therefore, the curves shifted towards the left side for higher values of output voltage V_{CB}.

Output characteristics

- The output characteristics is the relationship between output current (I_C) and the output voltage (V_{CB}) at constant emitter current I_E .
- A curve is then drawn between output current I_C and output voltage V_{CB} at constant input current I_E (0 mA). When the emitter current or input current I_E is equal to 0 mA, the transistor operates in the cut-off region.



O/P characteristics CB configuration

- After we kept the input current (I_E) constant at 1 mA, the output voltage (V_{CB}) is increased from zero volts to different voltage levels. For each voltage level of the output voltage (V_{CB}), the output current (I_C) is recorded. A curve is then drawn between output current I_C and

output voltage V_{CB} at constant input current I_E (1 mA). This region is known as the active region of a transistor. This is repeated for higher fixed values of input current I_E (I.e. 2 mA, 3 mA, 4 mA and so on). From the above characteristics, we can see that for a constant input current I_E, when the output voltage V_{CB} is increased, the output current I_C remains constant.

- At saturation region, both emitter-base junction J_E and collector-base junction J_C are forward biased. From the above graph, we can see that a sudden increase in the collector current when the output voltage V_{CB} makes the collector-base junction J_C forward biased.

Transistor parameters:

- **Dynamic input resistance (r_i)**

  Dynamic input resistance is defined as the ratio of change in input voltage or emitter voltage (V_{BE}) to the corresponding change in input current or emitter current (I_E), with the output voltage or collector voltage (V_{CB}) kept at constant.

$$r_i = \frac{\Delta V_{BE}}{\Delta I_E}, \qquad V_{CB} = \text{constant}$$

  The input resistance of common base amplifier is very low.

- **Dynamic output resistance (r_o)**

  Dynamic output resistance is defined as the ratio of change in output voltage or collector voltage (V_{CB}) to the corresponding change in output current or collector current (I_C), with the input current or emitter current (I_E) kept at constant.

$$r_o = \frac{\Delta V_{CB}}{\Delta I_C}, \qquad I_E = \text{constant}$$

  The output resistance of common base amplifier is very high.

- **Current gain (α)**

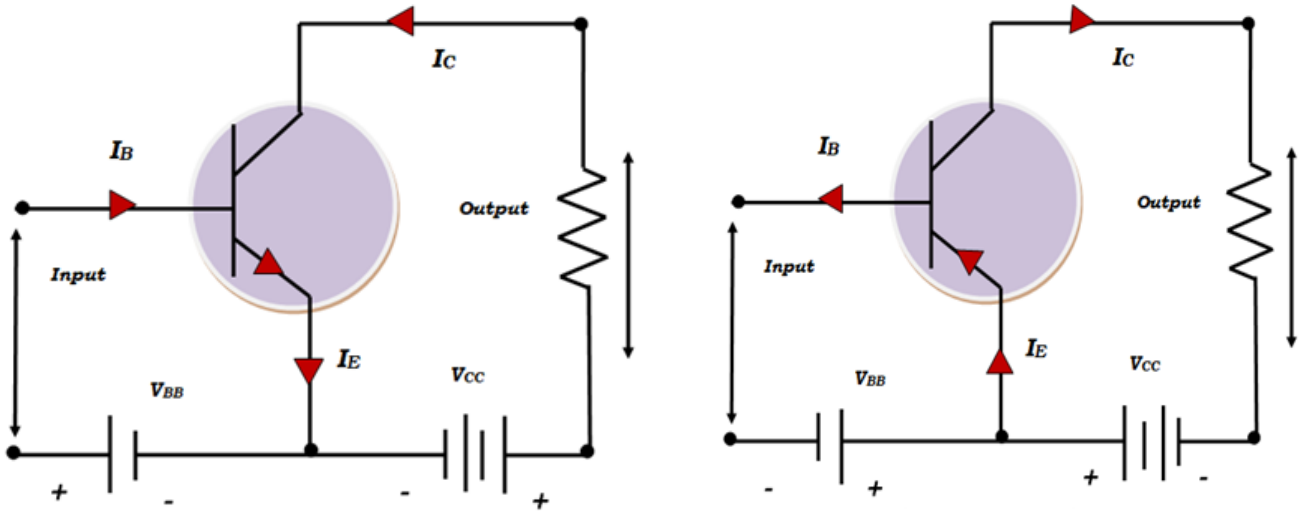
  The current gain of a transistor in CB configuration is defined as the ratio of output current or collector current (I_C) to the input current or emitter current (I_E).

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

  The current gain of a transistor in CB configuration is less than unity. The typical current gain of a common base amplifier is 0.98.

Common Emitter Configuration:

Circuit diagram of Common Emitter NPN and PNP Transistor:



The input signal is applied between the base and emitter terminals while the output signal is taken between the collector and emitter terminals. Thus, the emitter terminal of a transistor is common for both input and output and hence it is named as common emitter configuration. The supply voltage between base and emitter is denoted by V_{BE} while the supply voltage between collector and emitter is denoted by V_{CE}. In common emitter (CE) configuration, input current or base current is denoted by I_B and output current or collector current is denoted by I_C.

Base Current Amplification factor β

The ratio of change in collector current ΔIC to the change in base current ΔIB is known as Base Current Amplification Factor. It is denoted by β

$$\beta = \frac{\Delta I_C}{\Delta I_B}$$

Relation between β and α

Let us try to derive the relation between base current amplification factor and emitter current amplification factor.

$$\beta = \frac{\Delta I_C}{\Delta I_B}$$

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

$$I_E = I_B + I_C$$

$$\Delta I_E = \Delta I_B + \Delta I_C$$

$$\Delta I_B = \Delta I_E - \Delta I_C$$

$$\beta = \frac{\Delta I_C}{\Delta I_E - \Delta I_C}$$

$$\beta = \frac{\frac{\Delta I_C}{\Delta I_E}}{\frac{\Delta I_E}{\Delta I_E} - \frac{\Delta I_C}{\Delta I_E}}$$

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

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

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

From the above equation, it is evident that, as α approaches 1, β reaches infinity. Hence, the current gain in Common Emitter connection is very high. This is the reason this circuit connection is mostly used in all transistor applications.

Expression for Collector Current

In the Common Emitter configuration, $\mathbf{I_B}$ is the input current and $\mathbf{I_C}$ is the output current.

We know

$$I_E = I_B + I_C$$

And

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

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

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

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

If base circuit is open, i.e. if $\mathbf{I_B} = 0$,

The collector emitter current with base open is I_{CEO}

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

Substituting the value of this in the previous equation, we get

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

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

Hence the equation for collector current is obtained.

Knee Voltage

In CE configuration, by keeping the base current I_B constant, if V_{CE} is varied, I_C increases nearly to 1v of V_{CE} and stays constant thereafter. This value of V_{CE} up to which collector current I_C changes with V_{CE} is called the Knee Voltage. The transistors while operating in CE configuration, they are operated above this knee voltage.

Characteristics of CE Configuration

- This configuration provides good current gain and voltage gain.

- Keeping $\mathbf{V_{CE}}$ constant, with a small increase in $\mathbf{V_{BE}}$ the base current $\mathbf{I_B}$ increases rapidly than in CB configurations.
- For any value of $\mathbf{V_{CE}}$ above knee voltage, $\mathbf{I_C}$ is approximately equal to $\beta\mathbf{I_B}$.
- The input resistance $\mathbf{r_i}$ is the ratio of change in base emitter voltage ΔV_{BE} to the change in base current ΔI_B at constant collector emitter voltage $\mathbf{V_{CE}}$.

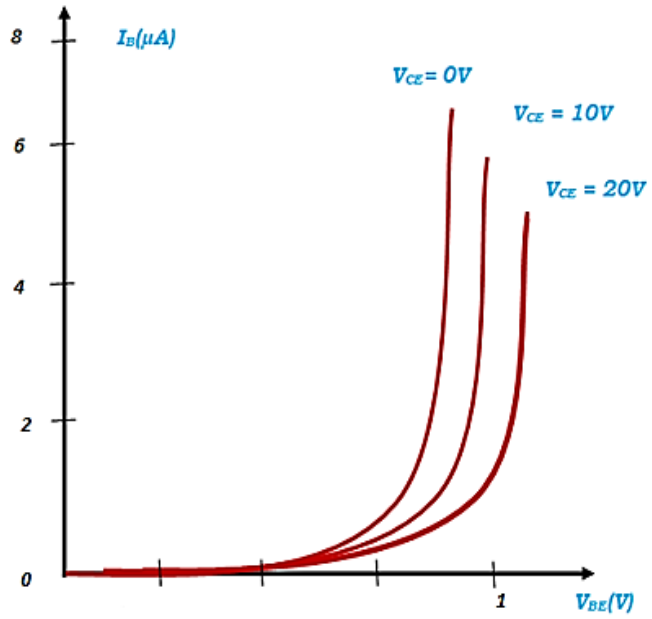
$$r_i = \frac{\Delta V_{BE}}{\Delta I_B} \text{ at constant } V_{CE}$$

- As the input resistance is of very low value, a small value of $\mathbf{V_{BE}}$ is enough to produce a large current flow of base current $\mathbf{I_B}$.
- The output resistance $\mathbf{r_o}$ is the ratio of change in collector emitter voltage ΔVCE to the change in collector current ΔIC at constant $\mathbf{I_B}$.

$$r_o = \frac{\Delta V_{CE}}{\Delta I_C} \text{ at constant } I_B$$

- As the output resistance of CE circuit is less than that of CB circuit.
- This configuration is usually used for bias stabilization methods and audio frequency applications.

Input Characteristics of Common Emitter Configuration:



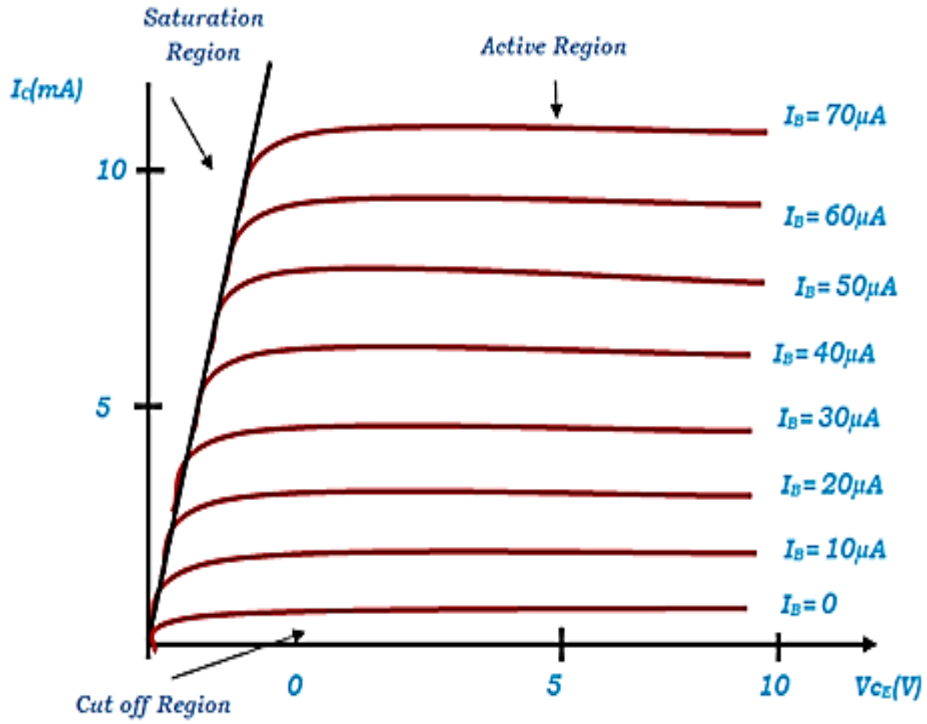
Input characteristics are the relationship between the input current and the input voltage keeping output voltage constant. Here the input current is the base current IB, input voltage is base emitter voltage VBE and the output voltage is collector emitter voltage VCE.

First the output voltage VCE is kept at zero and the input voltage VBE is gradually increased and the input current IB is noted. Then again, the output voltage VCE is increased like 10V, 20V and kept constant and by increasing the input voltage VBE, the input current IB is noted.

From the results it is observed that when the input voltage VBE is increased initially there is no current produced, further when it is increased the input current IB increases steeply. When the output voltage VCE is further increased the curve shifts right side.

Output Characteristics of Common Emitter Configuration:

Output characteristics is the relationship between the output current and the output voltage keeping input current constant. Here the values of output current IC and the output voltage VCE is noted keeping input current IB constant. In active region when the output voltage is increased there is very slight change in the output voltage. The curve looks almost flat in the active region. Cut off region is the region where the input current is below zero. When both the junctions are forward biased, it is in saturation region.



Transistor parameters

Dynamic input resistance (r_i)

Dynamic input resistance is defined as the ratio of change in input voltage or base voltage (V_{BE}) to the corresponding change in input current or base current (I_B), with the output voltage or collector voltage (V_{CE}) kept at constant.

$$r_i = \frac{\Delta V_{BE}}{\Delta I_B}, \qquad V_{CE} = \text{constant}$$

In CE configuration, the input resistance is very low.

Dynamic output resistance (r_o)

Dynamic output resistance is defined as the ratio of change in output voltage or collector voltage (V_{CE}) to the corresponding change in output current or collector current (I_C), with the input current or base current (I_B) kept at constant.

$$r_o = \frac{\Delta V_{CE}}{\Delta I_C}, \qquad I_B = \text{constant}$$

In CE configuration, the output resistance is high.

Current gain (α)

The current gain of a transistor in CE configuration is defined as the ratio of output current or collector current (I_C) to the input current or base current (I_B).

$$\alpha = \frac{I_C}{I_B}$$

The current gain of a transistor in CE configuration is high. Therefore, the transistor in CE configuration is used for amplifying the current.

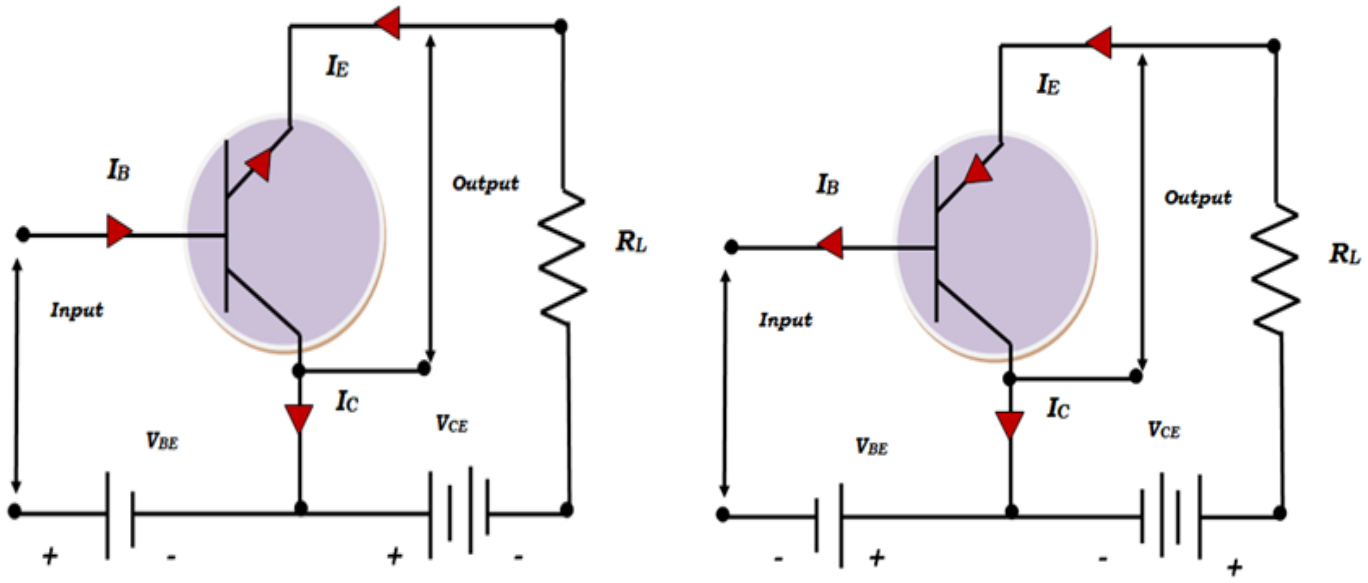
Common Collector Configuration

In this configuration, the base terminal of the transistor serves as the input, the emitter terminal is the output and the collector terminal is common for both input and output. Hence, it is named as common collector configuration. The input is applied between the base and collector while the output is taken from the emitter and collector.

The common collector configuration is also called emitter follower or voltage follower because the output emitter voltage always follows the base input voltage.

For example, the base emitter voltage is 0.7v and if the input is 5V then the output is 4.3V. Output voltage is always near the input voltage. This configuration is widely used as a buffer and it is also called as voltage buffer.

Circuit diagram of NPN and PNP configuration:



Current Amplification Factor γ

The ratio of change in emitter current $ΔIE$$ΔIE$ to the change in base current ΔIB is known as Current Amplification factor in common collector CC configuration. It is denoted by γ.

$$\gamma = \frac{\Delta I_E}{\Delta I_B}$$

- The current gain in CC configuration is same as in CE configuration.
- The voltage gain in CC configuration is always less than 1.

Relation between γ and α

Let us try to draw some relation between γ and α

$$\gamma = \frac{\Delta I_E}{\Delta I_B}$$

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

$$I_E = I_B + I_C$$

$$\Delta I_E = \Delta I_B + \Delta I_C$$

$$\Delta I_B = \Delta I_E - \Delta I_C$$

Substituting the value of I_B, we get

$$\gamma = \frac{\Delta I_E}{\Delta I_E - \Delta I_C}$$

Dividing by ΔI_E

$$\gamma = \frac{\frac{\Delta I_E}{\Delta I_E}}{\frac{\Delta I_E}{\Delta I_E} - \frac{\Delta I_C}{\Delta I_E}}$$

$$\frac{1}{1 - \alpha}$$

$$\gamma = \frac{1}{1 - \alpha}$$

Expression for collector current

We know

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

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

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

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

$$I_C \cong I_E = (\beta + 1)I_B + (\beta + 1)I_{CBO}$$

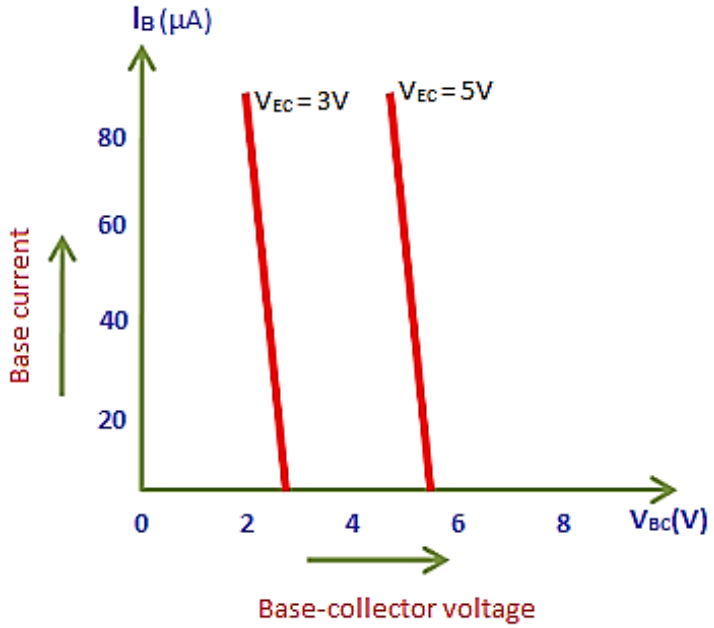
The above is the expression for collector current.

Characteristics of CC Configuration

- This configuration provides current gain but no voltage gain.
- In CC configuration, the input resistance is high and the output resistance is low.
- The voltage gain provided by this circuit is less than 1.
- The sum of collector current and base current equals emitter current.
- The input and output signals are in phase.
- This configuration works as non-inverting amplifier output.
- This circuit is mostly used for impedance matching. That means, to drive a low impedance load from a high impedance source.

Input characteristics

The input characteristics describe the relationship between input current or base current (I_B) and input voltage or base-collector voltage (V_{BC}).

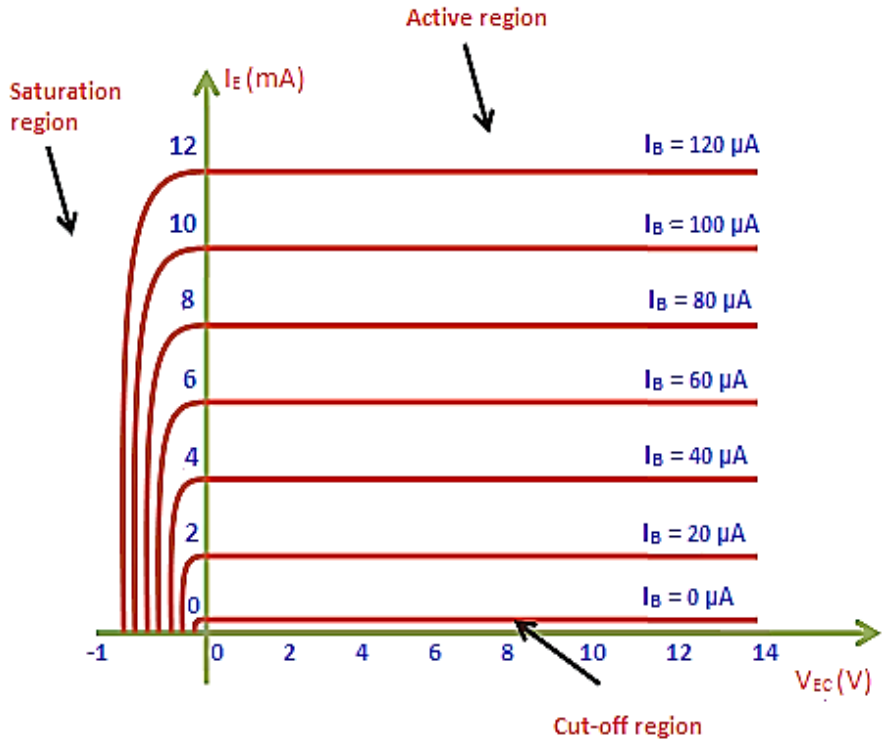


Input characteristics

The input current or base current (I_B) is taken along y-axis (vertical line) and the input voltage or base-collector voltage (V_{BC}) is taken along x-axis (horizontal line). To determine the input characteristics, the output voltage V_{EC} is kept constant at 3V and the input voltage V_{BC} is increased from zero volts to different voltage levels. For each level of input voltage V_{BC}, the corresponding input current I_B is noted. A curve is then drawn between input current I_B and input voltage V_{BC} at constant output voltage V_{EC} (3V). This process is repeated for higher fixed values of output voltage (V_{EC}).

Output characteristics

The output characteristics describe the relationship between output current or emitter current (I_E) and output voltage or emitter-collector voltage (V_{EC}).



Output characteristics

The output current or emitter current (I_E) is taken along y-axis (vertical line) and the output voltage or emitter-collector voltage (V_{EC}) is taken along x-axis (horizontal line). To determine the output characteristics, the input current I_B is kept constant at zero micro amperes and the output voltage V_{EC} is increased from zero volts to different voltage levels. For each level of output voltage V_{EC}, the corresponding output current I_E is noted. A curve is then drawn between output current I_E and output voltage V_{EC} at constant input current I_B (0 µA). Next, the input current (I_B) is increased from 0 µA to 20 µA and then kept constant at 20 µA. While increasing the input current (I_B), the output voltage (V_{EC}) is kept constant at 0 volts. This process is repeated for higher fixed values of input current I_B (I.e. 40 µA, 60 µA, 80 µA and so on).

In common collector configuration, if the input current or base current is zero then the output current or emitter current is also zero. As a result, no current flows through the transistor. So the transistor will be in the cutoff region. If the base current is slightly increased then the output current or emitter current also increases. So the transistor falls into the active region. If the base current is heavily increased then the current flowing through the transistor also heavily increases. As a result, the transistor falls into the saturation region.

Transistor parameters

Dynamic input resistance (r_i)

Dynamic input resistance is defined as the ratio of change in input voltage or base voltage (V_{BC}) to the corresponding change in input current or base current (I_B), with the output voltage or emitter voltage (V_{EC}) kept at constant.

$$r_i = \frac{\Delta V_{BC}}{\Delta I_B}, \qquad V_{EC} = \text{constant}$$

The input resistance of common collector amplifier is high.

