AP102BS/AP202BS: APPLIED PHYSICS (R22)

Ist Year B.Tech I/II Sem.

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Course Objectives:
The course primarily aims at understanding the behavior of matter in the condensed state and tries to explore the causes with reference to micro level mechanism of the solid matter.

- The objective of the first chapter is to study the micro level behavior of the quantum particles of the matter and assess the draw backs of the free electron theory leading to the introduction of the Band Theory of Solids.
- The second chapter focuses on the working principles and applications of basic semiconductor devices.
- In the third chapter task to discuss dielectric, magnetic properties of the materials and applications.
- In the fourth chapter plan to discuss on fabrication of nanoparticles and their characterization techniques.
- In the fifth chapter, it is expected to understand the basic principles behind the coherent artificial light source (LASER) with reference to their construction, mechanism, operation and classification etc. In second part of this chapter aimed at to study an advanced communication system presently ruling the world throughout i.e. Fiber Optic communication system.

Course Outcomes: After learning the contents of this paper the student must be able to

CO1: Predict the behavior of particle and wave and **solve** their wave functions.
CO2: Distinguish the different types of Semiconductor devices
CO3: Recall and **choose** different materials based on their properties.
CO4: Categorize Nano materials by fabrication methods.
CO5: Examine normal light and laser light and its **application** in communication.

UNIT - I: QUANTUM PHYSICS AND SOLIDS 10hrs

Quantum Mechanics: Introduction to quantum physics, blackbody radiation – Stefan-Boltzmann's law, Wein's and Rayleigh-Jean's law, Planck's radiation law - photoelectric effect –de-Broglie hypothesis- Davisson and Germer experiment –Heisenberg uncertainty principle - Born interpretation of the wave function – time independent Schrodinger wave equation - particle in one dimensional potential box.

Solids: Symmetry in solids, free electron theory (Drude & Lorentz) Variation of Fermi level- with temperature - Bloch's theorem -Kronig-Penney model – E-K diagram- effective mass of electron-origin of energy bands- classification of solids.

UNIT - II: SEMICONDUCTORS AND DEVICES 10hrs

Intrinsic and extrinsic semiconductors – Hall effect - direct and indirect band gap semiconductors - construction, principle of operation and characteristics of P-N Junction diode, Zener diode and bipolar junction transistor (BJT) – structure, materials, working principle and characteristics: LED, PIN diode, avalanche photo diode (APD) and solar cells.

UNIT - III: DIELECTRIC, MAGNETIC AND ENERGY MATERIALS 10hrs

Dielectric Materials: Basic definitions- types of polarizations (qualitative) – piezoelectric, ferroelectric and pyroelectric materials – applications – liquid crystal displays (LCD).

Magnetic Materials: Basic definitions- Hysteresis - soft and hard magnetic materials - magnetostriction, magnetoresistance - applications - memory devices, magnetic field sensors and multiferroics.

UNIT - IV: NANOTECHNOLOGY 10hrs

Introduction, Nanoscale, quantum confinement, surface to volume ratio, bottom-up fabrication: sol-gel, precipitation, combustion methods – top-down fabrication: ball milling - physical vapor deposition (PVD) - chemical vapor deposition (CVD) - characterization techniques - XRD, SEM &TEM - applications of nanomaterials.

UNIT - V: LASER AND FIBER OPTICS 10hrs

Lasers: Laser beam characteristics-three quantum processes-Einstein coefficients and their relations-lasing action - pumping methods- ruby laser, He-Ne laser , CO2 laser, semiconductor laser-applications of laser.

Fiber Optics: Introduction to optical fiber- advantages of optical Fibers - total internal reflection, construction of optical fiber - acceptance angle - numerical aperture- classification of optical fibers-losses in optical fiber- optical fiber for communication system – applications: medical, sensor and communication.

