Institute of Aeronautical Engineering

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ENGINEERING PHYSICS

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Dielectrics

Introduction

- Dielectrics are insulation materials.
- In dielectrics, all the electrons are bound to their parent molecules and there are no free charges.
- Even with normal voltage or thermal energy electrons are not released.
- Dielectrics are non metallic materials of high specific resistance and have negative temperature coefficient of resistance.

Fundamental definitions

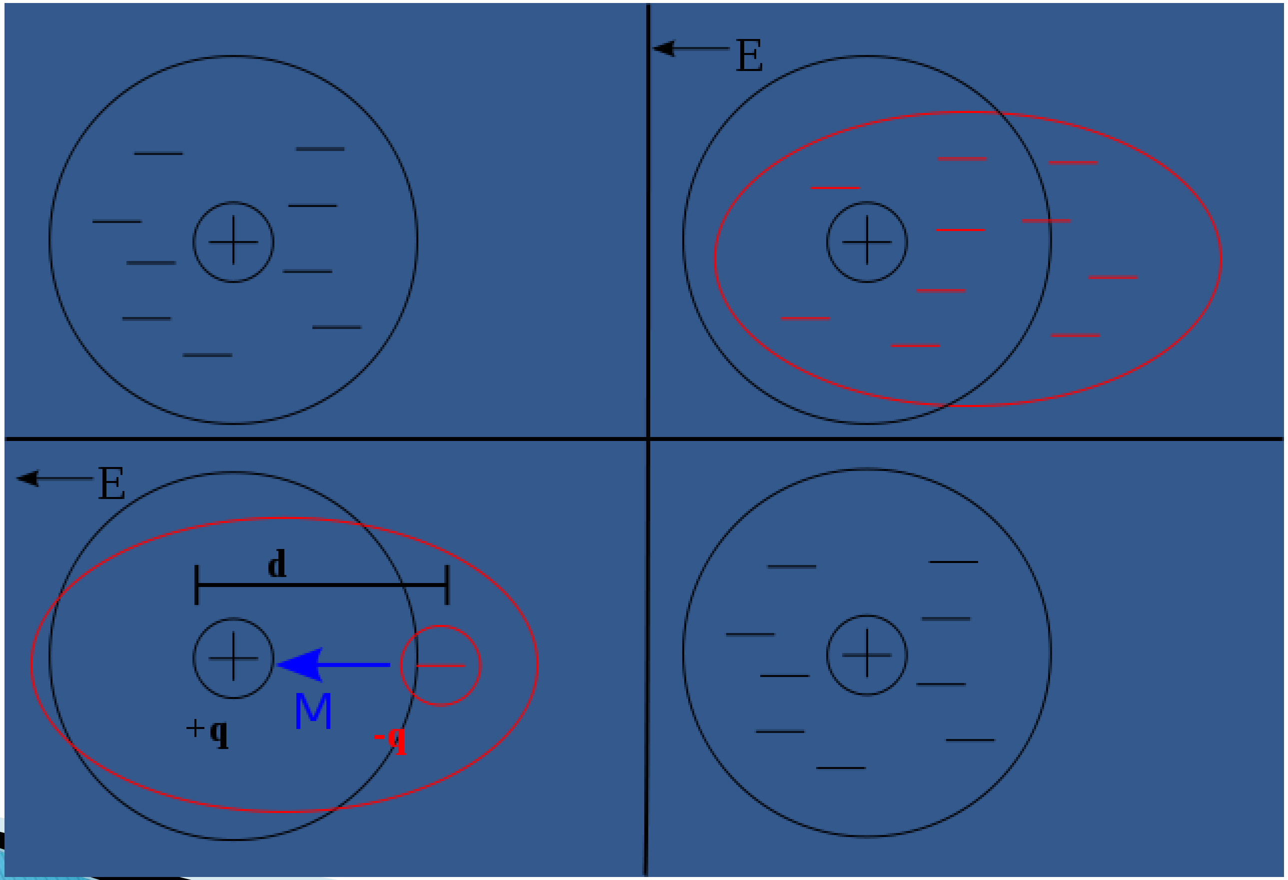
- **Dielectric constant (ε_r) :** The ratio between the permittivity of the medium (ε) and the permittivity of free space (ε_0).

$$\varepsilon_r = \varepsilon / \varepsilon_0$$

- The dielectric characteristics of a material are determined by the dielectric constant or relative permittivity ε_r of the material.
- Since it is a ratio of same quantity. ε_r has no unit. It is a measure of polarization in the dielectric material.

Fundamental definitions

- **Electric Polarization:**



Fundamental definitions

- **Electric Dipole** : Let us consider an atom placed inside an electric field. The centre of positive charge is displaced along the applied field direction while the centre of negative charge is displaced in the opposite direction. Thus a **dipole** is produced.
- When a dielectric material is placed inside an electric field such dipoles are created in all the atoms inside.

Fundamental definitions

- This process of producing electric dipoles which are oriented along the field direction is called polarization in dielectrics.
- **Polarizability (α):** When the strength of the electric field E is increased the strength of the induced dipole μ also increases. Thus the induced dipole moment is proportional to the intensity of the electric field.

  i.e. $\mu = \alpha E$

Fundamental definitions

- Where α, the constant of proportionality is called Polarizability. It can be defined as ***induced dipole moment per unit electric field.***
- **Polarization vector P:** ***The dipole moment per unit volume of the dielectric material is called Polarization vector P***
- If μ is the average dipole moment per molecule and N is the number of molecules per unit volume the polarization vector P = Nμ

Fundamental definitions

- The dipole moment per unit volume of the solid is the sum of all the individual dipole moments within that volume and is called the polarization P of the solid.

Fundamental definitions

- **Electric flux density (or) Electric displacement D:**

$$D = \varepsilon_r \varepsilon_0 E$$

When E = electric field,

ε_r= Dielectric constant or permittivity of the material

ε_o= Dielectric constant or permittivity of the free space.

Fundamental definitions

- As the polarization measures the additional flux density arising from the presence of the material as compared to free space, it has the same units as D and is related to it as

$$D = \varepsilon_o E + P$$

$$\text{Since } D = \varepsilon_r \varepsilon_0 E$$

$$\therefore \varepsilon_r \varepsilon_0 E = \varepsilon_o E + P$$

$$P = \varepsilon_o(\varepsilon_r - 1)E$$

Electric flux density D is similar to magnetic induction B in magnetism

Fundamental definitions

- Electric Susceptibility χ_e :.

The polarization vector P is proportional to the total electric flux density E and is in the same direction of E.

Therefore the polarization vector can be written as

$$P = \varepsilon_o \chi_e E$$

Where the constant χ_e is the electric susceptibility

Fundamental definitions

$$X_e = P / \varepsilon_o E$$

$$= \varepsilon_o(\varepsilon_r - 1)E / \varepsilon_o E$$

$$X_e = \varepsilon_r - 1$$

Polarization

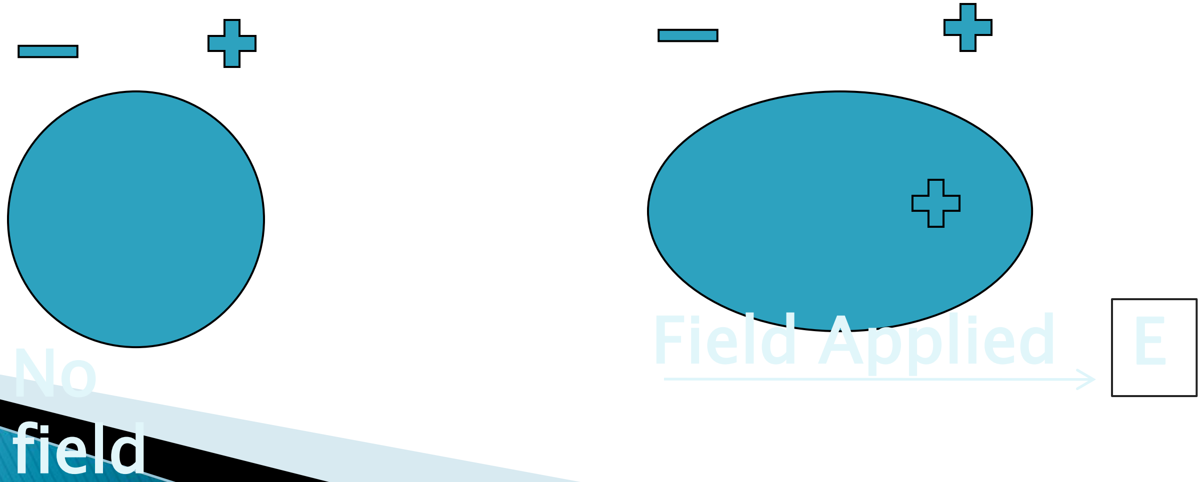
- **The specimen is placed inside a d.c. electric field, polarization is due to four types of process**
- **Electronic polarization**
- **Ionic polarization**
- **Orientation polarization**

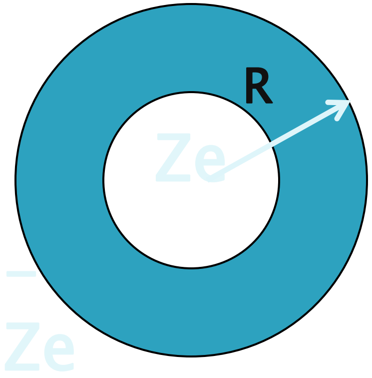
- **Electronic Polarization:** **The displacement of the positively charged nucleus and the (negative) electrons of an atom in opposite directions, on application of an electric field, result in electronic polarization.**

Induced dipole moment $\mu \propto E$

$$\mu = \alpha_e E$$

Where α_e is the electronic Polarizability.





Here the Nucleus of charge Ze is surrounded by an electron cloud of charge – Ze distributed in a sphere of radius R. The charge density ***ρ*** is given by

$$\rho = \frac{-Ze}{{}^{4}/_{3}\,\pi R^3} = \frac{-3}{4}\left(\frac{Ze}{\pi R^3}\right)$$

When an external field of intensity E is applied, the nucleus and the electrons experience Lorentz forces of magnitude ZeE in opposite directions. Hence the nucleus and electron cloud are pulled apart.

- **When they are separated a coulomb force develops between them, which tends to oppose the displacement.**
- **When these forces namely Lorentz force and Coulomb force are equal and opposite, equilibrium is reached.**
- **Let x be the displacement under the condition**
- **Since nucleus is much heavier than the electron cloud it is assumed that only the electron cloud is displaced when the external field is applied**

Lorentz force = -ZeE

Coulomb force

$$= Ze\ x\ \frac{\text{Charge enclosed in the sphere of radius x}}{4\pi\varepsilon_0 x^2}$$

The charge enclosed =

$$= \frac{4}{3}\pi x^3\rho$$

$$\frac{4}{3}\pi x^3\left[\cdot\frac{3}{4}\left(\frac{Ze}{\pi R^3}\right)\right.$$

$$= \frac{Zex^3}{R^3}$$

Hence coulomb force is

$$\frac{Ze}{4\pi\varepsilon_o x^2}\left(\frac{Zex^3}{R^3}\right) = \frac{Z^2e^2x}{4\pi\varepsilon_o R^3}$$

In the equilibrium position

$$-ZeE = \frac{Z^2e^2x}{4\pi\varepsilon_o R^3}$$

$$E = \frac{Zex}{4\pi\varepsilon_o R^3}$$

Or

$$x = \frac{4\pi\varepsilon_o R^3E}{Ze}$$

- **Thus the displacement of the electron cloud is proportional to the applied field.**
- **Thus the two electric charges +Ze and –ze are separated by a distance x under the action of the applied field thus consisting induced electric dipoles.**
- **Induced electric dipole moment**

i.e.,

$$\mu_e = Zex = Ze\,\frac{4\pi\varepsilon_0 R^3 E}{Ze}$$

$$= 4\pi\varepsilon_0 R^3 E$$

$$\mu_e = \alpha_e E$$

- Where $\alpha_e = 4\pi\varepsilon_0 R^3$ is called electronic Polarizability. **The dipole moment per unit volume is called electronic polarization.** It is independent of temperature.

$$P_e = N \mu_e = N \alpha_e E$$

Where N is the number of atoms/m^3

From $P_e = \varepsilon_0 E(\varepsilon_r - 1) = N \alpha_e E$

Or $(\varepsilon_r - 1) = \frac{N \alpha_e}{\varepsilon_0}$

$$\boxed{\alpha_e = \frac{\varepsilon_0(\varepsilon_r - 1)}{N}}$$

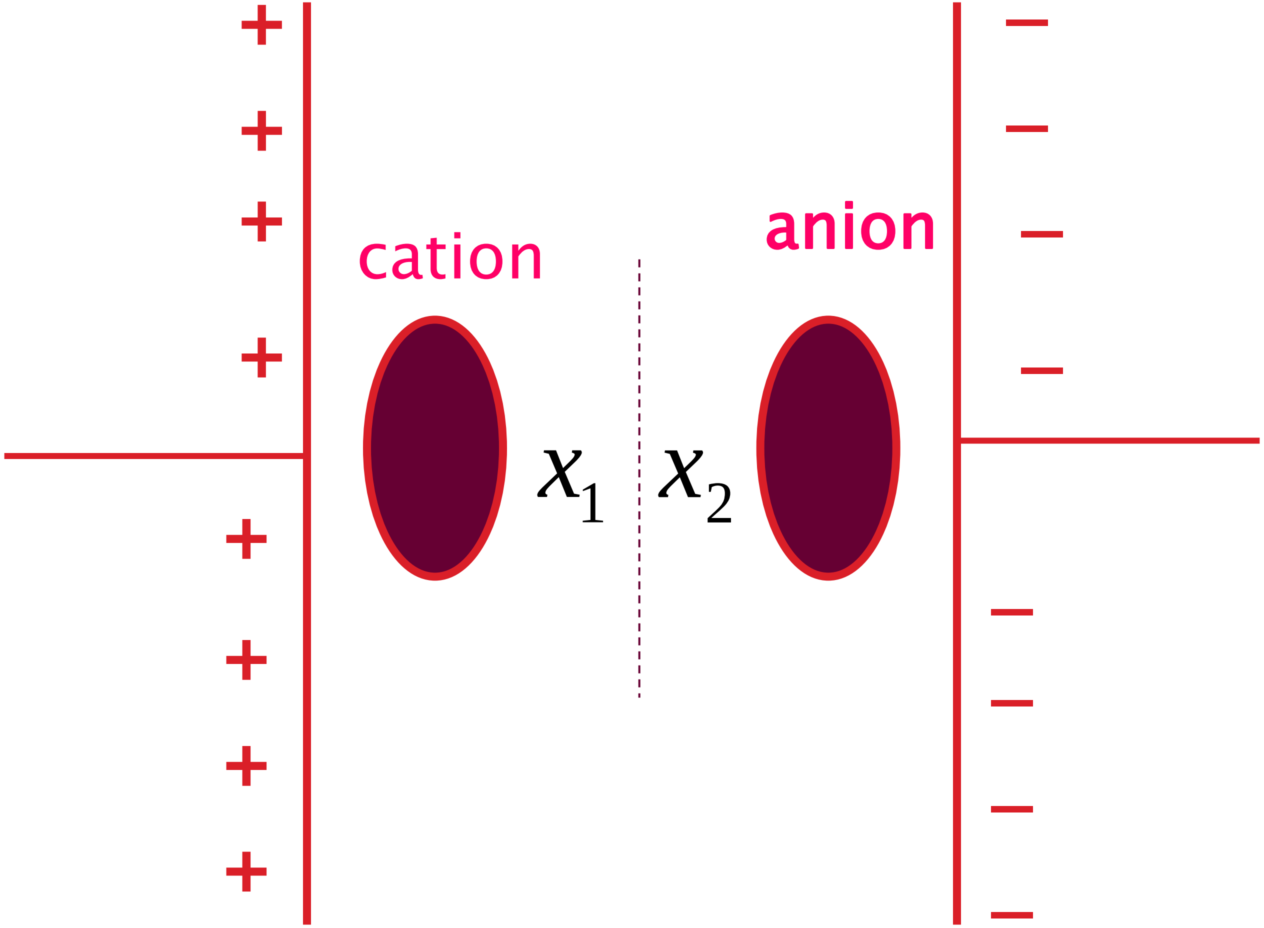
Ionic polarization

- The ionic polarization occurs, when atoms form molecules and it is mainly due to a relative displacement of the atomic components of the molecule in the presence of an electric field.

- When a EF is applied to the molecule, the positive ions displaced by X_1 to the negative side electric field and negative ions displaced by X_2 to the positive side of field.

- The resultant dipole moment $\mu = q (X_1 + X_2)$..

Electric field



Restoring force constant depend upon the mass of the ion and natural frequency and is given by

Where ‘M’ mass of anion and ‘m’ is mass of cat ion

This polarization occurs at frequency 10^{13} Hz (IR).

It is a slower process compared to electronic polarization.

It is independent of temperature.

Orientational Polarization

It is also called dipolar or molecular polarization. The molecules such as H_2 , N_2,O_2,Cl_2 ,CH_4,CCl_4 etc., does not carry any dipole because centre of positive charge and centre of negative charge coincides. On the other hand molecules like CH_3Cl, H_2O,HCl, ethyl acetate (polar molecules) carries dipoles even in the absence of electric field.

How ever the net dipole moment is negligibly small since all the molecular dipoles are oriented randomly when there is no EF. In the presence of the electric field these all dipoles orient them selves in the direction of field as a result the net dipole moment becomes enormous.

- It occurs at a frequency 10^6 Hz to 10^{10}Hz.
- It is slow process compare to ionic polarization.
- It greatly depends on temperature.

Expression for orientation polarization

$$P_o = N.\vec{\mu}_{orie} \Rightarrow \frac{N.\mu_{orie}^2.E}{3kT} = N.\alpha_o.E$$

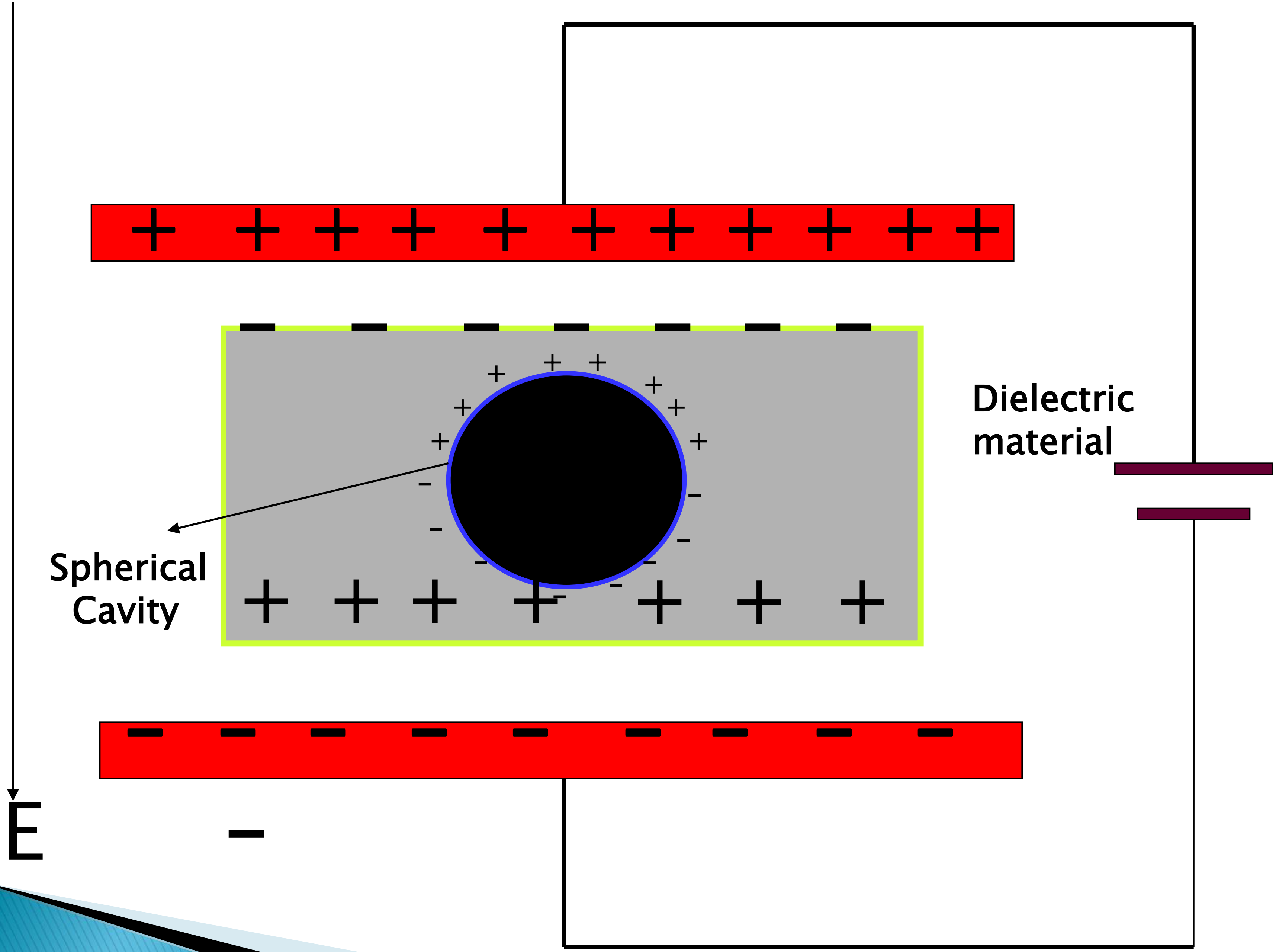
$$\alpha_o = \frac{\mu_{orie}^2}{3kT}$$

$$\therefore \alpha = \alpha_{elec} + \alpha_{ionic} + \alpha_{ori} = 4\pi\varepsilon_o R^3 + \frac{e^2}{w_0^2}\left[\frac{1}{M} + \frac{1}{m}\right] + \frac{\mu_{ori}^2}{3kT}$$

This is called **Langevin – Debye** equation for total Polaris ability in dielectrics.

Internal fields or local fields in Solids

Local field or internal field in a dielectric is the space and time average of the electric field intensity acting on a particular molecule in the dielectric material.



Dielectric material

Spherical Cavity

Evaluation of internal field

Consider a dielectric be placed between the plates of a parallel plate capacitor and let there be an imaginary spherical cavity around the atom A inside the dielectric.

The internal field at the atom site ‘A’ can be made up of four components E_1 ,E_2, E_3 & E_4.

Evaluation of internal field

Consider a dielectric be placed between the plates of a parallel plate capacitor and let there be an imaginary spherical cavity around the atom A inside the dielectric.

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Field E_1:

E_1 is the field intensity at A due to the charge density on the plates

$$E_1 = \frac{D}{\varepsilon_0}$$

$$D = \varepsilon_0 E + P$$

$$E_1 = \frac{\varepsilon_0 E + P}{\varepsilon_0}$$

$$E_1 = E + \frac{P}{\varepsilon_0} \text{..........(1)}$$

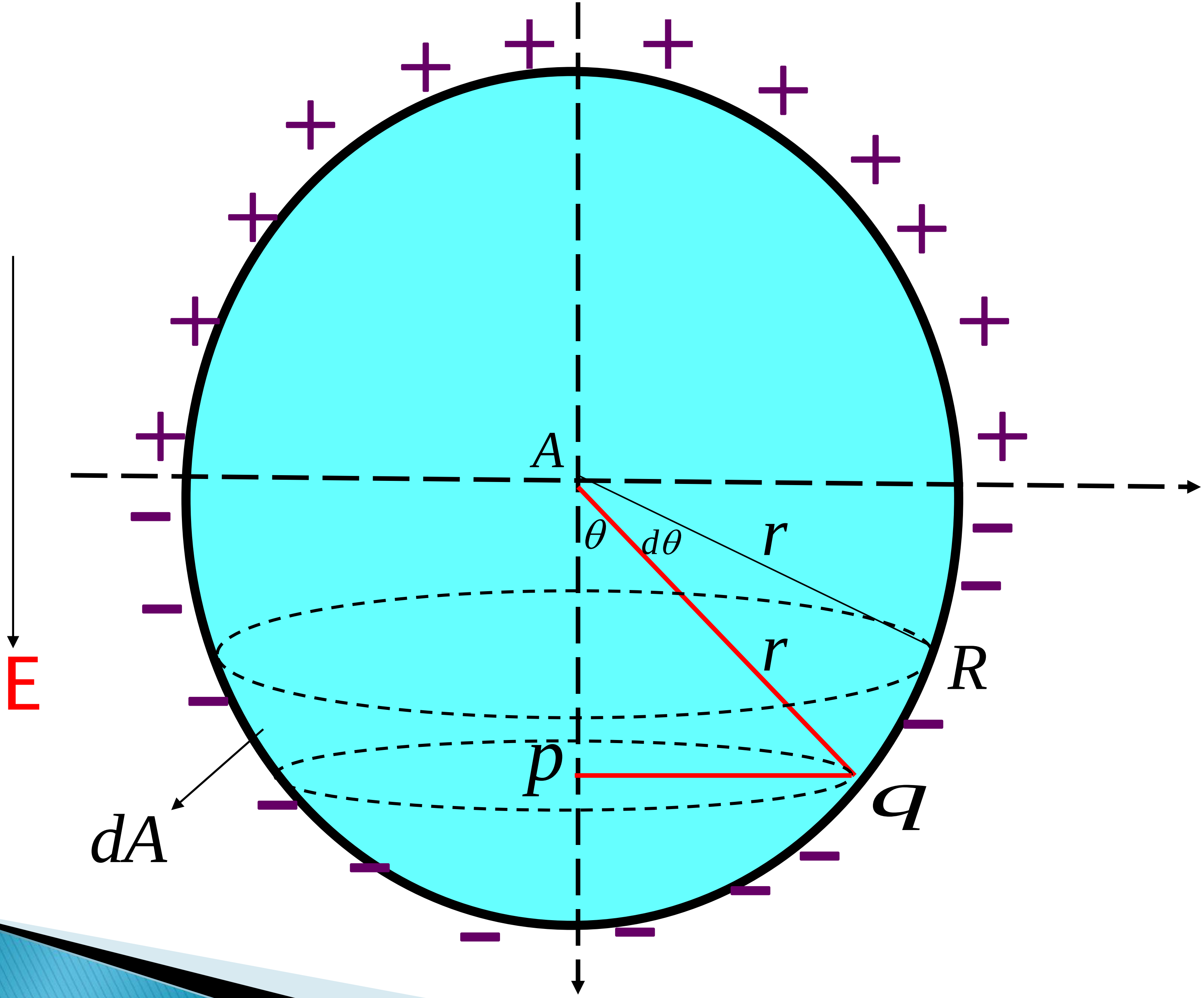
Field E_2:

E_2 is the field intensity at A due to the charge density induced on the two sides of the dielectric.

$$\boxed{E_2 = \frac{-P}{\varepsilon_0} \text{...........}(2)}$$

Field E_3:

E_3 is the field intensity at A due to the atoms contained in the cavity, we are assuming a cubic structure, so $E_3 = 0$.


A
θ
dθ
r
r
R
p
q
dA
E

Field E_4:

1.This is due to polarized charges on the surface of the spherical cavity.

$$\boxed{\begin{aligned} dA &= 2\pi.pq.qR \\ dA &= 2\pi.r\sin\theta.rd\theta \\ dA &= 2\pi.r^{2}\sin\theta d\theta \end{aligned}}$$

Where dA is Surface area between θ & θ+dθ…

2.The total charge present on the surface area dA is…

dq = (normal component of polarization) X (surface area)

$$dq = p\cos\theta \times dA$$

$$dq = 2\pi r^2 p\cos\theta.\sin\theta.d\theta$$

3.The field due to this charge at A, denoted by dE_4 is given by

$$\boxed{dE_4 = \frac{1}{4\pi\varepsilon_0}\frac{dq}{r^2}}$$

The field in θ = 0 direction

$$\boxed{dE_4 = \frac{1}{4\pi\varepsilon_0}\frac{dq\cos\theta}{r^2}}$$

$$dE_4 = \frac{1}{4\pi\varepsilon_0 r^2}(2\pi r^2 p\cos\theta.\sin\theta.d\theta)\cos\theta$$

$$dE_4 = \frac{P}{2\varepsilon_0}\cos^2\theta.\sin\theta.d\theta$$

4.Thus the total field E_4 due to the charges on the surface of the entire cavity is

$$E_4 = \int_0^{\pi} dE_4$$

$$= \int_0^{\pi} \frac{P}{2\varepsilon_0} \cos^2\theta.\sin\theta.d\theta$$

$$= \frac{P}{2\varepsilon_0} \int_0^{\pi} \cos^2\theta.\sin\theta.d\theta$$

$$let..x = \cos\theta \rightarrow dx = -\sin\theta d\theta$$

$$= \frac{P}{2\varepsilon_0} \int_1^{-1} x^2.dx$$

$$= \frac{-P}{2\varepsilon_0} (\frac{x^3}{3})_1^{-1} \Rightarrow \frac{-P}{2\varepsilon_0} (\frac{-1-1}{3})$$

$$E_4 = \frac{P}{3\varepsilon_0}$$

The internal field or Lorentz field can be written as

$$E_i = E_1 + E_2 + E_3 + E_4$$

$$E_i = (E + \frac{p}{\varepsilon_o}) - \frac{p}{\varepsilon_o} + 0 + \frac{p}{3\varepsilon_o}$$

$$E_i = E + \frac{p}{3\varepsilon_o}$$

MAGNETIC PROPERTIES

Introduction to magnetic properties

- Magnetic materials play a prominent role in modern technology.
- They are widely used in industrial electronics and computer industry.
- The traditional methods of information storage and retrieval are rapidly replaced by magnetic storage.

- The magnetism of materials is mainly a consequence of interactions of uncompensated magnetic moments of constituent atoms and molecules.

- Basing on the response of materials in external magnetic field, and on the alignment of magnetic moments in the materials, they are classified into five types.
- Magnetic field : The space around a magnet where its influence is felt is called magnetic field.
- Magnetic induction or Magnetic flux density (B):
- In any material is the number of lines of magnetic force passing through unit area perpendicularly.
- Units of B : Tesla (or) Weber/m^2

Intensity of magnetic field (H)

- At any point in the magnetic field is the force experienced by an unit north pole placed at that point. Or
- It is defined as the field that induces magnetism in a magnetic material.
- H is measured in Ampere/meter.
- When a medium is exposed to magnetic field of intensity H it causes an induction B in the medium.

Magnetic permeability:

- It is defined as the ability of a medium to allow the magnetic lines of force to pass through it.
- $\mu = B/H$
- $B = \mu_o(H+M)$
- Relative permeability $\mu_r = \mu / \mu_0$
- $B = \mu_o \mu_r H$.
- $\mu_r = \mu / \mu_0 = \frac{B/H}{B/H+M} = 1+M/H$
- Where $\mu_r = 1+\chi$
- Which is called relative permeability.

Intensity of magnetization :

- It is the magnetic moment per unit volume or pole strength per unit area.
- $I = M/V = (2l.m)/(2l.a)$

a= area of cross section.

It is measured in Weber/m^2

- **Magnetic flux(Φ) Magnetic flux(Φ):**
- It is the total number of lines of induction passing normal to the cross section.
- Φ is a scalar.
- S I unit : Weber.

Magnetic moment

- It is a product of Magnetic length and pole strength of a magnet .
- Magnetic moment M=2l.m.
- S.I unit of Magnetic moment is **Weber-meter.**

Magnetic susceptibility

- Magnetic susceptibility is defined as the ratio of intensity of magnetization (I) to intensity of magnetizing field.
- Magnetic susceptibility(χ): $\chi = I/H$.

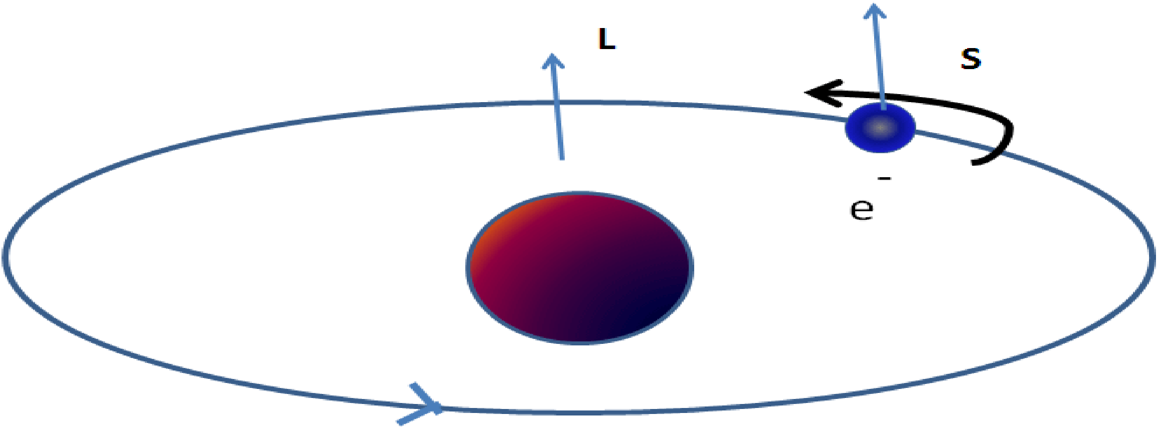
Susceptibility(χ) has no units.

Origin of Magnetic moment and Bohr magneton

- Magnetism originates from the spin and orbital magnetic moment of an electron.

- Spin and Orbital motion of an electron

- The orbital motion of an electron around the nucleus is analogous to the current in a loop of wire.



- The magnetic moment of a current carrying conductor is given by

$$\mu = I.A$$

where I is the current and A is the area in m^2.