Dynamic output resistance (r_o)

Dynamic output resistance is defined as the ratio of change in output voltage or emitter voltage (V_{EC}) to the corresponding change in output current or emitter current (I_E), with the input current or base current (I_B) kept at constant. The output resistance of common collector amplifier is low.

$$r_o = \frac{\Delta V_{EC}}{\Delta I_E}, \qquad I_B = \text{constant}$$

Current amplification factor (γ)

The current amplification factor is defined as the ratio of change in output current or emitter current I_E to the change in input current or base current I_B. It is expressed by γ.

$$\gamma = \frac{\Delta I_E}{\Delta I_B}$$

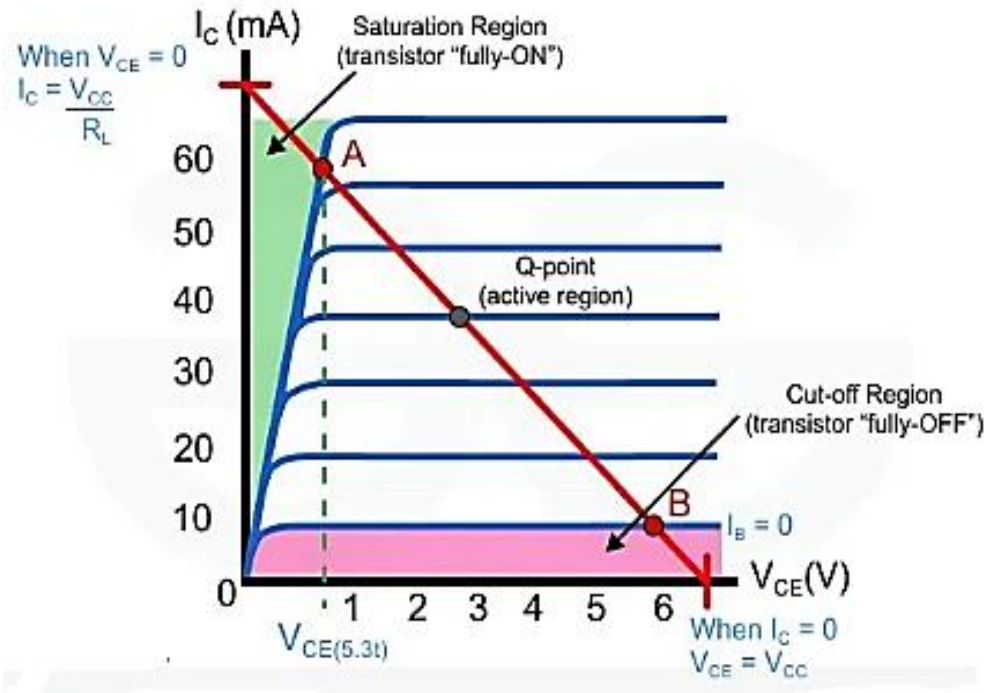
The current gain of a common collector amplifier is high.

Transistor as a Switch

Transistor as a switch is the simplest application of the devices. A transistor can be used for switching operations or opening or closing of the circuit. The main or basic concept of this operation relies on it's operation generally low voltage DC is on or off by the transistor in this mode. The both type of the PNP and NPM transistor are used as switches. The terminal transistor can be handled different from a single amplifier by biasing both the NPM and PNP bipolar transistor with "ON/OF" static switch. One of the basic and main use of the transistor is to transform a DC signal "ON" or "OFF" is solid state switch. Many devices such as LED's, lights requires very small milliamps logic level DC voltage and can directly drive by the output of a logic. If any circuit requires Bipolar Transistor Switch then the biasing of the transistor is either PNP or NPM which are arranged for operating the transistor for both sides of the "I-V" characteristics curves.

The operating area of the transistor switch called saturation region and the cut-off Region.

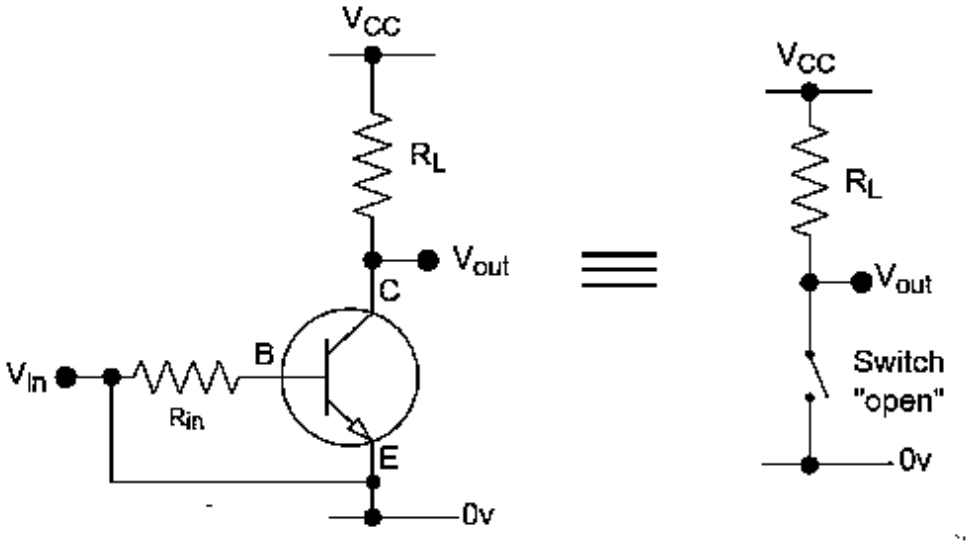
Operating Region



In the above operating region the pink shaded area at the bottom represents at the "Cut-Off" region while the blue shaded area on the left represents the **saturation** region of the transistor.

Cut-off Region

In the cut-off region of the transistor, it operates under conditions of zero input base current (Ib), zero output collector current (Ic), and maximum collector voltage (Vce). This configuration creates a significant depletion layer, preventing the flow of current through the device and effectively switching it off.



Cut-off Region

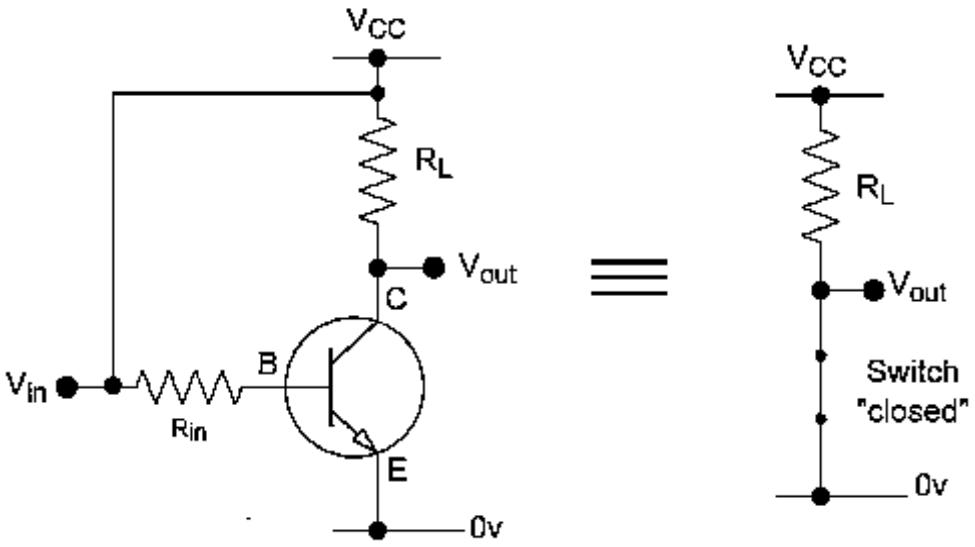
Cut-off Characteristics:

- The input and base are grounded.
- Base emitter voltage Vbe<0.7v
- Base Emitter junctions is reversed.
- Base- collector junction us reversed biased.
- Transistor is "fully-Off" (cut off region)
- No collector current flows(Ic=0)
- Vout = Vcr = Vcc= 1
- Transistor operates as open switch

  The cut off region of off mod when using a bipolar transistor as a switch, both junctions are reverse biased Vb<0.7 and Ic=0. For PNP transistor the emitter potential must be negative with respect to base.

Saturation Region

In this the transistor will be biased so the maximum amount of the current is applied, which results in the maximum collector current results in the minimum collector emitter voltage drop which cause in depletion layer as a small as possible and maximum current flowing through the transistor so the transistor is switched "Fully ON".



Saturation Region

Saturation Characteristics:

- The base and input are connected to Vcc.
- Base-Emitter voltage Vbe>0.7V.
- Base-Emitter junction is forward biased.
- Base-collector junction is forward biased.
- Transistor is "fully-On"
- Max Collector current flows (Ic=Vcc/Rl)
- Vce=0 (ideal saturation)
- Vout = Vce="0".
- Transistor operates as a closed switch.

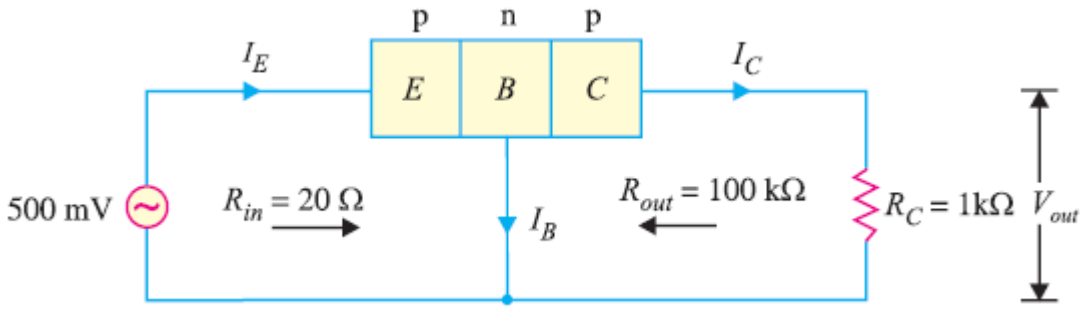
The saturation region or ON mode when use the bipolar transistor as a switch the junctions forward biased Vb>0.7v and

Ic = Maximum. In PNP transistor the emitter potential must be positive with respect to the Base.

Q1. A common base transistor amplifier has an input resistance of 20 Ω and output resistance of 100 kΩ. The collector load is 1 kΩ. If a signal of 500 mV is applied between emitter and base, find the voltage amplification. Assume α_{ac} to be nearly one.

Solution :

Fig.1 shows the conditions of the problem. Here the output resistance is very high as compared to input resistance, since the input junction (base to emitter) of the transistor is forward biased while the output junction (base to collector) is reverse biased.



Input current, $I_E = \dfrac{\text{Signal}}{R_{in}} = \dfrac{500\ \text{mV}}{20\ \Omega} = 25\ \text{mA}$. Since α_{ac} is nearly 1, output current, $I_C = I_E = 25\ \text{mA}$.

$$\text{Output voltage, } V_{out} = I_C R_C = 25\ \text{mA} \times 1\ \text{k}\Omega = 25\ \text{V}$$

$$\therefore \quad \text{Voltage amplification, } A_v = \frac{V_{out}}{\text{signal}} = \frac{25\ V}{500\ mV} = 50$$

Q2. In a common base connection, I_E = 1mA, I_C = 0.95mA. Calculate the value of I_B .

$$\text{Using the relation, } \quad I_E = I_B + I_C$$

$$1 = I_B + 0.95$$

$$I_B = 1 - 0.95 = 0.05\ \text{mA}$$

Q3. In a common base connection, current amplification factor is 0.9. If the emitter current is 1mA, determine the value of base current.

Solution :

$$\text{Here, } \alpha = 0.9, \quad I_E = 1\text{ mA}$$

$$\text{Now} \qquad \alpha = \frac{I_C}{I_E}$$

$$\textit{or} \qquad I_C = \alpha I_E = 0.9 \times 1 = 0.9\text{ mA}$$

$$\text{Also} \qquad I_E = I_B + I_C$$

$$\therefore \qquad \text{Base current, } I_B = I_E - I_C = 1 - 0.9 = \mathbf{0.1\text{ mA}}$$

Q4. In a common base connection, IC = 0.95 mA and IB = 0.05 mA. Find the value of α.

Solution :

$$\text{We know } I_E = I_B + I_C = 0.05 + 0.95 = 1\text{ mA}$$

$$\therefore \quad \text{Current amplification factor, } \alpha = \frac{I_C}{I_E} = \frac{0.95}{1} = \mathbf{0.95}$$

Q5. In a common base connection, the emitter current is 1mA. If the emitter circuit is open, the collector current is 50 μA. Find the total collector current. Given that α = 0.92.

Solution :

$$\text{Here, } I_E = 1\text{ mA}, \alpha = 0.92, \quad I_{CBO} = 50\ \mu\text{A}$$

$$\therefore \quad \text{Total collector current, } I_C = \alpha I_E + I_{CBO} = 0.92 \times 1 + 50 \times 10^{-3}$$

$$= 0.92 + 0.05 = \mathbf{0.97\text{ mA}}$$

Q6. In a common base connection, α = 0.95. The voltage drop across 2 kΩ resistance which is connected in the collector is 2V. Find the base current.

Solution :

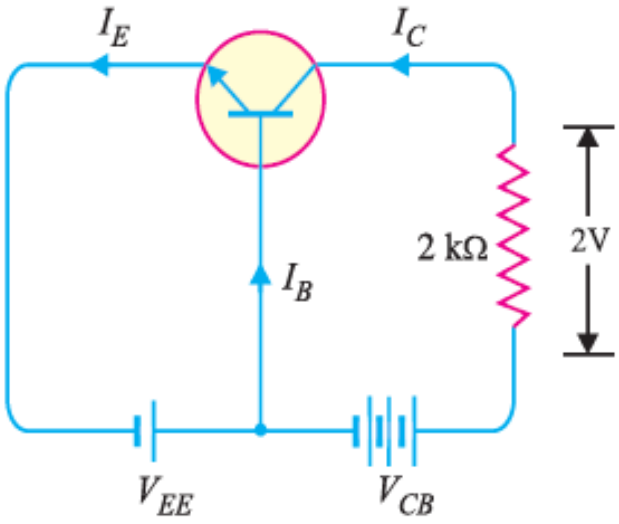


Fig. 2

Fig. 2 shows the required common base connection.

The voltage drop across RC (= 2 kΩ) is 2V.

$$\therefore \quad I_C = 2\text{ V}/2\text{ k}\Omega = 1\text{ mA}$$

Now $\alpha = I_C/I_E$

$$\therefore \quad I_E = \frac{I_C}{\alpha} = \frac{1}{0.95} = 1.05\text{ mA}$$

Using the relation, $I_E = I_B + I_C$

$$\therefore \quad I_B = I_E - I_C = 1.05 - 1$$

$$= \mathbf{0.05\text{ mA}}$$

Q7. For the common base circuit shown in Fig. 3, determine I_C and V_{CB}. Assume the transistor to be of silicon.

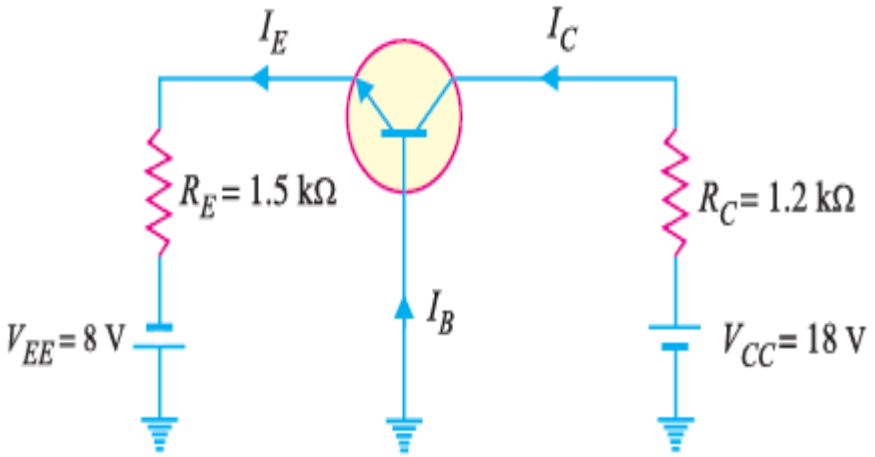


Fig. 3

Solution :

Since the transistor is of silicon, V_{BE} = 0.7V.

Applying Kirchhoff's voltage law to the emitter-side loop,we get,

$$V_{EE} = I_E R_E + V_{BE}$$

$$\text{or} \quad I_E = \frac{V_{EE} - V_{BE}}{R_E}$$

$$= \frac{8V - 0.7V}{1.5\ \text{k}\Omega} = 4.87\ \text{mA}$$

$$\therefore \quad I_C \simeq I_E = \mathbf{4.87\ mA}$$

Applying Kirchhoff's voltage law to the collector-side loop, we have,

$$V_{CC} = I_C R_C + V_{CB}$$

$$\therefore \quad V_{CB} = V_{CC} - I_C R_C$$

$$= 18\ \text{V} - 4.87\ \text{mA} \times 1.2\ \text{k}\Omega = \mathbf{12.16\ V}$$

Q8. Find the value of β if (i) α = 0.9 (ii) α = 0.98 (iii) α = 0.99.

Solution :

(i) α = 0.9

$$\beta = \frac{\alpha}{1-\alpha} = \frac{0.9}{1-0.9} = 9$$

(ii) α = 0.98

$$\beta = \frac{\alpha}{1-\alpha} = \frac{0.98}{1-0.98} = 49$$

(iii) α = 0.99

$$\beta = \frac{\alpha}{1-\alpha} = \frac{0.99}{1-0.99} = 99$$

Q9. Calculate I_E in a transistor for which β = 50 and I_B = 20 μA.

Solution :

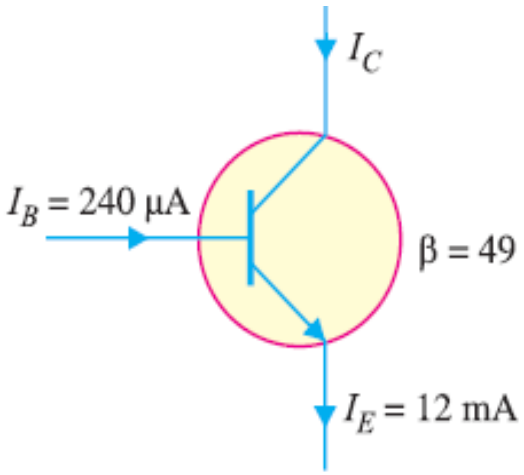
Here $\beta = 50, \quad I_B = 20\mu A = 0.02\,mA$

Now $\beta = \dfrac{I_C}{I_B}$

$\therefore \quad I_C = \beta I_B = 50 \times 0.02 = 1\,mA$

Using the relation, $I_E = I_B + I_C = 0.02 + 1 = 1.02\,mA$

Q10. Find the α rating of the transistor shown in Fig. Hence determine the value of I_C using both α and β rating of the transistor.



Solution :

Fig. 8.20 shows the conditions of the problem.

$$\alpha = \frac{\beta}{1+\beta} = \frac{49}{1+49} = 0.98$$

The value of I_C can be found by using either α or β rating as under :

$$I_C = \alpha I_E = 0.98\ (12\ \text{mA}) = 11.76\ \text{mA}$$

Also $$I_C = \beta I_B = 49\ (240\ \mu\text{A}) = 11.76\ \text{mA}$$

Q11. For a transistor, β = 45 and voltage drop across 1kΩ which is connected in the collector circuit is 1 volt. Find the base current for common emitter connection.

Solution :

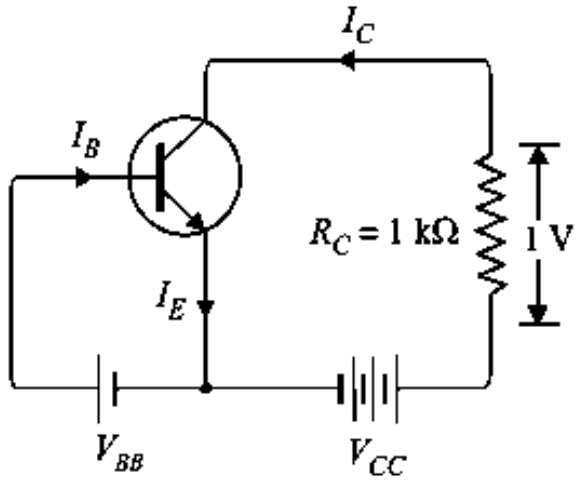


Fig. shows the required common emitter connection. The voltage drop across RC (= 1 kΩ) is 1 volt.

$$\therefore \quad I_C = \frac{1\,V}{1\,k\Omega} = 1\ \text{mA}$$

Now $$\beta = \frac{I_C}{I_B}$$

$$\therefore \quad I_B = \frac{I_C}{\beta} = \frac{1}{45} = 0.022\ \text{mA}$$

Q12. A transistor is connected in common emitter (CE) configuration in which collector supply is 8 V and the voltage drop across resistance R_C connected in the collector circuit is 0.5 V. The value of R_C = 800 Ω. If α = 0.96, determine: (i) collector-emitter voltage (ii) base current.

Solution :

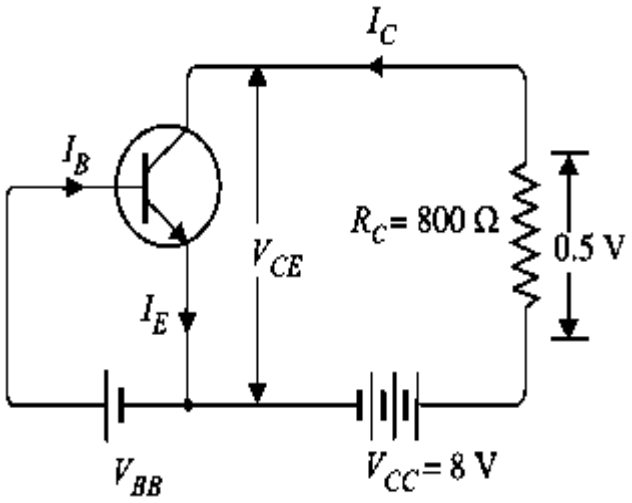


Fig. 6 shows the required common emitter connection with various values.

(i)

Collector-emitter voltage,

$$V_{CE} = V_{CC} - 0.5 = 8 - 0.5 = \mathbf{7.5\ V}$$

(ii)

The voltage drop across R_C (= 800 Ω) is 0.5 V.

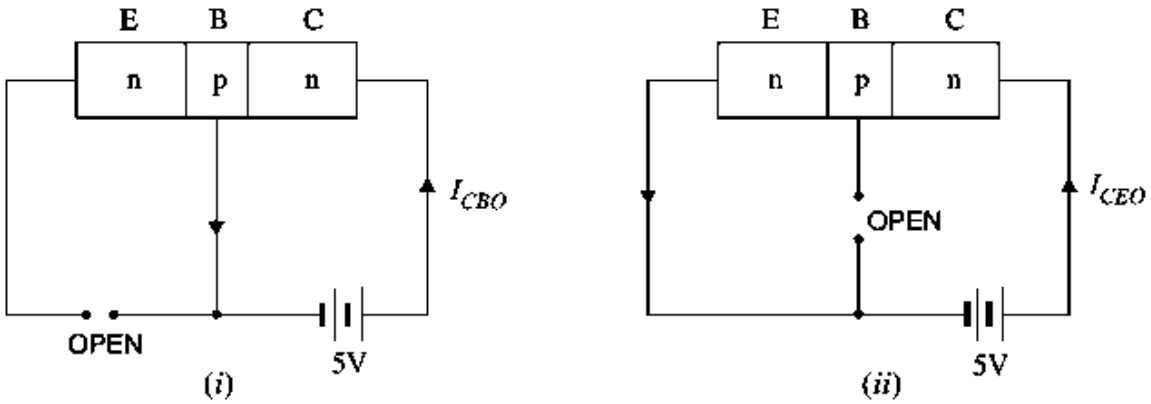
$$I_C = \frac{0.5\ \text{V}}{800\ \Omega} = \frac{5}{8}\ \text{mA} = 0.625\ \text{mA}$$

Now $$\beta = \frac{\alpha}{1-\alpha} = \frac{0.96}{1-0.96} = 24$$

$$\therefore \quad \text{Base current, } I_B = \frac{I_C}{\beta} = \frac{0.625}{24} = \mathbf{0.026\ mA}$$

Q13. An n-p-n transistor at room temperature has its emitter disconnected. A voltage of 5 V is applied between collector and base. With collector positive, a current of 0.2 μA flows. When the base is disconnected and the same voltage is applied between collector and emitter, the current **is** found to be 20 μA. Find α, I_E and I_B when collector current is 1 mA.

Solution :



When the emitter circuit is open as shown in Fig.7 (i) , the collector-base junction is reverse biased. A small leakage current I_{CBO} flows due to minority carriers.

$\therefore \quad I_{CBO} = 0.2\ \mu A$ ...*given*

When base is open [See Fig. 8.23 (*ii*)], a small leakage current I_{CEO} flows due to minority carriers.

$\therefore \quad I_{CEO} = 20\ \mu A$ ... *given*

We know $I_{CEO} = \dfrac{I_{CBO}}{1-\alpha}$

or $20 = \dfrac{0.2}{1-\alpha}$

$\therefore \quad \alpha = 0.99$

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

Here $I_C = 1\text{mA} = 1000\ \mu\text{A}\ ;\ \alpha = 0.99\ ;\ I_{CBO} = 0.2\ \mu\text{A}$

$\therefore \quad 1000 = 0.99 \times I_E + 0.2$

or $I_E = \dfrac{1000 - 0.2}{0.99} = 1010\ \mu\text{A}$

and $I_B = I_E - I_C = 1010 - 1000 = 10\ \mu\text{A}$

Q14. The collector leakage current in a transistor is 300 μA in CE arrangement. If now the transistor is connected in CB arrangement, what will be the leakage current? Given that β = 120.