TEXT BOOKS:

1. M. N. Avadhanulu, P.G. Kshirsagar & TVS Arun Murthy" A Text book of Engineering Physics"- S. Chand Publications, 11th Edition 2019.
2. Engineering Physics by Shatendra Sharma and Jyotsna Sharma, Pearson Publication,2019
3. Semiconductor Physics and Devices- Basic Principle – Donald A, Neamen, Mc Graw Hill, 4 thEdition,2021.
4. B.K. Pandey and S. Chaturvedi, Engineering Physics, Cengage Learning, 2ndEdition,2022.
5. Essentials of Nanoscience & Nanotechnology by Narasimha Reddy Katta, Typical Creatives NANO DIGEST, 1st Edition, 2021.

REFERENCE BOOKS:

1. Quantum Physics, H.C. Verma, TBS Publication, 2nd Edition 2012.

2. Fundamentals of Physics – Halliday, Resnick and Walker, John Wiley &Sons,11th Edition, 2018.
3. Elementary Solid State Physics, S.L. Gupta and V. Kumar, Pragathi Prakashan, 2019.
4. A.K. Bhandhopadhya - Nano Materials, New Age International, 1stEdition, 2007.
5. Energy Materials a Short Introduction to Functional Materials for Energy Conversion and Storage Aliaksandr S. Bandarenka, CRC Press Taylor & Francis Group.
6. Energy Materials, Taylor & Francis Group, 1st Edition, 2022.

UNIT-I

Quantum Physics

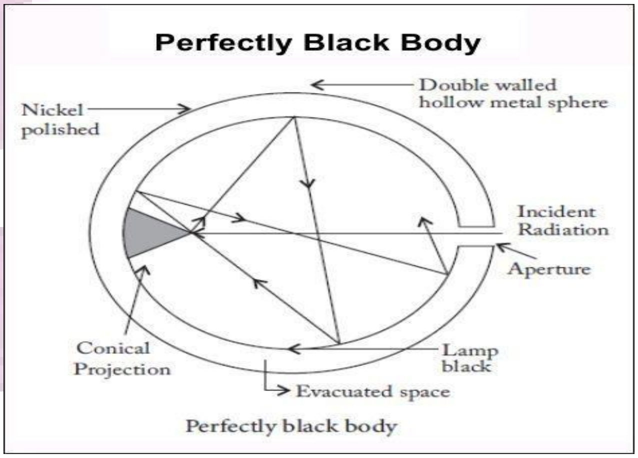
Introduction:

Advances in solid state physics are made by using the principles of Quantum mechanics. The energy of the electron in the solid, black body radiation, Spectra of solids, magnetism, superconductivity, etc., are all explained only by quantum mechanics.

At the end of the 19th century, physicists had every reason to regard the Newtonian laws governing the motion of material bodies and man well less of electromagnetism, as fundamental laws of Physics. They believed that there should be some limitation on the validity of these laws which constitute "classical mechanics" to understand the submicroscopic world of the atom and its constitutes, it became necessary to introduce new ideas and concepts which led to the mathematical formulation of "Quantum mechanics" during 1925, that had no immediate and spectacular success in the explanation of the experimental observations. Quantum mechanics provided the key to the understanding of the behavior of very small objects like the atoms and it constitutes the failure of classical mechanics when applied to the submicroscopic world of the atom arose from the possibility the characterizing the instantaneous stale of the particle in motion by privies positions and velocities.

In this unit we will study the development of the Quantum mechanics, Blck body radiation, planck's law, photoelectric effect, compton effect, Broglie hypothesis, Heisenberg's uncertainly principle, Schrödinger's wave equation and its application.

1.1 Black body radiation:



A black body is a theoretical object that absorbs 100% of the radiation that hits it. Therefore it reflects no radiation and appears perfectly black.

Roughly we can say that the stars radiate like blackbody radiators. This is important because it means that we can use the theory for blackbody radiators to infer things about stars.

At a particular temperature the black body would emit the maximum amount of energy possible for that temperature. The radiation emitted by black body is known as black body radiation.