Orbital magnetic moment

- The magnetic moment of an electron in orbit is given by

$$\mu = \pi r^2 (-ev/2\pi r)$$

$$= -evr/2 \text{------} (1)$$

where r is the radius of orbit, e -charge and v is the velocity

- The angular momentum of an electron must be an integral multiple of Planck's const.

$$mvr = nh/2\pi \qquad \text{-- (2)}$$

where m is the mass and h is the Planck's const.

- If the electron revolves in the first orbit then n=1

- Therefore orbital magnetic moment of an electron is given by from (1) and (2)

$$\mu = eh/4\pi m \qquad \text{-- (3)}$$

which is known as Bohr magneton, the smallest possible orbital magnetic moment

Spin magnetic moment

- Similarly the smallest possible magnetic moment due to spin of the electron is

$$\mu = eh/4\pi m$$

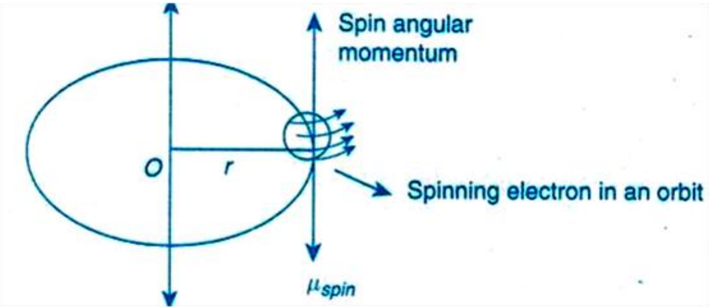
- According to quantum theory the spin of electrons have only two possibilites +1/2 or -1/2.

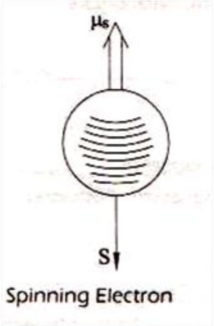
- Similar to eqn (3) we can write in the form

$$\mu = (e/2m)\, S \qquad \text{--(4)}$$

where S is the spin quantum number here given by $(1/2).(h/2\pi)$

$$\mu = g.(e/2m).S \qquad \text{--(5)}$$





Here g is the term known as g- factor.

- When g=2, the spin contribution arises and when g=1 the orbital contribution arises.

- The mass of the nucleus is so large that the magnetic moment contribution can be neglected compared to the electronic magnetic moment.

- The gryomagnetic ratio is proportional to the g-factor and 'g' arises due to the precession of the electrons similar to the precession of a top in a gravitational force. the value of g tells us whether the origin of magnetic moment is spin or orbital motion of electrons.

Magnetic materials

- These are the substances, which upon which being introduced into the external magnetic field, change so that they themselves become sources of an additional magnetic field.
- And they are classified into 3 groups.
- Diamagnetic, Paramagnetic, Ferromagnetic,

Diamagnetic materials

- The materials which when placed in magnetic field acquire feeble magnetism in the direction opposite to that of field are known as Diamagnetic substances.
- Diamagnetic materials exhibit negative magnetic susceptibility.
- The magnetization in diamagnetic materials is directed in opposite direction of the field applied.

- The relative permeability of a diamagnetic substance is slightly less than unity.
- $\mu_r < 1$; which implies that substances are repelled by a magnetic field.
- The magnetic susceptibility of diamagnetic materials is practically independent of temperature.
- Examples: Hydrogen, air, water, gold silver.

Paramagnetic materials

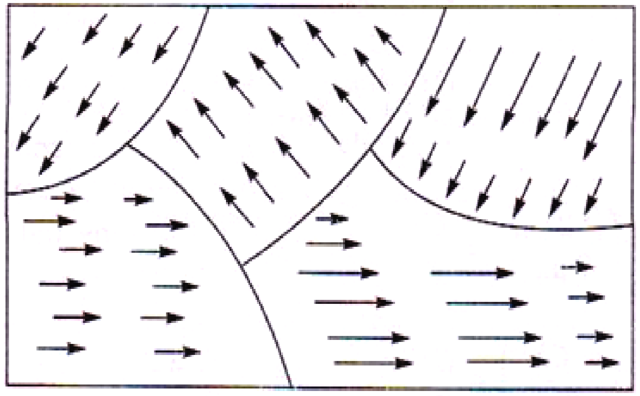
- These are the substances which when placed in magnetic field acquire feeble magnetism in the direction of magnetic field.
- It is the property of the material which has weak attractive force.
- The property is due to spin of electrons
- Spin is random
- These materials have permanent dipoles
- They possess permanent magnetic dipole moment.
- But there is no spontaneous magnetization in the absence of external field. Due to random spin.
- The relative permeability $\mu_r > 1$

Ferromagnetic materials

- It is property of the material which has strong attractive force.
- The property is due to spin of electrons
- Spin is parallel
- They have permanent magnetic dipoles
- They possess permanent magnetic dipole moment. Also in the absence of field they have spontaneous magnetization even in the absence of external field due to parallel
- The relative permeability $\mu_r >> 1$
  - Susceptibility is large and positive

Domain theory (or) Weiss theory of Ferromagnetism

- According to Weiss, Ferromagnetic material consists of a number of regions called “Domains” [~10^{-6} mts] which are spontaneously magnetized.

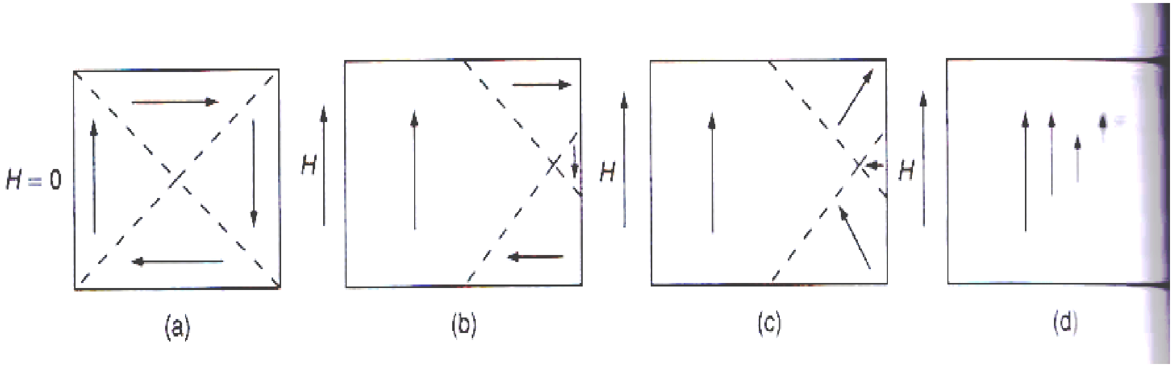


- Spontaneous magnetization is due to parallel alignment of all magnetic dipoles (in each domain) even when no external field is applied.

- Spontaneous magnetization is due to parallel alignment of all magnetic dipoles (in each domain) even when no external field is applied.
- Different domains possess different orientations hence net magnetization is zero.
- When an external field is applied there are two possible ways of alignment of domains. They are

- 1.By motion of domain walls
- 2.By rotation of domain walls

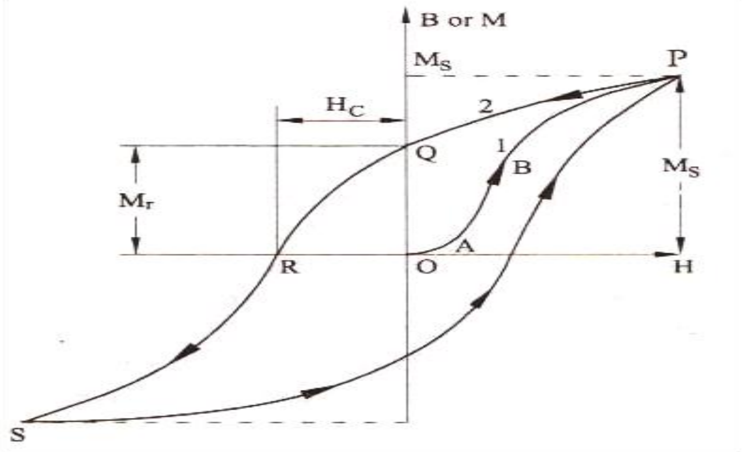
- Domains arise to minimize the energy of the material. The total internal energy is minimum. The alignment of domains, parallel to field is discussed as follows:



- The domains which are parallel to the direction of applied magnetic field will grow in size than other domains. This is called “Motion of domain walls”. Also other domains which are opposite to the field direction are reduced.
- As the magnetic field is strong, the magnetic moments of the domains can rotate in the applied field direction. This is called “rotation of domain walls”.

Hysteresis loop

- **Definition:** Hysteresis means the lagging of magnetization “B” behind the applied magnetizing field “H”. The energy supplied to the specimen during magnetization is not fully used. The balance of energy left in the material is produced as heat i.e. loss of heat called” Hysteresis Loss”.
- This phenomenon of magnetic Hysteresis is an “Irreversible” characteristic of ferromagnetic material. The loop (or) area refers to the hysteresis loop. Hysteresis loss occurs in ferromagnetic materials below Curie temperature.



- When the magnetic field is applied on a ferromagnetic material the magnetization increases slowly and reaches a constant M_s called saturation magnetization
- In figure from point O to A, the displacement of domain walls takes place. When the field is suddenly off, the domains again go for original position.
- From point A to B, as the field is further increased, the magnetization also increases. Here when the field is made off the domain displacement does not return back to original condition.

- For higher fields the magnetization reaches maximum ie saturation magnetization M_s due to rotation of domain walls.
- In this case at the region B to P, if the field is suddenly made off, the domains does not return back to original direction. But there is some magnetic field remained inside the specimen.
- The point M_s is called saturation of magnetization. When the field is off, the curve does not go back to ‘O’[as shown in fig] but creates a new path to a point M_r called “retentivity” (or) residual (or) remanence Magnetization
- To reduce the residual magnetism to zero, a negative field ‘Hc’ has to be applied. When the sufficient negative field is applied, the residual; magnetization becomes zero and this field is known as “negative coercive field” ($-H_c$) or coercively. Further again if the negative field is applied then magnetization increases but in negative direction. This is known as negative saturation magnetization ($-M_s$).

- If the negative field is decreased back to zero the negative saturation of magnetization will not reach the initial path at ‘0’ but creates a new path and reaches a point called negative residual magnetism ‘-M_r’ know as negative receptivity.
- To decrease the negative residual magnetism to zero some positive field is applied. The amount of magnetic field required to bring residual magnetization to zero is known as positive coercive field (H_c).
- Further the increase of positive magnetic field the magnetization reaches again to positive saturation (M_s) and this is a cyclic process.
- The final conclusion is that when the magnetization vector is started from origin ‘O’ will not reach back to that point. “The magnetization lags behind H”. This is called magnetic hysteresis loss measured in the area of the loop (or) curve. If the loop area of a ferromagnetic material is large, more energy is wasted. This is also called as “dielectric loss” for one complete cyclic operation.

LASERS

A laser is a device that emits light through a process of optical amplification based on the stimulated emission of electromagnetic radiation.

The term “LASER" originated as an acronym for "light amplification by stimulated emission of radiation".

Stimulated emission was first used by Townes and Schawlov in USA & Bosov & Prokhrov in USSR.

Maiman demonstrated the first Laser in 1960.

Characteristics of Laser light

The most important characteristics of a Laser beam are,

1. **High Monochromaticity**
2. **High degree of coherence**
3. **High directionality**
4. **High brightness**

1.Monochromaticity:

- Laser light is monochromatic or very pure in color.
- A Laser beam is in single wavelength i.e., the line width of a laser beam is extremely narrow.
- In conventional light sources, the wavelength spread is usually 1 in 10^6
- In case of laser light, the spread will be 1 in 10^{15}

  This means that if the frequency of radiation is 10^{15} Hz, then the width of the line will be 1 Hz

2.Directionality:

Laser beam emits light only in one direction.

It travels very long distances without divergence. And so, Laser communication is carried on between the earth and the moon.

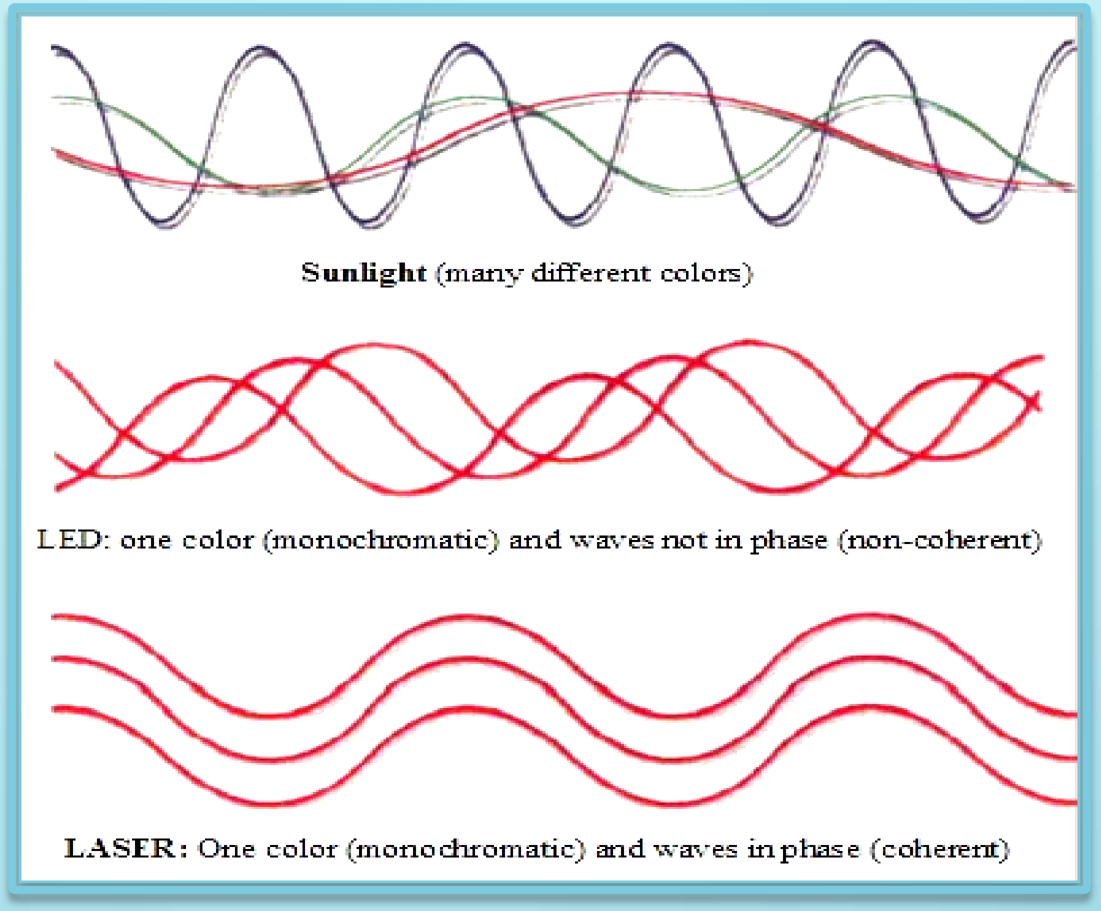
The directionality of a Laser beam is expressed in terms of divergence.

Suppose r_1 and r_2 are the radii of a laser beam at distances D_1 and D_2 from a laser, then the divergence, $\Delta\theta = (r_1 - r_2)/ D_2 - D_1$

The divergence for a laser beam is 0.01 milliradian where as incase of search light it is 0.5 radian.

3. Coherence:

- Two sources of light are said to be coherent if they have zero or a constant phase difference between them.
- Laser beam is both Spatially and temporally coherent.



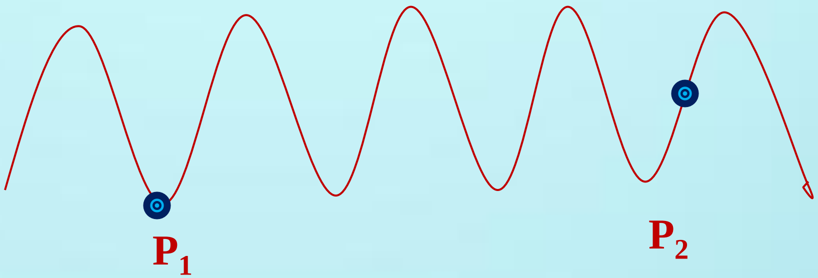
Sunlight (many different colors)

LED: one color (monochromatic) and waves not in phase (non-coherent)

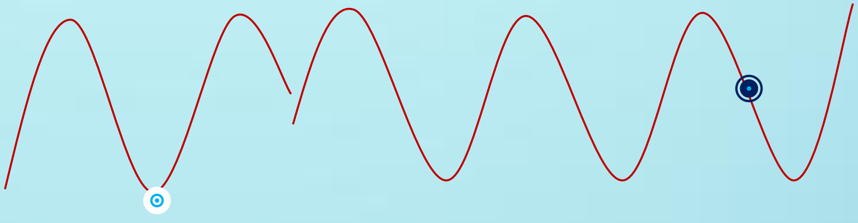
LASER: One color (monochromatic) and waves in phase (coherent)

Temporal coherence:

- Temporal coherence refers to the correlation between the light fields at different times at a point on the wave.
- Temporal coherence refers to the fact that the wave is polarized and retains the same frequency and phase over the entire length of the beam. Hence, lasers have a long coherence length
- If there is no change in phase over a time ‘t’ at a point on the wave, then it is said to be temporally coherent during that time.
- since the two points P_1 and P_2 are on the same wave train which is continuous, they have correlation.



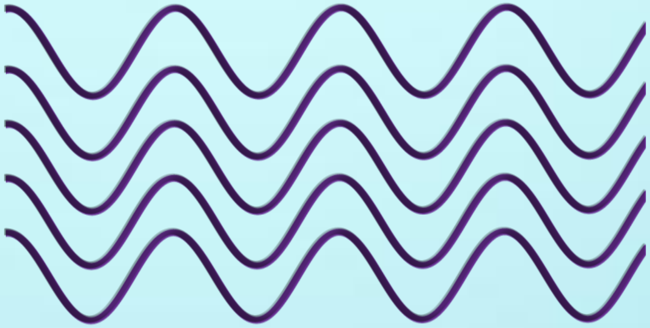
Continuous wave



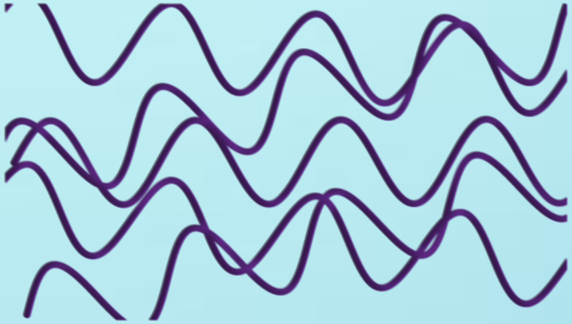
Discontinuous wave

Spatial Coherence:

- If a wave maintains a constant phase difference or is in phase at two different points on the wave over a time ‘t’, then the wave is said to be in spatial coherence.
- Spatial coherence refers to the laser beam output being narrow and resistant to diffraction, essentially retaining its narrow shape.
- This allows lasers to be focused in small spots as well as reach large distances.



Spatially coherent waves



Spatially incoherent waves

4.Brightness:

The Laser beam is highly bright (intense) as compared to the conventional light because more light is concentrated in a small region.

It is observed that the intensity of 1mV laser light is 10,000 times brighter than the light from the sun at the earth’s surface.

The number of photons coming out from a laser per second per unit area is about 10^{22} to 10^{34} where as the number of photons coming out per second per unit area of a black body at 1000K having a wavelength of 6000 is 10^{16}

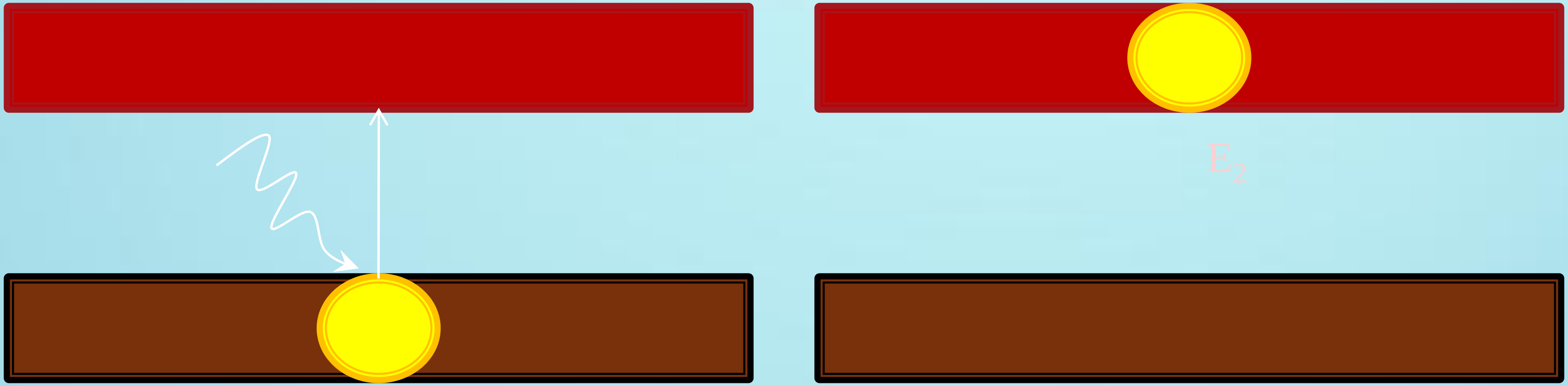
Laser light is coherent and so at a time many photons are in phase and they superimpose to produce a wave of larger amplitude.

The intensity is proportional to the square of the amplitude and hence the intensity of the resultant laser beam is very high.

Mechanism of Light Emission

For atomic systems in thermal equilibrium with their surrounding, the emission of light is the result of:

Absorption: If a photon of energy $h\nu_{12}(E_2-E_1)$ collides with an atom present in the ground state of energy E_1, then the atom completely absorbs the incident photon and makes transition to excited state E_2.

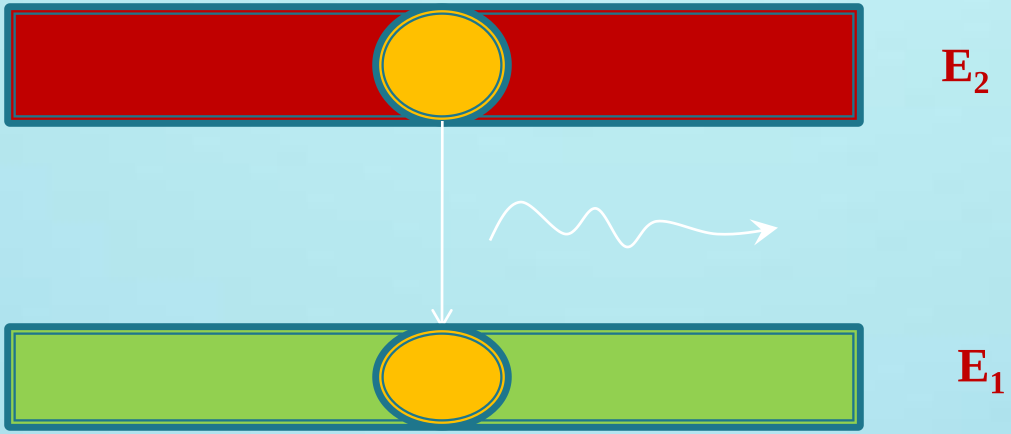


Before Absorption

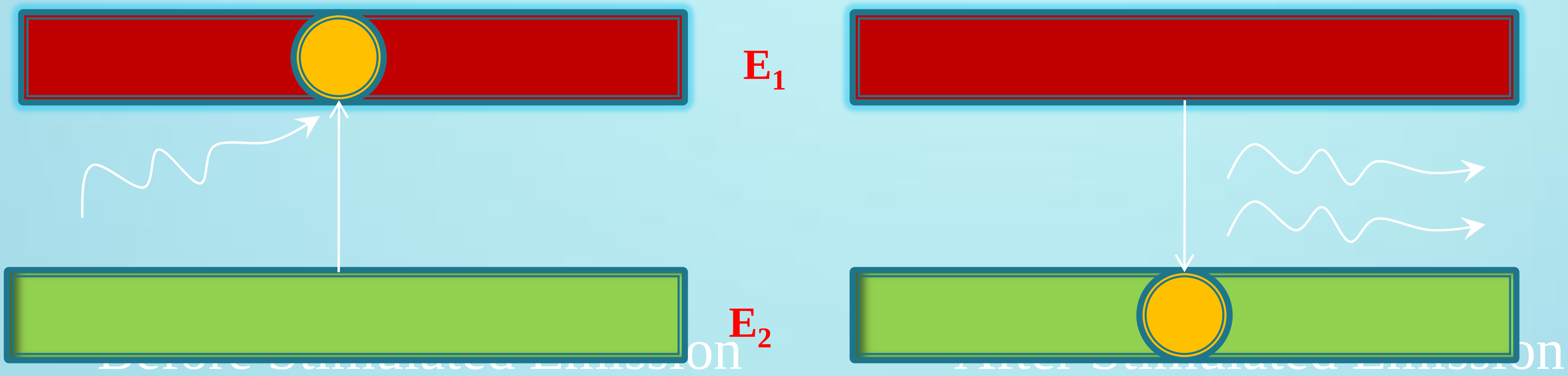
After Absorption

Spontaneous emission: An atom initially present in the excited state makes transition voluntarily on its own ,without any aid of external stimulus or an agency ,to the ground state and emits a photon of energy $h\nu = E_2 - E_1$. The period of stay of the atom (electron) in the excited state is called its life time.

This process of emission of light is called spontaneous emission.



Stimulated Emission: A photon having energy $h\nu_{12}$ (E_2-E_1) impinges on an atom present in the excited state and the atom is stimulated to make transition to the ground state. This gives off a photon of energy $h\nu_{12}$. The emitted photon is in phase with the incident photon. These are coherent. This type of emission is known as stimulated emission.

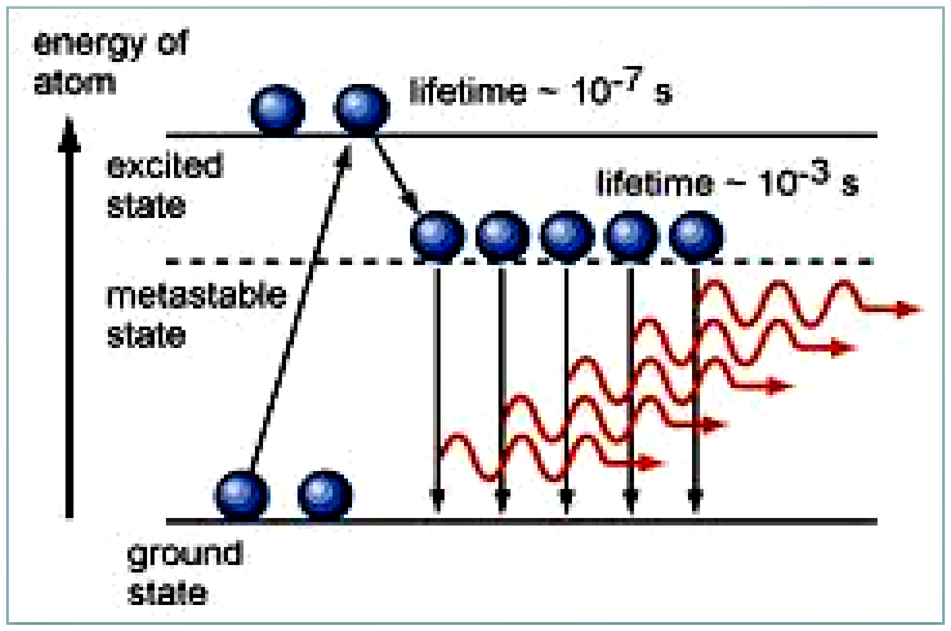


Difference between Spontaneous and Stimulated Emission of radiation

Spontaneous Emission of Radiation	Stimulated Emission of Radiation
It is a Polychromatic radiation.	It is a Monochromatic radiation.
It has less intensity.	It has High intensity.
It has less directionality and more angular spread during propagation.	It has high directionality and so less angular spread during propagation.
It is Spatially and temporally incoherent radiation.	It is Specially and temporally coherent radiation.
In this emission ,light is not amplified.	In this emission , light is amplified.
Spontaneous emission takes place when excited atoms make a transition to lower energy level voluntarily without any external stimulation.	Stimulated emission takes place when a photon of energy equal to $h\nu_{12}$ $(=E_2-E_1)$ stimulates an excited atom ,to make transition to lower energy level.
In a single downward transition, Spontaneous emission results in the emission of one photon.	In a single downward transition , Stimulated emission results in the emission of two photons.
Ex: Light from an ordinary electric bulb, Light from an LED.	Ex: Light from a Laser source.

Meta Stable state

- An excited state with relatively more life time(10^{-3} sec) is called a Meta stable state.
- The necessary condition for population inversion is the presence of a meta stable state.

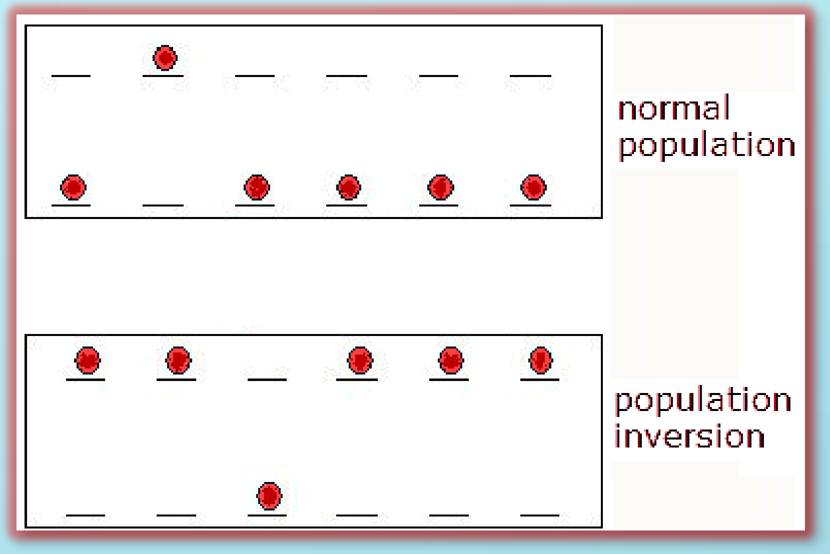


Population Inversion

- Usually in a system, the number of atoms (N_1) present in the ground state (E_1) is larger than the number of atoms (N_2) present in the higher energy state. The process of making $N_2>N_1$ is called population inversion.
- Conditions for population inversion are:
- The system should posses at least a pair of energy levels ($E_2>E_1$), separated by an energy equal to the energy of a photon ($h\nu$).
- There should be a continuous supply of energy to the system such that the atoms must be raised continuously to the excited state.

Population inversion can be achieved by a number of ways. Some of them are,

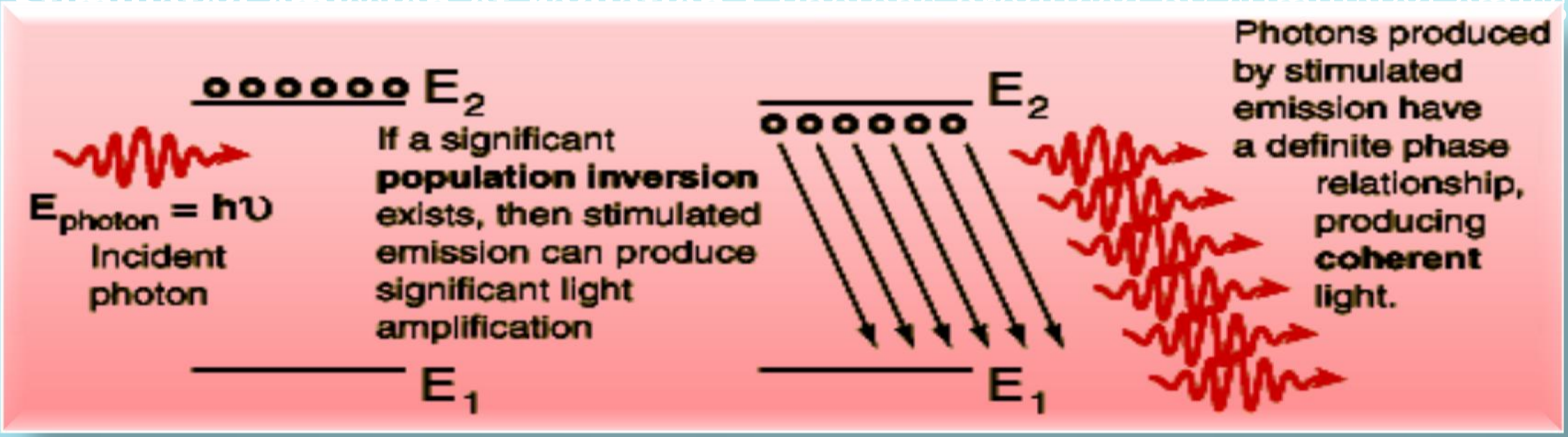
(i) Optical pumping
(ii) Electrical discharge
(iii) Inelastic collision of atoms
(iv) Chemical reaction and
(v) Direct conversion



Lasing Action

The steps involved in Lasing action are,

1. **Pumping:** The process of sending atoms from lower energy state to higher energy state is called Pumping..Different pumping mechanisms are adopted depending on the type of the laser. For Ruby laser, Optical pumping is adopted. For He-Ne laser, the pumping mechanism is Electric discharge. In Semi-conductor laser, it is Direct conversion and in the case of CO_2 laser, the mechanism is Chemical reaction.
2. **Population inversion :** Population inversion can be achieved with the presence of a meta stable state.
3. **Stimulated emission of radiation :** Photons produced by stimulated emission



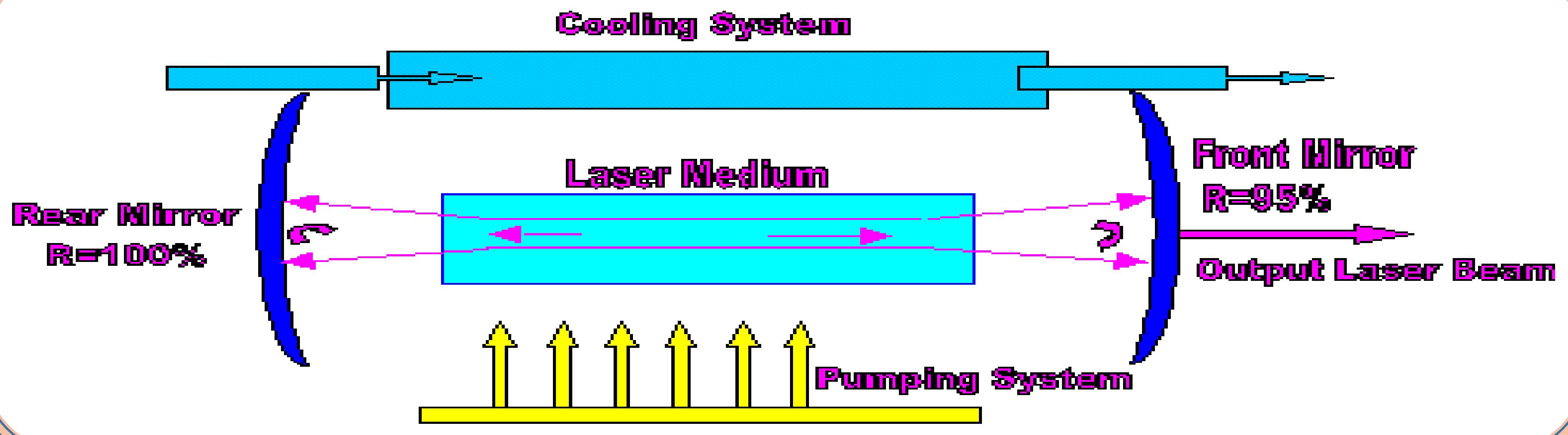
If a significant population inversion exists, then stimulated emission can produce significant light amplification

Photons produced by stimulated emission have a definite phase relationship, producing coherent light.