Solution :

$I_{CEO} = 300\,\mu A$

$$\beta = 120 \; ; \; \alpha = \frac{\beta}{\beta+1} = \frac{120}{120+1} = 0.992$$

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

$$\therefore \quad I_{CBO} = (1-\alpha)\, I_{CEO} = (1-0.992) \times 300 = \mathbf{2.4\,\mu A}$$

Note that leakage current in *CE* arrangement (*i.e.* I_{CEO}) is much more than in *CB* arrangement (*i.e.* I_{CBO}).

Q15. For a certain transistor, I_B = 20 μA; I_C = 2 mA and β = 80. Calculate I_{CBO}.

Solution :

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

or $$2 = 80 \times 0.02 + I_{CEO}$$

$$\therefore \quad I_{CEO} = 2 - 80 \times 0.02 = 0.4\ \text{mA}$$

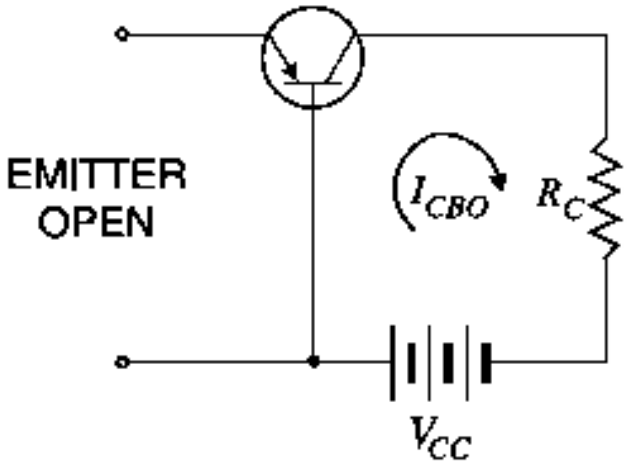
Now $$\alpha = \frac{\beta}{\beta+1} = \frac{80}{80+1} = 0.988$$

$$\therefore \quad I_{CBO} = (1-\alpha)\, I_{CEO} = (1-0.988) \times 0.4 = \mathbf{0.0048\ mA}$$

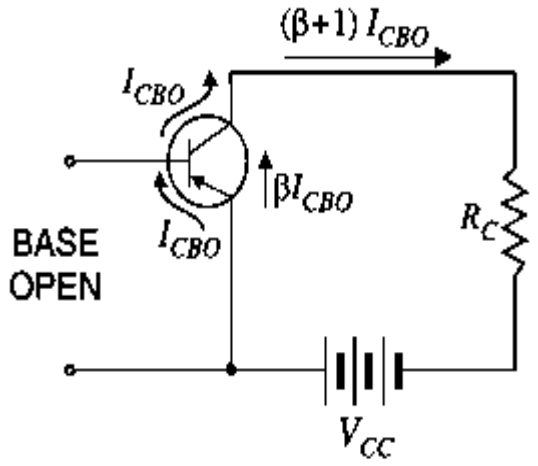
Q16. Using diagrams, explain the correctness of the relation $I_{CEO} = (\beta + 1)I_{CBO}$.

Solution :

The leakage current ICBO is the current that flows through the base-collector junction when emitter is open as shown is Fig.



When the transistor is in CE arrangement, the base current (i.e. I_{CBO}) is multiplied by β in the collector as shown in Fig.



$$\therefore \qquad I_{CEO} = I_{CBO} + \beta I_{CBO} = (\beta + 1)\, I_{CBO}$$

Q17. Determine V_{CB} in the transistor circuit shown in Fig. 10 (i). The transistor is of silicon and has β = 150.

Solution :

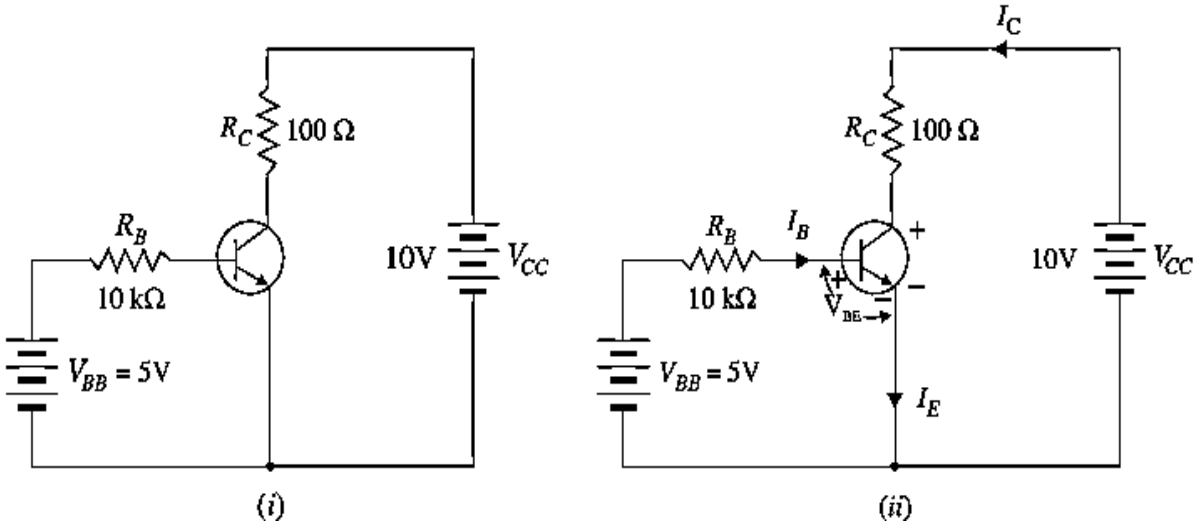


Fig. (i) Shows the transistor circuit while Fig. (ii) Shows the various currents and voltages along with polarities.

Applying Kirchhoff's voltage law to base-emitter loop, we have,

$$V_{BB} - I_B R_B - V_{BE} = 0$$

or $$I_B = \frac{V_{BB} - V_{BE}}{R_B} = \frac{5\text{V} - 0.7\text{V}}{10\ k\Omega} = 430\ \mu\text{A}$$

$\therefore$ $$I_C = \beta I_B = (150)(430\ \mu\text{A}) = 64.5\ \text{mA}$$

Now $$V_{CE} = V_{CC} - I_C R_C$$

$$= 10\text{V} - (64.5\ \text{mA})\ (100\Omega) = 10\text{V} - 6.45\text{V} = 3.55\text{V}$$

We know that : $$V_{CE} = V_{CB} + V_{BE}$$

$\therefore$ $$V_{CB} = V_{CE} - V_{BE} = 3.55 - 0.7 = \mathbf{2.85V}$$

Q18. In a transistor, I_B = 68 μA, I_E = 30 mA and β = 440. Determine the α rating of the transistor. Then determine the value of I_C using both the α rating and β rating of the transistor.

Solution :

$$\alpha = \frac{\beta}{\beta+1} = \frac{440}{440+1} = \mathbf{0.9977}$$

$$I_C = \alpha I_E = (0.9977)\ (30\ \text{mA}) = \mathbf{29.93\ mA}$$

Also

$$I_C = \beta I_B = (440)\ (68\ \mu\text{A}) = \mathbf{29.93\ mA}$$

Q19. A transistor has the following ratings : $I_{C\,(max)}$ = 500 mA and β_{max} = 300. Determine the maximum allowable value of I_B for the device.

Solution :

$$I_{B\,(max)} = \frac{I_{C\,(max)}}{\beta_{max}} = \frac{500\ \text{mA}}{300} = \mathbf{1.67\ mA}$$

For this transistor, if the base current is allowed to exceed 1.67 mA, the collector current will exceed its maximum rating of 500 mA and the transistor will probably be destroyed

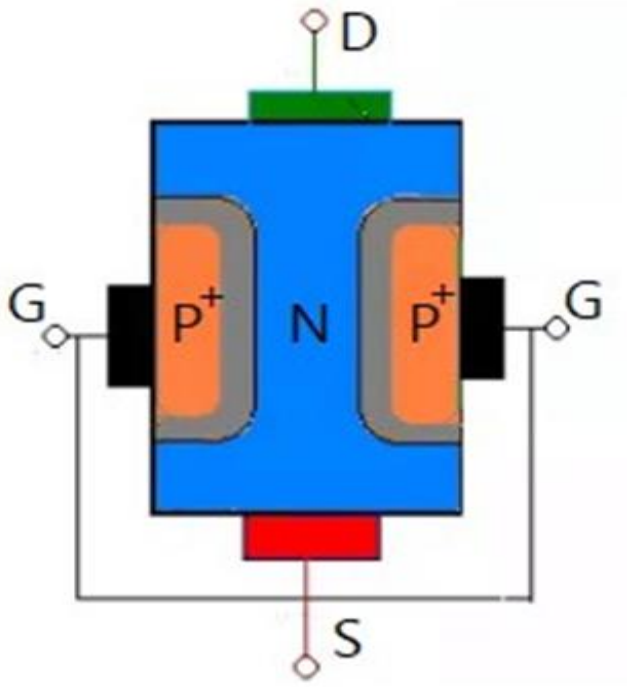
1. What is a transistor? Give its circuit symbol.
2. A transistor operating in the active region, although the collector junction is reverse biased the collector current is quite large. Explain.
3. Define current gain.
4. If the base current in the transistor is 30 micro amps when the emitter current is 2 mA. What value of α and β?
5. Give the relation between α and β.
6. Define α and β. Give the relationship between them.
7. List some applications of BJT.
8. Justify the cutoff and active region of a transistor.
9. Draw the Input characteristics of a transistor and resistance in CE configuration.
10. Draw the Input characteristics of a transistor and resistance in CB configuration.
11. Draw the Input characteristics of a transistor and resistance in CC configuration.
12. Among CE, CB and CC configurations, which is the most popular? Justify?
13. What is biasing of a transistor? Why it is needed?
14. In a common base, emitter current is 1 mA, I_{CBO} = 50 μA, α = 0.92 Find collector current.
15. Describe how switching achieved using a BJT, Justify it?
16. What are the bias conditions to operate a transistor in active mode?
17. Draw input characteristics of a transistor in CB configuration.
18. Draw output characteristics of a transistor in CE configuration.
19. Describe two applications of BJT.
20. Explain the operation of NPN and PNP transistors.
21. Distinguish between the different types of transistor configurations.
22. Draw transistor mode circuit diagrams in CB, CE and CC Modes.
23. Can a transistor be used as a switch?
24. Draw the symbols for NPN and PNP transistor.
25. Draw IV characteristics of BJT.
26. A transistor has α = 0.99. Calculate the base circuit, if the emitter current is 8mA.
27. Find α for each β = 190 and β = 50.
28. Find α for each β = 100 and β = 27.
29. Explain the working of an NPN transistor with a neat circuit diagram.
30. Draw and Explain I-V characteristics of BJT.

Module 5

FIELD EFFECT TRANSISTOR

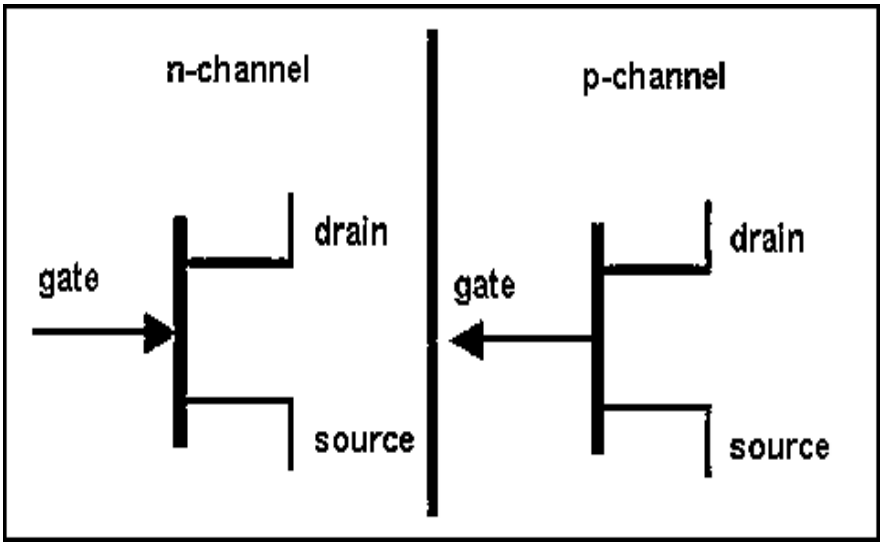
FIELD EFFECT TRANSISTOR

Field-Effect Transistors (FETs) - FET types: JFET, MOSFET, Structure and operation MOSFETs in Detail - MOSFET structure, Enhancement and depletion modes, Threshold voltage MOSFET Applications - MOSFET as a switch.



- "The Field effect transistor is a unipolar transistor made up of semiconductor material, which uses an electric field to control the current flow."
- It comes in two types: junction FET (JFET) and metal-oxide-semiconductor FET (MOSFET).
- FETs have three terminals: **source, gate, and drain**.
- FETs control the current by the application of a voltage to the gate, which controls the conductivity between the drain and source.
- FETs are also known as unipolar transistors since they involve single-carrier-type operation. That is, FETs use either electrons (n-channel) or holes (p-channel) as charge carriers in their operation, but not both.
- It is voltage-controlled device. JFET is used as a voltage-controlled resistor or switch or as an amplifier.

- FET has more temperature stability.
- Input impedance of FET is very high.
- There are two types of JFET namely N-Channel JFET and P-Channel JFET.
- In N channel the generation of the current is due to the movement of electrons, in P channel the generation of current is due to the movement of holes.
- Since the movement of electrons is faster than the movement of holes, N- Channel JFET is preferred more than the P-Channel JFET.
- Symbol of N channel and P channel JFET:



- JFET has three terminals Drain, Source and Gate equivalent to Collector, Base and Emitter in BJT.
- BJT have PN Junctions but JFET have channels made of either P type or N type.
- In P-Channel JFET arrow points outside and in N-Channel JFET arrow points inside.

Three terminals of JFET:

Source:

The majority carriers enter the Field Effect transistor through the source terminal.

Gate:

By controlling the Gate voltage, the flow of majority carriers from Source to drain can be controlled.

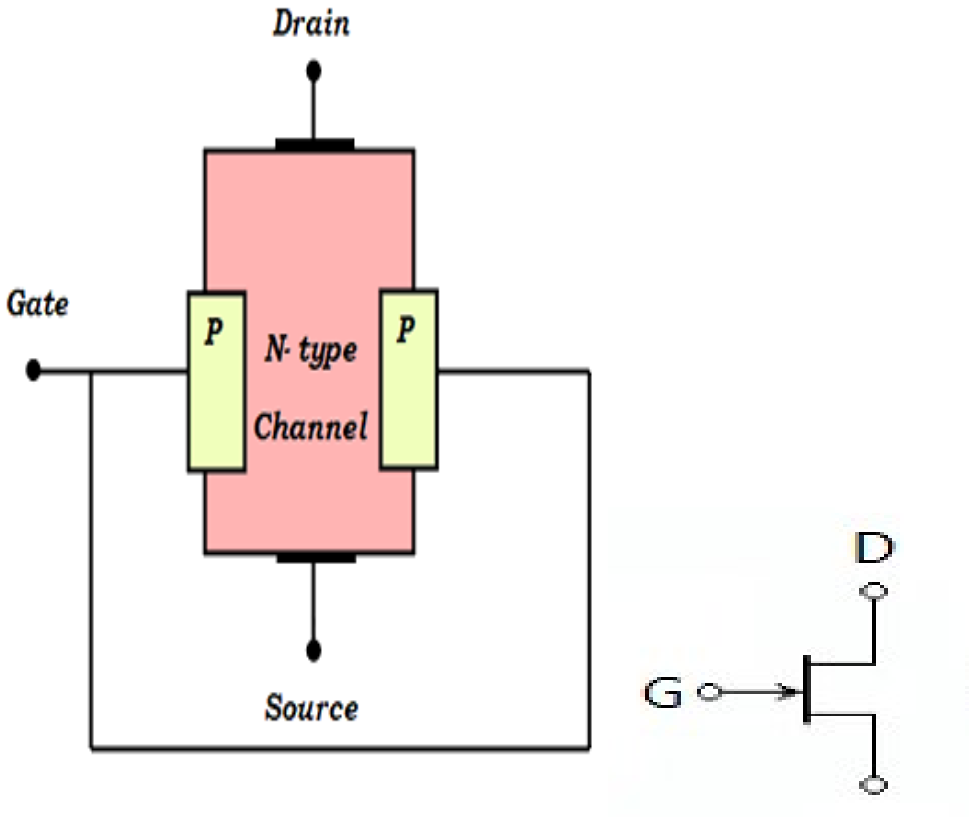
Drain:

The majority charge carriers leave the channel through drain. This current is designated by the source gate voltage VGS

Channel:

The region between source and drain and also between the gate regions is called the channel.

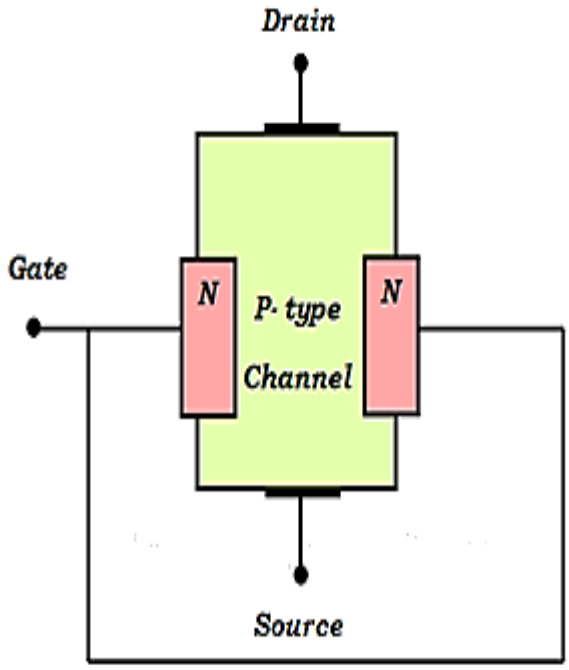
Construction of N- channel FET:



- It consists of N-type silicon bar. Ohmic contacts are made at the two ends of the rod are called source (S) and drain (D).
- Source terminal is connected to the –ve terminal of the battery. The mejority charge carriers electrons in N-type silicon are enters through this terminal.
- Drain terminal is connected to the +ve terminal of battery. The mejority charge carriers electrons leave the bar through this terminal.
- The PN junction is formed on both side of N-type silicon bar by diffusion of heavily doped P-type silicon. These layers are joined together and called gate (G)

- The this region between PN junction is called channel. Since this channel is in N-type silicon bar, FET is also known as N channel JFET.

Construction of P channel FET:



As it is shown in the figure in P Channel JFET in the P type substrate drain and source terminals are taken by creating ohmic contacts. N type material is used at the either side of the channel and the gate terminals are taken from the N type materials.

Characteristics of Junction field effect transistor (JFET)

• Temperature sensitivity: The JFETs are sensitive to temperature variations, which allows them to adapt their properties with changing temperatures. In certain applications, proper thermal management may be necessary.

• Low Noise: JFETs are known for their low noise, which is valuable in applications such as amplifier and sensors where signal integrity is essential.

• High input impedance: The high input impedance of JFETs remains relatively stable over a range of temperatures and voltages, making them suitable for precision applications.

• Variants: JFETs, which allow circuit design flexibility and enable applications that require both sourcing and sinking current, are available in two types of channels: N channel and P Channel.

Other characteristics majorly followed are mentioned below:

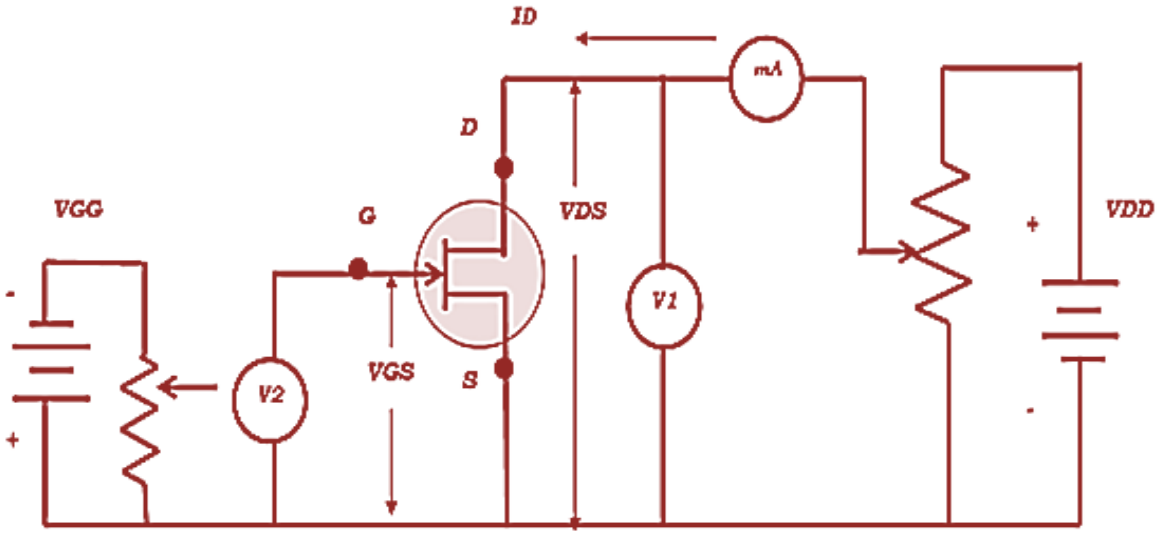
- Output characteristics
- Transfer characteristics

Working of N channel JFET:

Output characteristics:

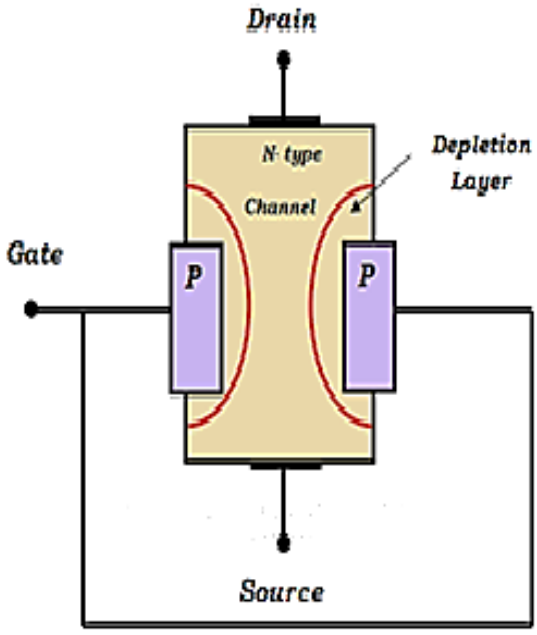
The working of JFET can be explained by discussing about how to turn on N-channel JFET and how to turn off N-channel JFET. For turning ON a N-channel JFET, positive voltage of VDD has to be applied to the drain terminal of the transistor w.r.t (with respect to) source terminal such that the drain terminal must be appropriately more positive than the source terminal. Thus, current flow is allowed through the drain to source channel. If the voltage at the gate terminal, VGG is 0V, then there will be maximum current at the drain terminal and N-channel JFET is said to be in ON condition.

For turning off the N-channel JFET, the positive bias voltage can be turned off or a negative voltage can be applied to the gate terminal. Thus, by changing the polarity of the gate voltage the drain current can be reduced and then N-channel JFET is said to be in OFF condition.



1) When VGS = 0 and VDS = 0:

   When no voltage is applied between drain and source and source and gate, the depletion region around the PN junction is uniform.

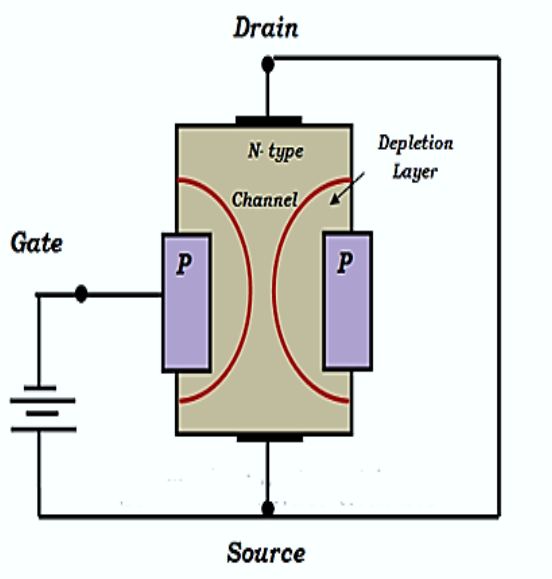


N Channel

1) Bias is Zero, thin depletion layer and low resistance channel between source and drain

2) When VDS = 0 and VGS is decreased from zero:

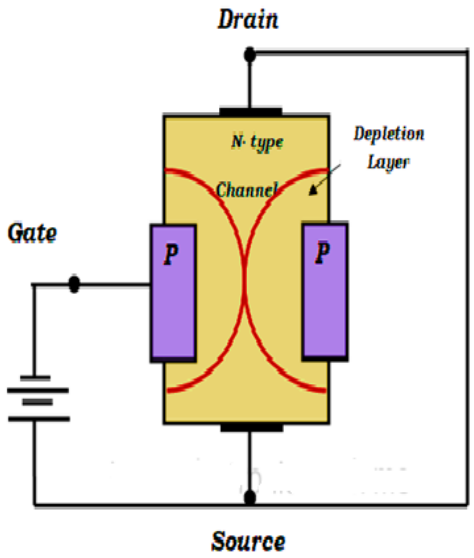
When the gate terminal is reverse biased or when negative gate source voltage (VGS) is applied the size of the depletion layer increases and the resistance in the channel increases. Thus, it controls the flow of current in the channel.