Blackbody radiation does not depend on the type of object emitting it. Entire spectrum of blackbody radiation depends on only one parameter, the temperature, T.

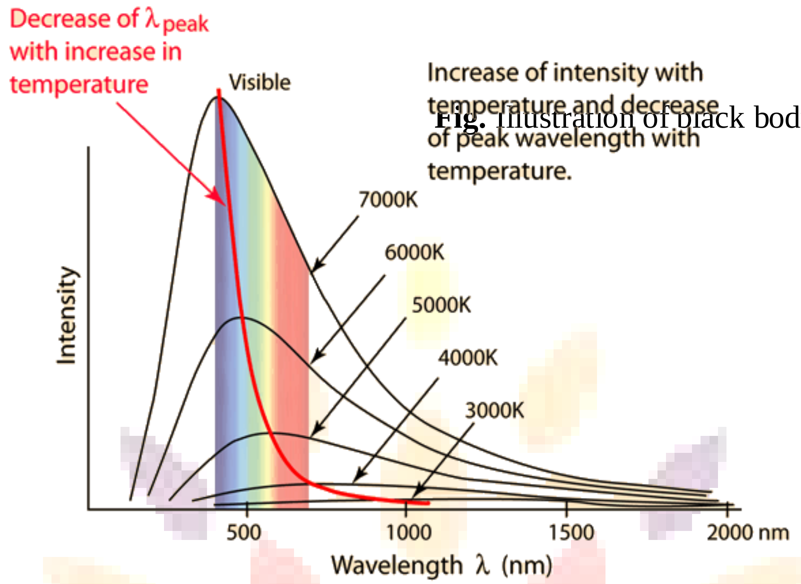


Fig. Illustration of black body

Fig. Energy density Vs wavelength at given temperature

1. At given temperature, the energy is not uniformly distributed in the radiation spectrum of the blackbody.

2. At a given temperature, the intensity of radiation increases with increase in wavelength and at a particular wavelength, its value is maximum. With further increase in wavelength, the intensity of radiation decreases.

3. With the increase in temperature, maximum wavelength (λ_m) decreases, when λ_m is the wavelength at which the maximum emission of energy takes place.

4. There is increase in energy emission with the increase in temperature corresponding to all the wavelengths.

5. The area under each curve the total energy emitted for the complete spectrum at a particular temperature. With the increase in temperature, this area increases.

1.2 Planck’s law of black body radiation:

Max Plank, a German physicist derived an equation which successfully accounted for the spectrum of the blackbody radiation. He incorporated a new idea in his deduction of Plank eqn. that the probability of emission of radiation decreases as its frequency increases so that, the curve slopes down in the high frequency region. The oscillators in the blackbody can have only a discrete set of energy values. Such an assumption was radically different from the basic principles of physics.

The assumption in the derivation of Plank's law is that the wall of the experimental blackbody consists of a very large number of electrical oscillators, with each oscillator vibrating with a frequency of its own. Plank brought two special conditions in his theory. They are

(1) Only an integral multiple of energies h ν where 'h' is Plank's constant and 'ν ' is frequency of vibration i e, the allowed energy values are $E = n h \nu$
where $n = 0, 1, 2, \ldots$
(2) An oscillator may lose or gain energy by emitting or absorbing radiation of frequency $\nu = (\Delta E / h)$,
where ΔE is the difference in the values of energies of the oscillator before and the emission or absorption had taken place.

Black Body:

A blackbody allows all incident radiation to pass into it (no reflected energy) and internally absorbs all the incident radiation (no energy transmitted through the body). This is true for radiation of all wavelengths and for all angles of incidence. Hence the blackbody is a perfect absorber for all incident radiation. The theory of the energy distribution of blackbody radiation was developed by Planck and first appeared in 1901.