Laser System

A Laser system consists of three basic parts.

1. An **Active medium,** with a suitable set of energy levels to support laser action. For example, in Ruby laser, Cr^{3+} ions are the active laser particles.
2. **Energy source,** (Source of Pumping) in order to establish population inversion.
3. An **Optical Cavity** or Resonator to introduce optical feedback and so maintain the gain of the system overcoming all losses. Depending on the type of the system, optical feedback is provided with the help of dielectric mirrors or polished and coated ends of a crystal rod or cleaved crystal face.



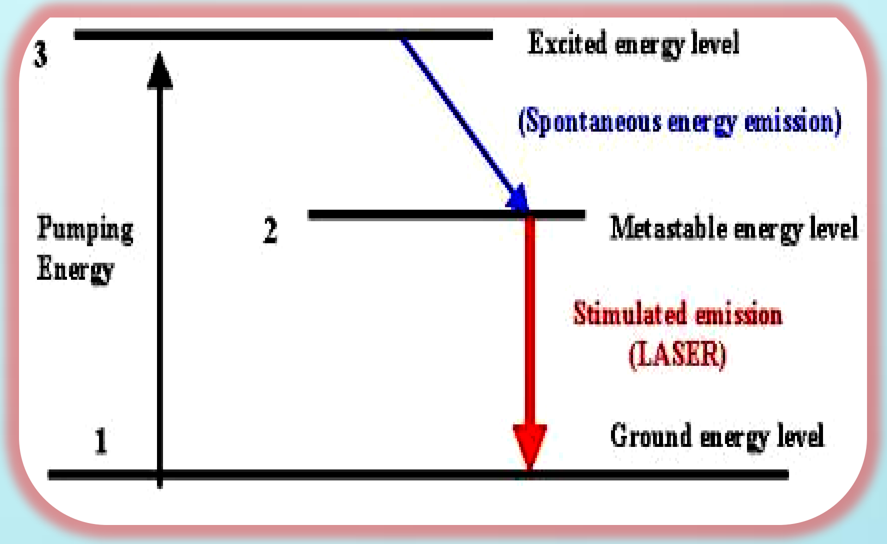
Ruby Laser

- Ruby Laser is the first type of laser, demonstrated in the year 1960 by T.H.Maiman.
- Ruby Laser is a solid state laser.
- It is a pulsed three level pumping scheme.

Active medium: The active medium in Ruby rod (Al_2O_3+Cr_2O_3) is Cr^{3+}ions.

- Some of the Aluminum atoms are replaced by 0.05% of Chromium atoms.
- Lasing action takes place in Chromium energy levels.

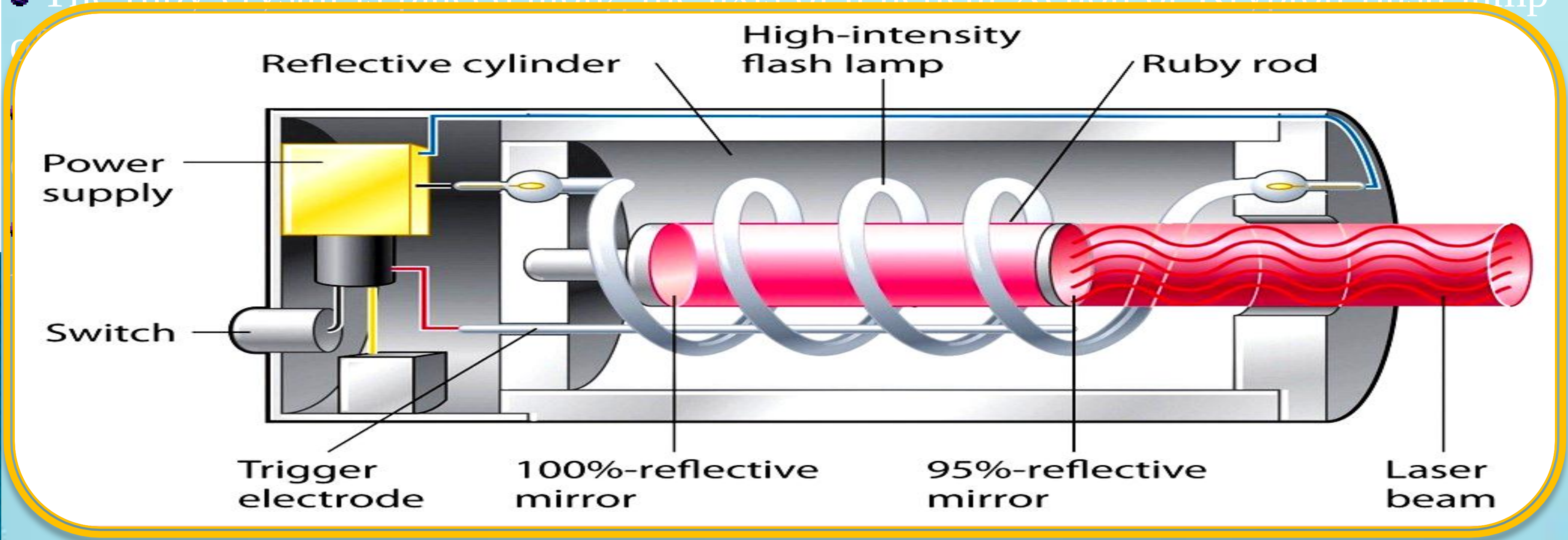
Energy Source: The pumping of ions is through optical pumping, using Xenon flash lamp.



Energy states of a Three level Active medium

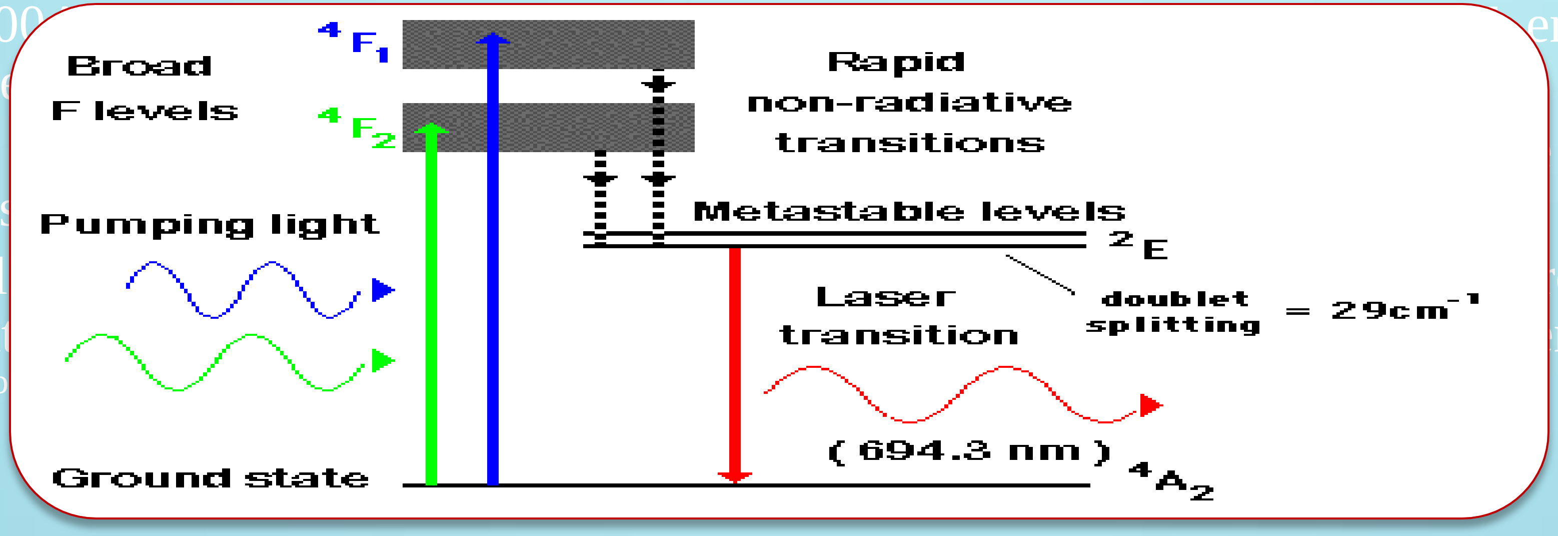
Construction:

- Ruby Laser consists of a cylindrical shaped Ruby crystal rod. One of the end faces is highly silvered and the other face is partially silvered so that it transmits 10-25% of the incident light and reflects the rest.
- The ruby crystal is placed along the axis of a helical Xenon or Krypton flash lamp



Working:

- The Chromium ions are responsible for the stimulated emission of radiation, whereas Aluminum and Oxygen ions are passive, sustaining the lasing action.
- The Chromium ions absorb the radiations of wavelength around 5500A° (Green) and 4000 … energy levels re
- After … state ²E, cons
- Popul … result, stimulat … ngths 6929A°



Applications

Ruby laser is used in Distance measurement using ‘pulse echo’ technique.

Ruby laser is used to create holograms of large objects such as aircraft tires to look for weaknesses in the lining.

Used in atmospheric ranging, scattering studies and LIDAR measurements.

Used for trimming resistors and integrated circuit masks.

Ruby lasers were used mainly in research One of the main industrial uses is drilling holes through diamond.

Used in military as target designators and range finders.

Used in research applications such as Plasma production and fluorescence spectroscopy.

Ruby lasers were used extensively in tattoo and hair removal.

Drawbacks

As Ruby laser is a three level pumping scheme, it generally requires very high pumping power.

Efficiency is very less, as only green and blue components of the incident light are absorbed and the remaining components are left unused.

The laser output is not continuous. It is in a pulsed mode.

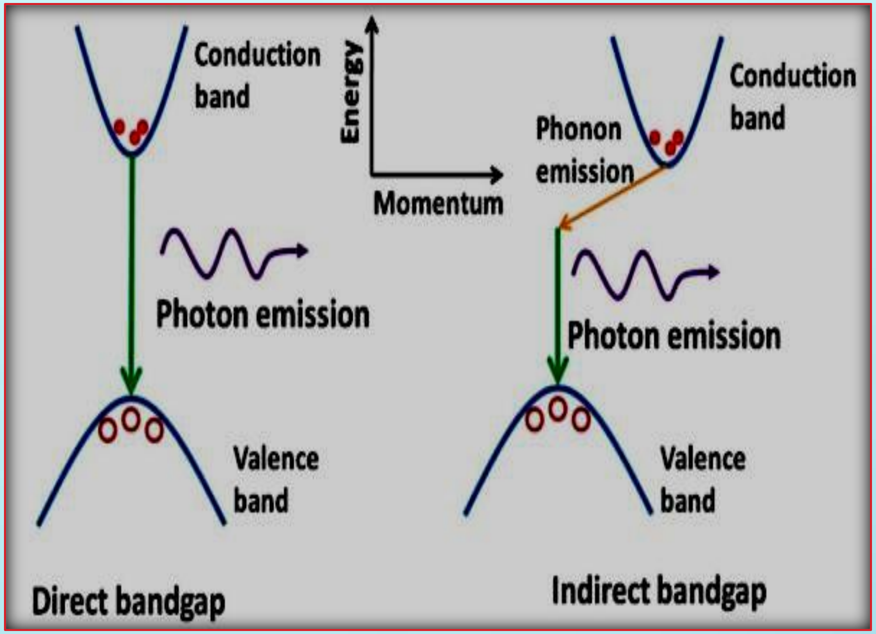
Semi-Conductor Diode Laser

Semiconductor laser is of two types:

- **Homo junction Laser:** A p-n junction formed by a single crystalline material such that the basic material is same on both the sides.
- **Hetero junction Laser:** The material on one side of the junction differs from that on the other side.

Principle:

- Among the Direct band gap and the Indirect band gap semiconductor, a Direct band gap semiconductor is used to make light emitting diodes and lasers.
- In Direct band gap semiconductor, there is a large possibility for the direct recombination of electron and hole, and the electron emitting a photon.



Direct and Indirect band gap Semiconductors

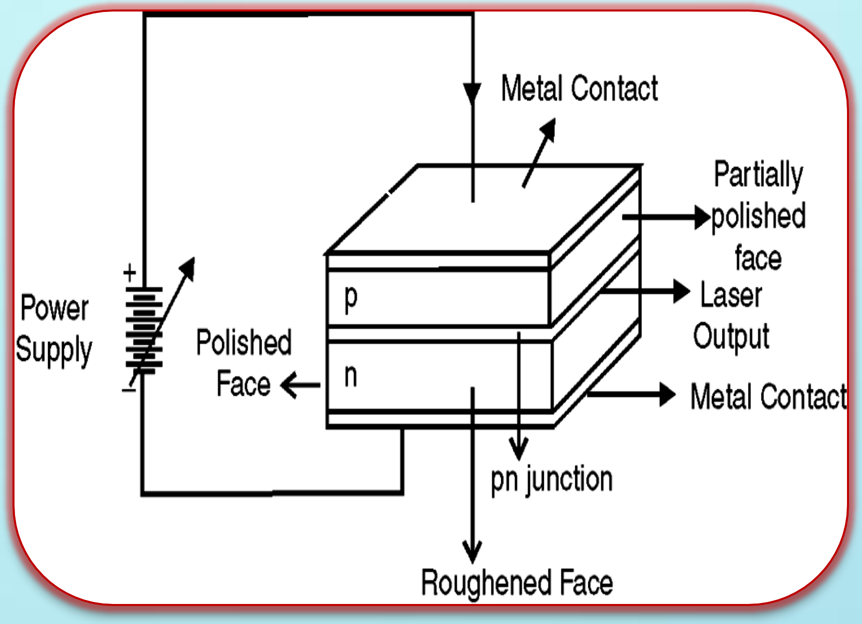
Construction:

Active medium:

- A p-n junction diode made from crystalline Gallium Arsenide is the active medium.
- The p-region and n-region in the diode are obtained by heavily doping Germanium and Tellurium respectively in GaAs.
- At the junction, the sides through which emitted light is coming out, are well polished and are parallel to each other.

Energy Source:

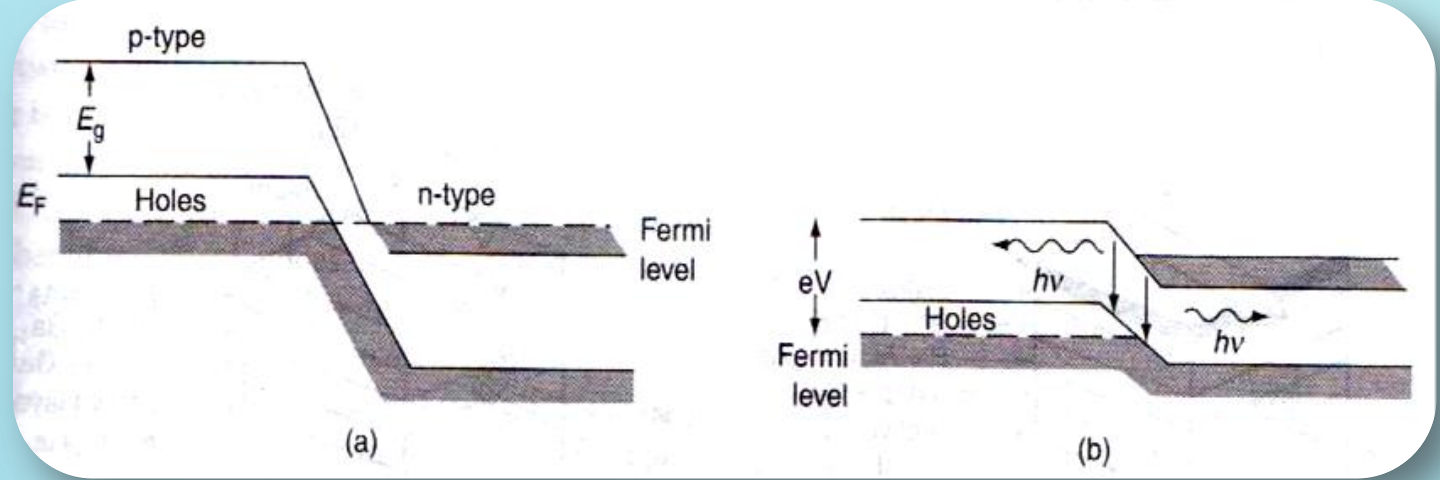
Electric current which is applied to the crystal platelet through a strip electrode fixed to its upper surface, is the energy source.



Ga As diode laser

Working:

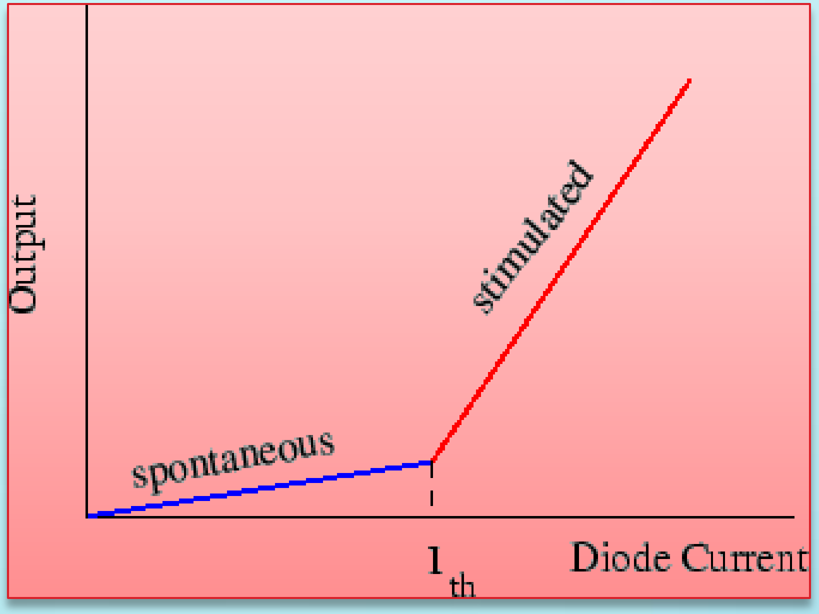
- Population inversion is achieved by injecting electrons across the junction from the n-region to the p-region by means of a forward bias voltage.
- When a large amount of current of the order 10^4 amp/cm^2 is passed through the junction to provide excitation, the direct recombination of electrons and holes take place resulting in the emission of photons. These photons further increase the rate of recombination .Thus, more number of photons are emitted.
- The wavelength of the emitted radiation depends upon the concentration of the donor and acceptor atoms in Ga As.
- In reverse bias, no carrier injection takes place and consequently no light is emitted.



Energy band diagram of heavily doped p-n junction (a) in equilibrium (b) Forward bias

Explanation:

- At thermal equilibrium, the Fermi level should be uniform throughout the junction. So the Fermi level in the n-side lies within the conduction band and in the p-side, it lies within the valence band.
- When the junction is forward biased, the energy levels shift and the electrons and holes are injected across the depletion layer, existing at the junction.
- At low threshold current, recombination of electrons and holes give spontaneous emission.
- Initially the spontaneously emitted photon starts the stimulated emission, at a current beyond the threshold value, and thus the number of photons increases with time.



Calculation of wavelength of the emitted radiation:

- Suppose the band gap of Ga As is 1.44eV

Therefore, $E_g=h\nu=hC/\lambda$

(or) $\lambda=hC/E_g = \frac{6.626\times10^{-34}\times3\times10^{8}}{1.44\times1.6\times10^{-19}}$

$=8623\times10^{-10}$ m

=8628 A°

- This wavelength corresponds to the near infrared region.
- Taking the wavelength in μm and E_g in eV, [illegible] relati[illegible] to

[illegible] V)

Drawbacks of homo-junction lasers:

- The threshold current density is very large (400 A/ mm^2)
- Only pulsed mode output is obtained.
- Laser output has large beam divergence.
- Laser output has poor coherence and poor stability.
- Electromagnetic field confinement is poor.

Advantages of hetero-junction lasers over Homo-junction lasers:

- The threshold current density is very low, (10 A/ mm^2) at room temperature.
- The laser output is continuous.
- High output power (10 mW) can be achieved even with low operating current (< 500 mA)
- Very narrow beam with high coherence and monochromaticity is achieved.
- The laser output is highly stable with longer life.

Hence hetero-junction laser diodes are used as optical sources in optical fibre communication.

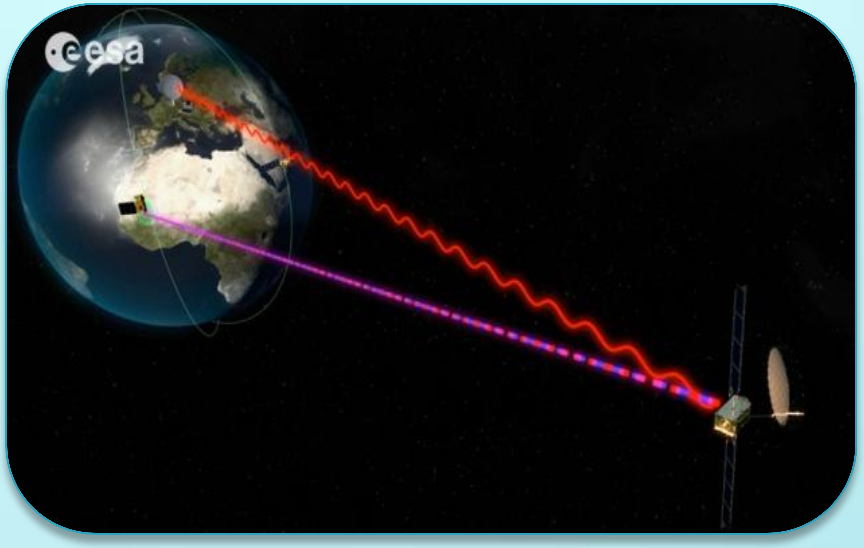
Applications of Lasers

Lasers in Communication:

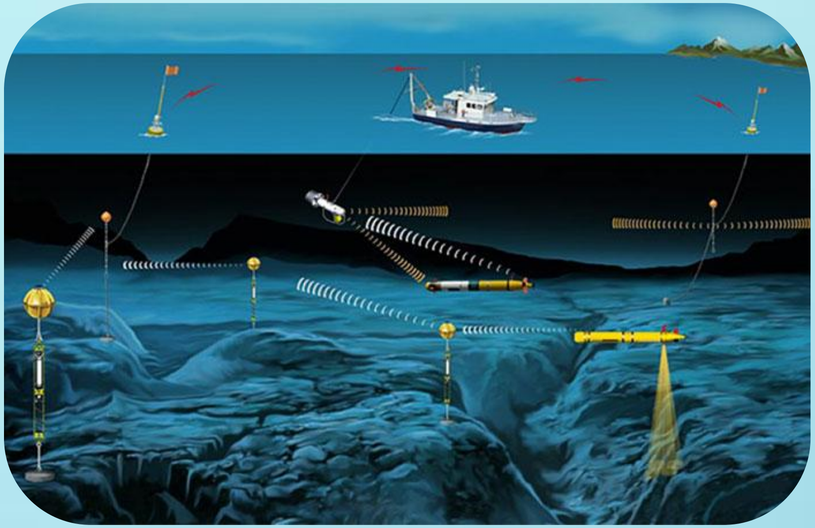
- Lasers are used in Optical fibre communication as light source to transmit audio, video signals and data to long distances without attenuation and distortion.

- Laser beam can be used for the communication between the earth and the moon or to other satellites.

- Laser beam can be used for under water communication, as laser radiation is not absorbed by water.



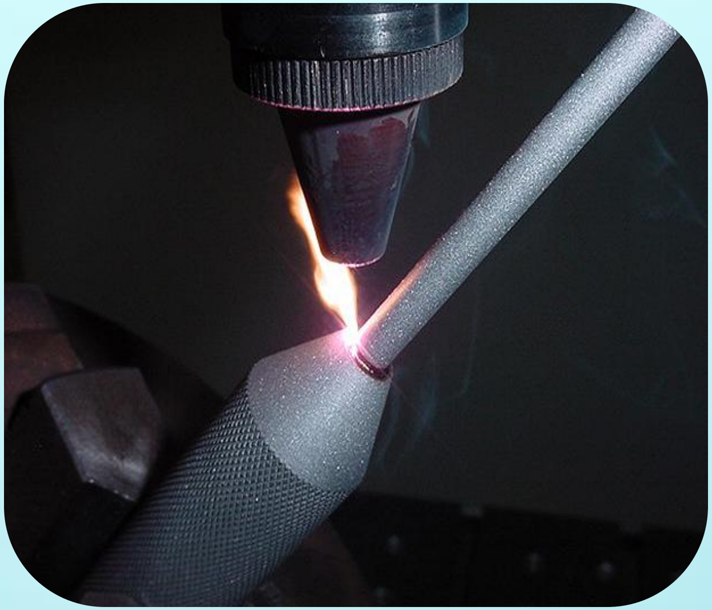
Lasers in Satellite communication



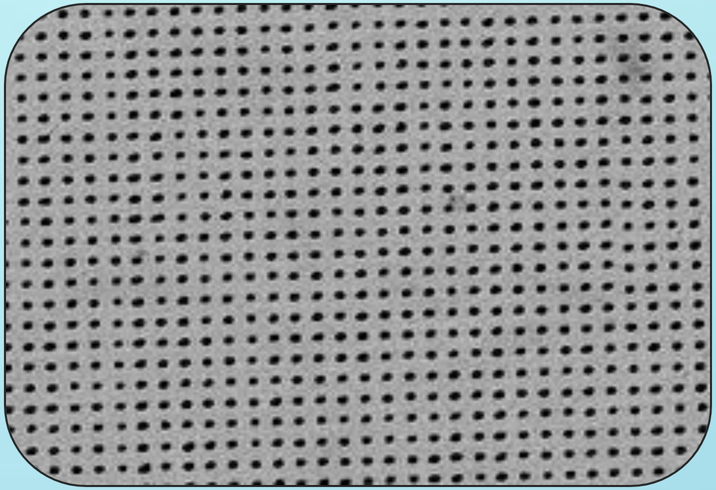
Lasers in under water communication

Lasers in Industry:

- Lasers are used for welding. Dissimilar metals can be welded using lasers.
- Holes with controlled precision can be drilled in steel, ceramics, diamond and alloys, using lasers.
- Lasers are widely used in electronic industry in trimming the components of ICs.



Lasers used in welding



Drilling Steel foil for high density filters

- Lasers are used in cutting metal sheets, diamond and cloths. In the mass production of stitched clothes, lasers are used to cut the cloth in a desired dimension, all at once.
- Lasers are used for surface treatment. Laser beam is used in selective heat treatment for tempering the desired parts in automobile industry.

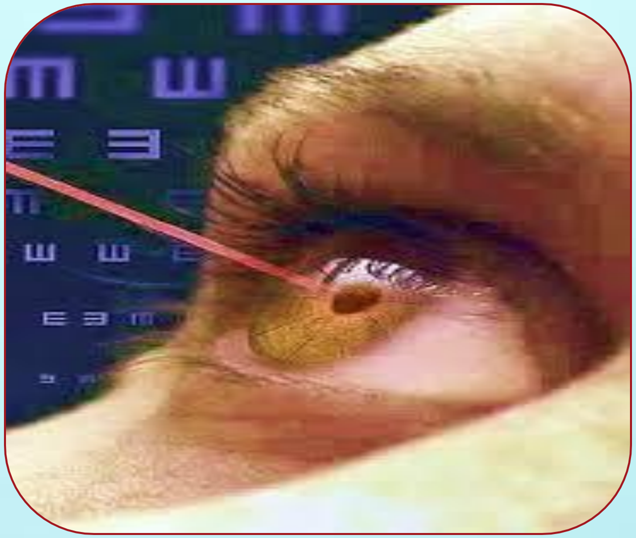
Cutting wood using laser

Laser surface treatment to change the micro structure of metals through controlled heating and cooling.

The world's first all-diamond ring, cut with Laser

Lasers in medicine:

- Lasers are used in eye surgery, especially to attach the detached retina.
- Lasers are used for treatments such as plastic surgery, skin injuries and to remove moles, tattoos and tumours developed in skin tissue.
- Lasers are used in stomatology-the study of mouth and its disease.



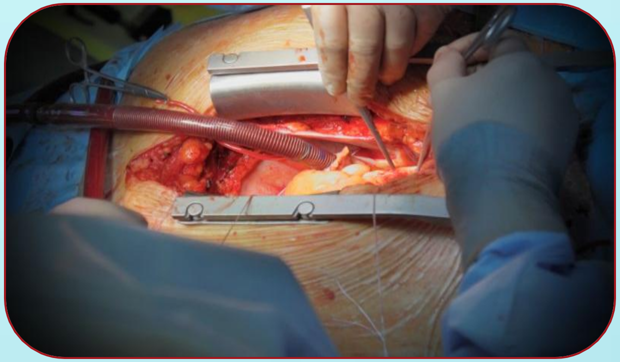
Lasers in Eye surgery

Lasers used in stomatology

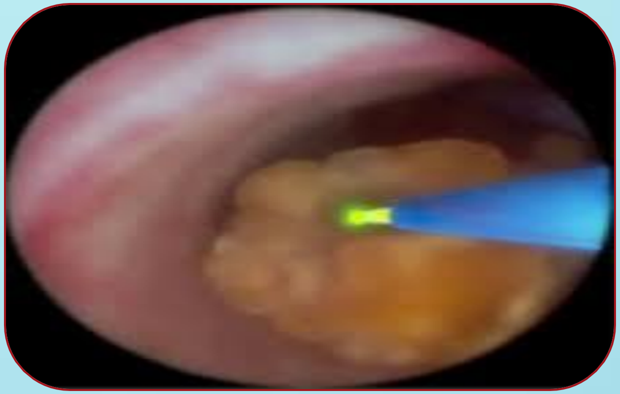
Lasers in tattoo removal

- Laser radiation is sent through optical fibre to open the blocked artery region.
- Lasers are used to destroy kidney stones and gall stones.
- Lasers are used in cancer diagnosis and therapy.
- Lasers are used in blood loss less surgery.
- Lasers are used to control hemorrhage.
- Using CO_2 laser, liver and lung treatment can be carried out.
- Lasers are used in endoscopes, to detect hidden parts.
- Laser Doppler velocimetry is used to measure the velocity of blood in blood vessels.

Red Argon laser used in throat cancer treatment



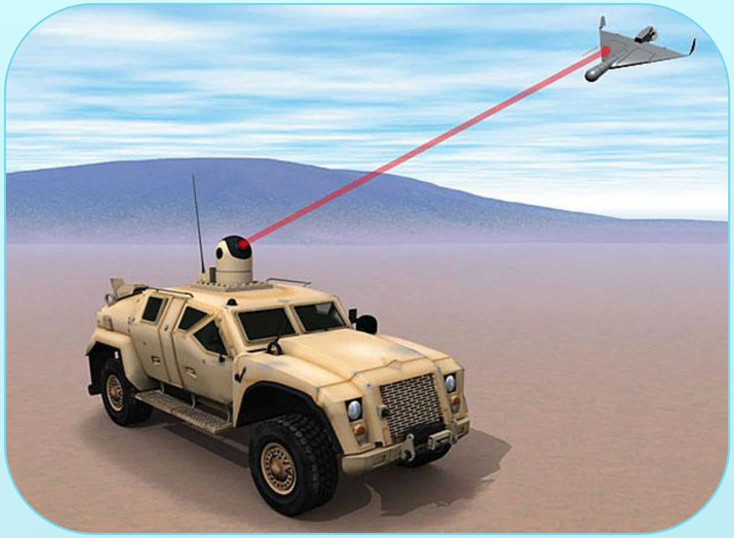
Lasers used to open artery block



Lasers used to destroy kidney stones

Lasers in Military:

- Focusing of high energetic laser beam for few seconds, destroys aircrafts, missiles, etc. These rays are called death rays.
- The vital part of the enemy's body can be evaporated by focusing a highly convergent laser beam from a laser gun.
- LIDAR (Light Detecting And Ranging) is used to estimate the size and shape of distant objects or war weapons.