N Channel

2) Moderate gate to source reverse bias, narrow channel

3) Further increase in negative gate source voltage (VGS) increases the width of depletion region till two depletion region meet each other. In this condition no current is flowing through the channel and channel is said to be cutoff. The negative gate source voltage VGS, required to cut-off the channel is called **cut-off voltage**.

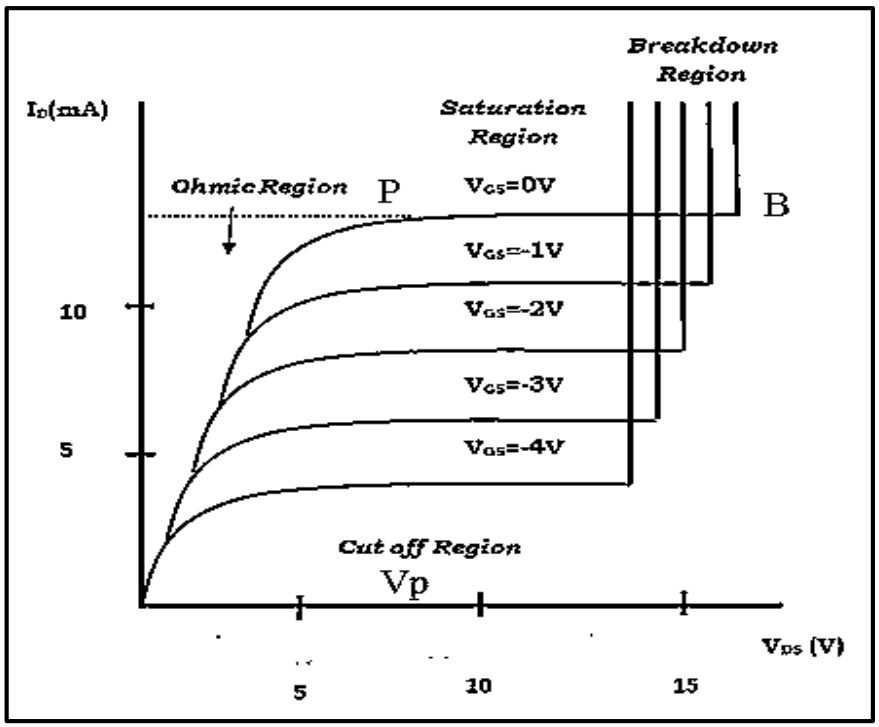


N Channel

2) Bias greater than pinch off, no conductive path between source to drain

4) When VGS = 0 and VDS is increased from zero:When VDS increased, the majority charge carriers i.e electrons in N channel FET starts to flow from source to drain and conventional current ID increases. Due to resistance of the channel and applied voltage VDS, there is increase in the potential along the channel from source to drain. The reverse voltage across the PN junction increases and depletion layer also increases. The conduction cross sectional area of the channel decreases and channel is said to be pinched off. The corresponding VDS is known as **pinched-off voltage.**

5) Characteristics curve of FET:



The N-channel JFET characteristics curve is shown in the figure. It is the graph between drain current and gate-source voltage. There are multiple regions in the curve and they are ohmic, saturation, cutoff, and breakdown regions.

Ohmic Region

- In this region. The drain current increases linearly with the increase in drain-source voltage.
- In this region N-type semiconductor acts like a simple resistor.

Pinch-off Region or Saturation Region:

- It is also called as **saturation region**. In this region drain current is constant at its maximum value. The JFET is in ON condition.
- The drain current in the pinch-off region depends upon gate to source voltage.
- In this region JFET works as an amplifier.

Breakdown Region

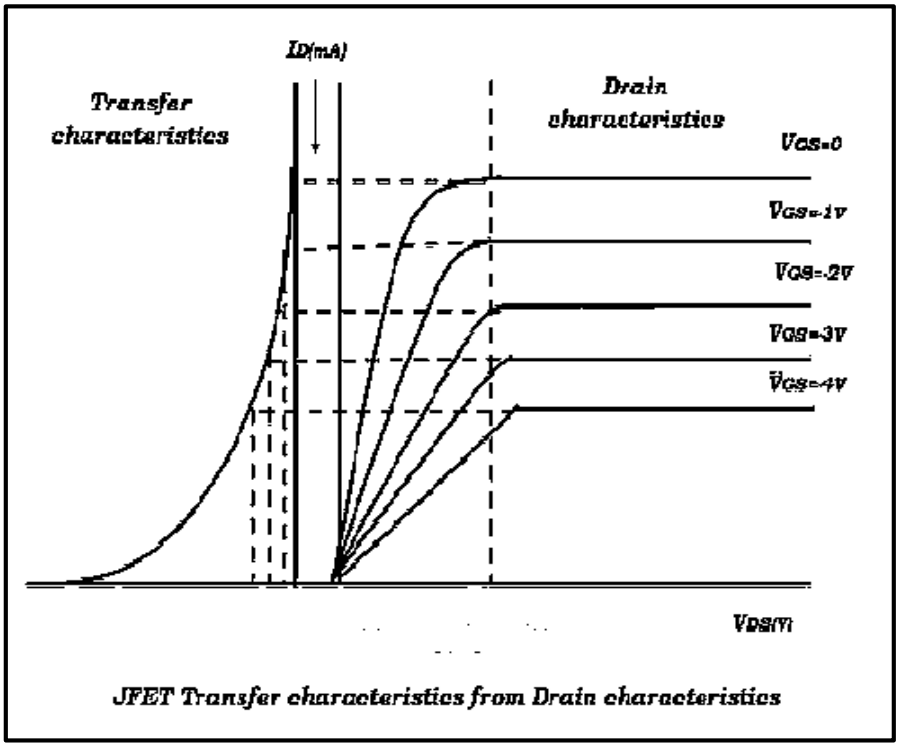
- If the VDD voltage applied to the drain terminal exceeds the maximum necessary voltage, then the transistor fails to resist the current and thus, the current flows from drain terminal to source terminal.
- Hence, the transistor enters into the breakdown region.

Cut-off region:

- In this region no drain current is flowing through the transistor, therefore FET is in OFF state.

Transfer Characteristics of JFET

- The transfer characteristics of a JFET plotted between the drain current (Id) and drain source voltage (Vds).
- It can be determined by keeping the Vds constant and drain current can be observed by changing the gate source voltage.
- When the gate source voltage Vgs is increased, the drain current Id decreases. When the drain source voltage is constant,
- The value of the drain current varies inversely with respect to the gate source voltage.



JFET Transfer characteristics from Drain characteristics

Parameters of JFET:

JFET has certain parameters which determine the performance. Such Parameters of JFET are

AC drain resistance, Trans conductance, Amplification factor, and DC drain resistance, Drain current

1. AC Drain Resistance: It is defined as the ratio of change in drain-source voltage VDS to change in drain current ID, at constant gate-source voltage VGS and is denoted by r_d.

i.e. AC drain resistance,

$$r_d = \frac{\Delta V_{DS}}{\Delta I_D} \text{ at constant } V_{GS}$$

It is also called the **dynamic drain resistance**.

Referring to the output or drain characteristic, it is clear that in the active region the change in drain current, I_D is very small for change in drain-source voltage, V_{DS} because the characteristic curves are almost flat. Hence ac drain resistance of a JFET is very large ranging from 10 kΩ to 1 MΩ.

2. Transconductance: The control of VGS on the drain current, I_D is measured by transconductance. It is denoted by g_m. Transconductions is defined as the ratio of change in drain current ID to the change in gate-source voltage VGS at constant drain-source voltage VDS.

i.e. Transconductance,

$$g_m = \frac{\Delta I_D}{\Delta V_{GS}} \text{ at constant } V_{DS}$$

It is also called the **forward transconductance** (g_{fs}) or forward transadmittance (Y_{fs}). It is measured in mA/volt or mho.

The transconductance measured at I_{DSS} is denoted by g_{mo}.

3. Amplification Factor: It is defined as the ratio of change in drain-source voltage to the change in gate-source voltage at constant drain current and is denoted by μ.

i.e. Amplification factor,

$$\mu = \frac{\Delta V_{DS}}{\Delta V_{GS}} \text{ at constant } I_D$$

Amplification factor of a JFET indicates how much more control the gate-source voltage has over drain current in comparison to the drain-source voltage.

Relation between Amplification factor & Trans conductance:

$$\mu = \frac{\Delta V_{DS}}{\Delta V_{GS}} \text{ at constant } I_D$$

$$\mu = \frac{\Delta V_{DS}}{\Delta V_{GS}}$$

$$= \frac{\Delta V_{DS}}{\Delta I_D} \times \frac{\Delta I_D}{\Delta V_{GS}} = r_d \times g_m$$

= ac drain resistance × transconductance

Amplification factor μ of a FET may be as high as 100.

4. DC Drain Resistance: It is also called the static or ohmic resistance of the channel and is defined as ratio of drain-source voltage VDS and drain current ID. It is denoted by R_{DS}

$$i.e., R_{DS} = \frac{V_{DS}}{I_D}$$

5. Drain current ID:

The drain current in JFET is given by

$$I_D = I_{DSS}\left(1 - \frac{V_{GS}}{V_p}\right)^2$$

Where,

V_{GS} = Gate to source voltage

I_{DSS} = Drain to source saturation current

V_p = Pinch-off voltage

The Drain current is zero when $V_{GS} = V_p$. For normal operation, V_{GS} is biased to be somewhere between V_p and 0.

Advantages of Junction Field Effect Transistor (JFET)

- **Stability**: It offers good stability in various operating conditions.
- **Low power consumption**: it consumes little power, which makes it energy efficient.
- **High impedance**: JFETs have a high input impedance; these high input impedances can be well suited for amplifier circuits.
- **Simplicity:** JFETs are relatively simple to use and do not require the complex biassing arrangements often found in other transistors.
- **No Gate Current:** JFETs have no gate current flow, which simplifies circuit design in applications where current flow must be avoided.

Disadvantages of Junction Field Effect Transistor (JFET)

- **Unipolar Device:** JFETs are unipolar devices, because the current flow can be controls through the movement of only one type of charge carrier (either electrons or holes).
- **Gate-Source Leakage:** JFETs can exhibit gate-source leakage currents, which is required in strict leakage current applications.
- **Limited Availability:** The availability is less**,** finding specific JFETs with specific characteristics can be challenging
- **Low gain**: it has low gain as compared to other types of transistors and cannot be used in high-gain applications.
- **Cost**: It is expensive, which can impact the overall cost of electronic devices.

Applications of Junction Field Effect Transistor

- **Low-Noise Amplifiers:** JFETs are ideal for low-noise amplifier applications in high-frequency signal processing, and audio circuits.
- **High-Impedance Preamplifiers:** JFETs are used in preamplifiers for high-impedance sensors, such as piezoelectric accelerometers and certain types of microphones, to maintain signal integrity.
- **Switching Circuits:** JFETs can be used as electronic switches in low-power and high-frequency applications where fast switching is required, such as in RF switching circuits.
- **Sample and Hold circuits:** In sample-and-hold circuits, JFETs can sample the input signal and hold its value until the next sampling period.
- **Voltage Regulators:** JFETs can also be used in voltage regulators to maintain stable output.
- **Oscillators**: JFETs are important in making oscillators that create repeating waveforms. They can also control the frequency, to generate stable waveforms.

Difference between FET and BJT

The following table gives all the important differences between FET (Field Effect Transistor) and BJT (Bipolar Junction Transistor):

Characteristic	BJT	FET
Full form	BJT is an acronym for Bipolar Junction Transistor.	FET is an acronym for Field Effect Transistor.
Control technology	BJT is a current-controlled device.	FET is a voltage-controlled device.
Terminals	BJT has three terminals namely, emitter, base, and collector.	FET has three terminals namely, source, gate, and drain.
Charge carries	In BJT, the current flows due to both majority and minority charge carriers.	In FET, the current flows due to majority charge carriers only.
Device types	BJT is a bipolar device, as the current flows due to both majority and minority charge carriers.	FET is a unipolar device, as the current flows due to only the majority charge carriers.
Input impedance	BJT has low input impedance.	FET has high input impedance.
Switching speed	BJT has a slower switching speed.	FET has a faster switching speed.
Fabrication as an IC	BJT is comparatively complex to fabricate as an integrated circuit.	FET is simpler to fabricate as an integrated circuit.
Gain bandwidth product	BJT has a higher gain bandwidth product.	FET has a lower gain bandwidth product.
Noise	BJT produces more noise.	FET produces less noise.
Types	NPN transistors and PNP transistors.	N-channel FET and P-channel FET.
Voltage drops	BJT has a higher voltage drop.	FET has a lower voltage drop.

Immunity to radiation	BJT is less immune to radiation.	FET is more immune to radiation.
Thermal stability	BJT has less thermal stability.	FET has better thermal stability.
Size	BJT has a bigger size.	FET has a smaller size.
Energy efficiency	BJT is less energy efficient.	FET is highly energy efficient.
Configurations	BJT has three configurations namely common-base, common-emitter, and common-collector.	FET has three configurations namely, common-gate, common-source, and common-drain.
Input-output relation	BJT has linear input-output relation.	FET has non-linear input-output relation.
Applications	BJT is mainly used in low-power applications. It is used in switching, amplification, filter circuits, oscillators, etc.	FET is mainly used in high-power and high-frequency applications. It is widely used in integrated circuits, digital circuits, operational amplifiers, measuring devices, oscilloscopes, RF amplifiers, etc.

Problem : when a reverse gate voltage of 12 V is applied to JFET, the gate current is 1 nA. Determine the resistance between gate and source.

Sol : $V_{GS} = 12\ V$, $I_G = 1 \times 10^{-9}\ A$

Therefore gate to source resistance $= \frac{V_{GS}}{I_G} = \frac{12}{10^{-9}} = 12000\ M\Omega$

Problem: when the reverse gate voltage of ~~12 V is applied~~ to JFET changes from 4 to 3.9 V, the drain current changes from 1.3 to 1.6 mA. Find the value of transconductance.

Sol : $\Delta V_{GS} = 4 - 3.9 = 0.1\ V$

$\Delta I_D = 1.6 - 1.3 = 0.3\ mA$

$\therefore g_m = \frac{\Delta I_D}{\Delta V_{GS}} = \frac{0.3 \times 10^{-3}}{0.1} = 3\ m\ mhos$.

Q1. Fig. 1 shows the transfer characteristic curve of a JFET. Write the equation for drain current.

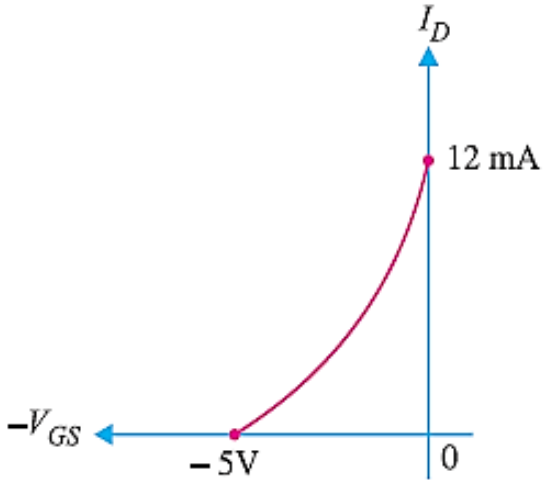


Fig.1

Solution. Referring to the transfer characteristic curve in Fig. 1, we have,

$$I_{DSS} = 12 \text{ mA}$$
$$V_{GS\,(off)} = -5 \text{ V}$$
$$\therefore \quad I_D = I_{DSS}\left[1 - \frac{V_{GS}}{V_{GS\,(off)}}\right]^2$$
$$\text{or} \quad I_D = 12\left[1 + \frac{V_{GS}}{5}\right]^2 \text{ mA Ans.}$$

Q2. A JFET has the following parameters: IDSS = 32 mA ; VGS (off) = – 8V ; VGS = – 4.5 V. Find the value of drain current.

Solution :

$$I_D = I_{DSS}\left[1 - \frac{V_{GS}}{V_{GS\,(off)}}\right]^2$$
$$= 32\left[1 - \frac{(-4.5)}{-8}\right]^2 \text{ mA}$$
$$= 6.12 \text{ mA}$$

Q3. A JFET has a drain current of 5 mA. If IDSS = 10 mA and VGS (off) = – 6 V, find the value of (i) VGS and (ii) VP.

Solution.

$$I_D = I_{DSS}\left[1 - \frac{V_{GS}}{V_{GS(off)}}\right]^2$$

or

$$5 = 10\left[1 + \frac{V_{GS}}{6}\right]^2$$

or

$$1 + \frac{V_{GS}}{6} = \sqrt{5/10} = 0.707$$

(*i*) ∴

$$V_{GS} = -1.76\ \text{V}$$

(*ii*) and

$$V_P = -V_{GS(off)} = 6\ \text{V}$$

Q5. Determine the value of drain current for the circuit shown in Fig. 3.

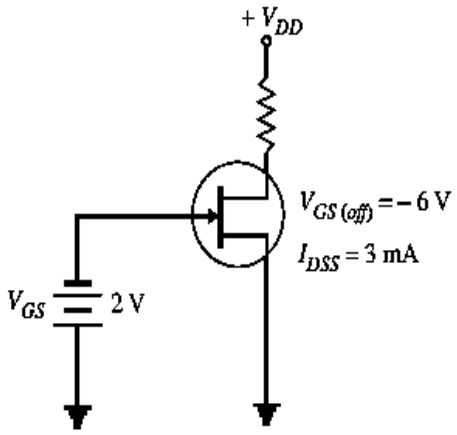


Fig.3

Solution. It is clear from Fig. 3 that VGS = – 2V. The drain current for the circuit is given by;

$$I_D = I_{DSS}\left(1 - \frac{V_{GS}}{V_{GS(off)}}\right)^2$$

$$= 3\ \text{mA}\left(1 - \frac{-2\text{V}}{-6\text{V}}\right)^2$$

$$= (3\ \text{mA})\,(0.444) = \mathbf{1.33\ mA}$$

Q6. When a reverse gate voltage of 15 V is applied to a JFET, the gate current is 10–3 μA. Find the resistance between gate and source.

Solution.

$$V_{GS} = 15\,\text{V};\ I_G = 10^{-3}\,\mu\text{A} = 10^{-9}\,\text{A}$$

$$\therefore \quad \text{Gate to source resistance} = \frac{V_{GS}}{I_G} = \frac{15\,\text{V}}{10^{-9}\,\text{A}} = 15 \times 10^9\,\Omega = \mathbf{15{,}000\ M\Omega}$$

Q7. When VGS of JFET changes from –3.1 V to –3 V, the drain current changes from 1 mA to 1.3 mA. What is the value of transconductance?

Solution.

$$\Delta V_{GS} = 3.1 - 3 = 0.1\,\text{V} \quad \text{... magnitude}$$

$$\Delta I_D = 1.3 - 1 = 0.3\,\text{mA}$$

$$\therefore \quad \text{Transconductance, } g_{fs} = \frac{\Delta I_D}{\Delta V_{GS}} = \frac{0.3\,\text{mA}}{0.1\,\text{V}} = 3\,\text{mA/V} = \mathbf{3000\ \mu\ mho}$$

Q8. A JFET has a value of gmo = 4000 μS. Determine the value of gm at VGS = – 3V. Given that VGS (off) = – 8V.

Solution.

$$g_m = g_{mo}\left(1 - \frac{V_{GS}}{V_{GS\,(off)}}\right)$$

$$= 4000\,\mu\text{S}\left(1 - \frac{-3\text{V}}{-8\text{V}}\right)$$

$$= 4000\,\mu\text{S}\,(0.625) = \mathbf{2500\ \mu S}$$

Q9. The datasheet of a JFET gives the following information: IDSS = 3 mA, VGS (off) = – 6V and gm (max) = 5000 μS. Determine the transconductance for VGS = – 4V and find drain current ID at this point.

Solution. At $V_{GS} = 0$, the value of g_m is maximum *i.e.* g_{mo}.

$\therefore$ $g_{mo} = 5000\ \mu S$

Now
$$g_m = g_{mo}\left(1 - \frac{V_{GS}}{V_{GS(off)}}\right)$$
$$= 5000\ \mu S\left(1 - \frac{-4V}{-6V}\right)$$
$$= 5000\ \mu S\ (1/3) = 1667\ \mu S$$

Also
$$I_D = I_{DSS}\left(1 - \frac{V_{GS}}{V_{GS(off)}}\right)^2$$
$$= 3\ mA\left(1 - \frac{-4}{-6}\right)^2 = 333\ \mu A$$

Q10. A JFET in Fig. 4 has values of VGS (off) = – 8V and IDSS = 16 mA. Determine the values of VGS, ID and VDS for the circuit.

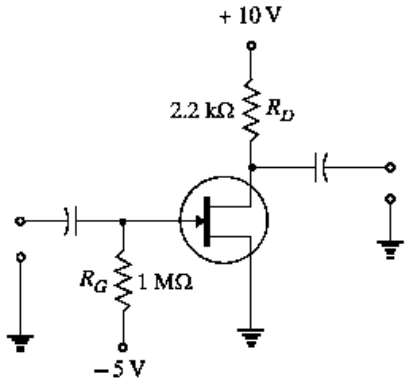


Fig. 4

Solution.

Since there is no gate current, there will be no voltage drop across RG.

$$\therefore \quad V_{GS} = V_{GG} = -5\text{V}$$

$$\text{Now} \quad I_D = I_{DSS}\left(1 - \frac{V_{GS}}{V_{GS(off)}}\right)^2$$

$$= 16\text{ mA}\left(1 - \frac{-5}{-8}\right)^2$$

$$= 16\text{ mA}\,(0.1406) = 2.25\text{ mA}$$

$$\text{Also} \quad V_{DS} = V_{DD} - I_D R_D$$

$$= 10\text{ V} - 2.25\text{ mA} \times 2.2\text{ k}\Omega = 5.05\text{ V}$$

Note that operating point for the circuit is 5.05V, 2.25 mA

Q11. Find VDS and VGS in Fig. 5, given that ID = 5 mA.

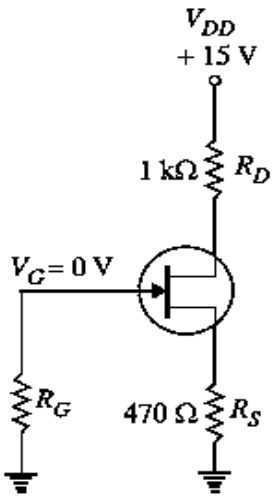


Fig. 5

Solution.

$$V_S = I_D R_S = (5\text{ mA})\,(470\ \Omega) = 2.35\text{ V}$$

$$\text{and} \quad V_D = V_{DD} - I_D R_D$$

$$= 15\text{V} - (5\text{ mA}) \times (1\text{ k}\Omega) = 10\text{V}$$

$$\therefore \quad V_{DS} = V_D - V_S = 10\text{V} - 2.35\text{ V} = 7.65\text{V}$$

Since there is no gate current, there will be no voltage drop across R_G and $V_G = 0$.

$$\text{Now} \quad V_{GS} = V_G - V_S = 0 - 2.35\text{V} = -2.35\text{ V}$$

Q12. The transfer characteristic of a JFET reveals that when VGS = – 5V, ID = 6.25 mA. Determine the value of RS required.

Solution.

$$R_S = \frac{|V_{GS}|}{|I_D|} = \frac{5\text{V}}{6.25\text{ mA}} = 800\ \Omega$$

Q13. Determine the value of RS required to self-bias a p-channel JFET with IDSS = 25 mA, VGS (off) = 15 V and VGS = 5V.

Solution.

$$I_D = I_{DSS}\left(1 - \frac{V_{GS}}{V_{GS(off)}}\right)^2 = 25\text{ mA}\left(1 - \frac{5\text{V}}{15\text{V}}\right)^2 = 25\text{mA}\ (1 - 0.333)^2 = 11.1\text{ mA}$$

$$\therefore \quad R_S = \frac{|V_{GS}|}{|I_D|} = \frac{5\text{V}}{11.1\text{ mA}} = 450\ \Omega$$

Q14. Select resistor values in Fig. 6 to set up an approximate midpoint bias. The JFET parameters are : IDSS = 15 mA and VGS (off) = – 8V. The voltage VD should be 6V (one-half of VDD).