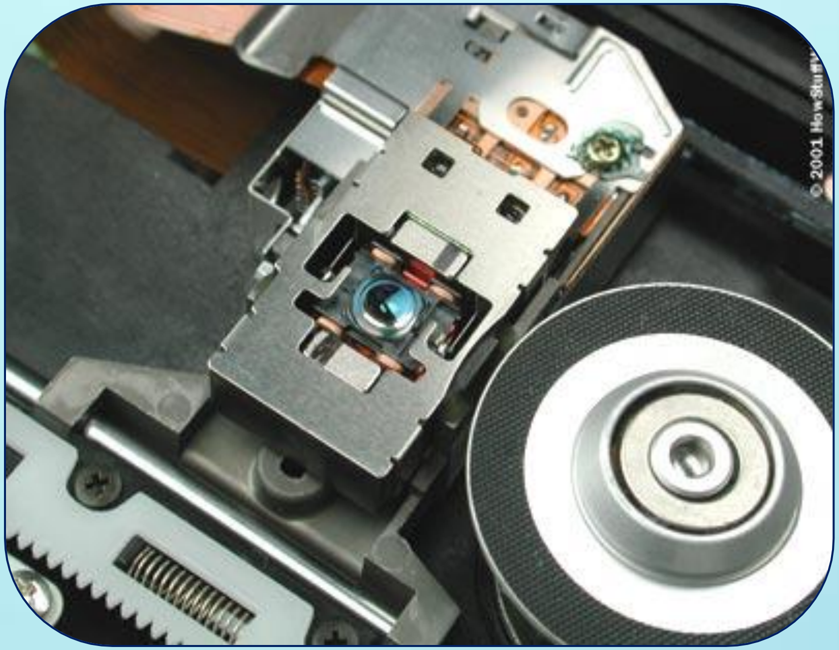
Laser armed Humvees shooting a Drone (flying Robot)

Lasers beams of RMR LIDAR at ALOMAR Observatory

Soldiers using laser gun

Lasers in Computers:

- By using Lasers, a large amount of information or data can be stored in CD-ROM or their storage capacity can be increased.
- Lasers are used in computer printers.



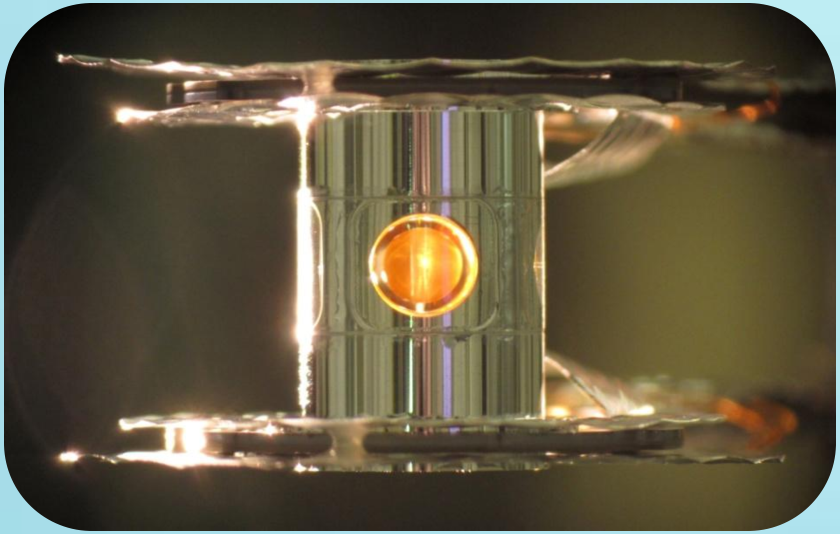
Laser assembly inside a CD burner

Laser Beam Printer (LBP) by Epson

Lasers in thermo nuclear fusion:

- A nuclear fusion reaction can be initiated by concentrating a large amount of laser energy in a small volume.
- For example, in the fusion of deuterium and tritium, irradiation with a high energy laser beam, develops a temperature of 10^{17} °C , which is sufficient to initiate nuclear fusion reaction.

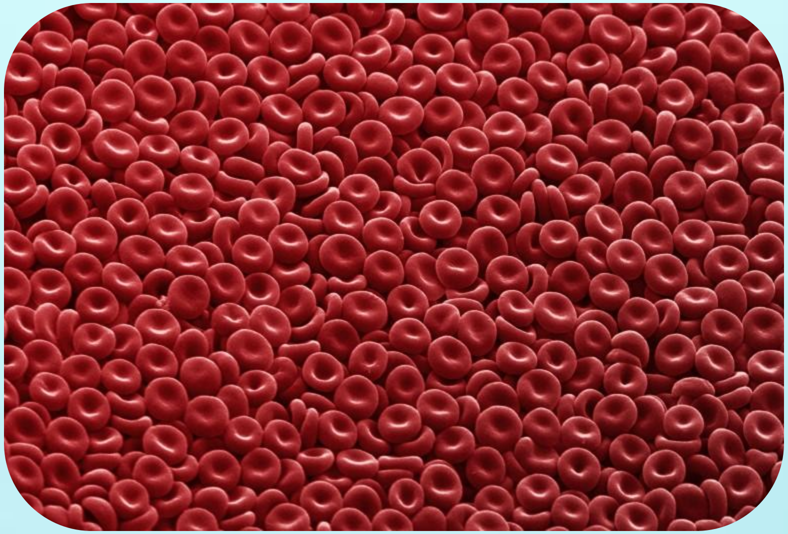
Lasers used in nuclear fusion reactors



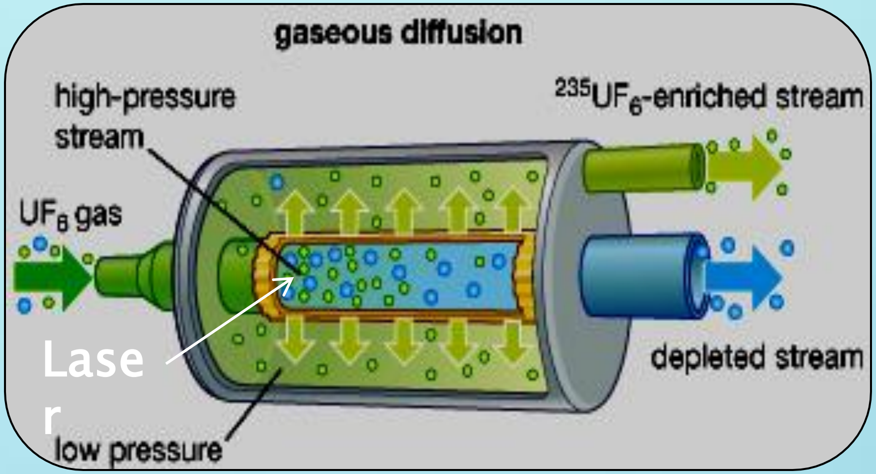
Fusion of deuterium and tritium using 192 lasers

Lasers in Scientific research:

- Laser beam can initiate chemical reactions, study the nature of chemical bonds and also can break molecules.
- Lasers are used to estimate the size and shape of biological cells such as erythrocytes.
- Lasers are used to find the size of dust particles.
- Lasers are used in counting the atoms in isotope separation.



Laser Scanning Microscope micrograph of human RBCs



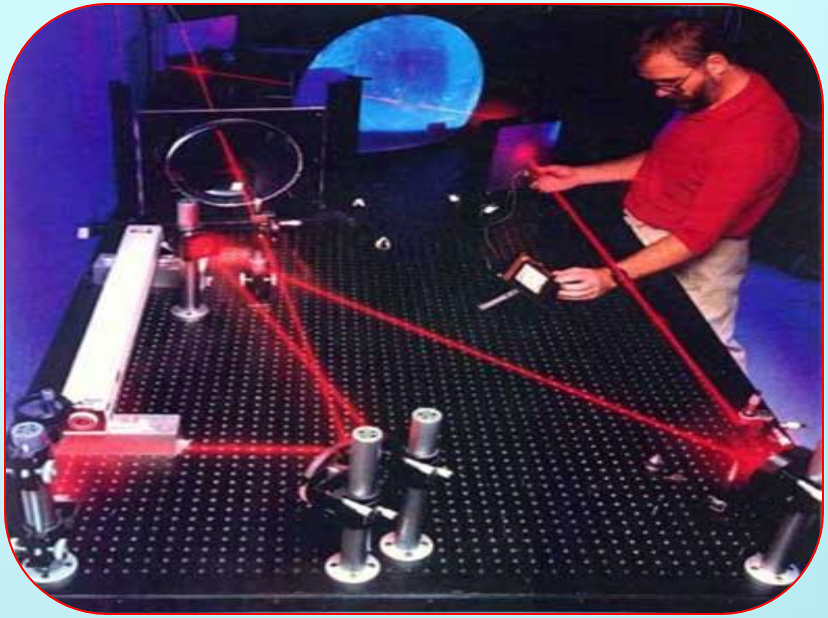
Laser used in isotope separation

- Lasers are used in holography, for recording and reconstructing of a hologram.

- Lasers are used to measure the constantly changing distance between the moon and the earth, by astronomers.

- Lasers are used in plastic industries to unite monomers to form polymers.

- Lasers are used to develop hidden finger prints and to clean delicate pieces of art.



Lasers used in Holography

Finger print scanning using Laser

THANK YOU

NANOTECHNOLOGY

ORGIN OF NANOTECHNOLOGY:

Nanotechnology is the extension of existing science into the nano scale .In recent years nanotechnology has become one of fields in physics, chemistry , biology and engineering and technology.

Through nano technology, we can understand many new things for example , if we arrange carbon atoms in coal then it become diamond. By rearranging atoms in sand, silicon chip can be made.

NANO SCALE

A nano means 10^{-9}. A nanometer (nm) is one thousand millionth of a meter (10^{-9})
i.e . 1 nm = 1/1,000,000,000 m or 10^{-9} m

NANOTECHNOLOGY

Nanotechnology is defined as the design, characterization , production and application of structures and system by controlling shape and size at nanometer scale.

NANO MATERIALS

Nanomaterials are defined as those matererials which have structured with size between 1 to 100nm.

NANO SCIENCE

Nano science is the study of the fundamental principles of molecules and structure having size with in the of range of nano scale.

FACTORS THAT DIFFERENTIATE NANO MATERIALS FROM BULK MATERIALS

They are two factors so that nano properties are changes they are ,

i). Increase in surface to volume ratio

ii).Quantum confinement effect

i).SURFACE TO VOLUME RATIO:

When bulk particles become nano sizes the surface to volume ratio increases .For this let us consider a sphere of radius ‘r’.

$$\frac{\text{Suraface area of sphere}}{\text{Volume of the sphere}} = \frac{4\pi r^2}{(\frac{4}{3})\pi r^3} = \frac{12\pi r^2}{4\pi r^3} = \frac{3}{r}$$

Thus when the radius of the sphere decreases , its surface volume ratio increases.

Let us consider another example,
as shown in figure .

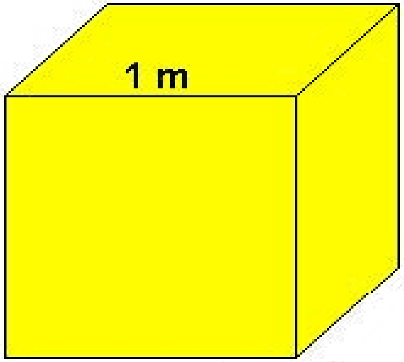
For one cube the surface area= $6m^2$

When I divided into 8 pieces the

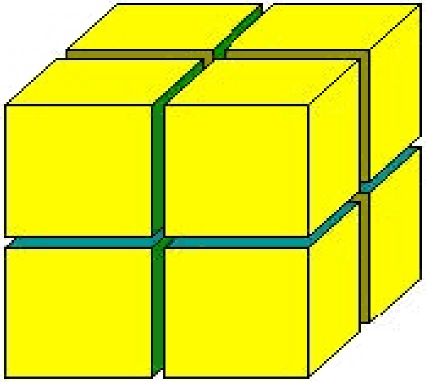
surface area= $12m^2$

When I divided into 8 pieces the surface

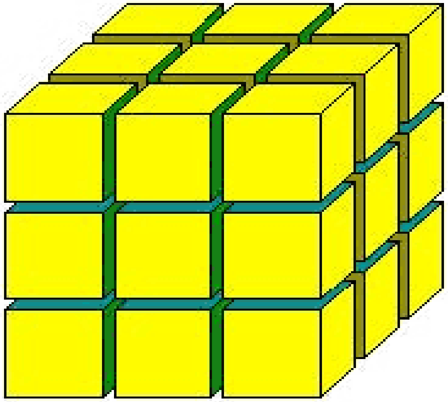
area= $27m^2$



Area = 6 x $1m^2$ = 6 m^2



Area = 6 x $(1/2m)^2$ x 8 = 12 m^2



Area = 6 x $(1/3m)^2$ x 27=18 m^2

Thus we find that when the given volume is divided into smaller pieces, hence the surface particle size decreases .

So we are coming to following conclusions:

- Nano particles are very small in size.
- Very high surface area to volume ratio
- In nano materials a large number of ato present on the surface.

- Its makes materials more chemically reactive which leads to changes of their properties .

ii). QUANTUM CONFINEMENT EFFECT

According to band theory, solid materials have energy bands and isolated atoms possess discrete energy levels.

Nanomaterials are in intermediate to the above two cases

*For nanonmaterials , if the dimensions of potential wells or potential boxes are of the order of the de Broglie wavelength of electrons (mean free path of electrons), then the energy levels of electrons change, and the electron will remain confined to a small region of the material This is called **quantum confinement***

Energy is discrete, not continuous in a quantum system.

The electrons and holes are being squeezed into a dimension that approaches a critical quantum measurement ,known as "exciton Bohr radius"

This effect , can changes the optical, electrical and magnetic behavior of materials of nano particles.

As the materials reduced to nanoscale can suddenly show very different properties compared to what they exhibit on a bulk. For examples,

- Opaque substances become transparent (Copper)
- Different sized nanoparticles scatter different wavelengths of light incident on it and hence, they appear with different colours.
- Inert materials become catalysts (Platinum).
- Stable materials become combustible (Aluminum).
- Insulators become conductors (Si).
- Solids turn into liquids at room temperature Gold)

Observe how the gold colour bulk to nano

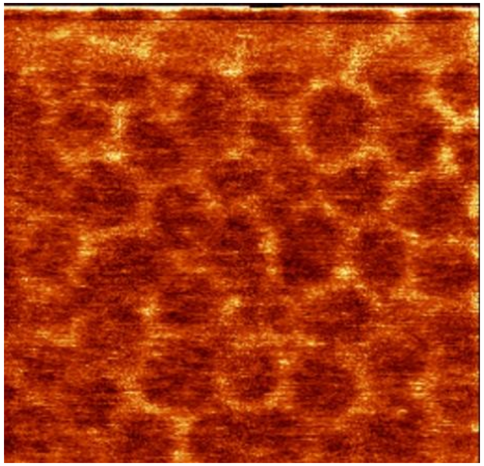
- **Bulk gold**

  appears yellow in colour.

- **Nano sized gold**

  appears red in colour.

The particles are so small that electrons are not free to move about as in bulk gold Because this movement is restricted, the particles react differently with light.



12 nanometer gold clusters of particles look red.

PROPERTIES OF NANO MATERIALS

As the size of the nano materials are very less, so these materials exhibits peculiar physical , chemical ,electronic ,magnetic ,mechanical, and optical properties.

i).Physical

- The particles are very close to each other and hence inter particle spacing is very less in nano materials.
- The melting point decreases with size and at very small sizes the decrease is faster.

ii).Chemical Properties

- Nano particles are very much useful in hydrogen storage devices in metals..
- Nanoparticles tend to be more chemically reactive than their ordinary sized counterparts because they have more surface area.

iii) .Electronic

- *The electrical conductivity and energy band width of some materials change when they pass from bulk phase to nanoparticle phase. For example bulk silicon is an insulator; it becomes a conductor in the nano phase. Nanomaterial semi-conductors such as Ge and Si do not show semi-conducting property.*
- *The energy band in these materials are very narrow and ionization potential is very high.*

iv) . Magnetic properties

- In nano materials a large number of atoms will be present at the surface . These atoms will have less co-ordination number and hence possess local magnetic moment due to a presence of large magnetic moment these nano materials exhibits spontaneous magnetization at smaller sizes.

v).Mechanical Properties

- because of the nano size , many of their mechanical properties such as hardness, toughness ,elastic modulus fatigue strength are modified.
- They exhibit super plastic behavior.

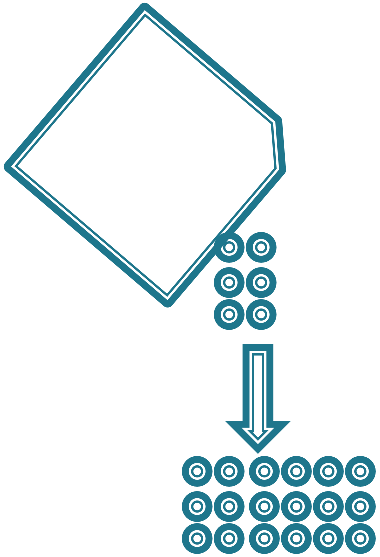
vi). Optical properties

- Depending on the particle size the colors of the particles changes as we seen incase of gold.

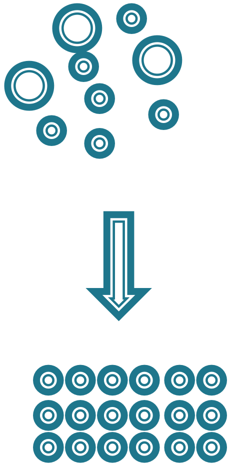
FABRICATION OF NANO -MATERILAS

Nano materials can be fabricated in any two ways ,they are,

(i). Top down approach, in which bulk materials are reduced into nano sizes as shown in figure



(ii).Bottom up approach , in which nano materials are made by building atom by atom as shown in below figure,



VARIOUS METHODS ADOPTED FOR THE FABRICATION OF NANOMATERIALS THEY ARE,

(i). Plasma-arching

(ii). Chemical Vapour Deposition

(iii). Sol-Gel method

(iv). Electro-Deposition

(v). Mechanical crushing (or) Ball milling

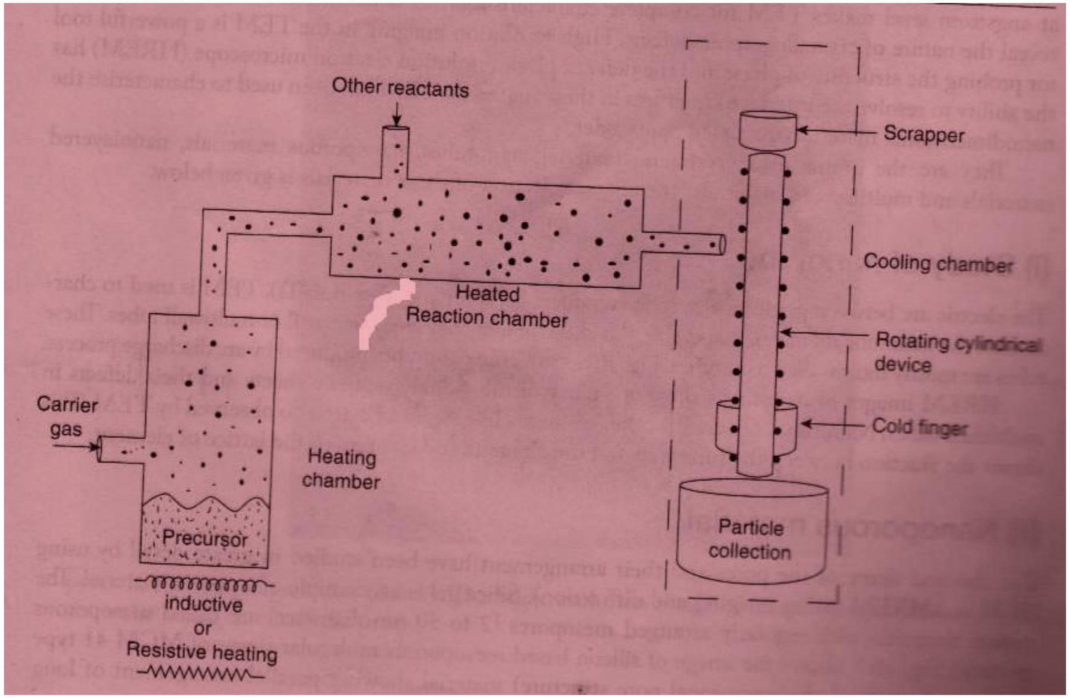
(vi). Laser synthesis

(vii). Inert gas condensation etc.

Using above methods it is possible to fabricate nano-materials in the form of nano-particles, nano-powders , nano-films , nano-crystals, nano-wires, nano-tubes, nano-dots etc.

FABRICATION OF NANOMATERIALS

1.CHEMICAL VAPOUR DEPOSITION METHOD(CVD)



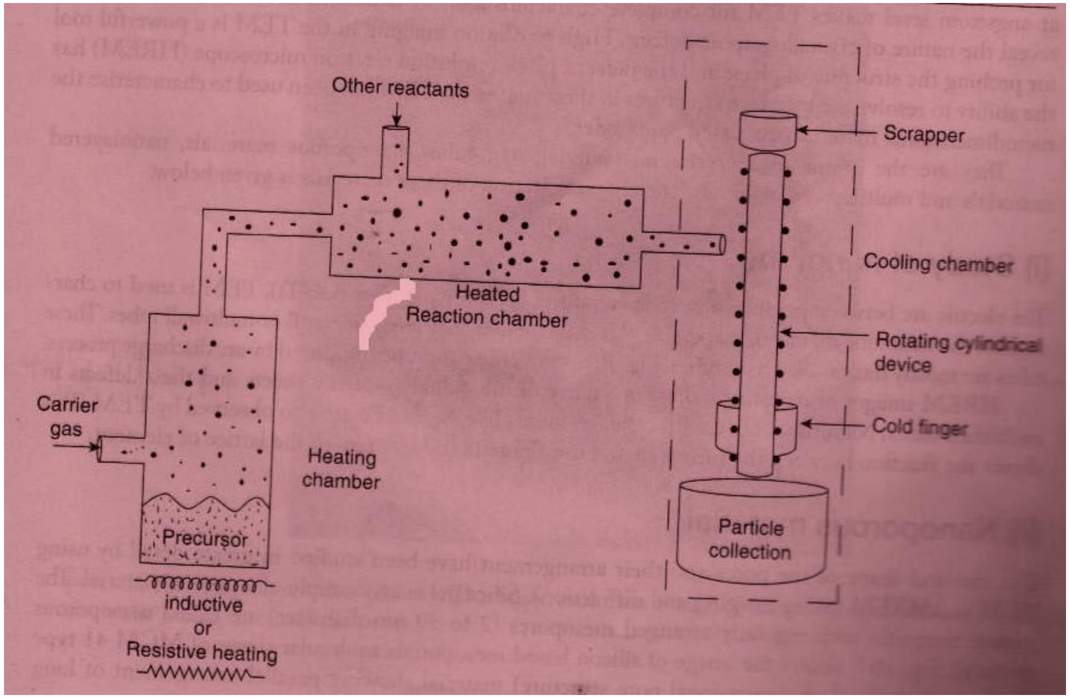
1).This method is used for prepare nano powders and this method is top down fabrication method.

2).As shown in figure the apparatus consists of
(a) Heating chamber
(b) Reaction chamber
(c) Cooling chamber

3).In this method the material is heated to form a gas and is allowed to deposit on a solid surface.

4).A metal organic precursor is taken in to heating chamber and heated to high temperature so that it can be melted and evaporated.

5).Inert gas like He or Ne can be introduced into the heating chamber this acts as a carrier gas and carries the precursor vapour to reaction chamber. Inside reaction chamber other Reactants are added



6). Some other reactants are introduced into reaction chamber to control reaction rate and the hot precursor atoms/Molecules collide with the cold reactance atoms/molecules through nucleation and form small clusters (nano particles).

7). Then the clusters from reaction chamber is passed into cooling chamber. Liquid nitrogen is used For cooling this chamber.

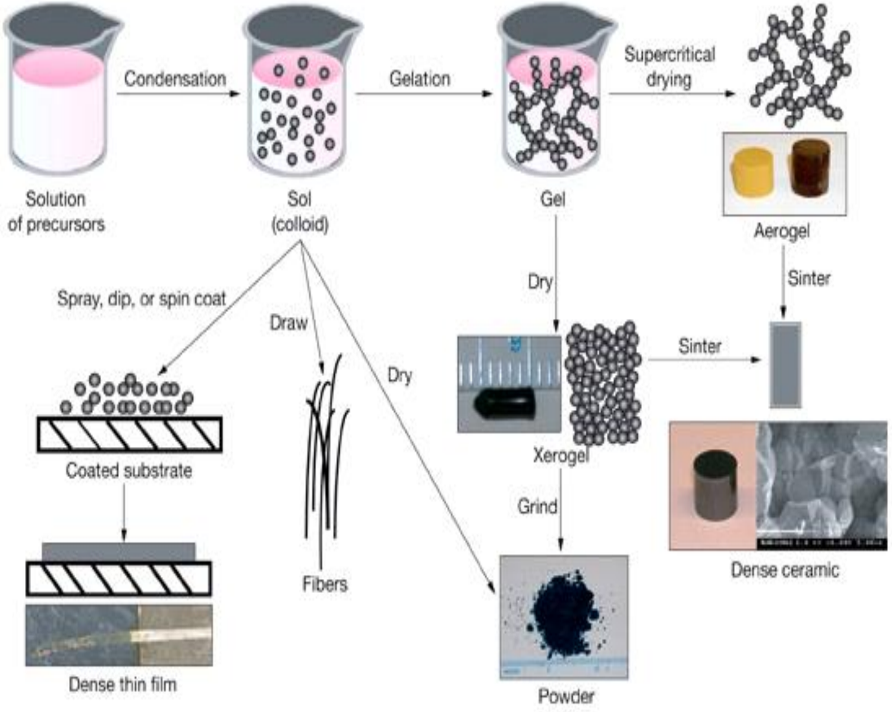
8). The cooling chamber contains a rotating cylindrical device on a cold finger as shown in figure .The nano particles(clusters) are allowed to condense on the rotating cylindrical device and scraper is used to collecting the nano particles.

2.SOL-GEL METHOD

- This method is Bottom up fabrication method

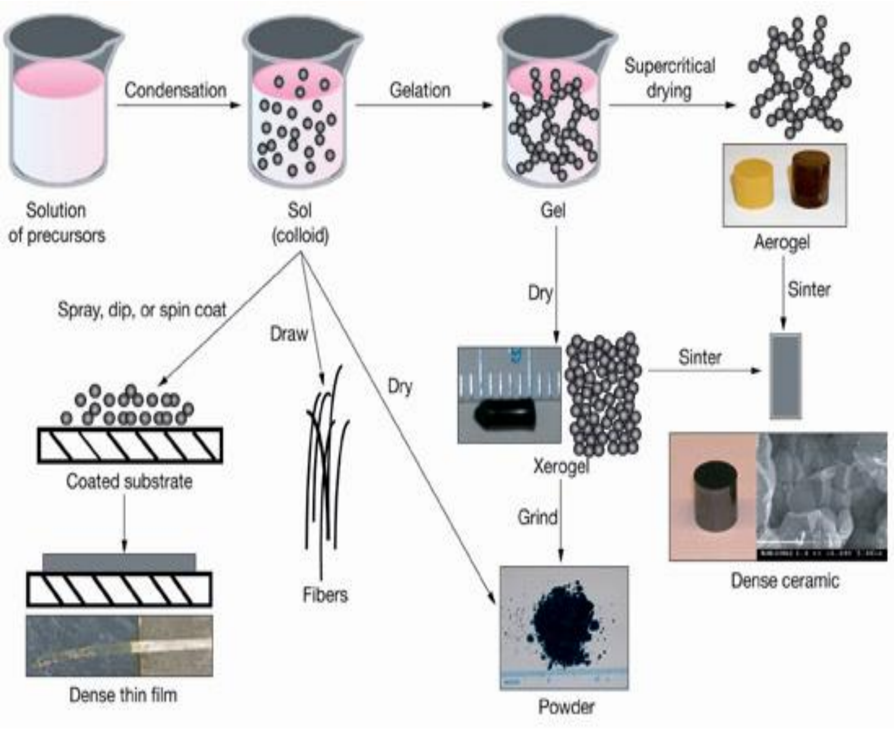
- *In solutions, nanosized molecules are dispersed randomly whereas in colloids, the molecules have diameters in the range of 20μm-100μm and are suspended in the solvent. So, the colloid appears cloudy.*
- *A colloid that is suspended in a liquid is called a **Sol**. The gelation of the sol in the liquid to form a network is called **gel**. Gel is the suspension that keeps its shape.*

- *Sol-gel formation occurs in different stages*
  - *a).Hydrolysis*
  - *b).Condensation and polymerization of monomers to form particles.*
  - *c). Agglomeration of particles.*



This is followed by the formation of networks which extends throughout the liquid medium and forms a gel.

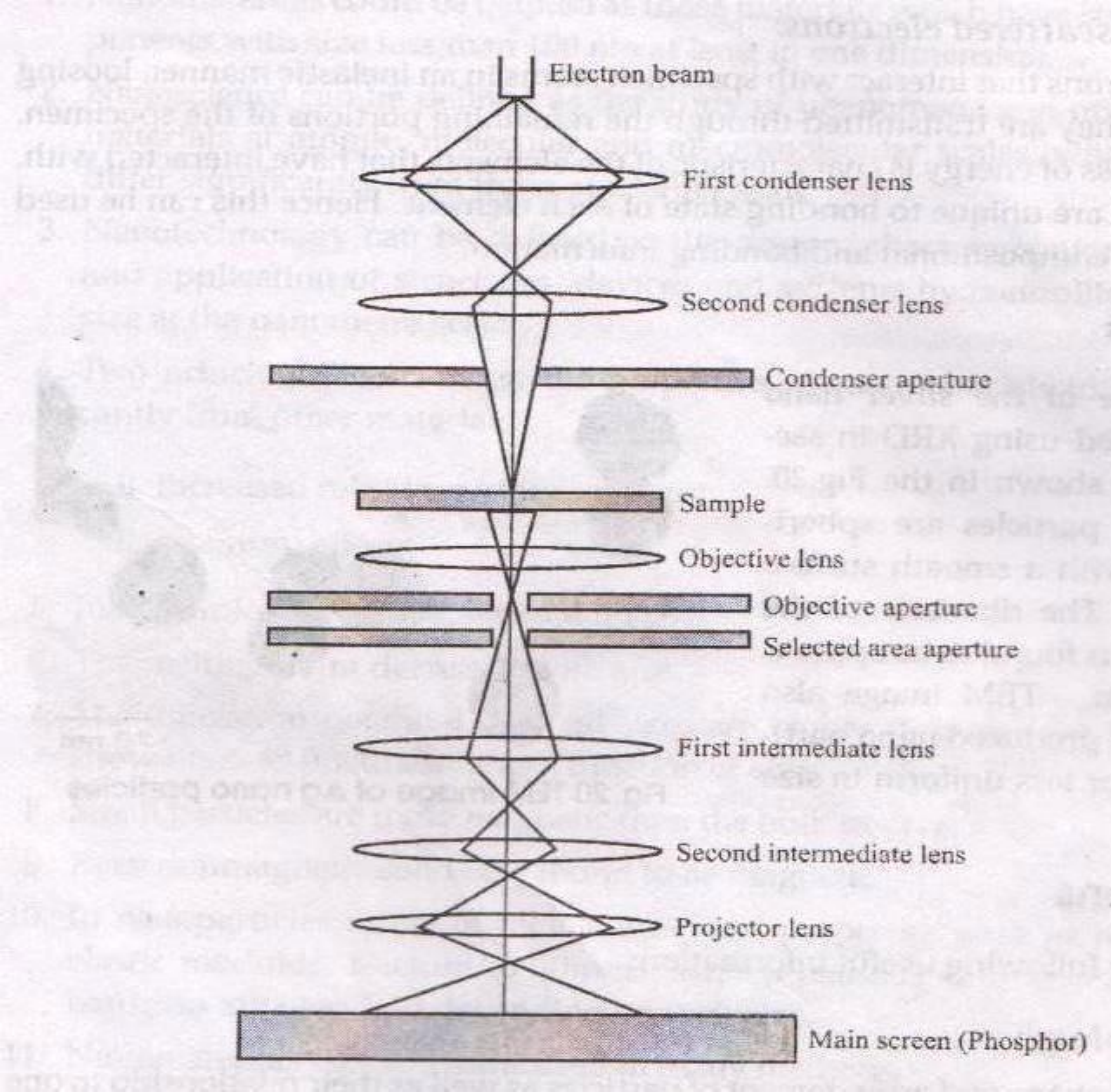
- *Using sol-gel method, silica gels, zirconia and yttrium gels and aluminosilicate gels are formed.*
- *Nanostructured surfaces are formed using the sol –gel method.*



Characterisation of Nanomatereials by TEM

Transmission electron microscope (TEM) is an instrument for complete characterisation of nanoscale microstructure materials or complete study of nano particles.

A schematic representation TEM is shown in figure . Each part is labelled and their functions are discussed below.