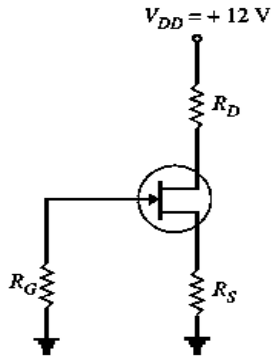


Fig.6

Solution. For midpoint bias, we have,

$$I_D \simeq \frac{I_{DSS}}{2} = \frac{15\text{ mA}}{2} = 7.5\text{ mA}$$

and $$V_{GS} = \frac{V_{GS(off)}}{3.4} = \frac{-8}{3.4} = -2.35\text{ V}$$

$$\therefore \quad R_S = \frac{|V_{GS}|}{|I_D|} = \frac{2.35\text{V}}{7.5\text{ mA}} = \mathbf{313\Omega}$$

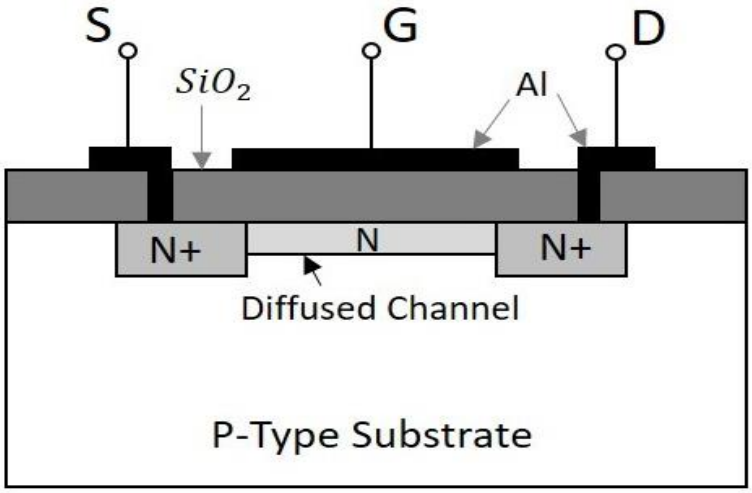
Now $$V_D = V_{DD} - I_D R_D$$

$$\therefore \quad R_D = \frac{V_{DD} - V_D}{I_D} = \frac{12\text{V} - 6\text{V}}{7.5\text{ mA}} = \mathbf{800\Omega}$$

MOSFET (METAL OXIDE SEMICONDUCTOR FIELD EFFECT TRANSISTOR)

MOSFET stands for Metal Oxide Semiconductor Field Effect Transistor. It is a type of Field Effect Transistor and it is voltage controlled device. It is also called as Insulated Gate Field Effect Transistor (IGFET). It is used for switching or amplifying electronic signals in the electronic devices. It is the most commonly used transistor and it can be used in both analog and digital circuits.

Construction of a MOSFET



Structure of N-channel MOSFET

- It is a four-terminal device with **Source (S)**, **Drain (D), Gate (G)**, and **body (B)** terminals. The body (B) is frequently connected to the source terminal, reducing the terminals to three.

A MOSFET can be constructed as follows:

- The body of a MOSFET is typically made from a lightly doped p-type semiconductor.
- The source and drain terminals are formed from heavily doped n-type regions on either side of the body.
- These doped regions are often denoted by n^+ in diagrams to indicate their high doping concentration.
- The MOSFET conducts current between its source and drain through a path called a channel. bb
- A layer of silicon dioxide is deposited on the silicon substrate to provide electrical isolation.

- There is no PN junction present between gate and channel.
- The diffused channel N between two N+ regions, the insulating dielectric SiO2 and the aluminum metal layer of the gate together form a parallel plate capacitor.
- The MOSFET conducts current between its source and drain through a path called a channel. The width of this channel is controlled by the voltage at the gate terminal.
- MOSFET works by varying the width of a channel along which charge carriers flow (electrons or holes).
- **Substrate**: MOSFET is constructed on a silicon wafer that is it acts as a base of the device.
- **SiO2:** A thin layer of insulating material is formed with SiO2 for the exchange of electrons and holes.
- **Gate Terminal:** A gate terminal is formed on the insulating layer. This controls the flow of current between the drain and source with the help of gate voltage.
- **Source and drain terminals:** These are created on the either side of the gate. These are basically heavily doped regions.
- **Channel:** Region between the gate, drain and source is known as channel which controls the flow of charge among them.

MOSFET is also classified into two types:-

Enhancement MOSFET and Depletion MOSFET:

When we provide external voltage in the channel, it can either increase or decrease the amount of charge carriers in the channel. If the number of charge carriers increases, it is known as **enhancement type MOSFET**. But if the number of charge carriers decrease then it is known as **depletion type MOSFET**.

What is Enhancement MOSFET ?

Enhancement MOSFET:

- In an Enhancement MOSFET, the channel between the source and drain is initially non-conductive or weakly conductive when no voltage is applied to the gate.

- An enhancement-type MOSFET requires a positive voltage on the gate to create an inversion layer or induce carriers in the channel, allowing current to flow.
- The threshold voltage for an enhancement MOSFET is positive, and the device is turned off when no voltage is applied to the gate.

What is Depletion MOSFET ?

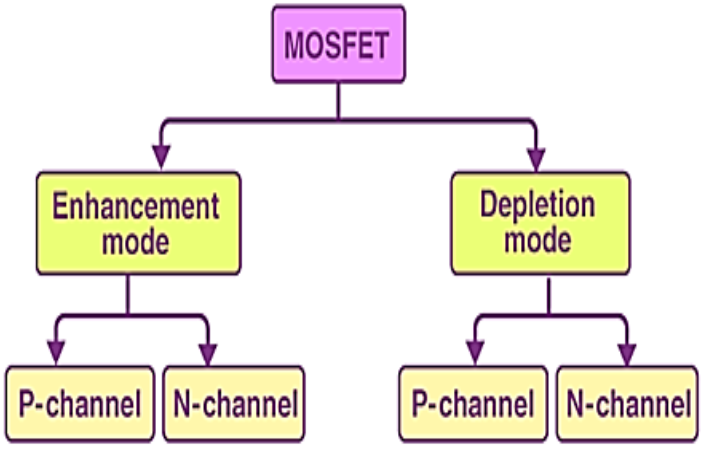
Depletion MOSFET:

- In a Depletion MOSFET, the channel between the source and drain is naturally present even when no voltage is applied to the gate.
- A depletion-type MOSFET conducts by default, and applying a voltage to the gate creates a depletion region in the channel, reducing the current flow.
- The threshold voltage for a depletion MOSFET is negative, and the device is turned off by applying a positive voltage to the gate.
- Depletion MOSFET can work in depletion mode as well as enhancement mode, depending upon gate voltage.

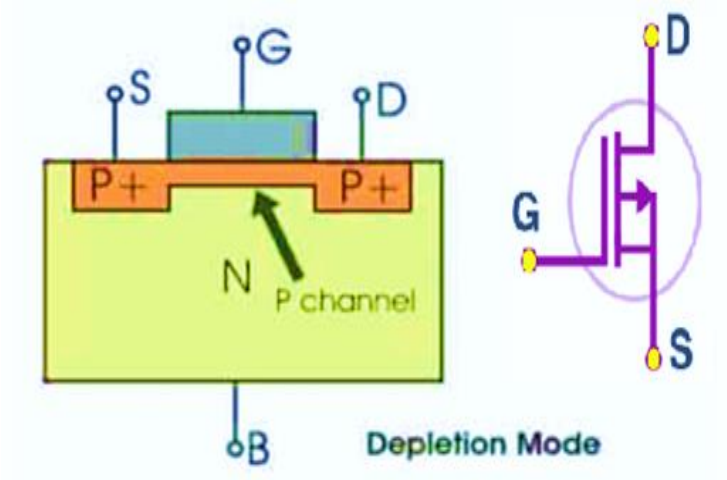
MOSFET works in two modes-

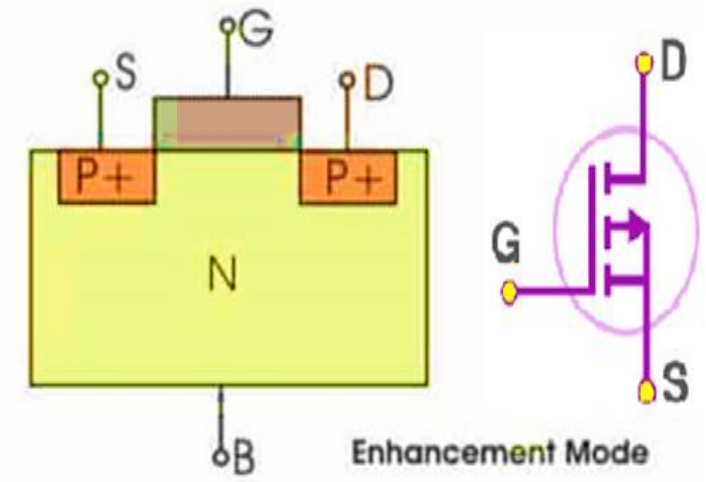
1. Depletion Mode: The transistor requires the Gate-Source voltage (VGS) to switch the device "OFF". The depletion-mode MOSFET is equivalent to a "Normally Closed" switch.

2. Enhancement Mode: The transistor requires a Gate-Source voltage (VGS) to switch the device "ON". The enhancement mode MOSFET is equivalent to a "Normally Open" switch.



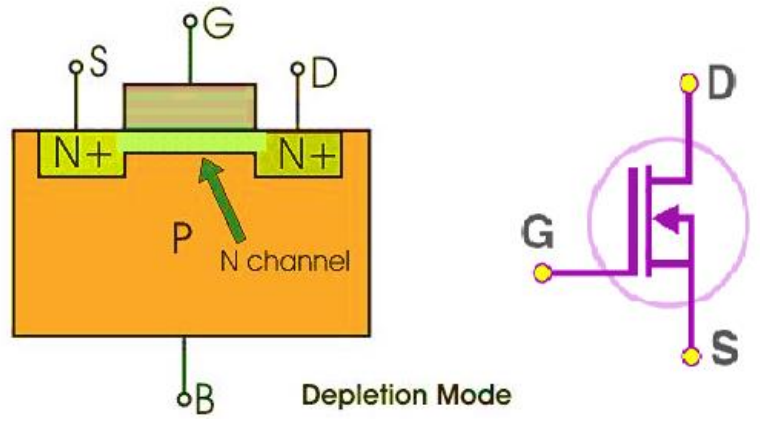
P Channel MOSFET Depletion and Enhancement Mode

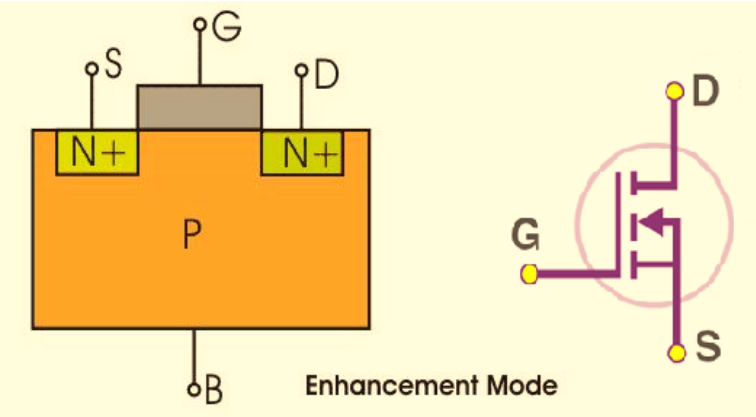




- The drain and source are heavily doped p+ region and the substrate is in n-type.
- The current flows due to the flow of positively charged holes, and that's why known as p-channel MOSFET.
- When we apply negative gate voltage, the electrons present beneath the oxide layer experience repulsive force and are pushed downward into the substrate, the depletion region is populated by the bound positive charges which are associated with the donor atoms.
- The negative gate voltage also attracts holes from the P+ source and drain region into the channel region.

N-channel MOSFET Enhancement and Depletion Mode



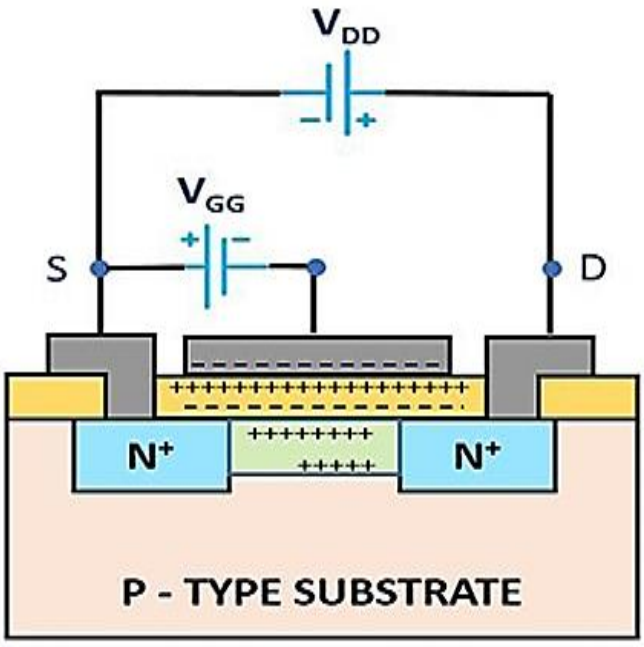


- The drain and source are heavily doped N+ region and the substrate is p-type.

- The current flows due to the flow of negatively charged electrons and that's why known as n-channel MOSFET.

- When we apply the positive gate voltage, the holes present beneath the oxide layer experience repulsive force, and the holes are pushed downwards into the bound negative charges which are associated with the acceptor atoms.

Working of N - Channel depletion mode MOSFET



- For working N-channel depletion mode MOSFET, the gate terminal should be at negative potential while drain is at positive potential, as shown in the figure.
- When no voltage is applied between gate and source, some current flows due to the voltage between drain and source.

- To get the more drain current, we have to create a channel for the free movement of charge carrier's electrons from source to drain.

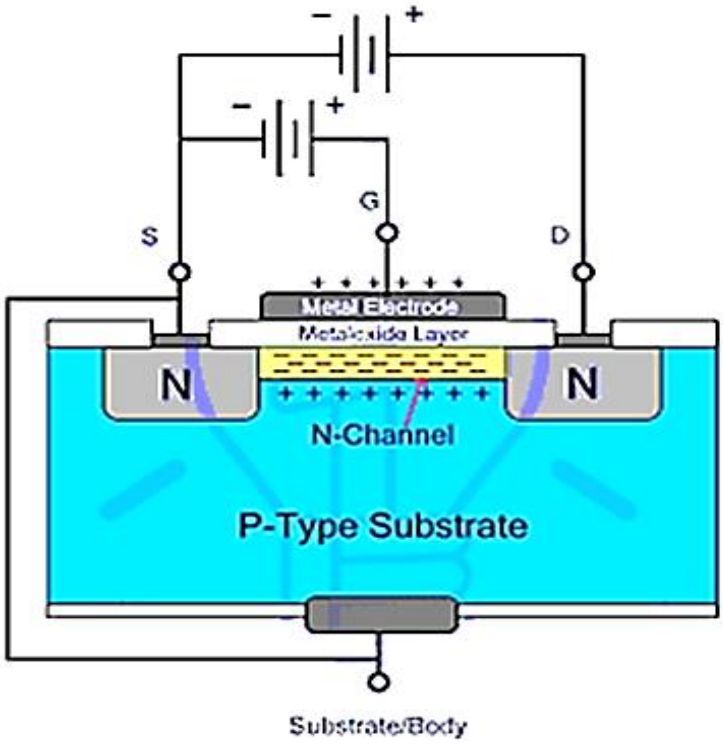
- Let some negative voltage is applied at $\mathbf{V_{GG}}$. Then the minority carriers i.e. holes, get attracted and settle near $\mathbf{SiO_2}$ layer and hole channel is formed near the oxide layer.
- If voltage is applied between the drain and source, the drain current ID flows freely between the source and drain and the gate voltage controls the holes in the channel.

- When gate negative potential VGG is further increased, the electrons get depleted and the current $\mathbf{I_D}$ decreases. Hence the more negative the applied $\mathbf{V_{GG}}$, the lesser the value of drain current $\mathbf{I_D}$ will be.

- On increasing the positive voltage VDD at the drain terminal, a reverse bias is formed at the PN junction near the drain terminal and thick depletion region is formed near the reverse biased PN junction. Hence on increasing VDS further, the channel near the drain terminal is becoming narrow. The drain current will face more resistance near the drain terminal and the drain current becomes constant and will not increase further.
- This situation is called the pinch-off situation and the drain current is called the saturation current. The voltage at which we will get saturation current is called saturation voltage.

- The channel nearer to drain gets more depleted than at source and the current flow decreases due to this effect. Hence it is called as depletion mode MOSFET.

Working of N - Channel Enhancement mode MOSFET



- For working N-channel enhancement mode MOSFET, the gate terminal should be at positive potential while drain is also at positive potential, as shown in the figure.
- When no voltage is applied between gate and source, some current flows due to the voltage between drain and source.
- Let some positive voltage is applied at $\mathbf{V_{GG}}$. Then the minority carriers i.e. holes, get repelled and the majority carriers i.e. electrons get attracted towards the $\mathbf{SiO_2}$ layer.
- With some amount of positive potential at $\mathbf{V_{GG}}$ a certain amount of drain current $\mathbf{I_D}$ flows through source to drain.

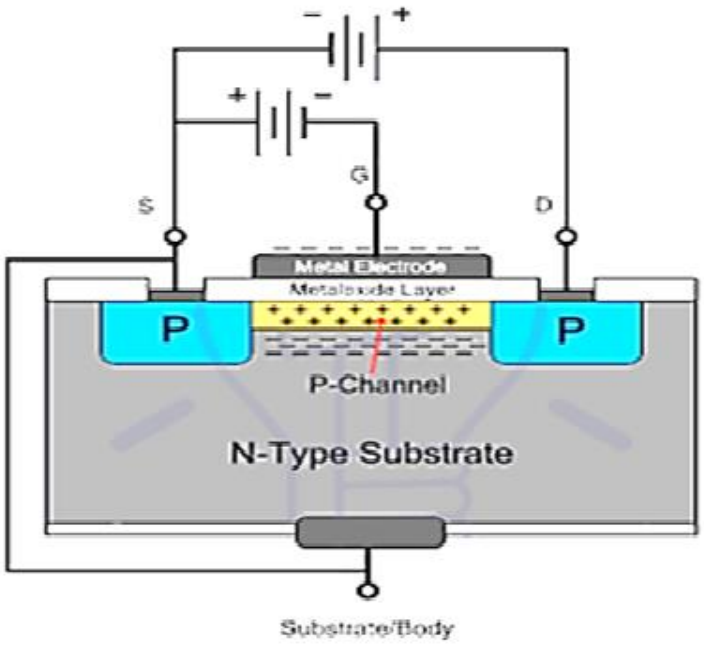
- Now **on increasing VGS** further, a high electric field is developed forcing atoms inside the P substrate to break. The free electrons generated will fill the holes near the gate region. This way holes are pushed away from the gate terminal increasing N-type behaviour near the gate terminal and N-channel is created between the two N wells. The current $\mathbf{I_D}$ increases due to the flow of electrons from source to drain.

- The VGS voltage at which the channel is created is called the threshold voltage or VT. Thus, when **VGS > VT** an N channel is induced near the gate terminal as shown in the figure

- Hence the more positive the applied $\mathbf{V_{GG}}$, the more the value of drain current $\mathbf{I_D}$ will be.
- The current flow gets enhanced due to the increase in electron flow better than in depletion mode. Hence this mode is termed as **Enhanced Mode MOSFET**.

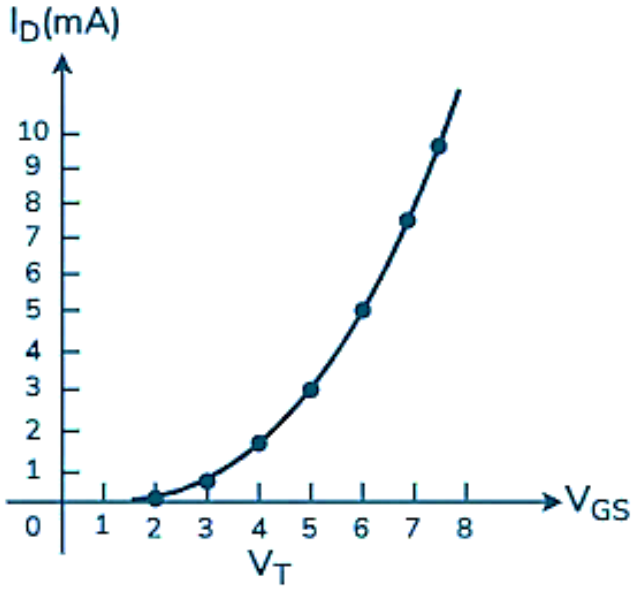
Working of P - Channel MOSFET

The construction and working of a PMOS is same as NMOS. A lightly doped **n-substrate** is taken into which two heavily doped **P+ regions** are diffused. These two P+ regions act as source and drain. A thin layer of $\mathbf{SiO_2}$ is grown over the surface. Holes are cut through this layer to make contacts with P+ regions, as shown in the following figure.



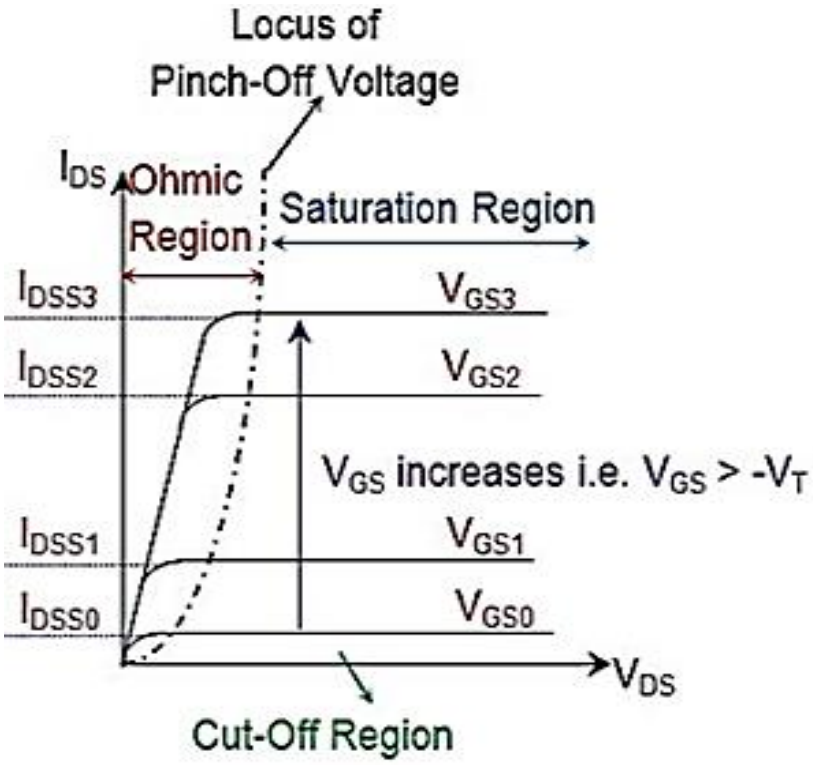
Drain & Transfer Characteristics of N channel Enhancement MOSFET

Transfer Characteristics of N-channel Enhancement Type MOSFET



- The transfer characteristics of N-Channel Enhancement type MOSFET is drawn between VGS (gate to source voltage) and ID (drain current).
- Drain current will be zero for the VGS is greater or equal to V_{TH}.
- The transfer characteristics will always be in positive region and zero till (VGS = V_{TH}).
- After Vth, drain current ID increases non linearly.
- The relation between ID (drain current) and VGS (gate to source voltage) is **$ID = k(VGS - V_{TH})^2$**.This expression is non-linear and is valid only for when (VGS > V_{TH}), therefore transfer characteristics is non-linear.

Drain (Output) Characteristics of N-Channel Enhancement Type MOSFET



- The Output characteristics of N-Channel Enhancement Type MOSFET is drawn between ID (drain current) and VDS (drain to source voltage), for various value of VGS (gate to source voltage).
- In an Enhancement MOSFET, the channel between the source and drain is initially non-conductive or weakly conductive when no voltage is applied to the gate.
- An enhancement-type MOSFET requires a positive voltage on the gate to create an inversion layer or induce carriers in the channel, allowing current to flow.
- When drain to source voltage will be Equal to the voltage difference between the gate to source voltage and threshold voltage **(VDS = VGS - VTH)**. This voltage is called pinch off voltage and thus drain current ID increases slowly with increase the voltage VDS.
- When drain to source voltage will be greater than the voltage difference between the gate to source voltage and threshold voltage **[VDS > (VGS - VTH)]**, then the drain current becomes constant and saturation occurred (ID = Constant).
- The current through the MOSFET is seen to increase with an increase in the value of VDS (Ohmic region) until VDS becomes equal to pinch-off voltage VP. After this, IDS will get saturated to a particular level IDS (saturation region of operation) which increases with an increase in VGS. Further, the locus of the pinch-off voltage also shows that VP increases with an increase in VGS.