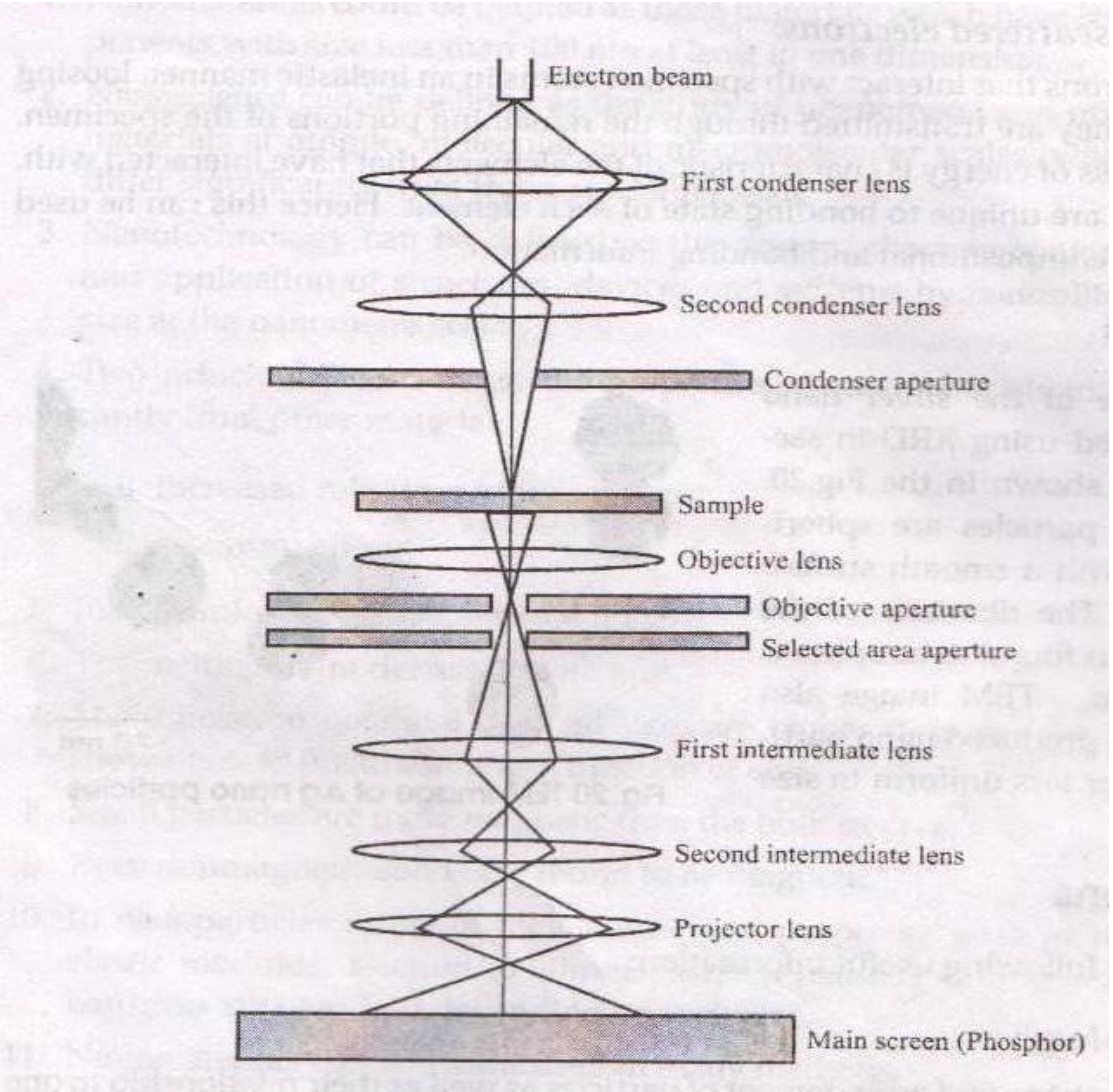
TRANSITION ELECTRON MICROSCOPE

1).The electron gun produces a stream of monochromatic electrons.

2).This stream is focused to a small coherent beam by the first and second condenser lenses.

3).The condenser aperture knocks off high angle electrons

TRANSITION ELECTRON MICROSCOPE

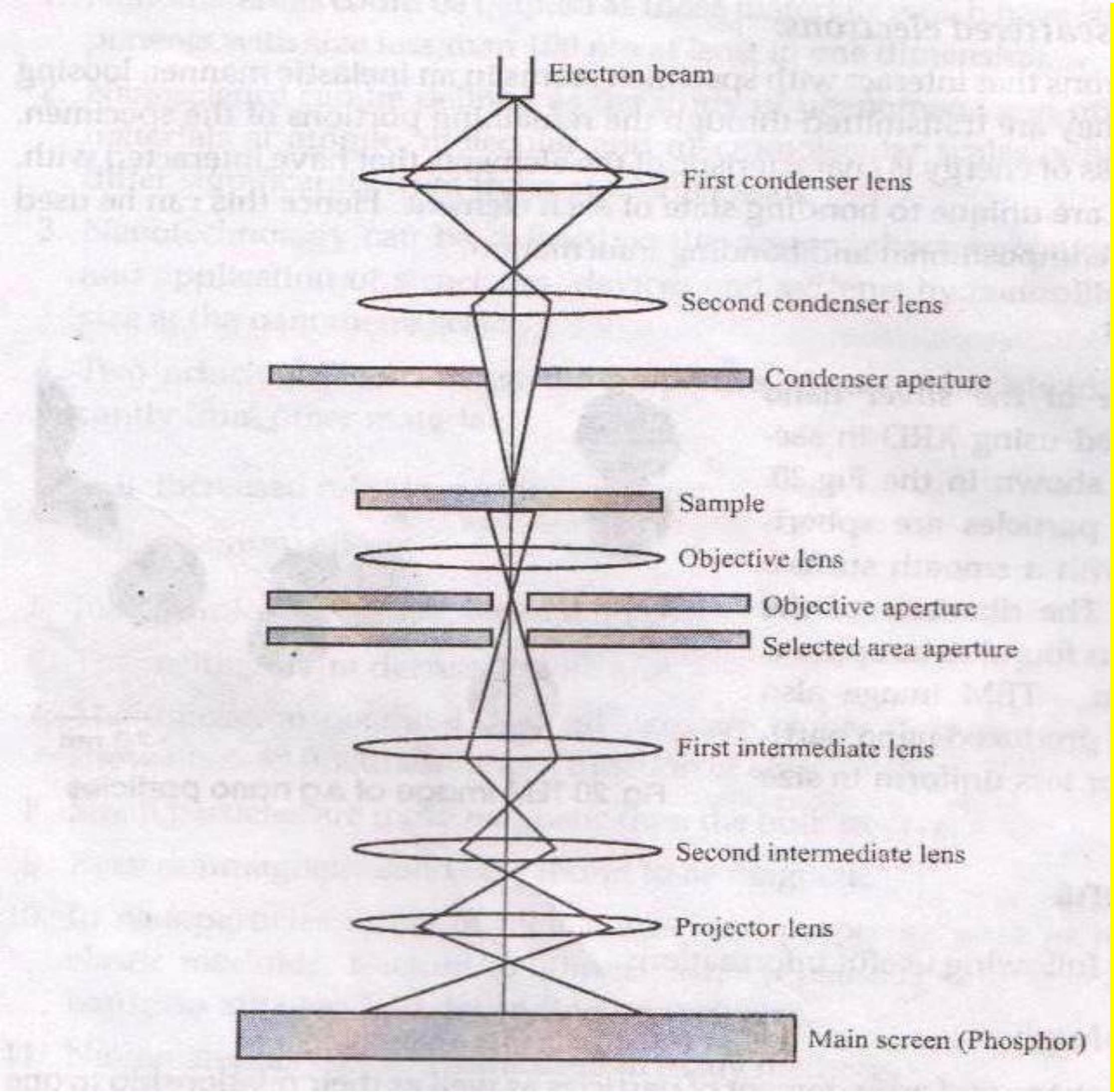


4)The beam strikes the specimen.

5).The transmitted portion is focused by the objective lens into an image.

6).Objective aperture enhances the contract by blocking out high angle diffracted electrons.
7).Selected area aperture enables to examine the periodic diffraction of electrons by an ordered of atoms in the sample.

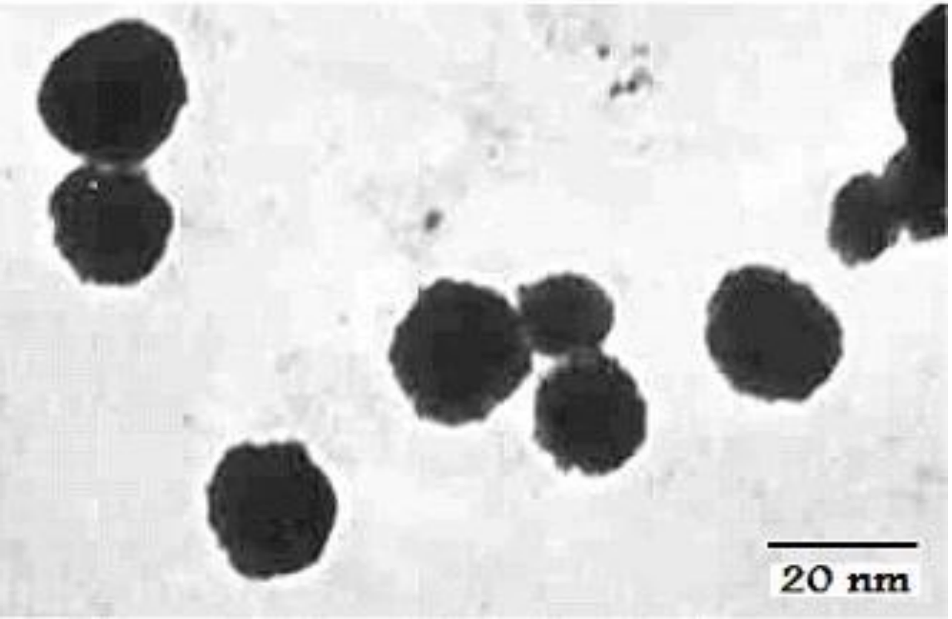
8).Intermediate and projector lenses enlarge the image.



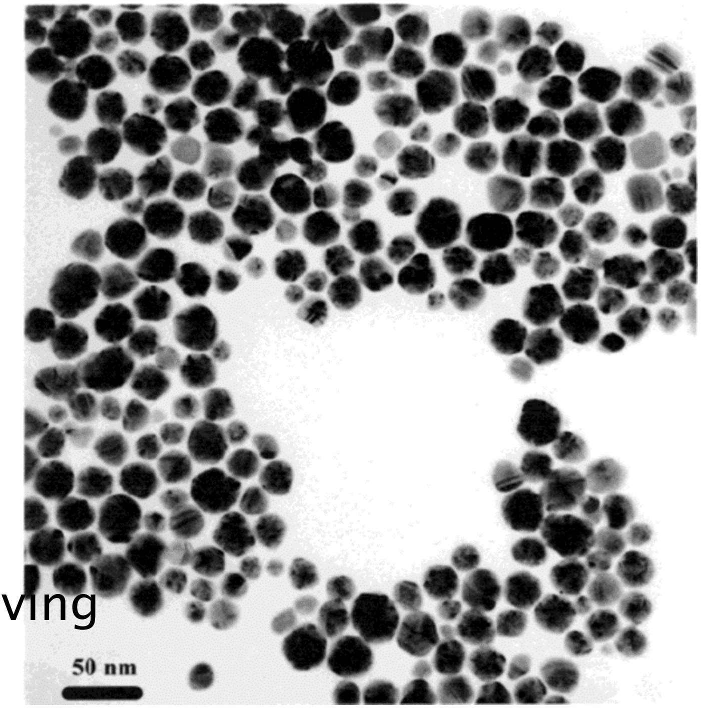
9).The beam strikes the phosphor screen and image is formed on the screen. The darker areas of the image represent thicker sample areas since these areas transmit lesser electrons. The brighter areas of the image represent thinner sample areas since these areas transmit more electrons.

TRANSITION ELECTRON MICROSCOPE

Case Study



A TEM image of the prepared silver nano particles is shown in the figure. The Ag nano particles are spherical in shape with a smooth surface morphology. The diameter of the nano particles is found to be approximately 16 nm.



TEM micrograph of gold nanoparticles having
Size less than 25 nm

Characterization of Nanomaterials using X-ray Diffraction (XRD)

The structure of prepared silver nanoparticles has been investigated by X-ray diffraction (XRD) analysis.

Average particle size **(D)** has been estimated by using Debye-Scherrer formula

$$D = \frac{K\lambda}{\beta \cos\theta}$$

Debye-Scherrer formula

λ = wavelength of X-rays used

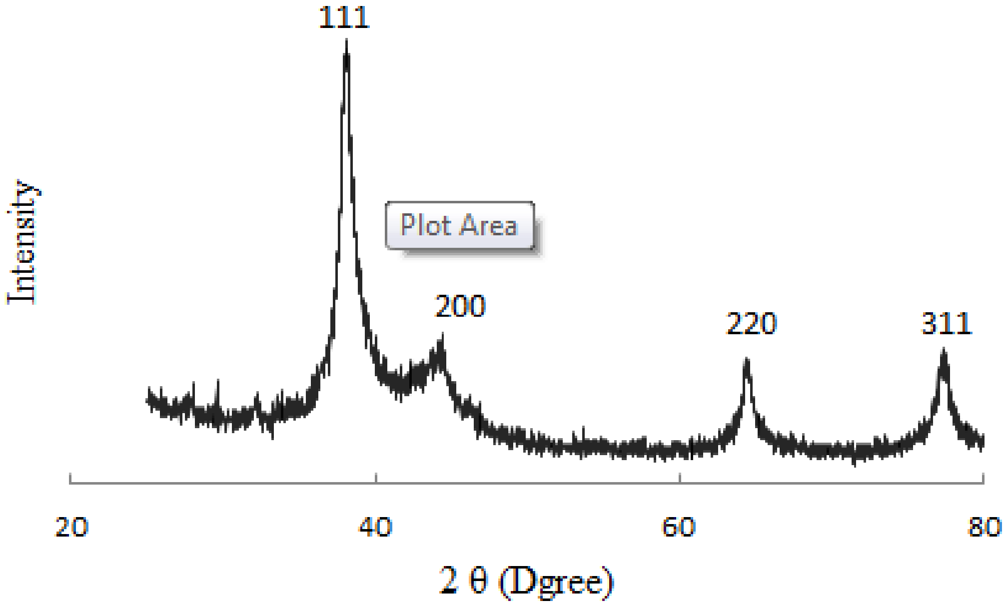
β = the FWHM of the XRD peak

Ө = Angle of Diffraction

K = constant which depends on Crystal

Case Study

It was found that the average
size from XRD data and using
Debye-Scherer equation
was 20 ± 2.8 nm.



XRD pattern of Ag Nanoparticles synthesized by mulberry leaves extract

TEM gives the information about,

1) Morphology: *The size, Shape and arrangement of particles as well as their relationship to one another on the scale of atomic diameters.*

2) Crystallographic information: *The arrangement of atoms in the specimen and their degree of order, detection of atomic scale defects, a few nanometers in diameter.*

3) Compositional information: *The elements and compounds, the sample is composed of and their relative ratios.*

APPLICATIONS OF NANO TECHNOLOGY

Though nano particle are very small ,they the important materials to built the future world. They have applications almost in all engineering fields as follows few of applications are given below,

1). Since they are stronger ,lighter so they are used to make hard metals.

2). Cutting tools made of nanocrystallines materials.

3). It is possible to produce unusual colours paints using nano particles.

4).Nano sized titanium dioxide and zinc oxide are currently used in sun screens.

5). These materials are used to store the information in smaller chips.

6). Nano-materials are used to make CD’s and semiconductor laser.

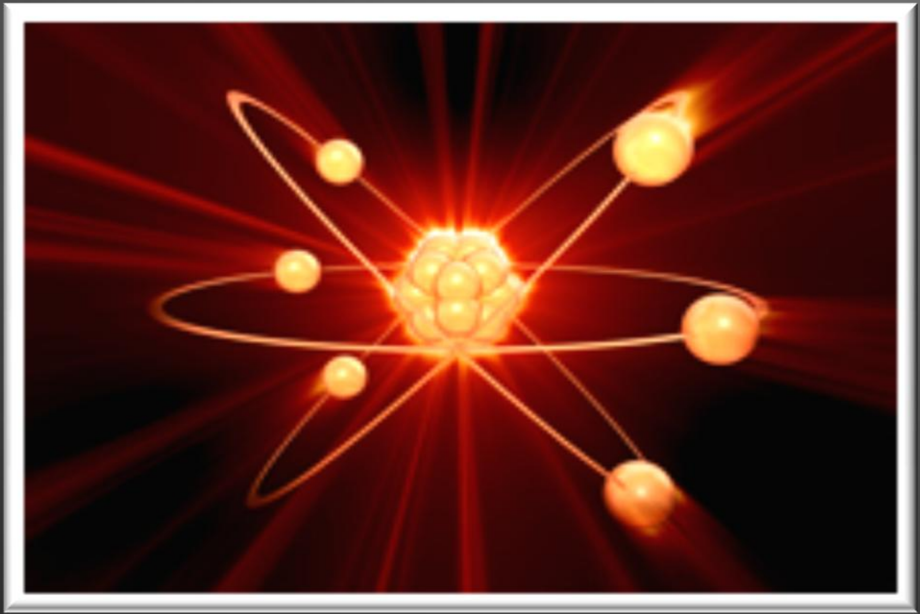
7).They are used in mobiles ,laptops etc.

8).Nanotechnology includes fabrication of nano wires used in semiconductors.

9).Recently nano-robots were designed, which were used to remove the damaged cancer cells and also modify the neuron network in human body.

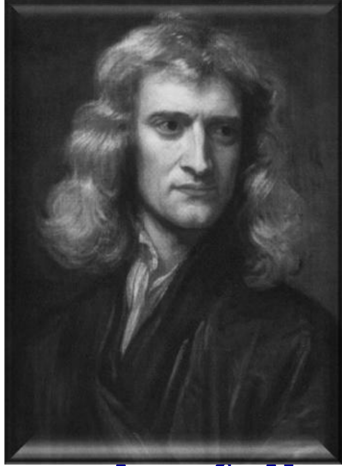
10)They are used in hydrogen storage devices.

QUANTUM MECHANICS



"If you can't explain it simply, you don't understand it well enough " ---- ***Albert Einstein***

Classical Mechanics :



Newton

This is one of the oldest and largest subjects in science, technology and engineering. which deals with the motion of *macroscopic* objects such as space crafts, galaxies, stars, objects on the earth, etc. But it fails to explain the motion of *microscopic* particles.

Quantum Mechanics :

This arises due to the failure of classical mechanics, in explaining motion of microscopic particles such as electrons, protons, neutrons, etc. which can be possible by using quantum mechanics.

WAVE:

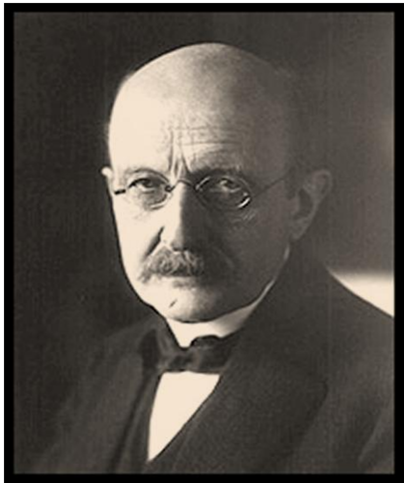
A wave is nothing but a disturbance caused In a medium and it is specified by Its *frequency, wavelength, phase, amplitude and intensity.*

Thomas Young---

PARTICLE:

A particle is specified by means of its mass-m, velocity-v, momentum-p, and energy-E.

Max Planck---



de Broglie hypothesis:

In 1924 the scientist named *de Broglie* introduced the concept of *dual nature* of matter Just like radiation.

The material particles like *electrons*, *protons* and *neutrons* ,when they are in motion behaves like waves called *matter waves* or *de Broglie waves*.

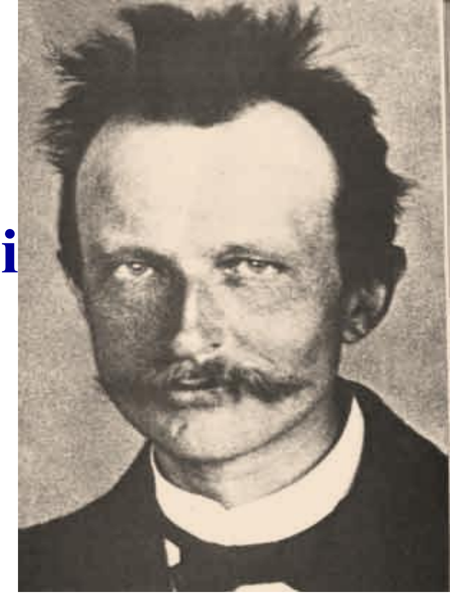
He derived an expression for the wavelength of matter waves on the analogy of radiation.

According to *Planck's radiation law*

$$E = h\upsilon$$

$$E = h\frac{c}{\lambda} ------(1)$$

Where 'c' is a velocity of li and 'λ'is wave length.



According to *Einstein mass-energy relation*

Planck

$$E = mc^2 ------(2),\ from\ (1)\ \&\ (2)$$

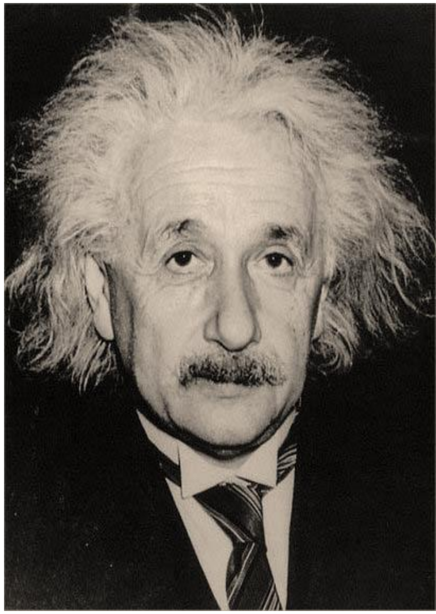
$$mc^2 = h\frac{c}{\lambda}$$

$$\lambda = \frac{h}{mc}$$

$$\lambda = \frac{h}{p}$$

Where p is momentum of a photon.

Einstein



The above relation is called *de Broglie's* relation or matter wave equation. This equation is applicable to all atomic particles.

If E is kinetic energy of a particle,

$$E = \frac{1}{2}mv^2$$

$$E = \frac{p^2}{2m}$$

$$p = \sqrt{2mE}$$

Hence the *de Broglie's* wave length,

$$\lambda = \frac{h}{\sqrt{2mE}}$$

De Broglie wavelength associated with electrons:

Let us consider the case of an electron of mass m ,and charge ‘ e ‘being accelerated by a potential V volts.

If v is the velocity attained by the electron due to acceleration

$$\boxed{\begin{aligned}\frac{1}{2}m\,v^2 &= eV\\ \therefore v &= \sqrt{\frac{2eV}{m}}\end{aligned}}$$

The de Broglie wavelength,

λ =h/mv and

$$\boxed{\begin{aligned}\lambda &= \frac{h}{m\sqrt{\frac{2eV}{m}}}\\ \lambda &= \frac{12.26}{\sqrt{V}}A^0\end{aligned}}$$

Characteristics of matter waves:

1. Lighter the particle, greater is the wavelength associated with it.

2. Lesser the velocity of the particle, longer the wavelength associated with it.

3. For $v = 0$, $\lambda=\infty$. This means that only with moving particle matter wave is associated.

4. Whether the particle is charged or not, matter wave is associated with it. This reveals that these waves are not electromagnetic but a new kind of waves .

5. It can be proved that the matter waves travel faster than light.

We know that

$$E = h\upsilon \quad and \quad E = mc^2$$

$$h\upsilon = mc^2 \quad and \quad \upsilon = \frac{mc^2}{h}$$

The wave velocity (ω) is given by

$$w = \upsilon\lambda = (\frac{mc^2}{h})\lambda$$

$$but \quad \lambda = \frac{h}{mv}$$

$$\therefore w = (\frac{mc^2}{h})\frac{h}{mv} = \frac{c^2}{v}$$

As the particle velocity v cannot exceed velocity of light c, ω is greater than velocity of light.

6. No single phenomenon exhibits both particle nature and wave nature simultaneously.

Heisenberg's uncertainty principle:

It is impossible to specify precisely and simultaneously the values of both members of particular pair of physical variables that describe the behavior of an atomic system.

This principle states that the product of uncertainties in determining the both position and momentum of particle is approximately equal to h / 4Π.

i.e. $\Delta x \, \Delta p \geq h / 4\Pi$

where Δx is the uncertainty in determine the position and Δp is the uncertainty in determining momentum.

The relation shows that it is impossible to determine simultaneously both the position and momentum of the particle accurately.

The relation is universal and holds for all canonically conjugate physical quantities like angular momentum- angle and time-energy .

$$\Delta \theta \, \Delta J \geq h / 4\Pi , \text{ and}$$

$$\Delta t \, \Delta E \geq h / 4\Pi$$

$\Psi\Psi^*$ or $|\Psi|^2$ is the probability density function. $\Psi\Psi^*\,dx\,dy\,dz$ gives the probability of finding the electron in the region of space between x and x + dx, y and y + dy, z and z + dz.

$$\int_{-\infty}^{+\infty} \psi\psi^* dxdydz = 1$$

(or)

$$\int_{-\infty}^{+\infty} |\psi|^2 dxdydz = 1$$

The above relation shows that's a normalization condition of particle.

DAVISSON & GERMER'S EXPERMENT:

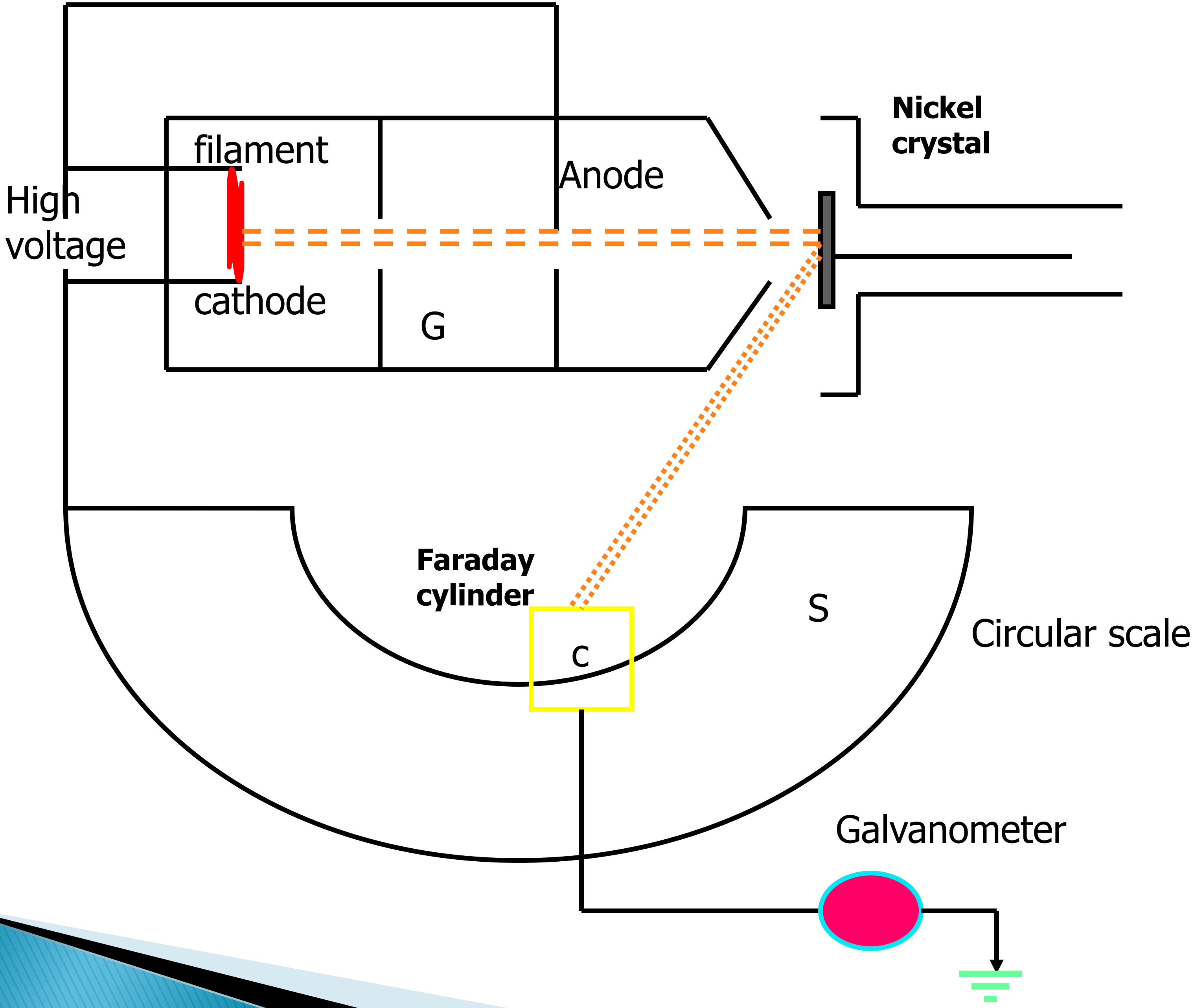
Davisson **and** ***Germer*** **first detected electron waves in *1927*.**

They have also measured *de Broglie* wave lengths of *slow electrons* by using diffraction methods.

Principle:

Based on the concept of wave nature of matter moving electrons behave like waves.

Hence accelerated electron beam can be used for diffraction studies in crystals.


Nickel crystal
filament
Anode
High voltage
cathode
G
Faraday cylinder
S
c
Circular scale
Galvanometer

Experimental arrangement:

The electron gun ‘G’ produces a fine beam of electrons.

It consists of a heated filament ‘F’,which emits electrons due to thermo ionic emission.

The accelerated electron beam of electrons are incident on a nickel plate, called target ‘T’.

The target crystal can be rotated about an axis parallel to the direction of incident electron beam.

The distribution of electrons is measured by using a detector called faraday cylinder ‘C’ and which is moving along a graduated circular scale ‘S’.

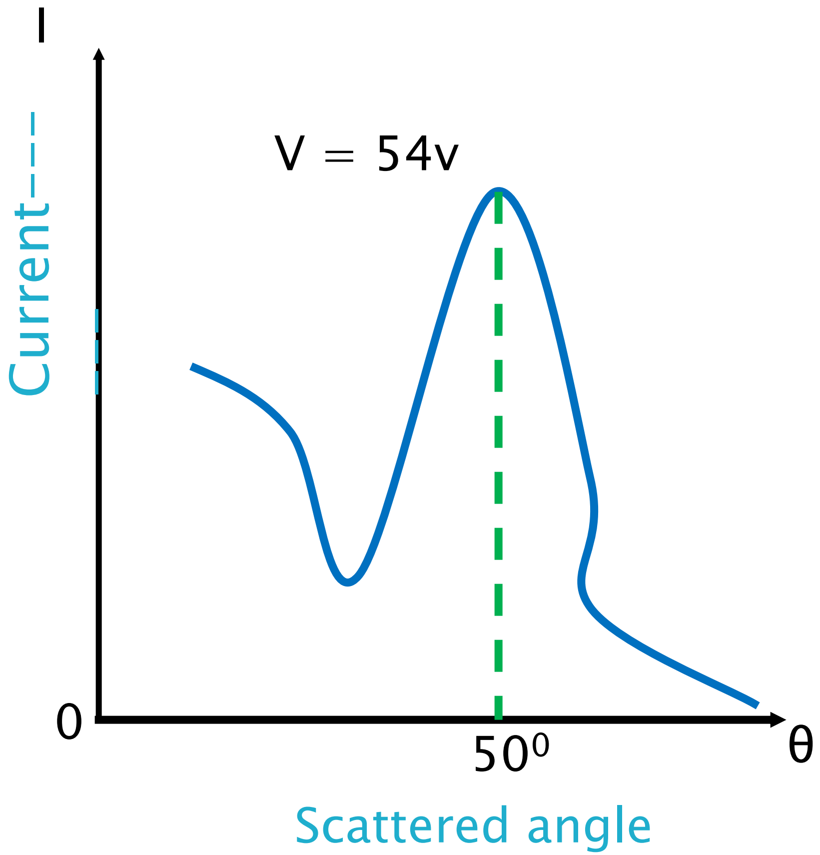
A sensitive galvanometer connected to the detector.

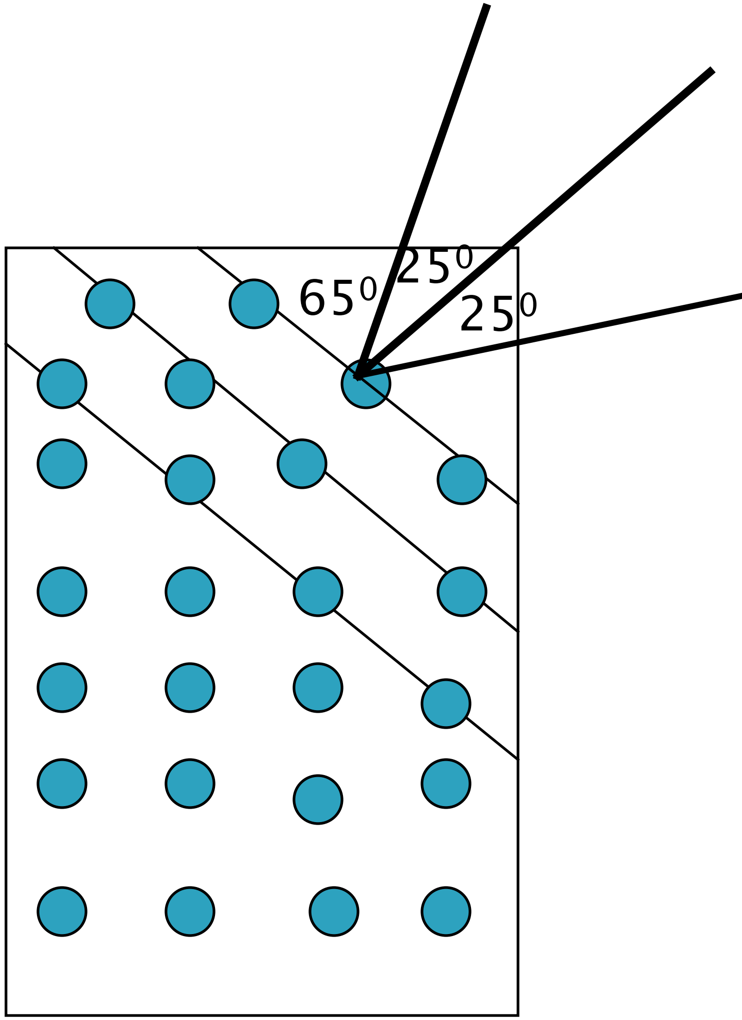
Results:

When the electron beam accelerated by 54 volts was directed to strike the nickel crystal, a sharp maximum in the electron distribution occurred at an angle of 50^0 with the incident beam.