In general, any MOSFET is seen to exhibit three operating regions viz.,

Cut-Off Region

Cut-off region is a region in which the MOSFET will be OFF as there will be no current flow through it. In this region, MOSFET behaves like an open switch and is thus used when they are required to function as electronic switches.

Ohmic or Linear Region

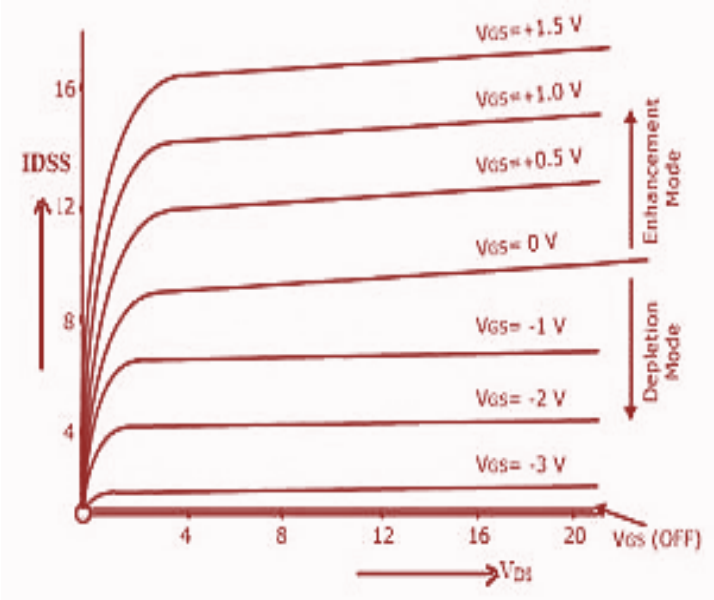
Ohmic or linear region is a region where in the current IDS increases with an increase in the value of VDS. When MOSFET's are made to operate in this region, they can be used as amplifiers.

Saturation Region

In saturation region, the MOSFETs have their IDS constant in spite of an increase in VDS and occurs once VDS exceeds the value of pinch-off voltage VP. Under this condition, the device will act like a closed switch through which a saturated value of IDS flows. As a result, this operating region is chosen whenever MOSFET's are required to perform switching operations.

Drain & Transfer Characteristics of N channel Depletion MOSFET

Drain Characteristics of N channel Depletion MOSFET



- The drain characteristics of the n channel depletion MOSFET is shown in fig.. These characteristics are plotted between the VDS and IDSS.

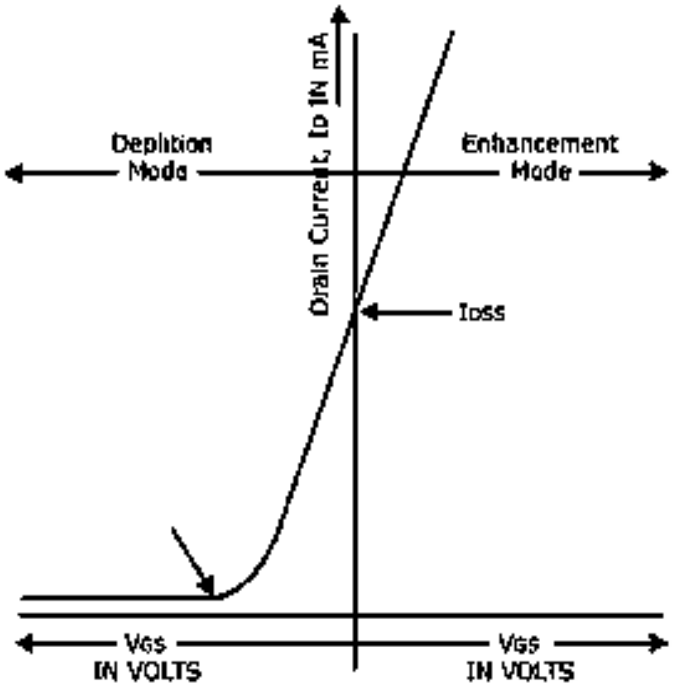
- In a Depletion MOSFET, the channel between the source and drain is naturally present even when no voltage is applied to the gate.
- When we keep on increasing the VDS value then the ID will increase. After a certain voltage, the drain current ID will become constant. The saturation current value for VGS = 0 is called IDSS.

- Whenever the voltage VGS applied is negative, and then this voltage VGS at the gate terminal will push the charge carriers like electrons to the substrate. And also, holes within this p-type substrate will be attracted by these electrons. So due to this voltage, the electrons within the channel will be recombined with holes and drain current ID decreases.

- The rate of the recombination will depend on the negative voltage applied. Once we increase this negative voltage, the recombination rate will also increase so which will decrease the no. of electrons available within this channel and will reduce the current flow effectively. When the VGS value will becomes more negative, then the drain current will decrease. At a certain voltage, this negative voltage will become zero. This voltage is known as pinch-off voltage.

- This MOSFET also works for the positive voltage, so when we apply the positive voltage at the gate terminal then the electrons will be attracted to N-channel. So, the no. of electrons within this channel will increase. So, the current flow within this channel will increase. So, for the positive VGS value, the ID will be even more than IDSS.

Transfer Characteristics of N channel Depletion MOSFET



- The transfer characteristics of N channel depletion MOSFET are shown in figure which is similar to JFET.

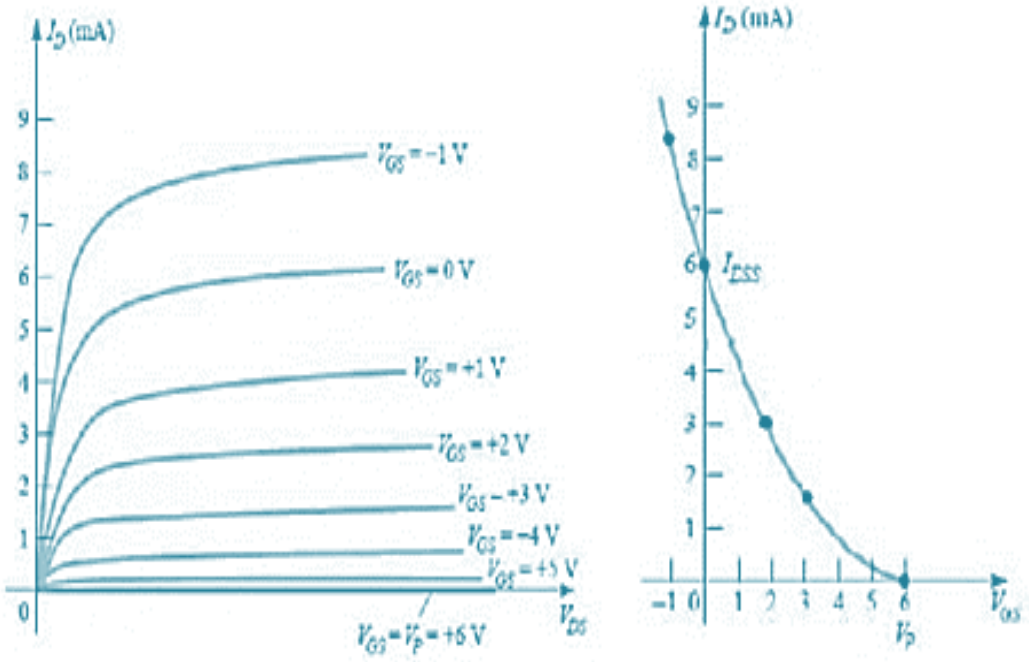
- These characteristics define the main relationship between the ID and VGS for the fixed VDS value.

- For the positive VGS values, we can also get the ID value. So due to that, the curve in the characteristics will extend to the right-hand side. Whenever the VGS value is positive, the no. of electrons within the channel will increase.

- When the VGS is positive then this region is the enhancement region. Similarly, when the VGS is negative then this region is known as the depletion region.

- The main relationship between the ID and VGS can be expressed through ID = IDSS (1-VGS/VP)^2. By using this expression, we can find the ID value for the VGS.

Drain & Transfer Characteristics of P channel Depletion MOSFET



Drain Characteristics of P channel Depletion MOSFET

The drain characteristics of P channel depletion MOSFET is shown below. Here, the VDS voltage is negative and the VGS voltage is positive. Once we keep on increasing the VGS then ID (drain current) will decrease. At the pinch-off voltage, this ID (drain current) will become zero. Once the VGS is negative, then the ID value will be even higher than IDSS.

Transfer Characteristics of P channel Depletion MOSFET

The transfer characteristics of P channel depletion MOSFET is a mirror image of n channel depletion MOSFET transfer characteristics. Here we can observe that the drain current enhances in the positive VGS region from the cut-off point until IDSS, and then it continues to increase when the negative VGS value increases.

Applications of MOSFET

- It is used as an inverter.
- It can be used in digital circuit.
- MOSFET can be used as a high frequency amplifier.
- It can be used in electronics DC relay.
- It can be used in brushless DC motor drive.
- It is used in switch mode power supply (SMPS).

Difference between depletion MOSFET & enhancement MOSFET

Depletion MOSFET	Enhancement MOSFET
The type of MOSFET where the channel depletes with the gate voltage is know as depletion or simply D-MOSFET.	The type of the MOSFET where the channel is enhanced or induced using the gate voltage is known as E-MOSFET.
The channel is fabricated during manufacturing.	There is no channel during its manufacturing.
It conducts current between its source and drains when there is no Gate voltage V_{GS}.	It does not conduct current when there is no Gate voltage V_{GS}.
Applying reverse voltage to the gate reduces the channel width.	Applying reverse voltage does not affect E-MOSFET since there is no channel.
Applying forward voltage to the gate increases the channel width.	Applying the forward voltage generates and increases the width of the channel.
It can work in both depletion and enhancement mode.	It can only work in enhancement mode.
It is a normally ON transistor.	It is a normally OFF transistor.
It switches OFF with reverse biasing of gate.	It switches ON with the forward biasing of the gate.
There is no threshold voltage for switching ON the MOSFET.	There a threshold voltage at which the MOSFET switches ON.
Diffusion or sub threshold current does not exist.	E-MOSFET has sub-threshold current leakage between its source and drain.

Difference between JFET & MOSFET

Parameter	JFET	MOSFET
Full form	JFET stands for Junction Field Effect Transistor.	MOSFET stands for Metal Oxide Semiconductor Field Effect Transistor.
Terminals	JFET is a three terminal device, where the terminals are named – Source (S), Drain (D) and Gate (G).	MOSFET is also a four terminal device, where the terminals are – Source (S), Drain (D), Gate (G) and Body or Substrate (B).
Mode of operation	JFET operates only in depletion mode.	MOSFET can be operated in both enhancement mode and depletion mode.
Gate terminal	JFET has a gate terminal which is not insulated from the channel.	The gate terminal of the MOSFET is insulated from thin layer of metal-oxide.
Channel	JFET has a continuous channel. The channel exists permanently.	MOSFET has a continuous channel only in depilation type, but not in the enhancement type. Thus, the channel exists permanently in depletion type, but not in enhancement type.
Types	JFETs are of two type: N-channel JFET and P-channel JFET.	MOSFETs are of four types: P-channel enhancement MOSFET, P-channel depletion MOSFET, N-channel enhancement MOSFET and N-channel depletion MOSFET.
Input impedance	JFET has a high input impedance which is of the order of 10^9 ΩΩ.	MOSFET has very high input impedance of the order of 10^{14} ΩΩ.
Conductivity control	In JFET, the conductivity of the device is controlled by the reverse biasing of the gate.	In MOSFET, the conductivity is controlled by the charge carriers induced in the channel.
Signal handling capacity	The signal capacity of the JFET is less.	MOSFET has more signal handling capacity than JFET.
Applications	JFET is mainly used in low noise applications.	MOSFET is extensively used in high noise applications.

Calculate I_D for the n-channel MOSFET with V_{GS} = -4 V, I_{DSS} = 10 mA and $V_{GS(off)}$ = -8 V.

Given,

V_{GS} = -4 V

I_{DSS} = 10 mA

$V_{GS(off)} = V_p$ = -8 V

Drain current $I_D = I_{DSS}\left(1 - \frac{V_{GS}}{V_P}\right)^2 = 10 \times 10^{-3}\left(1 - \frac{-4}{-8}\right)^2 = 2.5 \times 10^{-3}\ A$

I_D = 2.5 mA

Ques. What is a MOSFET and what does it stand for?

Ans. A MOSFET, or Metal-Oxide-Silicon Field-Effect Transistor, is a type of transistor that is widely used in electronic devices for switching and amplifying signals.

Ques. What are the three terminals of a MOSFET and what are their functions?

Ans. The three terminals of a MOSFET are the gate, source, and drain. The gate terminal controls the flow of current between the source and the drain.

Ques. How does a MOSFET differ from a BJT (Bipolar Junction Transistor)?

Ans. One key difference is that MOSFETs have higher input impedance and lower power consumption compared to BJTs.

Ques. What is the significance of the threshold voltage in a MOSFET?

Ans. The threshold voltage is the minimum voltage required at the gate terminal to turn on the MOSFET and allow current to flow between the source and drain.

Ques. What are the two main types of MOSFETs and how do they differ?

Ans. The two main types are N-channel and P-channel MOSFETs. N-channel MOSFETs have a negative threshold voltage, while P-channel MOSFETs have a positive threshold voltage.

Ques. What is the role of the inversion layer in a MOSFET?

Ans. The inversion layer forms under the gate terminal when a voltage is applied, allowing current to flow between the source and drain.

Ques. What are some common applications of MOSFETs in electronic devices?

Ans. MOSFETs are used in power supplies, motor control, amplifiers, and switching circuits due to their high efficiency and fast switching speeds.

Ques. What is the basic operating principle of a MOSFET?

Ans. A MOSFET operates based on the modulation of the conductivity of a channel between the source and drain terminals by varying the voltage applied to the gate terminal. When a positive voltage is applied to the gate, it creates an electric field that attracts or repels charge carriers in the channel, allowing or blocking current flow between the source and drain.

Ques. What are the advantages of using MOSFETs in power electronics applications?

Ans. MOSFETs offer several advantages in power electronics, including high efficiency, fast switching speeds, low on-state resistance, and low input capacitance. These characteristics make them ideal for applications requiring precise control and high power handling capabilities.

Ques. How does the gate oxide thickness affect the performance of a MOSFET?

Ans. The gate oxide thickness plays a crucial role in determining the switching speed and breakdown voltage of a MOSFET. Thinner gate oxides allow for faster switching speeds but may result in lower breakdown voltages, while thicker gate oxides provide higher breakdown voltages but slower switching speeds.

Ques. How does the threshold voltage of a MOSFET impact its performance and characteristics?

Ans. The threshold voltage of a MOSFET is the minimum gate-to-source voltage required to turn the device on and allow current flow between the source and drain terminals. It plays a crucial role in determining the switching behavior and overall performance of the MOSFET. A lower threshold voltage results in easier turn-on and higher conductivity, making the MOSFET more suitable for low-power applications. On the other hand, a higher threshold voltage requires a larger gate-to-source voltage to turn on the device, which can be beneficial for high-power applications where precise control is needed to prevent accidental turn-on.

1. With relevant diagrams and characteristic curves, explain the operation of JFET.
2. Draw the drain and transfer characteristics of n-channel JFET and explain.
3. Explain the construction of an N channel JFET. Also explain drain and transfer characteristics
4. Explain three distinct regions of the output characteristics.
5. Define the pinch-off voltage of JFET.
6. Draw the drain characteristics of FET and indicate important operating regions.
7. State any two advantages of FET over BJT.
8. State any four applications of FET
9. Define intrinsic stand-off ratio.
10. Define
    (i) I_{DSS}
    (ii) V_{GS} (cut off)
11. What is meant by Pinch-off voltage?
12. Define amplification factor.
13. Draw the symbol of n-channel JFETs and P-channel JFETs.
14. Draw Drain Characteristics of JFET
15. Draw the transfer characteristics of JFET.
16. Define parameters of FET
    (i) A.C. drain resistance
    (ii) D.C. drain resistance
17. Define parameters of FET
    (i) Trans conductance
    (ii) Amplification factor
18. Comment "FET is a unipolar device while BJT is a bipolar device."
19. Comment "The input Impedance of FET amplifier is higher than that of a BJT amplifier"
20. What are the parameters of JFET?
21. Why is the noise level in FET is smaller than in BJT?
22. Define drain resistance and Transconductance.
23. Define Transconductance and amplification factor of FET.
24. Give the relationship between different JFET parameters?
25. Compare P-channel JFET with N-channel JFET.
26. Compare FET and BJT.
27. Compare FET and MOSFET.
28. What are the differences between BJT and JFET?
29. What are the applications of JFET?

30. Define the threshold voltage of a MOSFET
31. What are the differences between JFETs and MOSFETs?
32. What precautions are to be taken when handling MOSFET?
33. Depletion MOSFET is commonly known as "Normally-on" MOSFET. Why?
34. State specification parameters for JFET and MOSFET.
35. Compare N channel MOSFETs with P-channel MOSFETs.
36. Draw symbol
    (i) P-channel depletion MOSFET
    (ii) N-channel depletion MOSFET
37. Draw and explain the characteristics of JFET.
38. Explain FET as a Voltage Variable Resistor.
39. Explain JFET as a switch.
40. Explain the working of a P channel JFET and draw its V-I characteristics.
41. Explain the working of an N channel JFET and draw its V-I characteristics.
42. Why is the input impedance in FET very high in comparison with BJT?
43. Why is FET preferred as a Buffer Amplifier?
44. In an n-channel JFET, I_{DSS} = 20 mA and V_P = – 6V. Calculate the drain current when V_{GS} = – 3V.
45. Determine the trans-conductance of a JFET. If its amplification factor is 96 and drain resistance is 32 KΩ.
46. Define and explain the three parameters of a JFET and give the relation between them.
47. Explain with the help of neat diagrams, the structure of an N-channel FET and its Volt-ampere characteristics. In what ways is it different from a bipolar transistor.
48. Explain working of depletion mode MOSFET with circuit diagram.
49. Explain working of Enhancement mode MOSFET with circuit diagram.
50. What is the major difference in the construction of the D-MOSFET and E-MOSFET.
51. Draw the transfer characteristics for JFET and N-Channel MOSFET.
52. Explain MOSFET as a switch.
53. What is the major difference in the construction of the D-MOSFET and the E-MOSFET?
54. Draw the transfer characteristics for JFET and N-Channel MOSFET.
55. Describe the kind of operation that takes place in an enhancement mode MOSFET. How does this differ from depletion mode?
56. Describe construction and explain the operation of depletion mode MOSFET. Also draw the static characteristics.

Module 6

NANO TECHNOLOGY

NANO TECHNOLOGY

Introduction to Nano technology, Properties (Optical, Electrical, Structural, Mechanical) Importance of surface to Volume ratio, Bonding in solids (Vander walls interactions), Application: Lithography, Single Electron Transfer (SET), Spin Valves.

Introduction to Nano technology:

Nanotechnology refers to the practice of manipulating atoms and molecules at the nano scale, which is between one and 100 nanometers.

Surface-to-Volume ratio of nanomaterial

The materials with one external dimensions between 1 nm to 100 nm are called nanomaterial.

Nanoparticles are mixture of atoms or molecules with a complex structure in three dimensions in nano scale.

Nanomaterial has large surface area to volume ratio (A / V).

Atom is in the form of sphere of radius 'r'

Its surface area $A = 4\pi r^2$

Its volume $V = \frac{4}{3}\pi r^3$

Its surface area to volume ratio is

$$\frac{A}{V} = \frac{3}{r}$$

Thus, when radius 'r' of the sphere decreases, its surface area to volume ratio increases.

Therefore, physical and chemical properties like reactivity, resistivity, and viscosity are improved and nanomaterial becomes more chemically reactive. Study of nanomaterial is called nano science. Tools used to study nanomaterial are called nano technology.

Importance of surface-to-volume ratio of nanomaterial

The surface-to-volume ratio (SVR) of nanomaterial is a critical parameter that significantly influences their physical, chemical, and biological properties.

Some reasons why SVR is important:

1. Increased Reactivity:

- A higher SVR means more atoms or molecules are exposed on the surface, leading to increased reactivity.
- Examples: Catalysis, sensing, and energy storage applications.

2. Enhanced Optical Properties:

- A higher SVR can lead to enhanced optical properties, such as absorption, scattering, and fluorescence.
- Examples: Quantum dots, nano crystals, and metal nanoparticles.

3. Improved Electrical Properties:

- A higher SVR can lead to improved electrical properties, such as conductivity and dielectric constant.
- Examples: Nanowires, nanotubes, and graphene.

4. Increased Mechanical Strength:

- A higher SVR can lead to increased mechanical strength due to the increased surface area.
- Examples: Nanoparticles, nanowires, and nanotubes.

5. Biological Interactions:

- A higher SVR can influence biological interactions, such as cell adhesion, toxicity.
- Examples: Nanoparticles, nanowires, and nanotubes.

Factors Influencing SVR:

1. Size: Decreasing size increases SVR.

2. Shape: Non-spherical shapes can increase SVR.

3. Surface Roughness: Increased surface roughness can increase SVR.

Applications:

1. Catalysis: High SVR nanomaterial's are used as catalysts.
2. Sensing: High SVR nanomaterial's are used in sensors.
3. Energy Storage: High SVR nanomaterial's are used in energy storage devices.
4. Biomedical Applications: High SVR nanomaterials are used in biomedical applications.

Examples of High SVR Nanomaterial's:

1. Nanoparticles: High SVR due to their small size.
2. Nanowires: High SVR due to their high aspect ratio.
3. Nanotubes: High SVR due to their high aspect ratio and surface roughness.
4. Graphene: High SVR due to its high surface area and surface roughness.

Nanomaterial's vs. Nanoparticles:

Nanomaterials are materials that have at least one dimension that can be measured at the nanoscale. These materials can be manufactured or found in nature. Common examples of nanomaterials include:

- **Fullerenes:** Ultra-thin sheets of graphene — a form of carbon — that are rolled up into spheres or tubes
- **Nanotubes:** A form of carbon that takes on a tube shape and possesses a diameter that can be measured at the nanoscale.
- **Nanocrystals:** A solid material with a highly organized atomic structure that is measurable at the nanoscale.
- **Dendrimers:** Symmetrical molecules that contain branches of repeating groups of atoms and can be measured at the nanoscale.

On the other hand, nanoparticles are isolated solid-state objects that must be measurable at the nanoscale on all three dimensions. These particles are used to create nanomaterials and are considered a category of nanomaterials. Examples of nanoparticles include:

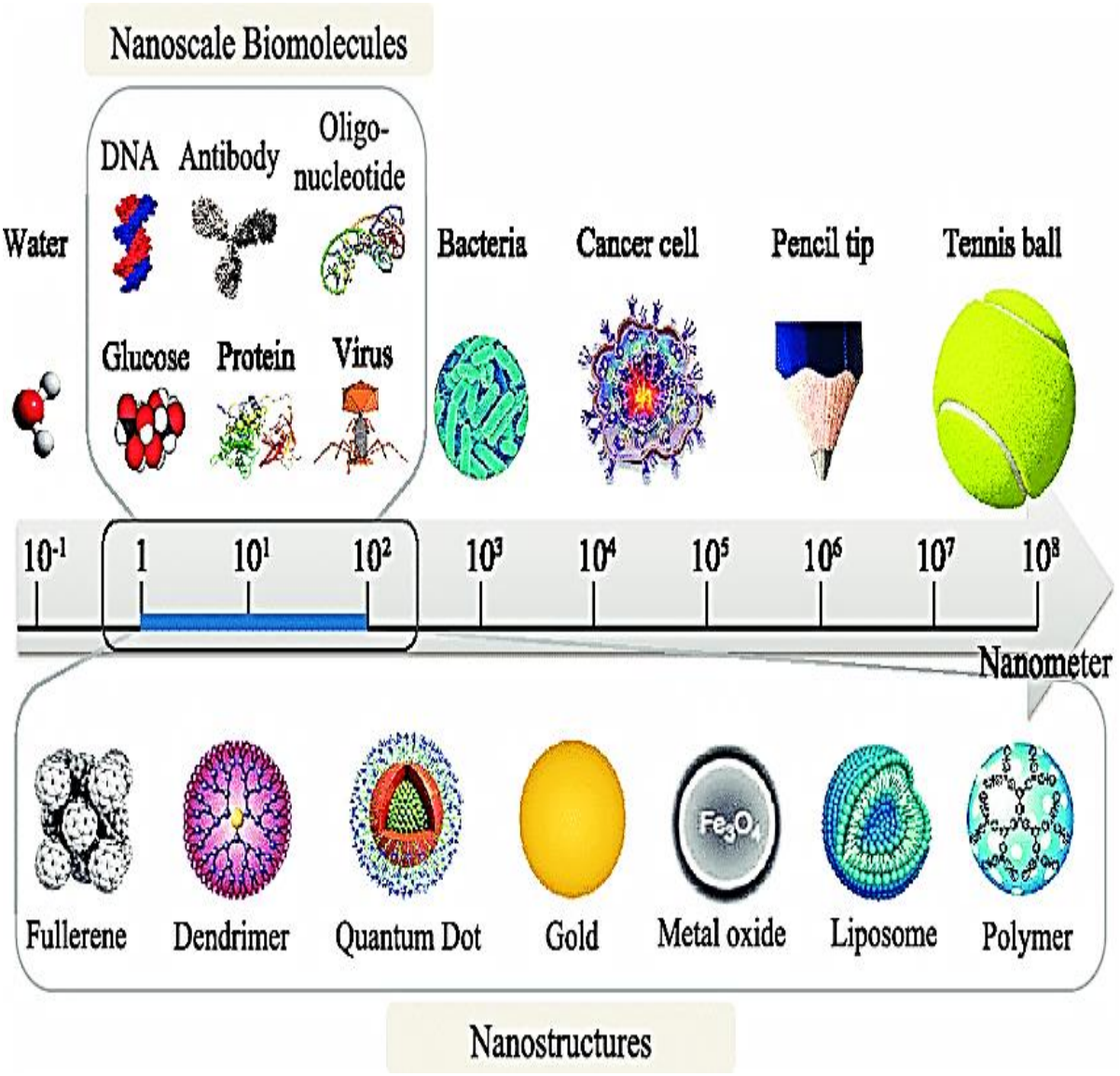
- **Gold nanoparticles:** Clusters of gold atoms measurable at the nanoscale.
- **Silver nanoparticles:** Clusters of silver atoms measurable at the nanoscale.
- **Quantum dots:** Nanocrystals known for having high conductivity.
- **Polymer nanoparticles:** Particles measurable at the nanoscale that contain large macromolecules, which include repeating chains of atoms.

Types of Nanomaterials

The broader category of nanotechnology can be broken down into four main types:

- **Carbon-based nanomaterials.** Include carbon nanotubes created through carbon-based vapor deposition, where heated carbon is added after a reaction between a surface and a catalyst.
- **Metal-based nanomaterials.** Include quantum dots, which are developed by growing nanoscale crystals of two different elements in a solution under specific conditions.

- **Dendrimers.** Exist as nanoparticles that consist of a core, inner shell and outer shell and can be constructed starting from the core or outer shell.
- **Nanocomposites.** Composed of either multiple nanomaterials or a mix of nanomaterials and larger materials, forming stronger metals, plastics and other substances.



Properties of Nano material (Optical, Electrical, Structural, Mechanical)

The significant physical and chemical properties of NPs include their composition, size and shape, and surface area as well as distribution, stability, surface chemistry, roughness, and topography

Mechanical properties of nanomaterial's

1. **Strength and Toughness:**

- Nanomaterial's can exhibit exceptional strength and toughness due to their small size and defect-free structure.
- Examples: Carbon nanotubes, graphene, and nano crystalline metals.

2. Elastic Modulus:

- The elastic modulus of nanomaterial's can be significantly higher than their bulk Counter parts.
- Examples: Nanowires, nanotubes, and nanoparticle-reinforced composites.

3. Hardness and Wear Resistance:

- Nanomaterial's can exhibit improved hardness and wear resistance due to their small size and high surface energy.
- Examples: Nan crystalline ceramics, nano composites, and nanostructured coatings.

4. Ductility and Plasticity:

- Nanomaterial's can exhibit unique ductility and plasticity behavior due to their small size and high surface-to-volume ratio.
- Examples: Nanowires, nanotubes, and nanoparticle-reinforced composites.

5. Fatigue and Fracture:

- Nanomaterial's can exhibit improved fatigue and fracture resistance due to their small size and defect-free structure.
- Examples: Nan crystalline metals, nano composites, and nanostructured coatings.

Factors Influencing Mechanical Properties:

1. **Size and Shape:** Nanomaterial's mechanical properties are strongly influenced by their size and shape.
2. **Surface Chemistry:** The surface chemistry of nanomaterial's can significantly impact their mechanical properties.
3. **Defects and Imperfections:** Defects and imperfections in nanomaterial's can affect their mechanical properties.
4. **Composition and Structure:** The composition and structure of nanomaterial's can influence their mechanical properties.

Applications:

1. **Nano composites:** Nanomaterial's are used to create high-performance nano composites for various applications.
2. **Nanostructured Coatings:** Nanomaterial's are used to create nanostructured coatings for improved mechanical properties.
3. **Nano devices:** Nanomaterial's are used to create nano devices, such as nano sensors and nano robotics.
4. **Biomedical Applications:** Nanomaterial's are used in biomedical applications, such as tissue engineering and drug delivery.

Electrical properties of nanomaterial's

1. Electrical Conductivity:

- Nanomaterial's can exhibit enhanced electrical conductivity due to their small size and high surface-to-volume ratio.
- Examples: Carbon nanotubes, graphene, and metal nanowires.

2. Electrical Resistivity:

- Nanomaterial's can exhibit reduced electrical resistivity due to their small size and defect- free structure.
- Examples: Nano crystalline metals, nano composites, and nanostructured thin films.

3. Dielectric Properties:

- Nanomaterial's can exhibit unique dielectric properties, such as high dielectric constants and low dielectric losses.
- Examples: Nan crystalline ceramics, nan composites, and nanostructured thin films.

4. Ferromagnetic and Ferroelectric Properties:

- Nanomaterial’s can exhibit enhanced ferromagnetic and ferroelectric properties due to their small size and high surface-to-volume ratio.
- Examples: Magnetic nanoparticles, ferroelectric nanowires, and nanostructured thin films.

5. Quantum Confinement Effects:

- Nanomaterial’s can exhibit quantum confinement effects, such as quantized energy levels and enhanced optical properties.
- Examples: Quantum dots, nanocrystals, and nanostructured thin films.

Factors Influencing Electrical Properties:

1. Size and Shape: Nanomaterial’s' electrical properties are strongly influenced by their size and shape.

2. Surface Chemistry: The surface chemistry of nanomaterial’s can significantly impact their electrical properties.

3. Defects and Imperfections: Defects and imperfections in nanomaterial’s can affect their electrical properties.

4. Composition and Structure: The composition and structure of nanomaterial’s can influence their electrical properties.

Applications:

1. Electronics: Nanomaterial’s are used in electronic devices, such as transistors, diodes, and sensors.

2. Energy Storage: Nanomaterial’s are used in energy storage devices, such as batteries and super capacitors.

3. Optoelectronics: Nanomaterial’s are used in optoelectronic devices, such as LEDs, lasers, and solar cells.

4. Biomedical Applications: Nanomaterial’s are used in biomedical applications, such as biosensors, bio imaging, and drug delivery.

Optical properties of nanomaterial's

1. Quantum Confinement Effect:

- Nanomaterials exhibit quantum confinement effects, which lead to changes in their optical properties.
- Examples: Quantum dots, nano crystals.

2. Surface Plasmon Resonance (SPR):

- Nanomaterial's exhibit surface Plasmon resonance (SPR), which leads to enhanced optical absorption and scattering.
- Examples: Metal nanoparticles, nanorods.

3. Fluorescence and Phosphorescence:

- Nanomaterials exhibit fluorescence and phosphorescence due to their high surface-to-volume ratio.
- Examples: Quantum dots, nanocrystals.

4. Nonlinear Optical Properties:

- Nanomaterials exhibit nonlinear optical properties, such as second-harmonic generation and two-photon absorption.
- Examples: Metal nanoparticles, nanorods.

5. Optical Absorption and Scattering:

- Nanomaterials exhibit unique optical absorption and scattering properties due to their small size and high surface-to-volume ratio.
- Examples: Metal nanoparticles, nanorods.

Factors Influencing Optical Properties:

1. **Size and Shape:** Nanomaterial's' optical properties are strongly influenced by their size and shape.
2. **Surface Chemistry:** The surface chemistry of nanomaterial's can significantly impact their optical properties.
3. **Composition and Structure:** The composition and structure of nanomaterial's can Influence their optical properties.
4. **Environmental Conditions:** Environmental conditions, such as temperature and humidity, can affect the optical properties of nanomaterial's.

Applications:

1. **Optoelectronics:** Nanomaterial's are used in optoelectronic devices, such as LEDs, lasers, and solar cells.
2. **Biomedical Imaging:** Nanomaterial's are used in biomedical imaging applications, such as fluorescence imaging and optical coherence tomography.
3. **Sensors:** Nanomaterial's are used in sensor applications, such as optical sensors and biosensors.
4. **Photovoltaics:** Nanomaterial's are used in photovoltaic applications, such as solar cells and photo detectors.

Nanomaterial's used:

1. Quantum Dots: Used for their unique optical properties and applications in biomedical imaging and optoelectronics.

2. Metal Nanoparticles: Used for their surface plasmon resonance and applications in sensors and optoelectronics.

3. Nanowires: Used for their unique optical properties and applications in optoelectronics and sensors.

4. Graphene: Used for its unique optical properties and applications in optoelectronics and sensors.

Structural properties of nanomaterial's

1. Crystal Structure:

- Nanomaterial's can exhibit different crystal structures, such as face-centered cubic (FCC), body-centered cubic (BCC), and hexagonal close-packed (HCP).
- Examples: Metal nanoparticles, nanowires, and nanotubes.

2. Lattice Parameters:

- Nanomaterial's can exhibit changes in lattice parameters, such as lattice constant and lattice spacing.
- Examples: Quantum dots, nano crystals, and nanoparticles.

3. Surface Roughness:

- Nanomaterial's can exhibit high surface roughness due to their small size and high surface-to-volume ratio.
- Examples: Nanoparticles, nanowires, and nanotubes.

4. Defects and Impurities:

- Nanomaterial's can exhibit defects and impurities, such as vacancies, interstitials, and substitutional impurities.
- Examples: Nanoparticles, nanowires, and nanotubes.

5. Nanostructure and Morphology:

- Nanomaterial's can exhibit unique nanostructures and morphologies, such as spheres, rods, wires, and tubes.
- Examples: Nanoparticles, nanowires, and nanotubes.

Factors Influencing Structural Properties:

1. Size and Shape: Nanomaterial's' structural properties are strongly influenced by their size and shape.
2. Composition and Structure: The composition and structure of nanomaterial's can influence their structural properties.
3. Synthesis Method: The synthesis method used to create nanomaterial's can influence their structural properties.
4. Environmental Conditions: Environmental conditions, such as temperature and humidity, can affect the structural properties of nanomaterial's.

Applications:

1. Electronics: Nanomaterial's are used in electronic devices, such as transistors and solar cells.
2. Optics: Nanomaterial's are used in optical devices, such as lasers and optical fibers.
3. Energy Storage: Nanomaterial's are used in energy storage devices, such as batteries and super capacitors.
4. Biomedical Applications: Nanomaterial's are used in biomedical applications, such as imaging and drug delivery.

Examples of Nanomaterial's:

1. Nanoparticles: Metal nanoparticles, semiconductor nanoparticles, and oxide nanoparticles.
2. Nanowires: Metal nanowires, semiconductor nanowires, and oxide nanowires.
3. Nanotubes: Carbon nanotubes, metal nanotubes, and oxide nanotubes.
4. Graphene: Graphene sheets, graphene nanoribbons, and graphene nanoparticles.

Magnetic properties of nanomaterial's

1. Super para magnetism:

- Nanomaterial's can exhibit super para magnetism, which is a phenomenon where the magnetic moment of the material is not stable.
- Examples: Magnetic nanoparticles, nano rods, and nanostructured thin films.

2. Ferromagnetism:

- Nanomaterials can exhibit ferromagnetism, which is a phenomenon where the material exhibits a permanent magnetic moment.
- Examples: Iron, nickel, and cobalt nanoparticles.

3. Antiferromagnetism:

- Nanomaterial's can exhibit anti ferromagnetism, which is a phenomenon where the material exhibits a zero net magnetic moment.
- Examples: Antiferromagnetic nanoparticles, nano rods, and nanostructured thin films.

4. Ferrimagnetism:

- Nanomaterial's can exhibit ferrimagnetism, which is a phenomenon where the material exhibits a permanent magnetic moment due to the alignment of magnetic moments.
- Examples: Ferrite nanoparticles, nano rods, and nanostructured thin films.

5. Magnetic Anisotropy:

- Nanomaterial's can exhibit magnetic anisotropy, which is a phenomenon where the material exhibits different magnetic properties in different directions.
- Examples: Magnetic nanoparticles, nano rods, and nanostructured thin films.

Factors Influencing Magnetic Properties:

1. Size and Shape: Nanomaterial's' magnetic properties are strongly influenced by their size and shape.

2. Surface Chemistry: The surface chemistry of nanomaterials can significantly impact their magnetic properties.

3. Composition and Structure: The composition and structure of nanomaterial's can influence their magnetic properties.

4. Environmental Conditions: Environmental conditions, such as temperature and humidity, can affect the magnetic properties of nanomaterials.

Applications:

1. **Magnetic Resonance Imaging (MRI):** Nanomaterial's are used as contrast agents in MRI applications.
2. **Magnetic Data Storage:** Nanomaterial's are used in magnetic data storage applications, such as hard drives and magnetic tapes.
3. **Magnetic Sensors:** Nanomaterial's are used in magnetic sensor applications, such as magnetometers and magnetic field sensors.
4. **Biomedical Applications:** Nanomaterial's are used in biomedical applications, such as magnetic hyperthermia and magnetic targeting.

Applications of Nano materials:

1) Nanomaterials are used to prepare hard and long-lasting cutting tools.
2) Nano materials are used as good insulators.
3) Nano materials are used to prepare good ductile and machinable ceramics.
4) Nano materials are used to prepare LCD, which increase the resolution, brightness and contrast of display.
5) To prevent environmental pollution produced due to burning of gasoline and coal. The nanomaterials are used as catalysts to react with pollutants like carbon monoxide and nitrogen oxides.
6) To prepare high power magnets useful in automobile engineering and medical instruments like MRI.
7) To prepare highly sensitive sensors which are used as smoke detector, ice detector om aircraft wings, machine performance sensor etc.
8) To prepare strong, tough and long-lasting aircraft components.
9) To prepare invisible sunscreen lotion.
10) To prepare cloth to prevent UV radiation.
11) To prepare scratch resistant coating on eye lenses, car windows etc.

APPLICATIONS OF NANOTECHNOLGY IN VARIOUS FIELD:

Nanotechnology and nanomaterials can be applied in all kinds of industrial sectors. They are usually found in these areas:

Electronics: Carbon nanotubes are close to replacing silicon as a material for making smaller, faster and more efficient microchips and devices, as well as lighter, more conductive and stronger quantum nanowires. Graphene's properties make it an ideal candidate for the development of flexible touchscreens.

Energy: A new semiconductor makes it possible to manufacture solar panels that double the amount of sunlight converted into electricity. Nanotechnology also lowers costs, produces stronger and lighter wind turbines, improves fuel efficiency and, thanks to the thermal insulation of some nanocomponents, can save energy.

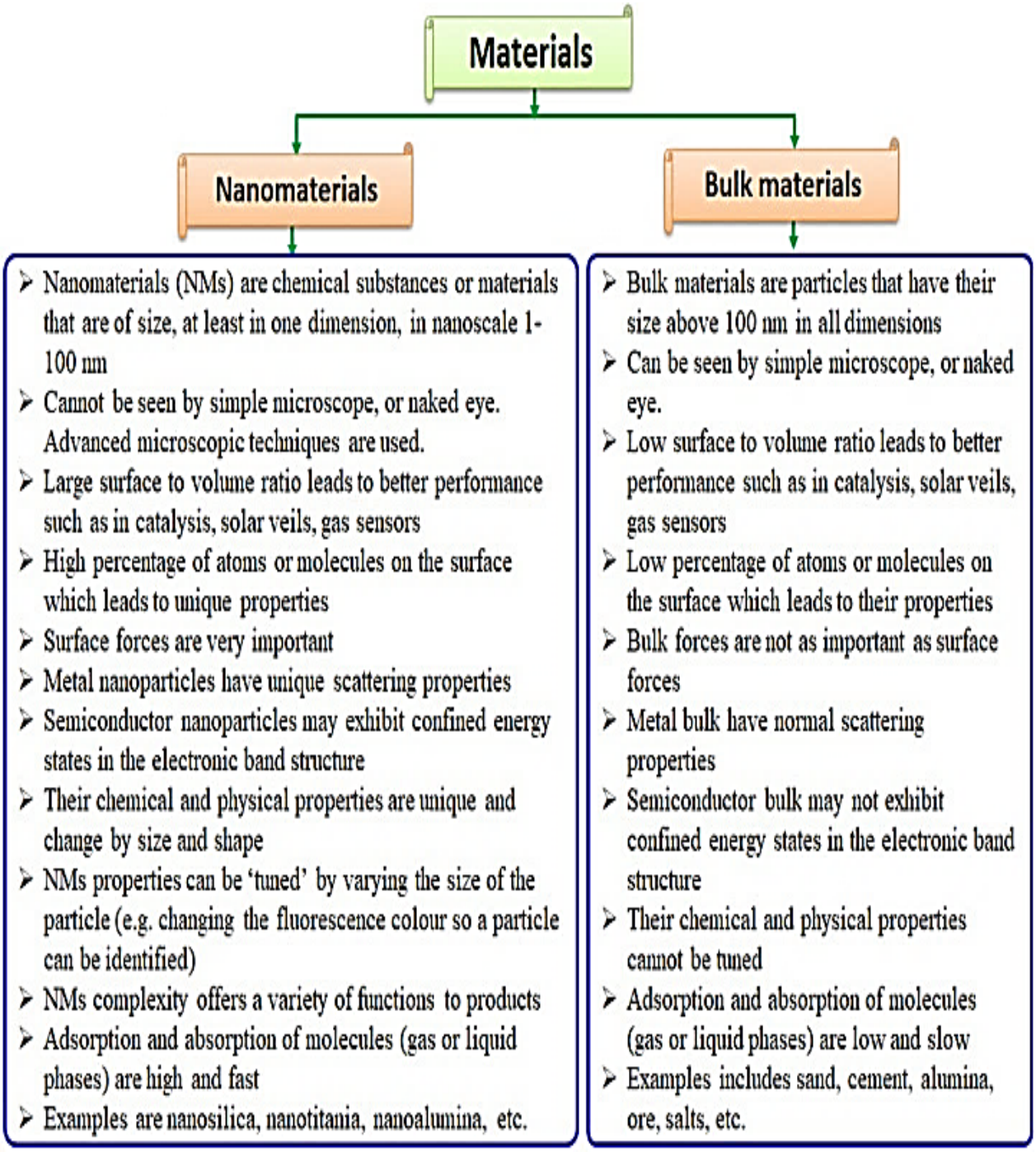
Biomedicine: The properties of some nanomaterials make them ideal for improving early diagnosis and treatment of neurodegenerative diseases or cancer. They are able to attack cancer cells selectively without harming other healthy cells. Some nanoparticles have also been used to enhance pharmaceutical products such as sunscreen.

Environment: Air purification with ions, wastewater purification with nanobubbles or nanofiltration systems for heavy metals are some of its environmentally-friendly applications. Nano catalysts are also available to make chemical reactions more efficient and less polluting.

Food: In this field, nano biosensors could be used to detect the presence of pathogens in food or nanocomposites to improve food production by increasing mechanical and thermal resistance and decreasing oxygen transfer in packaged products.

Textile: Nanotechnology makes it possible to develop smart fabrics that don't stain nor wrinkle, as well as stronger, lighter and more durable materials to make motorcycle helmets or sports equipment.

Difference between Nanomaterial & Bulk material:



Top down and Bottom-up approach to prepare nanomaterial?

Two approaches are used in nanotechnology to prepare nanomaterial.

1) **Top down approach: (Big to small particle)**
    a) In this technique, a bulk material is broken or reduces in size to form nanoparticles.
    b) The different methods such as cutting, carving and molding etc. are used in this technique.
    c) It is slow process approach.
    d) Different structural defects are produced in the material, but it is widely used due its simplicity.
2) **Bottom up approach: (Small to big particle)**
    a) In this technique, nano materials are made by building atom by atom or molecule by molecule till desire nano size particles are formed.
    b) In this method chemical property of molecule is used to make nano size particle.
    c) It is faster process approach.
    d) In this technique structural defects are not produced in the nanomaterial, but it is complicated method.

Bonding in solids (Vander walls interactions)

Van der Waals (VDW) interaction is a type of intermolecular force that arises between molecules or atoms in a solid. It's a crucial factor in determining the physical and chemical properties of solids.

What are Van der Waals forces?

VDW forces are weak electrostatic attractions between molecules or atoms that arise due to:

1. **Dipole-dipole interactions:** Permanent dipoles in molecules interact with each other.
2. **Dipole-induced dipole interactions:** A permanent dipole in one molecule induces a temporary dipole in another molecule.
3. **London dispersion forces:** Temporary dipoles in molecules interact with each other.

Characteristics of Van der Waals forces:

1. **Weak forces:** VDW forces are much weaker than ionic or covalent bonds.
2. **Long-range forces:** VDW forces can act over relatively long distances (up to 10 nm).
3. **Non-directional forces:** VDW forces are non-directional, meaning they don't depend on the orientation of the molecules.
4. **Dependence on molecular size and shape:** VDW forces increase with molecular size and depend on the shape of the molecules.

Examples of Van der Waals solids:

1. **Molecular crystals:** Solids composed of discrete molecules held together by VDW forces, such as argon, nitrogen, and oxygen.
2. **Layered solids:** Solids composed of layers of molecules held together by VDW forces, such as graphite and mica.
3. **Polymers:** Long-chain molecules held together by VDW forces, such as polyethylene and polypropylene.

Importance of Van der Waals forces:

1. **Physical properties:** VDW forces influence the physical properties of solids, such as melting and boiling points, solubility, and viscosity.
2. **Chemical properties:** VDW forces play a role in chemical reactions, such as adsorption and desorption.
3. **Biological systems:** VDW forces are important in biological systems, such as protein-ligand interactions and cell adhesion.

Applications of nano material's: Lithography, Single Electron Transfer (SET), Spin Valves.

Lithography:

Lithography is a process used to create high-resolution patterns on a substrate, typically a silicon wafer, in the production of microelectronic devices, such as integrated circuits (ICs) and micro electro mechanical systems (MEMS).

Types of Lithography:

1. **Optical Lithography:** Uses ultraviolet (UV) light to expose patterns on a photoresist material.
2. **Extreme Ultraviolet Lithography (EUVL):** Uses extreme ultraviolet (EUV) light to expose patterns on a photoresist material.
3. **Electron Beam Lithography (EBL):** Uses a focused beam of electrons to expose patterns on a resist material.
4. **Ion Beam Lithography (IBL):** Uses a focused beam of ions to expose patterns on a resist material.

Lithography Process:

1. **Wafer Preparation:** The substrate is cleaned and prepared for lithography.
2. **Photoresist Application:** A photoresist material is applied to the substrate.
3. **Exposure:** The photoresist is exposed to light or particles, creating a pattern.
4. **Development:** The exposed photoresist is developed, revealing the pattern.
5. **Etching:** The pattern is transferred to the substrate using etching techniques.

Lithography Techniques:

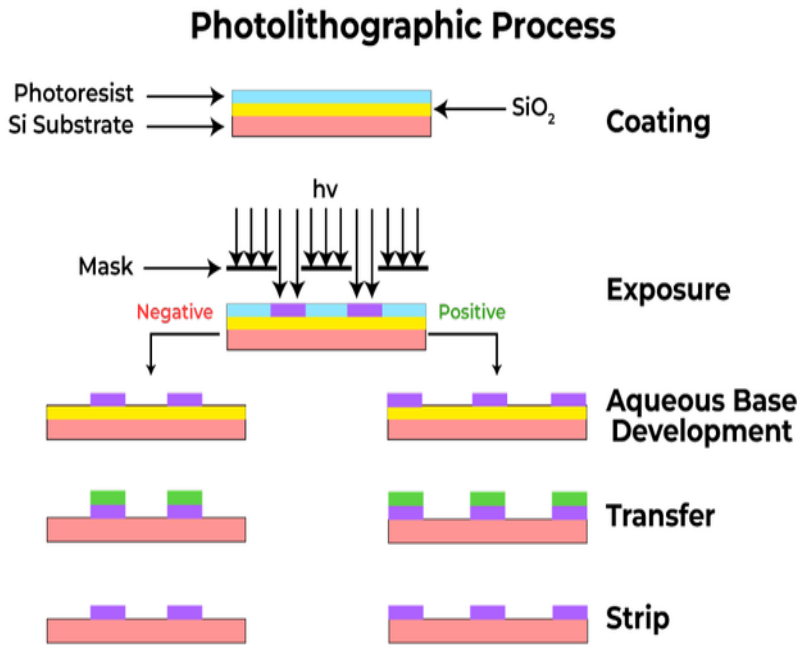
1. **Contact Lithography:** The mask is in contact with the photoresist.
2. **Proximity Lithography:** The mask is close to the photoresist, but not in contact.
3. **Projection Lithography:** The mask is projected onto the photoresist using a lens system.