For that incident beam the diffracted angle becomes 65^0

For a nickel crystal the inter planer separation , d=0.091nm.


I
Current---
V = 54v
0
50^0
θ
Scattered angle


65^0
25^0
25^0

According to Bragg's law

$$2d\sin\theta = n\lambda$$

$$2 \times 0.091 \times \sin 65^0 = n\lambda$$

$$\lambda = 0.165\text{nm.}$$

For a 54 volts , the de Broglie wave length associated with the electron is given by

$$\lambda = 12.26 / \sqrt{V}$$

$$= 12.26 / \sqrt{54}$$

$$= 0.166\text{nm.}$$

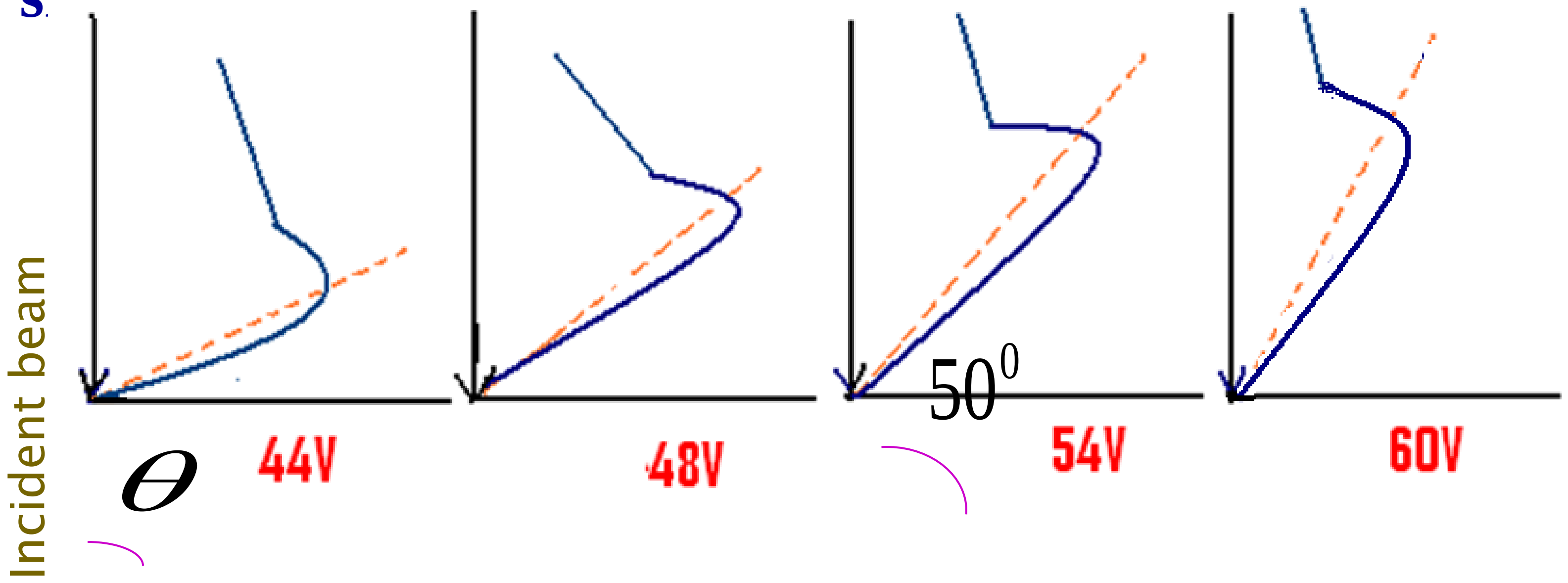
This is in excellent agreement with the experimental value.

The Davison- Germer experiment provides a direct verification of de Broglie hypothesis of the wave nature of moving particle.

e

θ s

s



Schrödinger time independent wave equation:

Schrödinger wave equation is a basic principle of a fundamental quantum mechanics.

This equation arrives at the equation stating with de Broglie's idea of matter wave.

According to de Broglie, a particle of mass m and moving with velocity v has a wavelength λ.

$$\boxed{\begin{aligned}\lambda &= \frac{h}{p}\\ \lambda &= \frac{h}{mv}\;..........(1)\end{aligned}}$$

According to classical physics, the displacement for a moving wave along x-direction is given by

$$\boxed{\psi(x) = A\sin(\frac{2\pi}{\lambda}\times x) --- (2)}$$

Where 'A' is amplitude, 'x' is position co-ordinate and 'λ' is wave length.

The displacement of debroglie wave associated with a moving wave along x-direction is given by,

$$\boxed{\psi(r,t) = A\sin(\frac{2\pi}{\lambda}\times x) --- (3)}$$

Periodic changes in Ψ are responsible for the wave nature of a moving particle, from (3)

$$\boxed{\frac{d(\psi)}{dx} = \frac{d}{dx}[A\sin\frac{2\pi}{\lambda}.x]}$$

$$\boxed{\frac{d\psi}{dx} = \frac{2\pi}{\lambda}A\cos\frac{2\pi}{\lambda}.x}$$

$$\boxed{\frac{d^2\psi}{dx^2} = -[\frac{2\pi}{\lambda}]^2 A\sin(\frac{2\pi}{\lambda}.x)}$$

$$\frac{d^2\psi}{dx^2} = -\frac{4\pi^2}{\lambda^2} A\sin[\frac{2\pi}{\lambda}.x]$$

$$\frac{d^2\psi}{dx^2} = -\frac{4\pi^2}{\lambda^2}\psi$$

$$\frac{1}{\lambda^2} = -\frac{1}{4\pi^2\psi}\frac{d^2\psi}{dx^2}$$

$$\boxed{\frac{h^2}{2m}\left[-\frac{1}{4\pi^2\psi}\frac{d^2\psi}{dx^2}\right]=[E-V]}$$

$$\boxed{\frac{-h^2}{8\pi^2 m\psi}\frac{d^2\psi}{dx^2}=[E-V]}$$

$$\boxed{\frac{d^2\psi}{dx^2}=-\frac{8\pi^2 m}{h^2}[E-V]\psi}$$

$$\boxed{\frac{d^2\psi}{dx^2}+\frac{8\pi^2 m}{h^2}[E-V]\psi=0}$$

This is Schrödinger time independent wave equation in one dimension.

3-dimensionally it becomes…..

$$\boxed{\frac{\partial^2\psi}{\partial x^2}+\frac{\partial^2\psi}{\partial y^2}+\frac{\partial^2\psi}{\partial z^2}+\frac{8\pi^2 m}{h^2}[E-V]\psi=0}$$

(or)

$$\boxed{\frac{\partial^2\psi}{\partial x^2}+\frac{\partial^2\psi}{\partial y^2}+\frac{\partial^2\psi}{\partial z^2}+\frac{2m}{\hbar^2}[E-V]\psi=0}$$

Physical significance of the wave function:

The wave function Ψ has no direct physical meaning. it is a complex quantity representing the variation of a matter wave.

The wave function Ψ(r, t) describes the position of a particle with respect to time.

It can be considered as probability amplitude since it is used to find the location of the particle.

If is total energy of the system, $E = K.E + P.E$ ---------(4)

According to de Broglie's principle, $\lambda = h / p$

(or) $p = h / \lambda$

And K.E $= \frac{1}{2} mv^2$

K.E $= p^2 / 2m$

(or) K.E $= h^2/2m\lambda$

The total energy is given by

$$E = P.E + K.E$$

$$E = V + \frac{h^2}{2m\lambda^2}$$

$$\therefore (E - V) = \frac{h^2}{2m\lambda^2} \text{..........}(5)$$

Where V is potential energy

SEMICONDUCTOR PHYSICS

Introduction

- Semiconductors are the materials whose conductivity (or resistivity) values lie between that of insulators and conductors.

- There is a large gap between valance band and conduction band of an insulator where as both the bands are partially overlapped in conductors at room temperature. The gap between both the bands of a semiconductor is small.

- The electrical conductivity of a conductor decreases with increase of temperature. But, the electrical conductivity of a semiconductor increases with increase of temperature.

- The semiconductor in its pure form (with no impurities) is called intrinsic semiconductor or pure semiconductor.

- Germanium and silicon are the best examples of Intrinsic semi conductors.

- In a pure silicon or germanium crystal, each atom is surrounded by four identical atoms. Each atom possesses four valence electrons and forms covalent bonds with its four neighboring atoms to attain closed shell configuration.

- At zero Kelvin, there are no electrons in the conduction band and hence electrical conductivity of pure semiconductor is zero.

- As the temperature increases, covalent bonds break, electrons become free to conduct electricity.

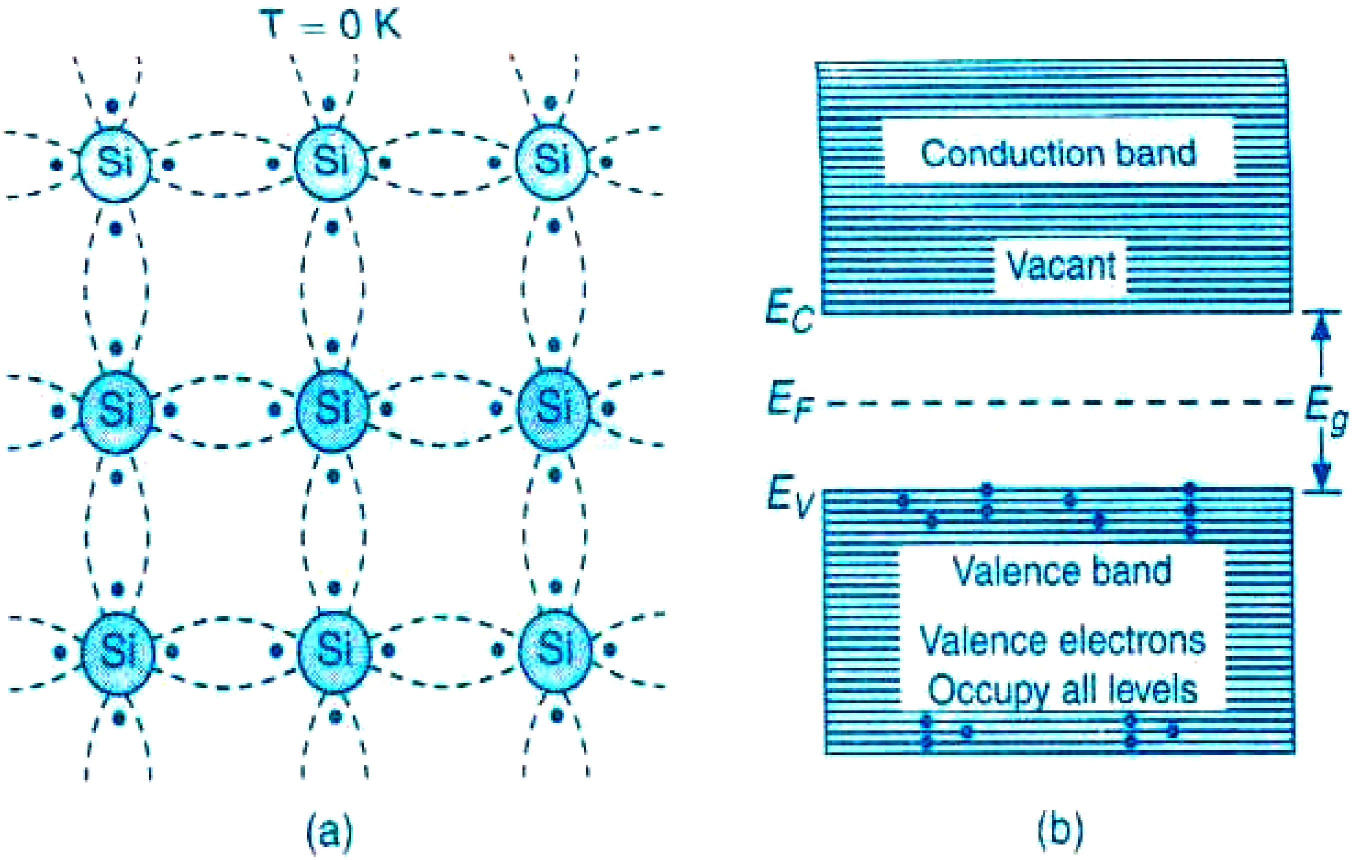
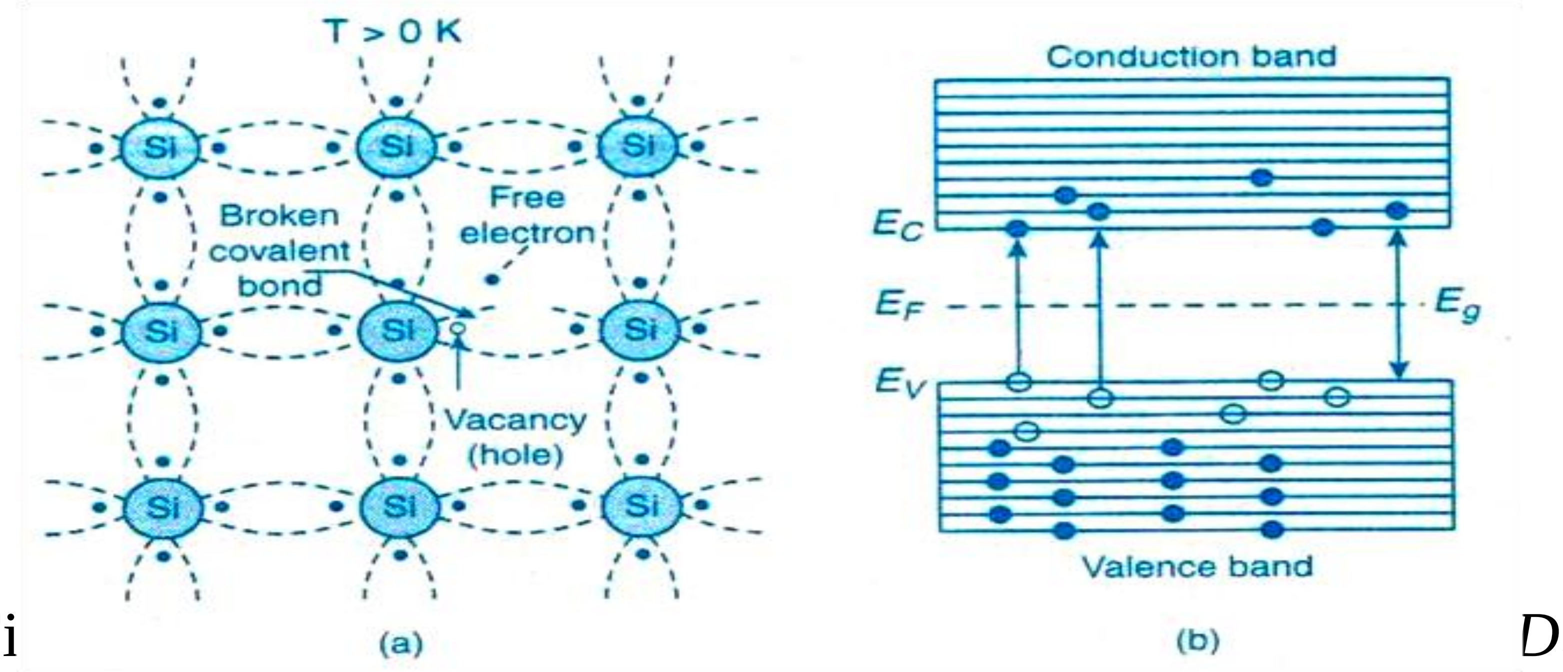


Figure 1. *Intrinsic silicon crystal at T =0K (a) 2-D representation of silicon crystal and b) Energy band diagram of intrinsic semiconductor*

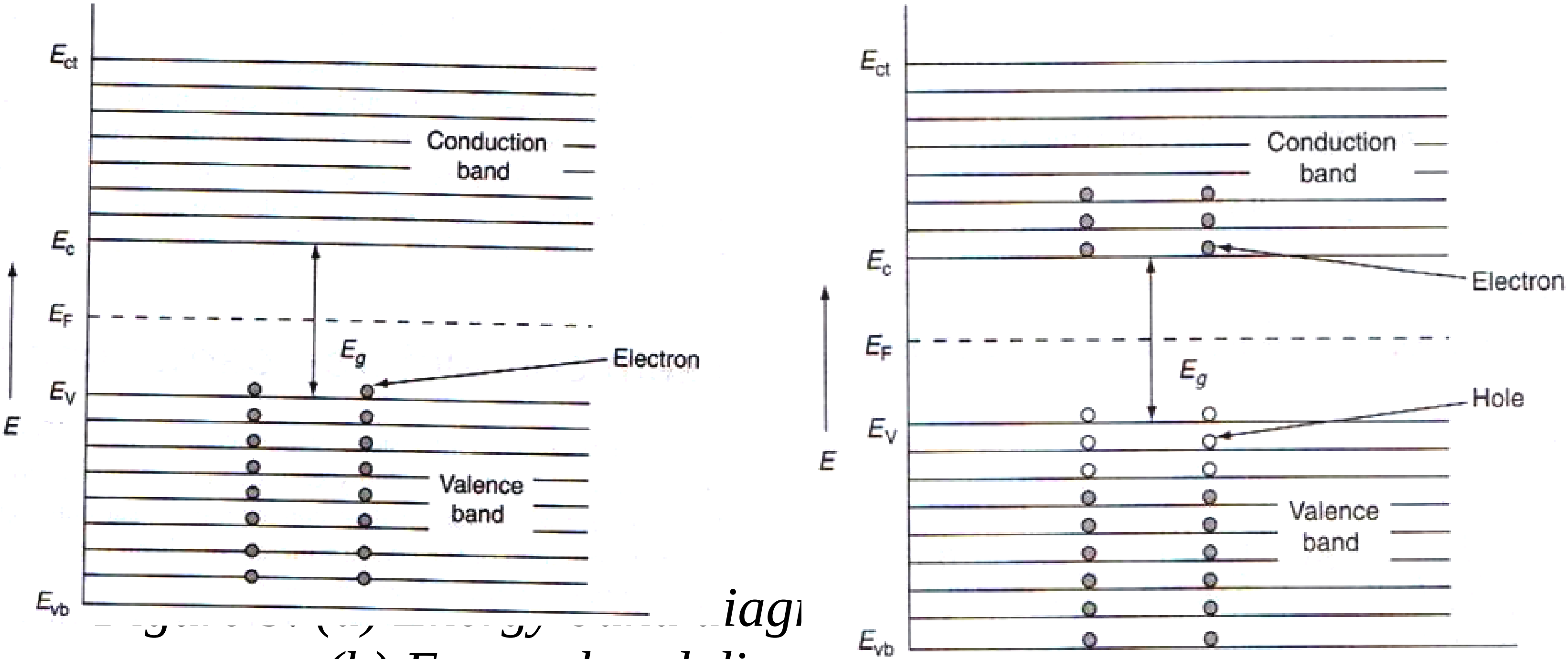
- As the covalent bonds are broken, electrons move to conduction band, leaving behind holes in the valence band.

- Therefore, the number of electrons in the conduction band of a semiconductor is **equal to** the number of holes in the valence band.



Fi *Due to thermal energy breaking of Covalent bonds take place (b) Energy band representation*

Energy level diagram of intrinsic semiconductor



Fig

iagr

(b) Energy band diagram of silicon at T > 0K

Electron concentration in the conduction band of an intrinsic semiconductor

The expression for Electron concentration in the conduction band of an intrinsic semiconductor is given by

$$n = 2\left[\frac{2\pi m_e{}^{*}kT}{h^2}\right]^{3/2}\exp\left[\frac{E_F - E_C}{kT}\right] \qquad \rightarrow (1)$$

Hole concentration in the valence band of an intrinsic semiconductor

- The expression for Electron concentration in the conduction band of an intrinsic semiconductor is given by

$$p = 2\left[\frac{2\pi m_h^{*} kT}{h^2}\right]^{3/2} \exp\left[\frac{E_v - E_F}{kT}\right] \rightarrow (2)$$

Fermi level in an intrinsic semiconductor

- In an intrinsic semiconductor, the concentration of electrons in the conduction band is equal to the concentration of holes in the valence band.

$$n = p \qquad \rightarrow (3)$$

i.e., On substituting eq (1) and eq (2) in eq(3) and simplifying, we get

$$E_F = \frac{E_c + E_v}{2} + \frac{3}{4} \ln \left(\frac{m_h^*}{m_e^*} \right) \qquad \rightarrow (4)$$

From eq (4), when T = 0K, then

$$E_F = \frac{E_c + E_v}{2} \qquad \rightarrow (5)$$

- Hence, in an intrinsic semiconductor, at 0K, Fermi level is located exactly half-way between the top of the valence band and the bottom of the conduction band.

- Generally, $m_h^* > m_e^*$ and as the temperature increases, Fermi energy E_F increases slightly.

Doping– Extrinsic semiconductors

- Generally, the electrical conductivity of an intrinsic semiconductor is low. It can be increased by adding a small quantity of impurities to an intrinsic semiconductor.

- "The process of adding impurities to an intrinsic semiconductor to enhance the electrical conductivity "is called **doping**.

- "The semiconductor formed after doping" is called extrinsic semiconductor.

- Extrinsic semiconductors are of **two** types namely, p-type and n-type.

n–type semiconductor

- When **pentavalent** impurity atom like antimony or phosphorous or arsenic is added to a pure silicon (or germanium) crystal, four of its five valence electrons form covalent bonds with its neighboring four silicon atoms.

- The fifth electron of each impurity atom is loosely held with its parent atom and can be easily detached by supplying a little amount of energy.

- Energy levels are introduced to all the fifth electrons of impurity atoms just below the bottom of the conduction band. These levels are called donor levels and the impurities added are called donor impurities.

- At room temperature and temperatures nearer to room temperature, almost all the electrons in the donor levels jump to conduction band but only a few electrons from valence band jump in to conduction band, leaving behind few holes in valences band.

- Therefore, electrons are the majority charge carriers and holes are the minority charge carriers.

- As there are excess conducting electrons, "the semiconductor thus formed after doping pentavalent impurities to a pure semiconductor" is called **n-type** semiconductor.

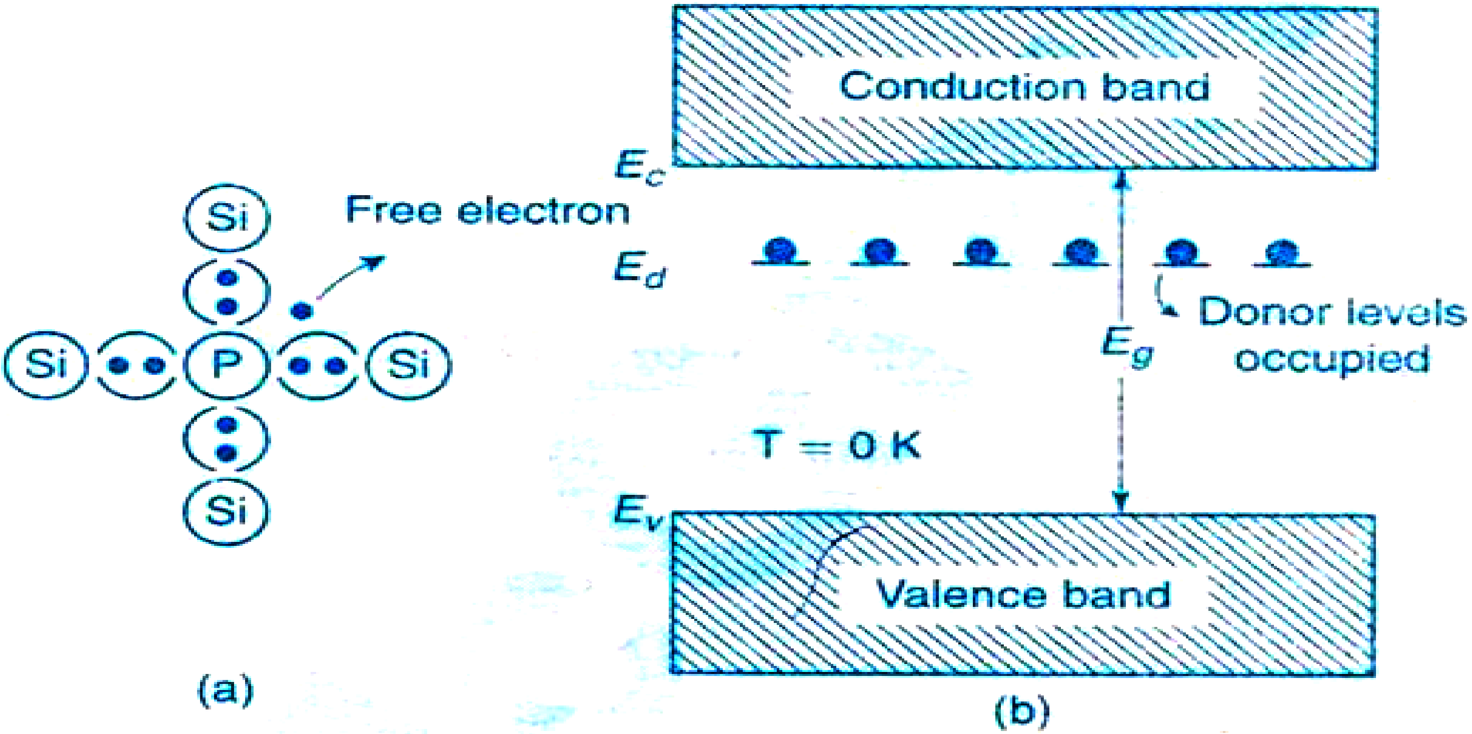


Figure 4. (a) Representation of n- type silicon at T = 0K and (b) Energy band diagram at T = 0 K

Carrier concentration in n–type semiconductor

- Electrons in conduction band are the majority charge carriers in an n-type semiconductor.

- The expression for electron concentration in the conduction band of an intrinsic semiconductor is given by

$$n = 2\left[\frac{2\pi m_e^{*} kT}{h^2}\right]^{3/2} \exp\left[\frac{E_F - E_C}{kT}\right] \qquad \rightarrow (1)$$

- But, in an n-type semiconductor, concentration of electrons in conduction band is equal to concentration of empty donors.

- The concentration of empty donors in an n-type semiconductor

$$= \frac{N_d}{1 + e^{\left(1 + \frac{E_F - E_d}{kT}\right)}} \qquad \rightarrow (2)$$

Where N_d is the concentration of donor levels

$$\therefore 2\left[\frac{2\pi m_e^{*} kT}{h^2}\right]^{3/2} e^{\left[\frac{E_F - E_c}{kT}\right]} = \frac{N_d}{1 + e^{\left(1 + \frac{E_F - E_d}{kT}\right)}} \rightarrow \qquad (3)$$

After simplification, we get

$$E_F = \frac{E_c + E_d}{2} + KT \ln\left[\frac{\left(\frac{N_d}{2}\right)^{\frac{1}{2}}}{\left(\frac{2\pi m_e^{*} KT}{h^2}\right)^{3/4}}\right] \rightarrow (4)$$

It is clear from eq(4) that, when T= 0K,

$$E_F = \frac{E_c + E_d}{2} \qquad \rightarrow (5)$$

i.e. At 0K, the Fermi level of an n-type semiconductor lies exactly half way between the bottom of the conduction band and the donor levels. But, as T increases, Fermi level falls.

Substituting eq (4) in eq (1), we get the expression for carrier concentration in the n-type semiconductor as

$$n=\left(2N_d\right)^{1/2}\left[\frac{2\pi m_e^{*}kT}{h^2}\right]^{3/4}\exp\left[\frac{E_d-E_C}{2kT}\right]\qquad\rightarrow(6)$$

p – type semiconductor

- When **trivalent** impurity atoms like boron or aluminium or gallium are added to pure silicon (or germanium crystal), each impurity atom forms three covalent bonds with three of its four neighboring silicon atoms. There is deficiency of electron to form fourth covalent bond and attain closed shell configuration.

- Energy levels are created to the electron deficiencies just above the top of the valence band. These levels are called acceptor levels.

- At around room temperatures, many electrons nearer to the top of the valence band jump into acceptor levels and only few electrons jump into conduction band, leaving behind holes in the valence band.

- Therefore, the majority charge carriers are holes in the valence band and minority charge carriers are a few electrons that are present in the conduction band.

- As there are excess holes, "the semiconductor thus formed after doping trivalent impurities to a pure semiconductor" is called p-type semiconductor and the impurities are called acceptor impurities.

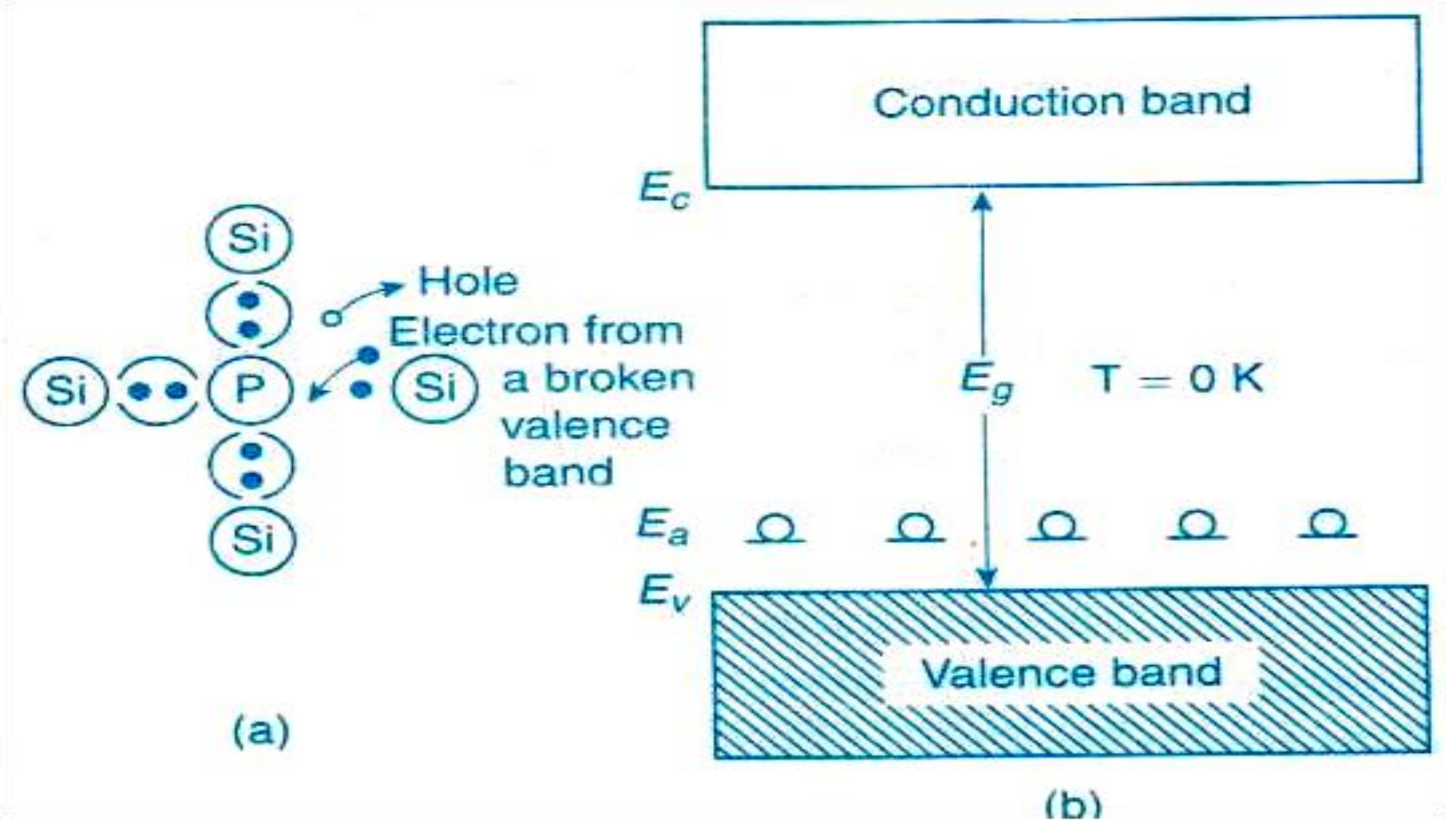


Figure 5 (a) Representation of p- type silicon at T = 0K and (b) Energy band diagram at T = 0 K

Carrier concentration in p-type semiconductor

- Holes in the valence band are the majority charge carriers in a p-type semiconductor.

- The expression for hole concentration in the valence band of an intrinsic semiconductor is given by

$$p = 2\left[\frac{2\pi m_h^{*} kT}{h^2}\right]^{3/2} \exp\left[\frac{E_V - E_F}{kT}\right] \qquad \rightarrow (1)$$

But, the concentration of electrons in the acceptor levels

$$= N_a \, e^{\left[\frac{E_F - E_c}{kT}\right]} \qquad \rightarrow (2)$$

where N_a is the concentration of acceptor levels.