Photolithography

Photolithography is a crucial process in the **production of semiconductors** that is used to create unpredictable models on silicon wafers.

Photolithography Process:

This technique is used in semiconductor manufacture for making circuits and micro devices.



Photolithography Process

Steps in Photolithography

1. Substrate Cleaning
2. Photoresist Covering
3. Soft Bake
4. Mask Alignment
5. Exposure
6. Post-Exposure Bake
7. Development
8. Hard Bake
9. Etching or Implantation
10. Photoresist Stripping

1. Substrate Cleaning: The substrate (typically a silicon wafer) is cleaned to eliminate pollutants.

2. Photoresist Covering: A slight layer of photoresist is covered onto the substrate, making an even surface.

3. Soft Bake: In order to eliminate solvent and uniformity, the coated substrate is gently heated.

4. Mask Alignment: Over the substrate, a photo mask with the desired pattern is aligned.

5. Exposure: UV light is radiated through the veil onto the photoresist, causing a substance change.

6. Post-Exposure Bake: The substrate is warmed again to balance out the the photoresist.

7. Development: Using a developer solution, the exposed photoresist is removed, revealing the pattern.

8. Hard Bake: The remaining photoresist is made more durable by performing a final heating step.

9. Etching or Implantation: The uncovered substrate regions are carved or adjusted depending on the situation.

10. Photoresist Stripping: The patterned substrate is left behind after the remaining photoresist is removed.

Advantages of Photolithography

- **High-Quality Patterns:** Photolithography creates precise and detailed patterns on various surfaces like computer chips.
- **Efficient Production:** It's effective in mass production, like production of computer chips in a factory.
- **Cost-Effective:** It is relatively affordable to make more items, after the initial setup.
- **Versatile:** It can be used with different materials, including metals and plastics.
- **Accurate Alignment:** It ensures that all parts fit together correctly.
- **Fast Processing:** It enhances the machine working which increases production speed.

Disadvantages of Photolithography

- **Size Limits:** Photolithography faces drawback in making extremely tiny structures due to the type of light it uses.
- **Complex Process:** It involves several steps and requires skilled operators.
- **Expensive Equipment's:** The necessary machines can be costly, and special clean rooms are needed.
- **Costly Pattern Design:** It proves to be expensive in creating custom designs, especially for unique templates.

- **Environmental Concerns:** Some of the chemicals and processes used in this process can impact environment if not handled properly.

Applications of Photolithography

1. **Semi-conductor Manufacturing:** Photolithography is important for creating components on computer chips.
2. **Electronics:** It is used in making small sensors, phone screens, and other electronic components.
3. **Circuit Boards:** It helps to define pathways for electricity in circuit boards.
4. **Optics:** It is used in the production of lenses and optical devices.
5. **Medical Devices:** Scientists use it to create tiny medical devices for tests and treatments.
6. **Nanotechnology:** Sometimes it is used for working with extremely small structures in nanotechnology.

What is Photoresist in Photolithography?

As a light-sensitive "mask" that enables the transfer of patterns onto a substrate during semiconductor fabrication, There are two principal types:

Positive Photoresist

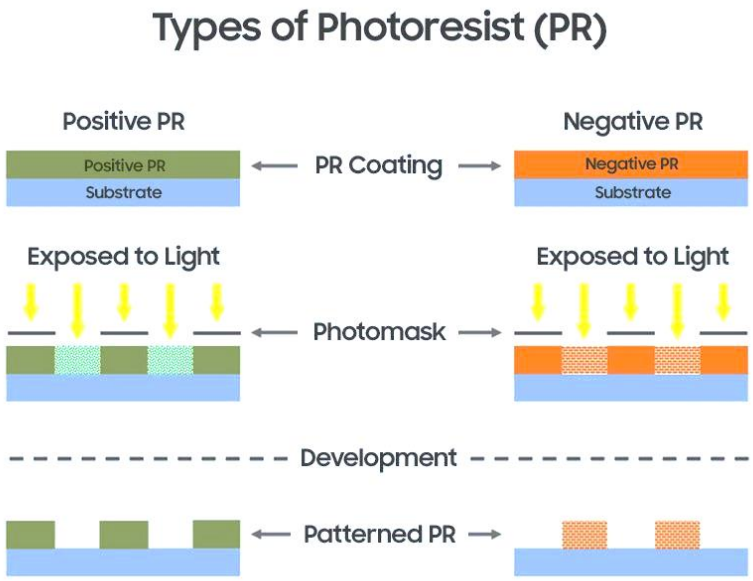
- **Exposure Reaction:** The photoresist molecules become more soluble when exposed to UV light.
- **Development:** The patterned resist is left behind after the exposed areas are dissolved in a developer solution.

Negative Photoresist

- **Exposure Reaction:** UV light makes the photoresist atoms less dissolvable.
- **Development:** The desired pattern is revealed as areas that were not exposed dissolve.

Sensitivity to particular wavelengths of light, resolution, and the capacity to withstand subsequent process steps are important properties of photoresist.

Types of Photoresist



Positive Photoresist

- **Mechanism:** Upon openness to bright (UV) light, positive photoresist particles go through a substance change, turning out to be more solvent in an engineer arrangement.
- **Process:** The resist-coated substrate is developed following exposure. The uncovered regions disintegrate in the designer, abandoning the ideal example. A resulting flush eliminates overabundance and finishes the interaction.
- **Advantages:** Offers high goal and astounding edge definition. Its aversion to UV light takes into consideration fine example creation.

Negative Photoresist

- **Mechanism:** Negative photoresist turns out to be less solvent in an engineer upon openness to UV light.
- **Process:** After openness and improvement, the unexposed regions are taken out, leaving the example. Developer remains after a rinse.
- **Advantages:** Simplifies the procedure by innately preventing UV light from reaching unexposed areas. Due to its self-defining nature, it is ideal for intricate designs. It resists chemical attack and displays clear difference among uncovered and unexposed areas.

Applications:

1. Microelectronics: Lithography is used to create ICs and MEMS devices.

2. Nanotechnology: Lithography is used to create nanostructures and nano devices.

3. Biotechnology: Lithography is used to create microfluidic devices and biosensors.

Applications of nanomaterial's in lithography

Nanomaterials are being increasingly used in lithography to enhance resolution, sensitivity, and throughput. Here are some applications of nanomaterials in lithography:

1. Nanostructured Photoresists:

- Nanoparticles, such as metal oxides, carbon nanotubes, and graphene, are incorporated into photoresist materials to enhance resolution, sensitivity, and etch resistance.
- Examples: Titanium dioxide (TiO2) nanoparticles, zinc oxide (ZnO) nanoparticles.

2. Nano imprint Lithography (NIL):

- NIL uses a nanostructured template to pattern a resist material, achieving high-resolution patterns.
- Nanomaterial's, such as silicon dioxide (SiO_2) and titanium dioxide (TiO_2), are used to create the nanostructured template.

3. Extreme Ultraviolet Lithography (EUVL):

- EUVL uses extreme ultraviolet light to pattern a resist material, achieving high-resolution patterns.
- Nanomaterial's, such as tin (Sn) and indium (In), are used to create the EUVL mask.

4. Nanostructured Masks:

- Nanostructured masks, such as nanowire and nanoparticle arrays, are used to create high-resolution patterns.
- Nanomaterial's, such as silver (Ag) and gold (Au), are used to create the nanostructured mask.

5. Directed Self-Assembly (DSA):

- DSA uses nanomaterials, such as block copolymers, to create high-resolution patterns.
- Nanomaterial's are designed to self-assemble into specific patterns, achieving high resolution structures.

Benefits:

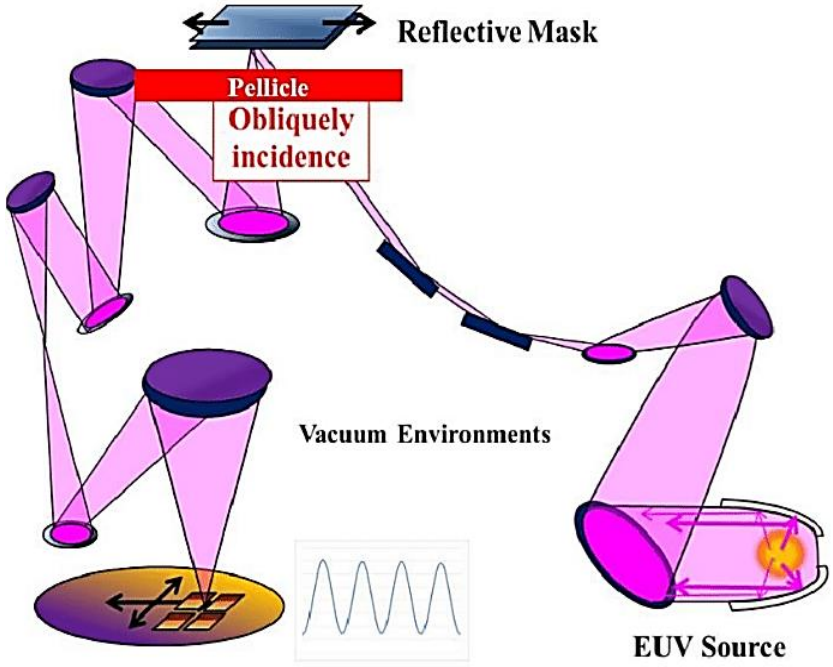
1. Improved Resolution: Nanomaterial's enable high-resolution patterning, achieving feature sizes below 10 nm.

2. **Increased Sensitivity:** Nanomaterial's enhance the sensitivity of lithography processes, reducing the required dose and exposure time.
3. **Enhanced Etch Resistance:** Nanomaterial's improve the etch resistance of photoresist materials, enabling more efficient pattern transfer.

Extreme Ultraviolet (EUV) Lithography

Extreme ultraviolet (EUV) lithography is a cutting-edge technique to manufacture modern computer chips

What Is Extreme Ultraviolet (EUV) Lithography?



Extreme ultraviolet (EUV) lithography is a cutting-edge technique to manufacture modern computer chips. It's a type of photolithography, which utilizes light to etch patterns onto silicon wafers, the foundation of integrated circuits (ICs).

How Does EUV Lithography Work?

The following is a step-by-step breakdown of the process:

- **EUV Light Source:** Extreme ultraviolet light is generated by firing a high-powered laser at a tiny droplet of molten tin. The laser vaporizes the tin, creating a hot plasma that emits EUV radiation at a specific wavelength (around 13.5 nanometers).

- **Capturing Light:** Air absorbs EUV light very efficiently. Therefore EUV systems operate in a vacuum chamber. Special mirrors with alternating layers of materials like molybdenum and silicon are used to capture and reflect the EUV light. These mirrors have an incredibly smooth and reflective surface, applicable for precise light control.
- **Projecting Pattern:** The captured EUV light is then projected through a photo mask. This mask contains the integrated design of the circuit, with areas transparent to EUV light and others opaque. The light passing through the mask creates a sharp image of the circuit pattern onto the silicon wafer coated with photoresist.
- **Exposing Resist:** The photoresist reacts differently to light and shadow. Areas exposed to EUV light undergo a chemical change, making them either more or less soluble in a developer solution.
- **Developing Pattern:** The wafer is then bathed in a developer solution. This selectively removes the exposed (or unexposed) photoresist regions, leaving behind a relief pattern of the circuit design on the wafer.
- **Etching & Cleaning:** This patterned photoresist acts as a mask for subsequent etching processes. The wafer is subjected to various etching techniques to transfer the circuit design onto the underlying silicon layer. Finally, the remaining photoresist is removed, and the wafer is meticulously cleaned to prepare it for further processing.
- **Repeating The Process:** Creating a modern chip involves building multiple layers of circuits on the silicon wafer. This often requires repeating the EUV lithography process numerous times (up to a hundred!), each with a different photo mask to create various chip components.

What Are The Advantages & Disadvantages Of EUV Lithography?

Advantages of EUV Lithography:

- **Higher Resolution:** The key advantage of EUV lithography lies in its use of extremely short-wavelength light (13.5 nanometers). This allows for the creation of much finer features on the silicon wafer compared to older techniques using longer wavelengths. This translates to:
- **Denser Circuits:** By enabling the fabrication of smaller transistors, EUV allows for cramming more transistors onto a single chip, leading to denser and more powerful integrated circuits.
- **Faster & More Efficient Chips:** Denser circuits translate to faster processing speeds and improved power efficiency in the final chip.

- **Improved Performance:** EUV lithography can achieve higher resolution and tighter patterning than alternative lithography techniques. This leads to better performance and capabilities in the final chips.
- **Potential for Future Advancements:** EUV is considered essential for the continued miniaturization of transistors, allowing the development of even more powerful and complex chips.

Disadvantages of EUV Lithography

- **Complexity & Cost:** EUV systems are incredibly complex and expensive. The light source itself requires a high-powered laser and a vacuum environment. Additionally, the specialized mirrors used to capture and reflect EUV light are highly intricate and costly to manufacture. As of now, only ASML manufactures these systems commercially.
- **Challenges with Materials:** EUV light is highly reactive and can damage many materials commonly used in chip manufacturing. This necessitates the use of specialized materials for the photo masks, resists, and other components within the EUV system, further adding to the cost and complexity.
- **Lower Throughput:** Compared to deep ultraviolet (DUV) lithography, EUV currently has a lower throughput, meaning it takes longer to manufacture each wafer. This can be a bottleneck in high-volume chip production.
- **Immature Infrastructure:** EUV technology is still relatively new, and the supporting infrastructure for mask making, defect inspection, and yield optimisation needs to be more mature.

Electron Beam Lithography:

Electron beam lithography is a technique for creating high-resolution patterns on a semiconductor substrate by directing a beam of electrons

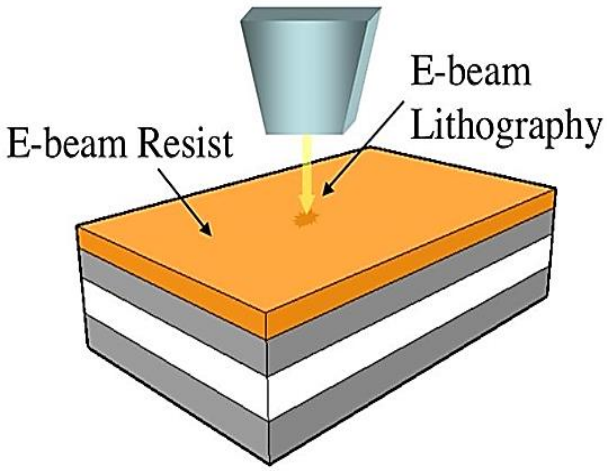
What Is Electron Beam Lithography?

Electron beam lithography (EBL) is a technique for creating high-resolution patterns on a semiconductor substrate by directing a beam of electrons to selectively modify a thin layer of electron resist.

The resist is a photosensitive material that changes its solubility upon exposure to electrons. This change in solubility can be either positive (increased solubility) or negative (decreased solubility) depending on the type of resist used. This process transfers the pattern defined by the electron beam onto the underlying substrate.

How Does Electron Beam Lithography Work?

Electron beam lithography works like a tiny, digital sculpting process using a focused beam of electrons. Here's a breakdown of the steps involved:



- **Substrate Preparation:** A silicon wafer or another material suitable for micro fabrication. is carefully cleaned to remove any contaminants.

- **Resist Coating:** A uniform thin layer of resist is applied onto the substrate. This resist is sensitive to electrons and comes in two main types: positive resist (becomes more soluble upon electron exposure) and negative resist (becomes less soluble).
- **Electron Beam Exposure:** The electron beam is then scanned across the resist-coated substrate in a computer-controlled pattern. As the beam scans, it interacts with the resist, altering its chemical properties in the exposed areas.
- **Development:** After exposure, the resist is immersed in a solvent. The type of solvent used depends on the type of resist – for positive resist, the exposed regions will dissolve away, while for negative resist, the unexposed areas will be removed.
- **Pattern Transfer (Optional):** Etching step can be used to transfer the pattern from the resist onto the underlying substrate material.
- Electron beam lithography machines require a high vacuum environment to allow the electron beam to travel freely without scattering. Further, the complex machinery and precise control needed for electron beam lithography make it a relatively expensive technique compared to other lithography methods.

Advantages

- **Ultra-High Resolution:** EBL excels at creating incredibly small features, reaching resolutions down to a few nanometers. This unmatched precision makes it ideal for cutting-edge research in nanotechnology and miniaturized electronics.
- **Mask less Flexibility:** Unlike photolithography which relies on pre-made masks, EBL offers great design freedom. The pattern is directly written onto the resist using a computer-controlled beam, allowing for rapid design changes and customization.
- **Environmentally Friendly:** EBL has a greener profile as it avoids the use of harsh chemicals often required in mask development processes.

Disadvantages

- **Slow and Impractical:** EBL's high precision comes at the cost of speed. The beam's point-by-point scanning makes it a slow process, unsuitable for high-volume manufacturing.
- **Expensive And Complex Setup:** The machinery involved in EBL is intricate and requires a high vacuum environment. This translates to a more expensive setup and operation compared to simpler techniques.

- **Susceptibility To Errors:** The focused electron beam can be affected by forward and backward scattering, leading to inaccuracies in the final pattern.

Is Electron Beam Lithography Better Than Traditional Lithography Methods?

Both electron beam lithography (EBL) and traditional lithography methods (like photolithography) have their strengths and weaknesses, making them suitable for different applications.

Single Electron Transfer (SET)

Single-electron transfer (SET) is a process where a single electron is transferred between molecules or devices. Nanomaterials have been increasingly used to enhance SET processes, enabling new applications in fields like:

1. Molecular Electronics:
- Nanomaterials, such as carbon nanotubes, graphene, and nanoparticles, are used to create molecular-scale electronic devices.
- SET processes are used to control the flow of electrons in these devices.

2. Quantum Computing:
- Nanomaterials, such as quantum dots and nanoparticles, are used to create quantum bits (qubits) for quantum computing.
- SET processes are used to manipulate the quantum states of qubits.

3. Sensing and Detection:
- Nanomaterials, such as nanoparticles and nanowires, are used to create ultra-sensitive sensors for detecting single molecules or electrons.
- SET processes are used to amplify the signals from these sensors.

4. Energy Storage and Conversion:
- Nanomaterials, such as nanoparticles and nanotubes, are used to create high-performance energy storage devices, such as batteries and supercapacitors.
- SET processes are used to enhance the efficiency of energy storage and conversion.

Benefits:

1. High Sensitivity: Nanomaterial's enable high-sensitivity detection of single electrons or molecules.
2. Low Power Consumption: SET processes can be operated at very low power

consumption, enabling energy-efficient devices.

3. High Speed: SET processes can be operated at very high speeds, enabling fast data transfer and processing.

Nanomaterial's used:

1. **Carbon Nanotubes:** Used for their high conductivity and mechanical strength.
2. **Graphene:** Used for its high conductivity and flexibility.
3. **Nanoparticles:** Used for their high surface area and reactivity.
4. **Quantum Dots:** Used for their unique optical and electrical properties.

Spin Valves:

Spin valves are devices that use the spin of electrons to control the flow of electric current. Nanomaterial's have been increasingly used to enhance the performance of spin valves, enabling new applications in fields like:

1. Magnetic Random Access Memory (MRAM):

- Nanomaterial's, such as nanoparticles and nanowires, are used to create high-Performance spin valves for MRAM applications.
- Spin valves are used to store data in MRAM devices.

2. Magnetic Sensors:

- Nanomaterial's, such as magnetic nanoparticles and nanowires, are used to create high-sensitivity magnetic sensors.
- Spin valves are used to detect changes in magnetic fields.

3. Spintronics:

- Nanomaterial's, such as graphene and carbon nanotubes, are used to create spintronics devices.
- Spin valves are used to manipulate the spin of electrons in spintronics devices.

Benefits:

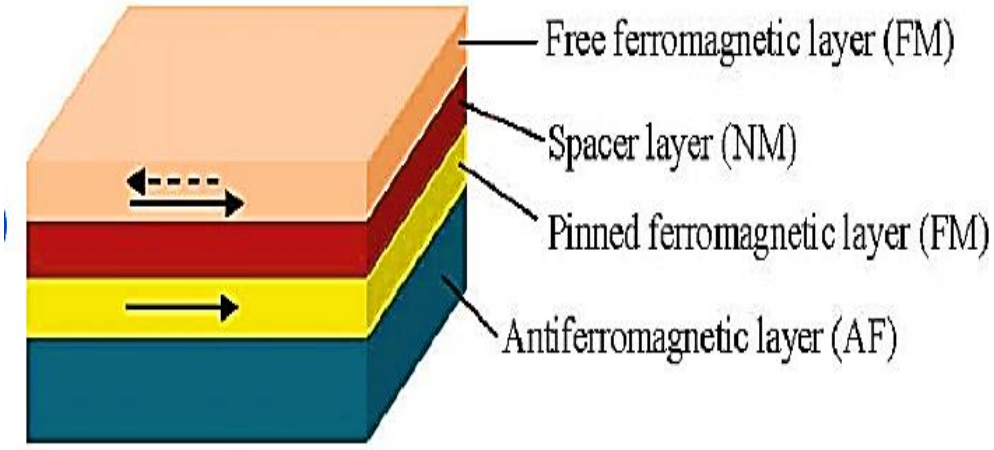
1. **High Sensitivity:** Nanomaterial's enable high-sensitivity detection of magnetic fields.
2. **Low Power Consumption:** Spin valves can be operated at very low power consumption, enabling energy-efficient devices.
3. **High Speed:** Spin valves can be operated at very high speeds, enabling fast data

transfer and processing.

Nanomaterial's used:

1. **Magnetic Nanoparticles:** Used for their high magnetic moment and stability.
2. **Nanowires:** Used for their high aspect ratio and magnetic properties.
3. **Graphene:** Used for its high conductivity and spin transport properties.
4. **Carbon Nanotubes:** Used for their high conductivity and spin transport properties.

Spin Valve Structure:



Typical spin valve structure.

1. **Ferromagnetic Layer:** A ferromagnetic material, such as iron or nickel, is used to create a magnetic field.
2. **Non-Magnetic Spacer Layer:** A non-magnetic material, such as copper or aluminum, is used to separate the ferromagnetic layers.
3. **Ferromagnetic Layer:** Another ferromagnetic layer is used to create a second magnetic field.

1. What is the size range of nanomaterials?
2. Define nanotechnology?
3. Discuss the applications of nanotechnology.
4. What are nanomaterials? Give their classifications?
5. Explain classification of nanomaterials in brief.
6. How are nanomaterials synthesized? Describe any one method.
7. Describe any one method of nanomaterials synthesis.
8. What are the approaches used in synthesis of nanomaterials?
9. Explain any two synthesis methods of nanomaterials preparation.
10. Describe Ball milling method of nanomaterials synthesis.
11. Discuss Sol-gel Method. Give its advantages.
12. What are nanomaterials? What is difference between top-down and bottom-up approach of synthesis?
13. How do the properties of nanomaterials differ from bulk materials?
14. Write the reasons for change in properties of materials at nanoscale.
15. Write short notes on surface to Volume ratio.
16. Define Specific surface area and surface area to volume ratio?
17. Compare specific surface area of cubic nanoparticles of side 100 nm and 5 nm.
18. Compare specific surface area of spherical nanoparticles of size 80 nm and 4 nm.
19. Define Van der Waal forces.
20. Write short note on Van der Waal forces.
21. State importance of Van der Waal forces.
22. Mention the importance of quantum confinement at nanoscale.
23. How are Van der Waals forces and ionic bonds similar?
24. What is meant by Quantum confinement?
25. Explain 0D, 1D, 2D and 3D nanomaterials.
26. Explain the term lithography.
27. State principle of lithography Give its types.
28. What is lithography?
29. Explain the basic steps involved in a typical lithography process.
30. State principle of electron beam lithography and explain its working.

31. Give the applications of Lithography.
32. Explain the term "single electron transfer".
33. Explain the term quantum dots.
34. Explain the term "Single valve".
35. Give the applications of single valves.
36. Explain the structure and operation of single valves.
37. State the applications of Nanomaterials in Engineering or any other fields.
38. Define top-down and bottom-up nanofabrication.
39. Explain briefly the advantages and applications of sol-gel process.
40. Discuss the main properties of nanomaterials.
41. Explain the mechanical properties of nanomaterials.
42. Explain the structural properties of nanomaterials.
43. Explain the optical properties of nanomaterials.
44. Explain the electrical properties of nanomaterials.
45. Write the names of synthesis techniques of nanomaterial.
46. State principle of Nano Imprint Lithography and explain its working.
47. Give any four applications of Nano Imprint lithography.
48. Explain the term: Reactive Ion Etching (RIE) in lithography.
49. What is 3D lithography?
50. Define the term: Sub Wavelength (SW) in lithography.
51. Justify, how Nano Imprint Lithography (NIL) works.