- Since the acceptor level is very nearer to the valence band, the effect of conduction band is negligible. So, the number of electrons in the acceptor levels is equal to the number of holes in the valence band.

$$\therefore \quad 2\left[\frac{2\pi m_h^{*}kT}{h^2}\right]^{3/2}\exp\left[\frac{E_V - E_F}{kT}\right] = N_a\, e^{\left[\frac{E_F - E_c}{kT}\right]} \rightarrow (3)$$

On further simplification, we get

$$E_F = \frac{E_a + E_v}{2} - KT \ \ln\left[\frac{\left(\frac{N_a}{2}\right)^{1/2}}{\left(\frac{2\pi m_h^{*}KT}{h^2}\right)^{3/4}}\right] \rightarrow (4)$$

It is clear from eq (4) that, when T = 0K,

$$E_F = \frac{E_a + E_v}{2} \rightarrow (5)$$

- Therefore, the Fermi level of a p-type semiconductor lies exactly half-way between the acceptor levels and top of the valence band. But , as T increases, the Fermi level rises.

Substituting eq (4) in eq (1), we get the expression for carrier concentration in the p- type semiconductor as

$$p = \left(2N_a\right)^{1/2}\left[\frac{2\pi m_h^{*}kT}{h^2}\right]^{3/4} e^{\left[\frac{E_v - E_a}{2kT}\right]} \qquad \rightarrow (6)$$

Direct and indirect band gap semiconductors

- Semiconductors can be classified under two categories namely, a) direct band gap semiconductors and b) indirect band gap semiconductors.

- The energy of free electron or hole comprises of both potential energy part and kinetic energy part. The kinetic energy part is due to their motion within the solid structure of the semiconductor.

- Because of [illegible] motion, both the holes and

- The momentum values are not random but depend upon the total energy value E. If a plot of energy E versus momentum k is made, typical curves as shown in figures [6(a)] and [6(b)] are obtained.

- In both the figures, lower curves represent variation of k with E for holes in the valence band, and the upper curves represent variation of k with E for electrons in the conduction band.

Direct bandgap semiconductors

- In direct band gap semiconductors, minima of conduction band curve is set right above the maxima of the valence band curve [Fig 6(a)].

- This indicates that the holes in the valence band corresponding to energy maxima, and the electron in the conduction band corresponding to energy minima possess same momentum values.

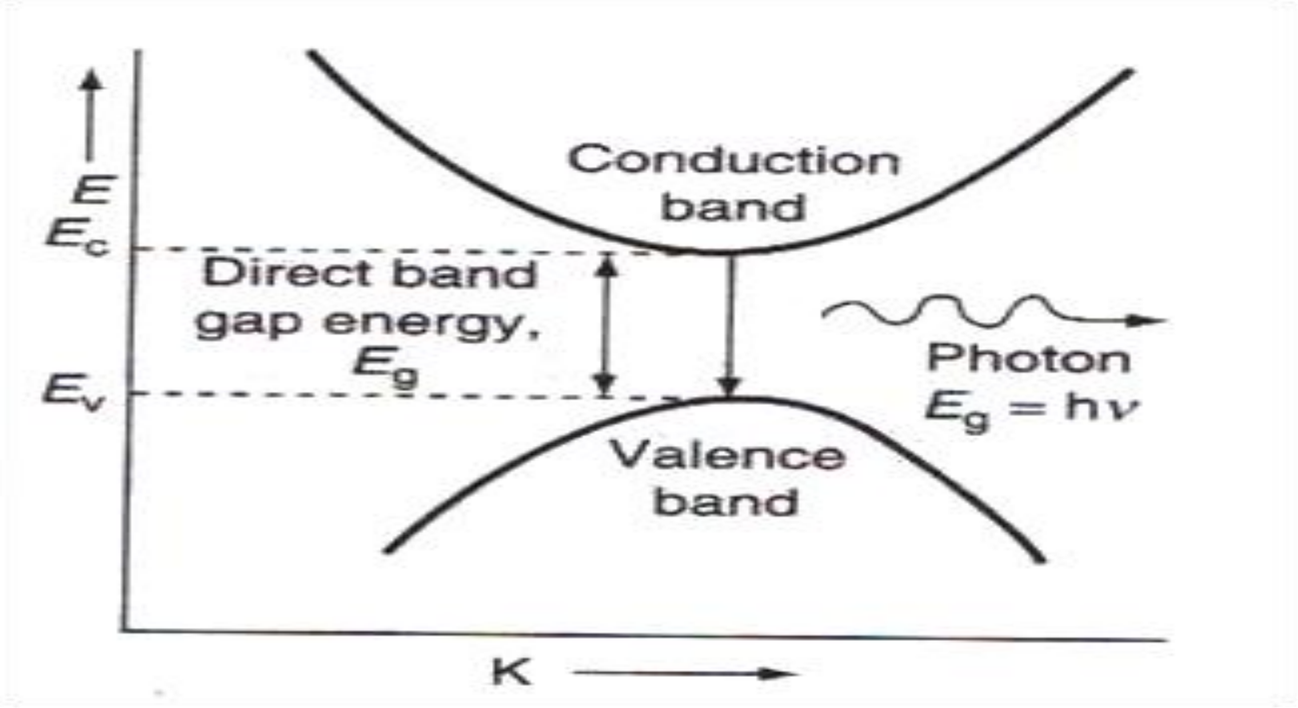


Figure 6. (a) Direct band gap semiconductor : E-k curve

- During the transition between the two bands, emission or absorption of photons takes place depending on the direction of transition.

- The laws of conversation of energy and momentum are obeyed during such transition.

- The momentum value is expected to remain unaltered in direct band gap transition and the condition holds good because the momentum of a photon (= h/λ) is very small, and will not disturb the momentum equality.

Indirect band gap semiconductors

- In an indirect band gap semiconductors, The minima of conduction band and the maxima of valence band are located at different momentum positions [Fig 6(b)].

- Since the photons have essentially zero momentum, the difference in momentum appears in the form of phonons which are quanta of crystal lattice vibrations, thus satisfying the law of conversation of momentum.

- The phonons dissipate energy Eph in the lattice before a transition occurs into the valence band.

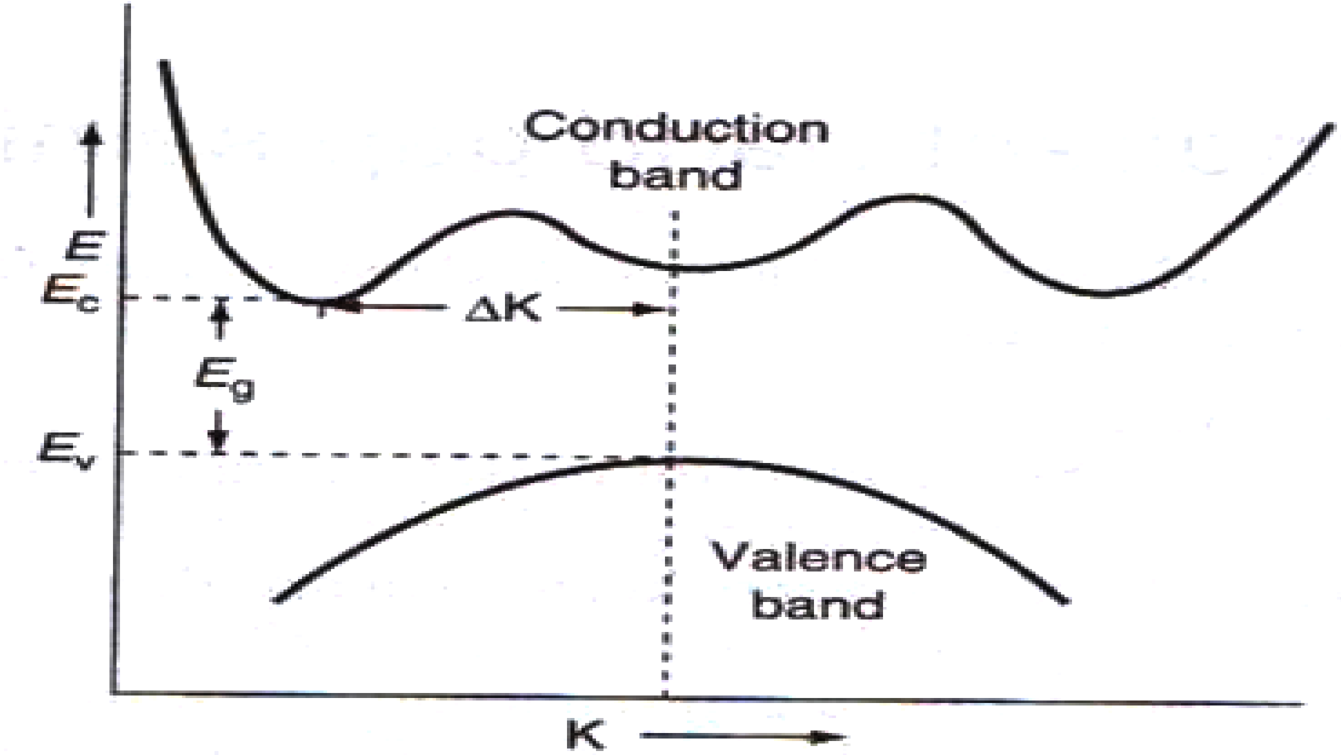


Figure 6. (b) Indirect band gap semiconductor : E-k curve

Hall Effect

When a material carrying current is subjected to a magnetic field in a direction perpendicular to the direction of current, an electric field is developed in a direction perpendicular to both the directions of magnetic field and current. This phenomenon is called Hall effect and the generated voltage is called Hall voltage.

- It was generally believed that the critical current in solids is due to the flow of only electrons.

- But, in semiconductors, the external effect of the current is due to the currents of both negative and positive charge carriers inside the solid.

- It is not possible to assert the sign of the charges from the direction of current , because, it is the same whether positive charges flow in that direction or negative

- Hall effect discovered by E.H. Hall in 1879 helps to resolve the dilemma on the sign of the charges.

- When a moving charge is subjected to the influence of a magnetic field, it experiences a force called Lorentz force.

- **<u>Fleming's left hand rule</u>** states that " if the first three fingers of the left hand are stretched mutually perpendicular to each other in such a way that, the forefinger is along the magnetic Field, mIddle finger is along the current (or charge), then the direction to which Thumb is pointing

- Consider a semiconducting specimen or a metallic specimen carrying a current along the X-direction.

- Let the specimen be subjected to magnetic field along the Z-direction. Then a force will be developed along the Y-direction.

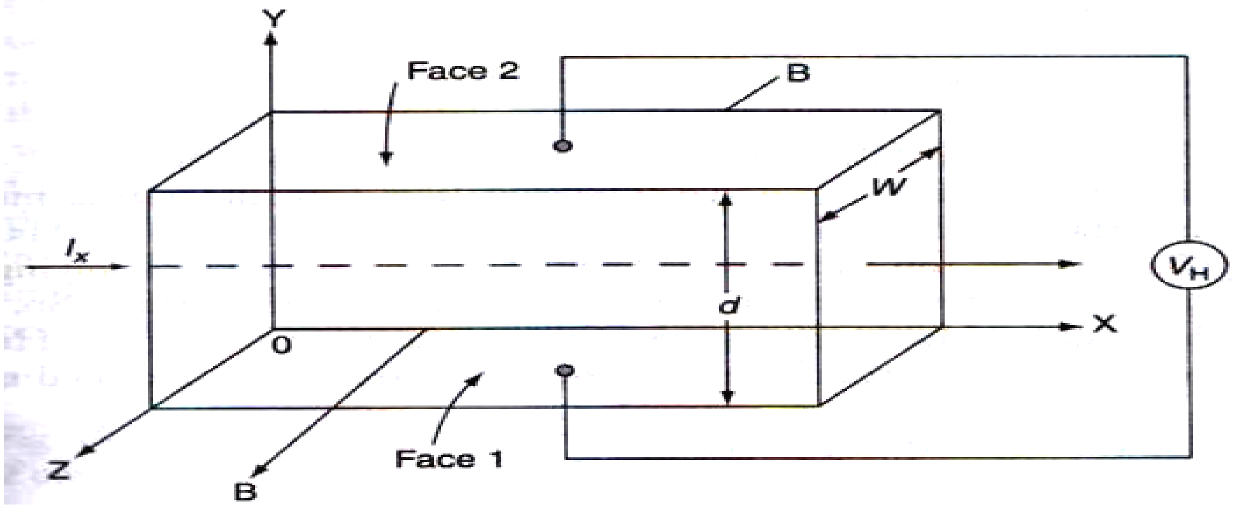


Figure 7. A semiconductor applied to current and magnetic field perpendicularly in Hall Effect

- If the specimen is a metal, since it has only one type of charge carriers, i.e. electrons, the electrons are forced down into the bottom surface.

- Therefore, the bottom surface becomes more negative compared to the upper surface. Hence, a potential difference is developed between the bottom and upper surfaces.

- If the specimen is an n-type semiconductor, since the electrons are the majority charge carriers, they are forced down into the bottom surface. Therefore, the upper surface becomes positive, whereas the bottom surface becomes negative.

- In a p-type semiconductor, the bottom surface is occupied by holes and it becomes more positive compared to the upper surface.

- The potential difference between the upper and lower surfaces is known as Hall voltage.

Expression for Hall Coefficient

- The Hall coefficient R_H is inversely proportional to the charge concentration and is negative for n-type semiconductors and positive for p-type semiconductors.

$$R_H(p-type) = \frac{1}{pe} \qquad \rightarrow (1)$$

$$R_H(n-type) = -\frac{1}{ne} \qquad \rightarrow (2)$$

Where p and n represent carrier concentration in p-type and n-type semiconductors respectively.

- If a magnetic field ‘B’ is applied to a specimen carrying current ‘I’ and a Hall voltage V_H is developed across it, then the Hall coefficient is given by

$$R_H = \frac{V_H t}{BI} \qquad \rightarrow (3)$$

Applications of Hall effect

1) **Determination of type of Semiconductor** For an n-type semiconductor, R_H is positive whereas for a p-type semiconductor it is positive. Thus, from the direction of Hall voltage developed, one can find out the type of semiconductor.
2) **Calculation of carrier concentration :** Once Hall coefficient is measured, the carrier concentration can be obtained from

$$R_H = \frac{1}{ne}$$

3) **Determination of mobility of charge carriers**

We know that the electrical conductivity

$$\sigma_n = ne\mu_e \left(for\ n-type\ semiconductor \right) \Rightarrow \mu_e = \frac{\sigma_n}{ne} = \sigma_n R_H$$

$$\sigma_p = pe\mu_p \left(for\ p-type\ semiconductor \right) \Rightarrow \mu_p = \frac{\sigma_p}{pe} = \sigma_p R_H$$

Therefore, after measuring the Hall coefficient and electrical conductivity, the mobility μ can be calculated

4) **Measurement of flux density Using a semiconductor**

sample of known Hall coefficient, the magnetic flux density can be deduced from the formula

$$B = \frac{V_H t}{I R_H}$$

p–n Junction

- When a layer of p–type semiconductor is placed with a layer of n–type semiconductor material in such a way that the atoms of p–type combine with the atoms of n–type across the surface of contact, such a surface contact or junction where combination has occurred is known as p–n junction.

- Combined p–type and n–type semiconductors with p–n junction

Formation of p–n junction

A p-n junction diode may be obtained in the following methods.

1) Grown junction type

2) Fused (or alloyed) junction type and

3) Diffused junction type

1) **Grown junction type**: When an extrinsic semiconductor is grown from melt, during the middle of the growth process, impurities of other kind are added to the melt so that the opposite type of crystal grows further.

2) **Fused (or alloyed) junction type**: In this process, p-type and n-type materials are kept in contact and fused together by proper heat treatment to form the p-n junction.

3) **Diffused junction type**:

This process involves either gas diffusion method or solid diffusion method.

a) In gas diffusion method, a wafer of n-type silicon is heated at about 1000°C in a gaseous atmosphere of high concentration boron atoms . At that temperature, due to concentration gradient the boron atoms diffuse in silicon forming p-n junction.

b) In solid diffusion process, a p-type impurity (say indium) is painted on an n-type substrate and both are heated.

Now impurity atoms diffuse into n-type substrate for a short time and form p-n junction.

Illustration of p–n junction

- The charges in circles represent impurity ions, and holes and electrons are represented by + and - respectively. The atomic plane that joins p-side and n-side regions is called p-n junction.
- In p-region, the electrons present in the upper energy levels of valence band go to the acceptor energy levels. Hence a large number of negative ions and holes are formed.
- In the n-region, the electrons present in the donor energy level go to the conduction band so that large number of positive ions and free electrons are formed.

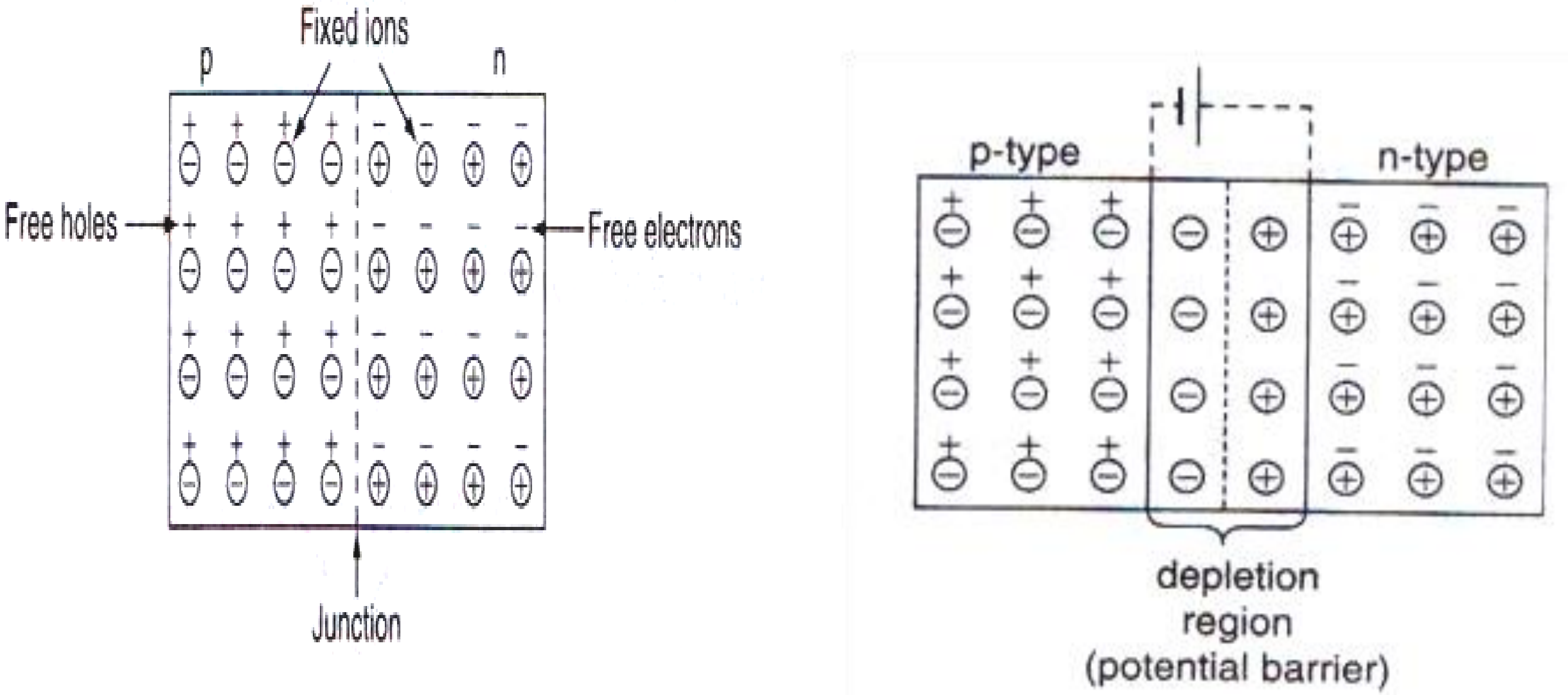


Figure 8(a) Newly made p n junction (b) Formation of P N Junction with potential barrier

- Immediately after the formation of the junction, a large number of holes near the junction in the p-region and a large number of free electrons near the junction in the n-region are seen.

- Due to thermal energy, these carriers may diffuse through the junction. Thus the holes diffuse from p-side to n-side and electrons diffuse from n-side to p-side.

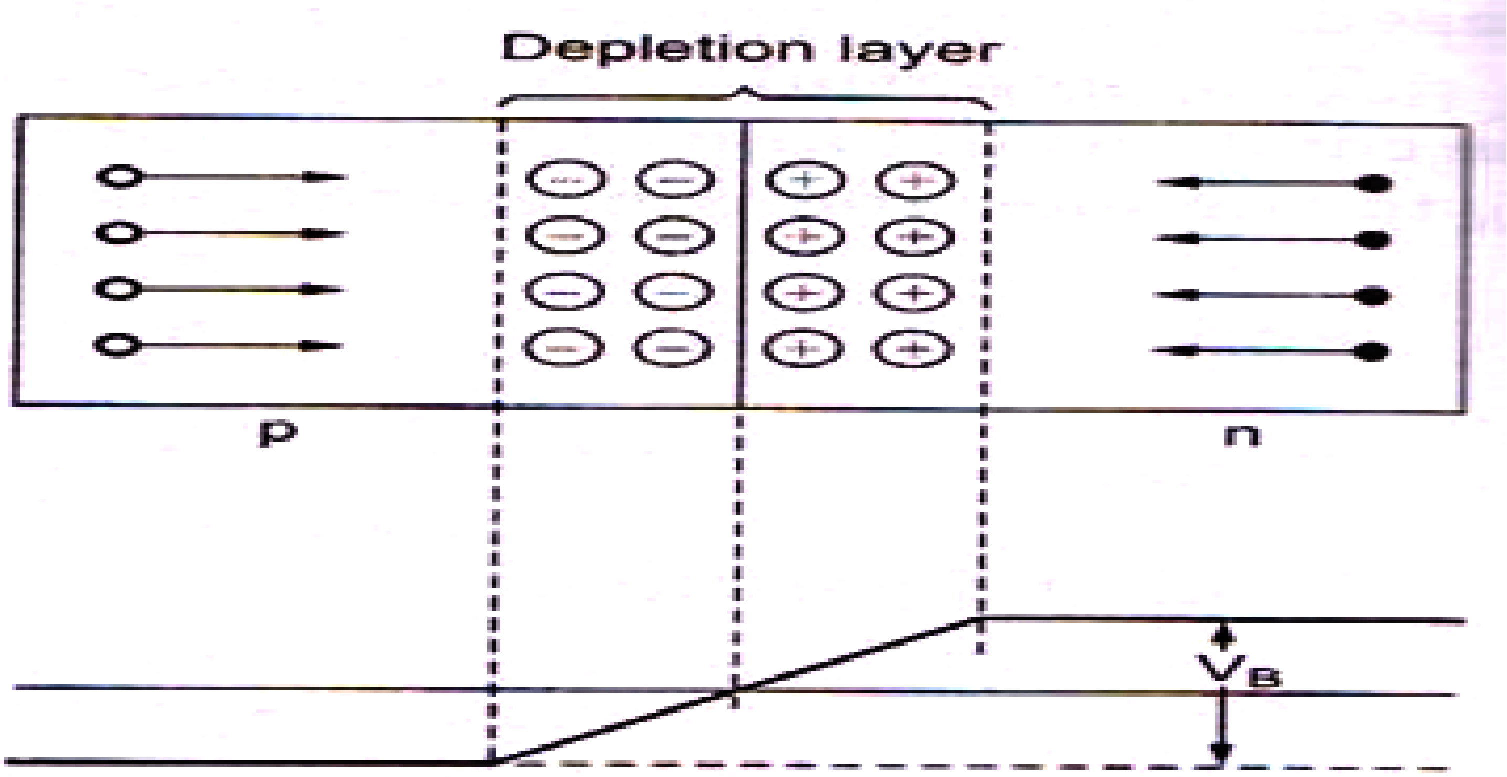


Figure *9. Unbiased p-n junction*

- The diffused carriers find a large number of opposite charges, hence electron-hole recombination takes place, due to recombination, a pair of opposite charges are lost soon after the formation of the p-n junction.

- The number of free charge carriers are continuously reduced due to recombinations and the junction becomes devoid of charge carriers. Far way from the junction, free charge carriers are present.

- This leaves a negative (or acceptor) ion near the junction in the p-region and positive (donor) ion near the junction in the n-region. The region across the junction in which the free charge carriers are absent is called 'depletion region' or 'charge free region'.

- These ions will form a barrier called potential barrier or junction barrier for further diffusion of charge carriers. It is because now the positive ions on the n-side repel holes to cross from p-type to n-type and negative ions on p-side repel electrons to enter from n-type to p-type. At 300K, the potential barrier is about 0.3V for Ge and 0.7V for Si.

Forward biased p–n junction

- If the positive terminal of the battery is connected to p-side and negative terminal to the n-side of the p-n junction diode, then the diode is said to be forward biased.
- The applied forward potential establishes an electric field which acts against the potential barrier field.
- Obviously, the resultant field is weakened and the barrier height is reduced at the p-n junction [Figure 10].

- Since the barrier height is very small, a small forward voltage is sufficient to completely eliminate the barrier.

- Obviously, at some forward voltage, the potential barrier at the p-n junction can be eliminated altogether.

- Then the junction resistance will become almost zero, and a low resistance path is established for the entire circuit.

- Thus a large current is generated in the circuit even for the small potential difference applied. Such a circuit is called forward biased circuit and the current is called current.

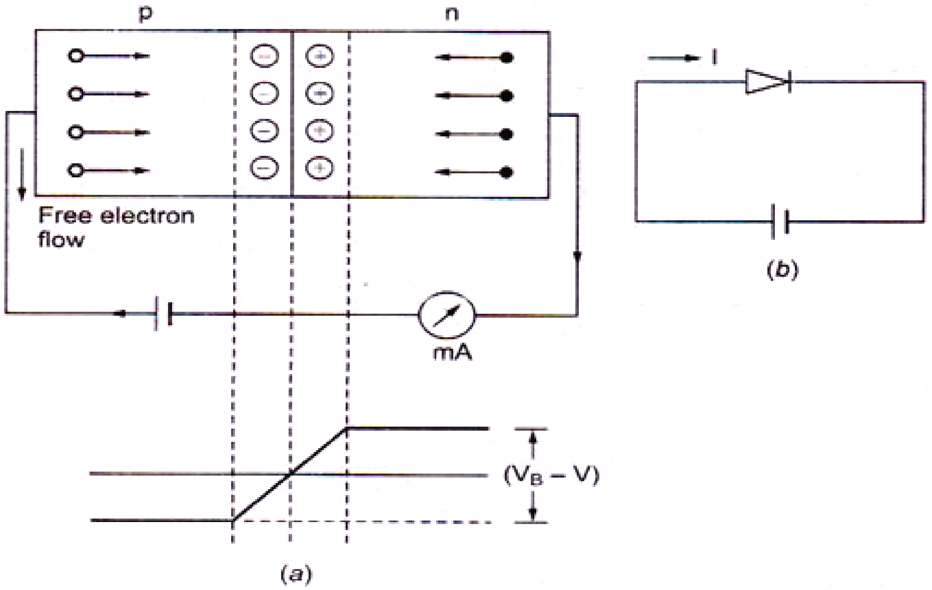


Figure 10. *Forward Biased Circuit*

Reverse biased (Open circuit) p-n junction

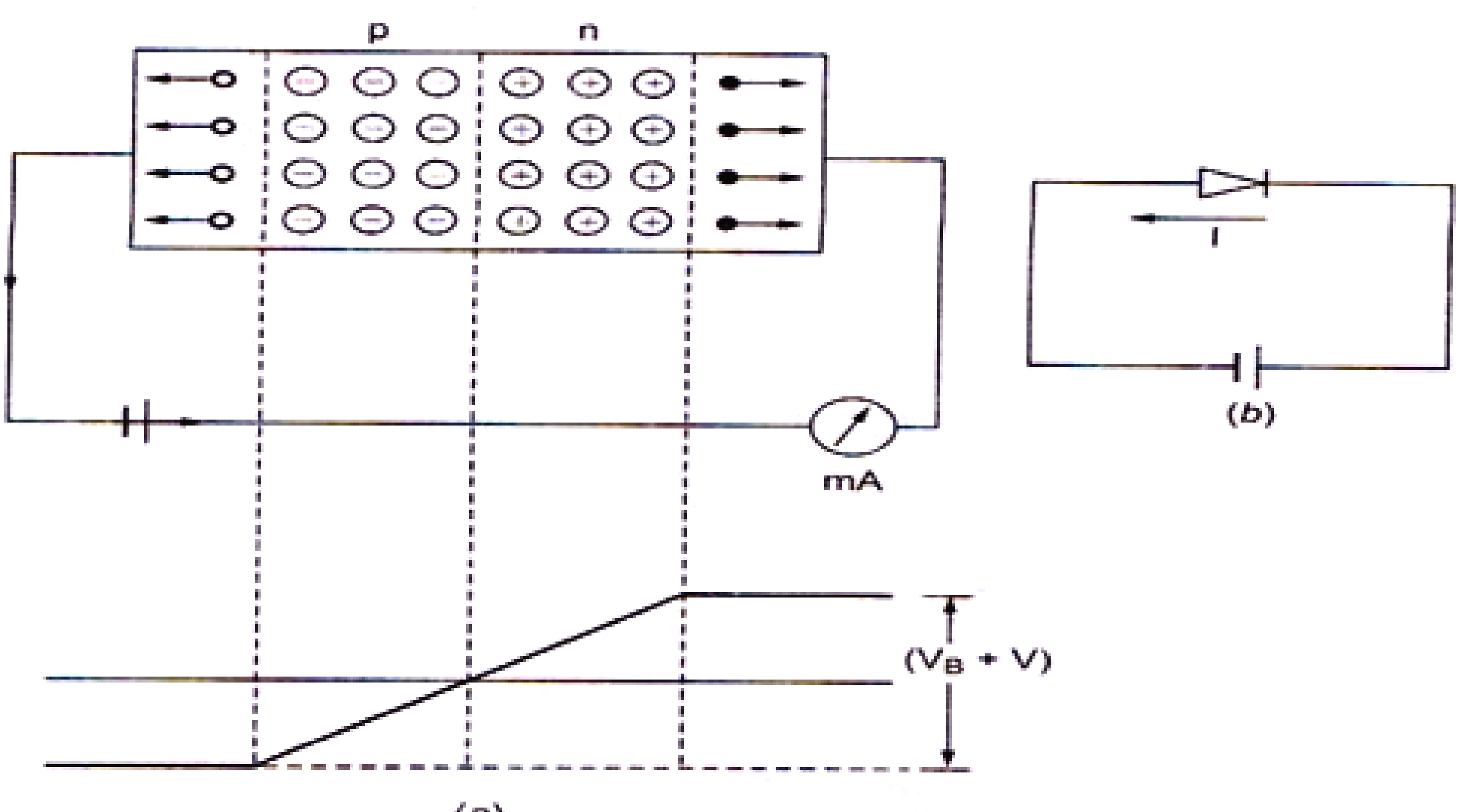
- If the positive terminal of the battery is connected to n-type and negative terminal is connected to p-type, then the p-n junction is said to be reverse biased.

- In this case, the applied voltage establishes an electric field in the same direction as that of the field due to barrier potential.

- As a result of this, the resultant field is strengthened and the barrier height is increased as shown in figure [11].

- It has been observed that the increased barrier potential prevents the flow of charge carriers across the junction.

- Thus a high resistance path is established for the entire circuit, and the current does not flow through the junction, i.e., the effect of reverse bias is to increase the potential barrier, thus allowing a very little current to flow.



(a)

(b)

Figure 11. *Reverse Biased Circuit*

V-I characteristics of p-n junction

i) **Zero biased or unbiased circuit**: When the junction is not connected to any voltage source, it is said to be unbiased. There is no flow of charge carriers and hence there is no current flow through the junction, due to barrier potential a cross the junction.

ii) **Forward biased circuit**: When positive terminal of the battery is connected to p-type and negative terminal to n-type, the junction is said to be forward biased.

- Since the potential barrier height is very small (0.2V), when the applied voltage exceeds that value, the junction resistance becomes almost zero and low resistance path is created.

- Hence even for small increase in applied voltage, we observe large increase in circuit current. Such a circuit is called forward biased circuit and current is called forward current.

- When the applied voltage is above the barrier potential, the forward current (in MA) is found to increase linearly with the applied voltages.

iii) **Reverse biased circuit**: When reverse biased, (I.e., when the positive terminal is connected to n-type and negative terminal is connected to p-type), a slight reverse current (in microamperes) flows in the circuit. Even for large increase in bias voltage (20 volts), there is negligible in reverse current.

When the applied reverse voltage is high enough to break the covalent bonds of the crystal, the current rises suddenly in the reverse direction. The breakdown voltage in reverse bias is called Zener voltage.

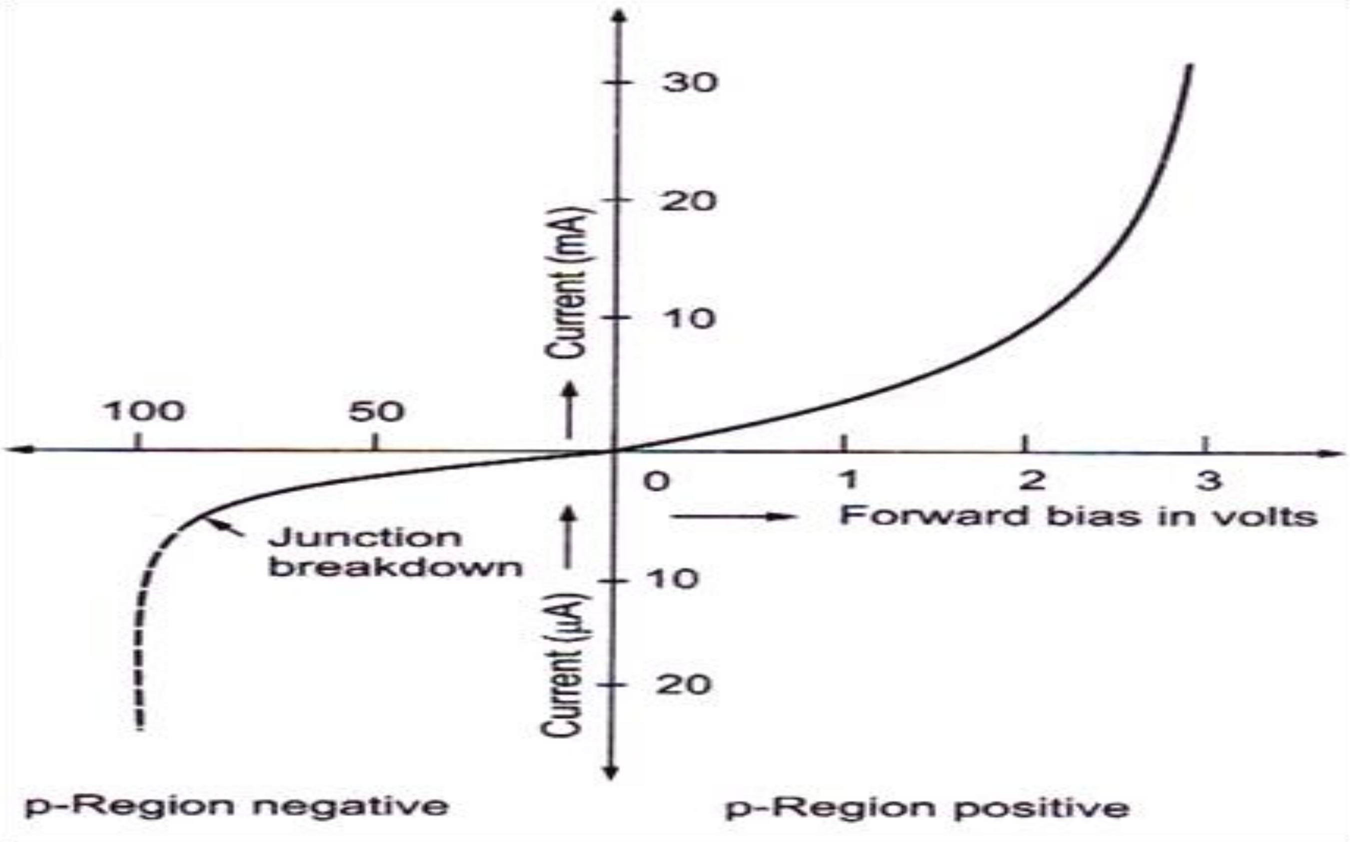


Figure 12. *V-I curve of p-n diode*

Energy band diagram of p-n diode

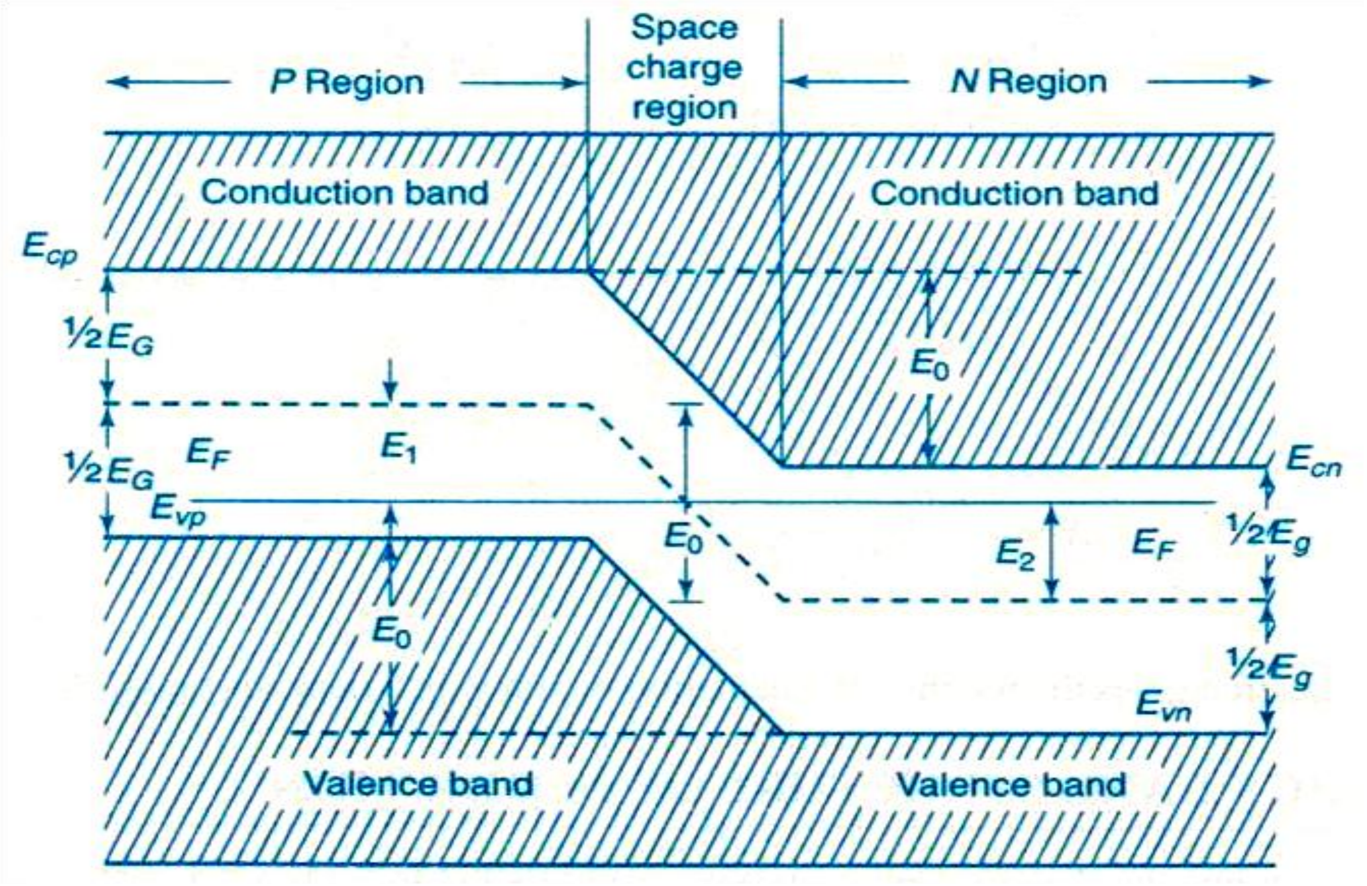


Figure 13. energy band diagram of p-n diode

- Consider that a p-n junction has p-type and n-type materials in close physical contact at the junction on an atomic scale. Hence, the energy band diagrams of these two regions undergo relative shift to equalize the Fermi level.

- The Fermi level should be constant through throughout the specimen at equilibrium. The distribution of electrons and holes in allowed energy states is dependent on the position of the Fermi level $E_{F.}$

- If this is not so, electrons on one side of the junction would have an average energy higher than those on the other side, and this causes transfer of electrons and energy until the Fermi levels on two sides get equalized.

- However, such a shift does not disturb the relative positions of conduction band, valence band and Fermi level in any region. (Equalization of Fermi levels in the p and n materials of a p-n junction is similar to equalization of levels of water in two containers on being joined).

- The energy band diagram for a p-n junction is shown in Figure[13], where Fermi level E_F is closer to the conduction band edge E_{cn} in the n-type material, while it is closer to the valence band edge E_{vp} in the p-type material.

- It is clear that the conduction band edge E_{cp} in the p-type material is higher than the conduction band edge E_{cn} in the n-type material. Similarly, the valence band edge E_{vp} in the p-type material is higher than the valence band edge E_{vn} in the n-type material.

- E_1 and E_2 indicate the shifts in the Femi level from the intrinsic conditions in the p and n materials respectively. Then the total shift in the energy level E_0 is given by

$$E_0 = E_1 + E_2 = E_{cp} - E_{cn} = E_{vp} - E_{vn}$$

- This energy (in eV) is the potential energy of the electrons at the p-n junction, and is equal to eV_0, where V_0 is the contact potential (in volts) or contact difference potential or the barrier potential.

Diode current equation

- The diode current equation relating the voltage V and current I is given by

$$I = I_0 \left[e^{\frac{V}{\eta V_T}} - 1 \right]$$

Where I = diode current

V = External voltage applied to the diode

η = a constant, 1 for germanium and 2 for silicon

VT = kT/e is volt equivalent temperature, i.e. thermal voltage.

Light Emitting Diode

- When a p-n junction diode is forward biased, the potential barrier is lowered. The majority carriers start crossing the junction.

- . The conduction band electrons from the n-region cross the barrier and enter the p-region. Immediately n entering the p-regiin, each electron falls into a hole and recombination takes place.

- Also some holes may cross the junction from the p region into the n-region. A conduction -band electron in the n-region may fall into a hole even before it crosses the junction. In either case, recombinations take place around the junction.

- Each recombination radiates energy. In an ordinary diode (power diode or signal diode), the radiated energy is in the form of heat. In the light emitting diode(LED), the radiated energy is in the form of light(or photons).

- Germanium and silicon diodes have less probabilities of radiating light.

- By using materials such as gallium arsenide phosphide (GaAsP) gallium phosphide(GaP), a manufacturer can produce LEDs that radiate red, green or orange lights.

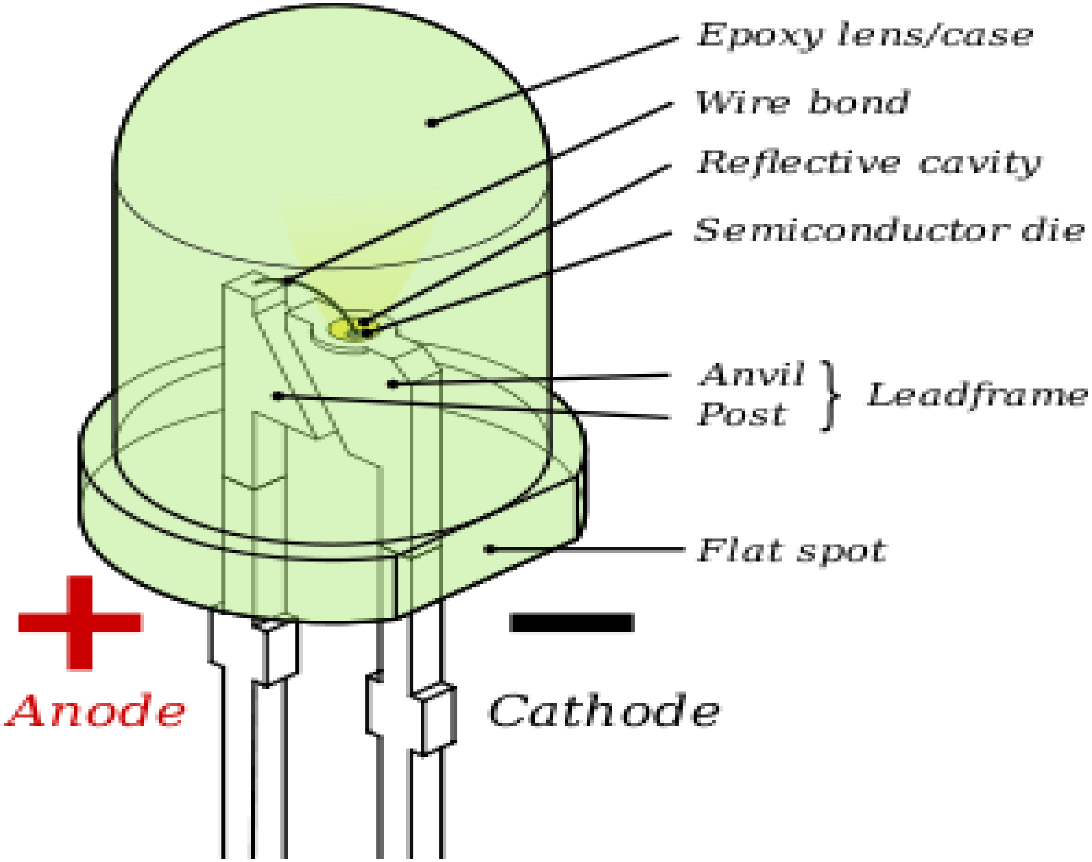
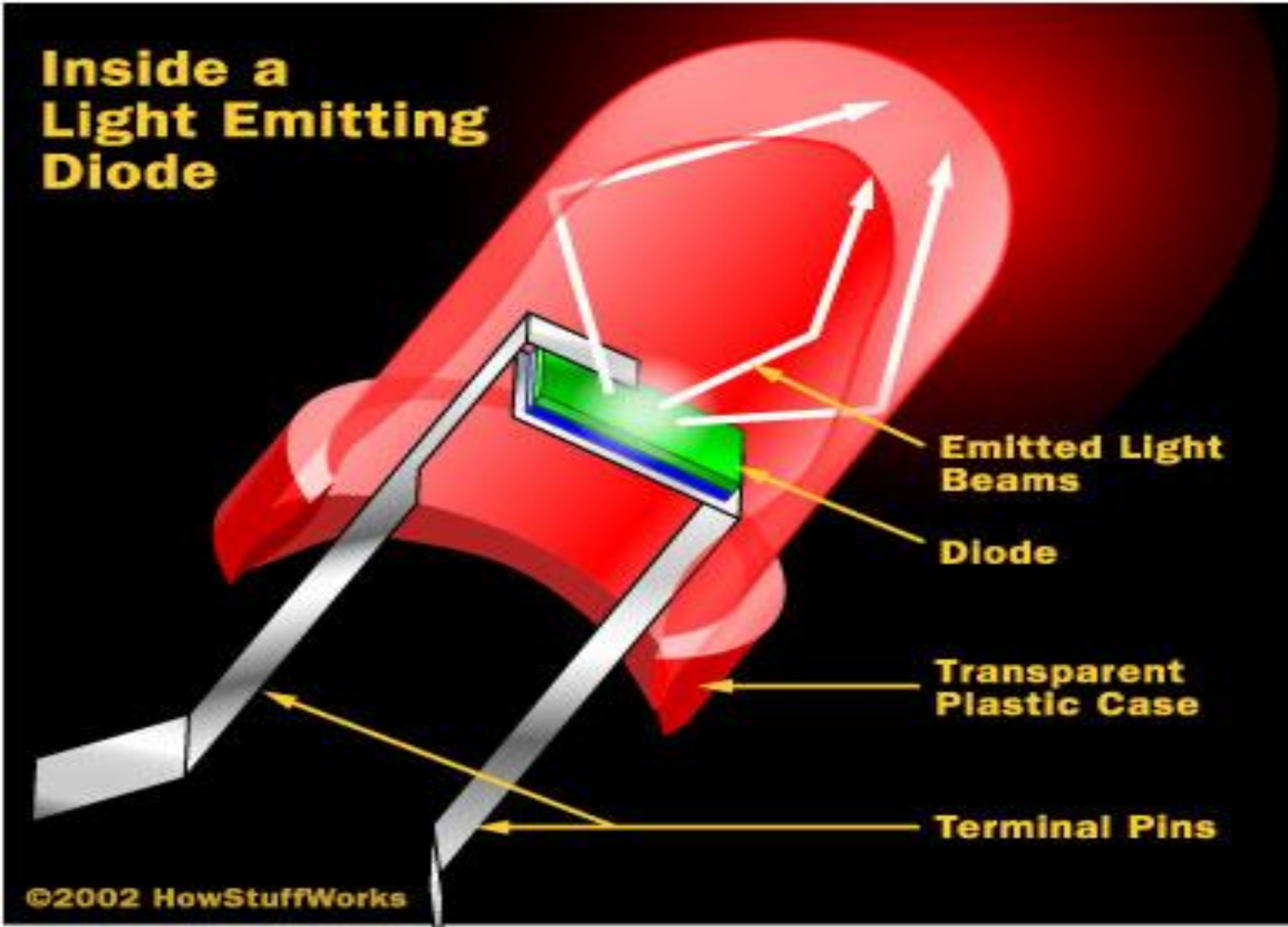


Figure 14. Light emitting diode



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Applications of LEDS

1) Gallium arsenide (GaAs) LEDs emit invisible (infra red) radiation. These find applications in burglar-alarm systems.

2) The LEDs that emit visible light find applications in instrument displays, panel indicators, digital watches, calculators, millimeters, intercoms, telephone switch boards etc.

Advantages of LEDs in electronic display

1. LEDs are available such that they emit light in different colours like red, green, yellow.

2. It has long life and has a high degree of removability.

3. The light intensity of the LEDs can be controlled easily by varying the current flow and the output intensity is bright.

4. They can be operated over a wide range of temperatures 0 to 70°C.

5. Very small in size and can be closely packed for high density of display.

Disadvantages of LEDs

- Not suited for large area display because of high cost.

- LEDs consume more energy than liquid crystal display display.

Requirements for suitable LED material

1. It must have an energy gap of appropriate width (the energy gaps greater than or equal to about 2eV are required to obtain visible radiation).

2. Both p and n-type must exist with low resistivities.

3. Efficient radiative path ways must be present.

Photo diode

- A photo diode is an optoelectronic light sensitive device which absorbs optical energy and converts it into electrical energy which usually appears as a photocurrent.

- The diode is made of a semiconductor p-n junction kept in a sealed plastic or glass casing.

- The cover is so designed that the light rays are allowed to fall on one surface across the junction. The remaining sides of the casing are painted to restrict the penetration of light rays. A lens permits light to fall on the junction.

- When light ray falls on the reverse biased p-n junction, electron-hole pai4 is created for every light photon absorption such that each photon energy is greater than the band gap energy. The movement of these hole-electron pair in a properly connected circuit results in current flow.

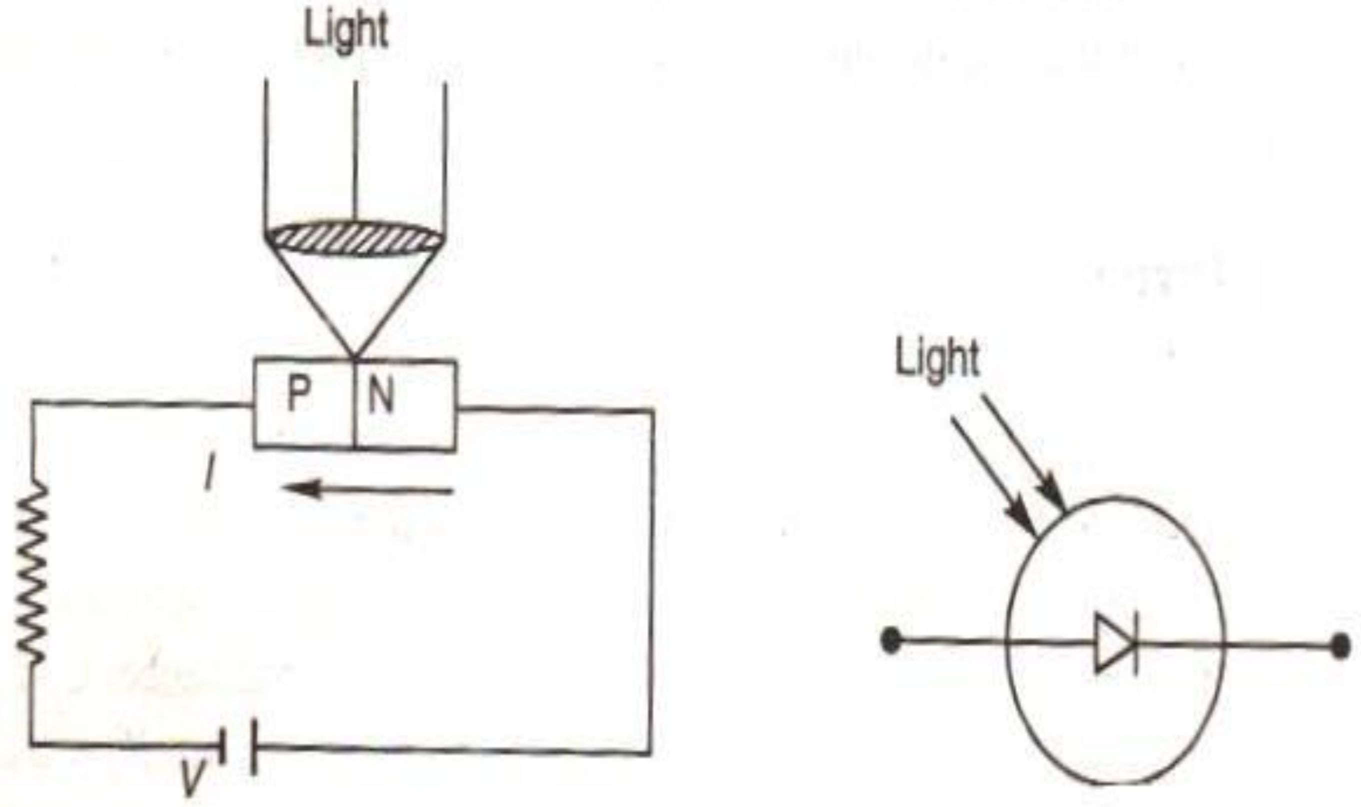

Figure 15 (a) Photo diode

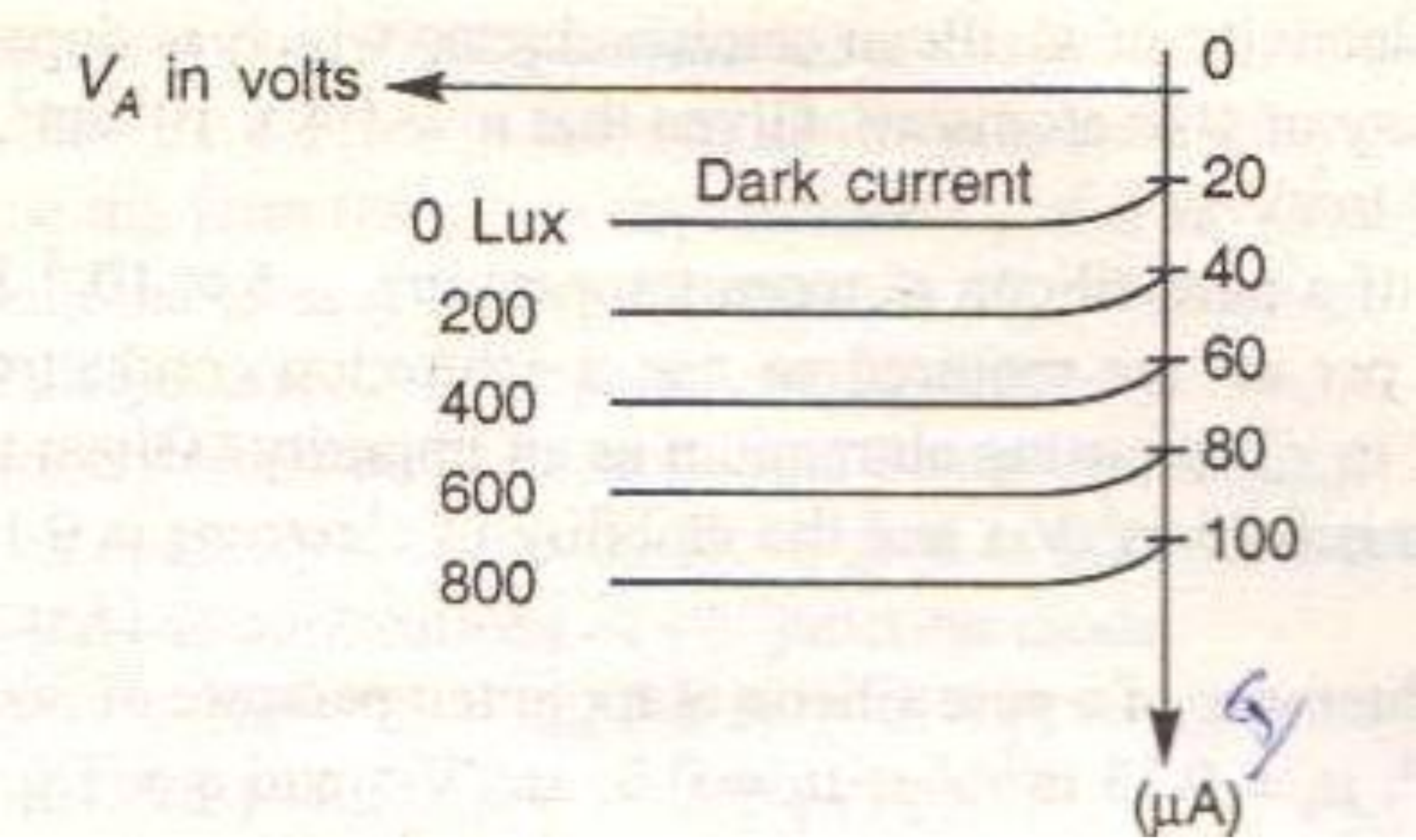

Figure 15 (b). V–I Characteristics of photo diode

Every photo should have:

1. High conversion efficiency which is the ratio between the number of electrons produced per incident photons.
2. It should have wide frequency response.
3. It should have low dark current which is the current flowing in the external circuit when there is no incidence of light.

Advantages of Photo diode mode

1. Linear response
2. Faster response
3. Better stability

Applications of photo diodes

- Photo diodes are used as light detectors, demodulators and encoders.

- They are also used in optical communication systems, high speed counting and switching circuits.

- Further, they are used in computer card punching and tapes, light operated switches, sound tracking films and electronic control circuits.

Solar cell

- Basically, a solar cell is a p-n diode, which converts light energy into electrical energy.

- A solar cell consists of thin circular wafer of 3 to 6cm diameter and about 300µm thick n-type (or p-type) silicon on which nearly 0.23µm thick p-type (or n-type) has been formed.

- A shallow junction is formed on one side of wafer face by diffusing other type of impurity. Ti – Ag alloy electrodes are soldered on the top and bottom surfaces of the solar cell.

- The top electrode is in the form of a metal grid with fingers, which allows the light reach the diode, where as the bottom electrode is a flat sheet.

- Nearly 0.1µm thick antireflection coating of SiO_2 is formed on the top surface of the solar cell.

Working of solar cell

- The radiation incident on the solar cells is absorbed by the cells and produces electron-hole pairs. These carriers are collected by the electrodes and flows through the external load.

- The accumulation of electrons and holes on the two sides of the junction gives rise to an open circuit voltage V_{oc}. This is a function of illumination.

- The open circuit voltage produced for silicon solar cell is 0.6V and short circuit current is about 400mA/cm^2 on a bright sunny day.

Working of solar cell

The solar cell works in three steps

1) Photons in sunlight hit the solar panel and are absorbed by semiconducting materials, such as silicon.
2) Electrons (negatively charged) are knocked from their atoms, causing an electric potential difference. Current starts flowing through the material to cancel the potential and this electricity is captured. Due to the special composition of solar cells, the electrons are only allowed to move in a single direction.
3) An array of solar cells converts solar energy into a usable amount of direct current (DC) electricity.

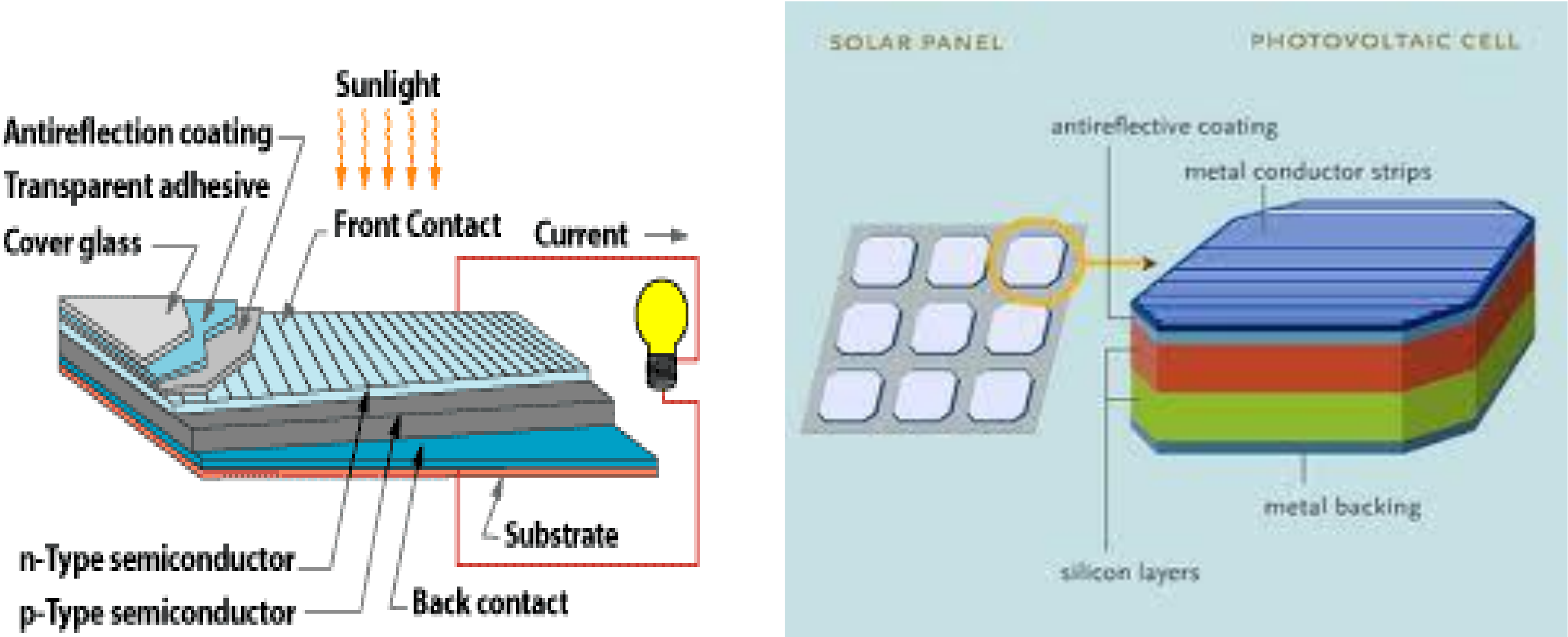

Figure 16. Solar cell

The action of solar cell is explained as follows:

- When a p – n junction diode is exposed to light, the photons are absorbed and electron pairs are generated in both in both the p – side and n – side of the junction, as shown in the figure below. The electrons and holes that are produced over a small distance from the junction reach the space charge region X by diffusion.

- The electron – hole pairs are then separated by the strong barrier field that exists across the region X. The electrons in the p – side slide down the barrier potential to move to the n – side while the holes in the n – side while the holes in the n – side move towards the p – side.

- The electron – hole pairs are then separated by the strong barrier field that exists across the region X. The electrons in the p – side slide down the barrier potential to move to the n – side while the holes in the n – side while the holes in the n – side move towards the p – side.
- When the p – n junction diode is open circuited, the accumulation of electrons and holes on the two sides of the junction gives rise to an open – circuit voltage V_0. If a load resistance is connected across the diode, a current will flow in the circuit. The maximum current, called the short – circuit current is obtained when an electric short is connected across the diode terminals. Note that the current flows as long as the diode is exposed to sunlight and the magnitude of the current is proportional to the light intensity

V-I characteristics of Solar cell

- For different levels of illumination of sunlight, the V-I characteristics are as shown in figure.
- The maximum power output is obtained at the knee point of the curve.

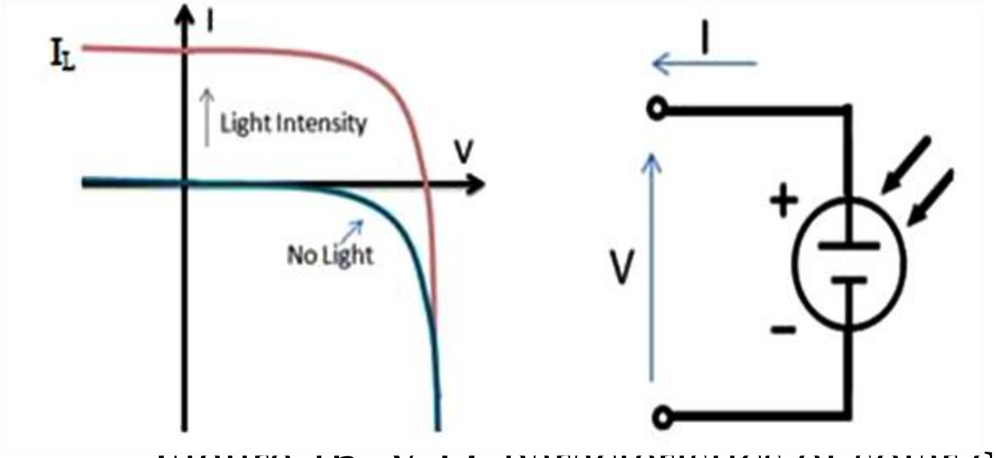

Figure 16. V-I Characteristics of solar cell

Efficiency of solar cell

- It is defined as the ratio of total power converted into electrical power to the solar power incident on the cell.

$$\eta = \frac{Maximum\ electrical\ output\ power}{Input\ light\ power}$$

$$= \frac{P_{\max}}{(Light\ intensity) \times (Area\ of\ the\ solar\ cell)} \times 100$$

Materials for solar cell

S. No	Material	Energy gap (eV)
1	Si	1.11
2	GaAs	1.40
3	CdTe	1.44
4	CdSe	1.74
5	ZnTe	2.20
6	CdS	2.42
7	ZnSe	2.60