1.3 Planck's Radiation Formula:

Planck assumed the presence of number of resonators (harmonic oscillators) inside the cavity of the black-body and used the quantum by hypothesis to derive the formula. According to planck's quantum hypothesis , an oscillator can have only discrete energies given by

$$E_n = nh\nu = nE$$

Where $n = 0,1,2\ldots$

ν is the frequency of the oscillator h is plank's constant n is an integer (including o) known as quantum number. Thus an oscillator can have energies o, hν, 2hν,…. And the oscillator cannot emit or absorb energy continuously but in quanta of energy hν. We shall first calculate average energy of the oscillator of frequency ν. if N is the total number of oscillators and E their total energy, then average energy per planck's oscillator is given by

$$\overline{E} = E/N$$

Let $N=N_0, N_1,\ldots\ldots, N_r\ldots\ldots$be the number of oscillators having o , hν, 2hν,…..rhν, respectively.

The relative probability that an oscillator will have the energy hν at temperature T is exp(-hν/kT) where k is Boltzmann constant. In other words, according to Maxwell's law of molecular motions if ε is a certain amount of energy, the probabilities that number of particles with energies o, ε, 2ε……rε are in the ratio

1: $e^{-\varepsilon/kT}$: $e^{-2\varepsilon/kT}$:…….$e^{-r\,\varepsilon/kT}$

As said earlier if N_o is the number of resonators having energy zero, then the number of resonators N_1 having energy ε will be No $e^{-\varepsilon/kT}$, the number of resontors N_2 having energy ε will be $N_o^{-2\varepsilon/kT}$ and so on.

Thus, we have

$$Nr = N_o \exp[-rhv/kT]$$

And N= $N_o + N_1 + N_2 + \ldots\ldots. N_r + \ldots\ldots$

$$= N_o + No\exp\left[\frac{-hv}{kT}\right] + No\exp\left[\frac{-2hv}{kT}\right] + \ldots.. No\exp\left[\frac{-rhv}{kT}\right] + \ldots.$$

$$\text{Put } exp\left[\frac{-hv}{kT}\right] = x$$

$$N = No\,(1+x+x^2+\ldots\ldots\ldots\ldots\ldots\, x^r$$

$$N = No\,(1-x)^{-1}$$

As $(1-x)^{-1} = 1+x+x^2+\ldots\ldots x^r$

Now the total energy E is given by

$$E = No\,X_O + hv\,No\exp[-hv/kT] + 2hvNo\exp[-2hv/kT] + \ldots.rhv\,No\exp[-rhv/kT] + \ldots.$$

$$Nohv\,(1+2x+3x^2+4x^3\ldots\ldots\ldots\,(r+1)\,x^r$$

$$E = \frac{N_a hv}{(1-x)^2}$$

As $1+2x+3x^2+\ldots\ldots\ldots rx^{r-1}+\ldots. = 1/(1-x)^2$

$$\overline{E} = N_o hv(1-x)^{-2}$$

Now the average energy of the oscillator is given by

$$\overline{E} = \frac{N_o hv}{(1-x)^{-2}} \Big/ \frac{N_0}{(1-x)}$$

$$= \frac{hv}{(1-x)}$$

$$= \frac{\mathrm{h}\nu}{1 - \mathrm{e}^{-\mathrm{h}\nu/\mathrm{kT}}} \qquad \text{with E = h}v$$

$$\bar{E} = \frac{hv}{\left\{\exp\left[\frac{hv}{kT}\right] - 1\right\}}$$

Thus we see that the average energy of oscillator given by Eqn. is different form the energy KT of a classical oscillator.

If we assume that the number of oscillator given by Eqn. $\left[\frac{8\pi\upsilon^3}{c^3}\right]d\upsilon$, then we get the total energy per unit volume belonging dv or the energy density belonging to the range dv as

$$Evdv = \left[\frac{8\pi v^3}{c^3}\right]\left[\frac{hv}{\exp\left[\frac{hv}{kT}\right] - 1}\right]dv$$

This is the famous Planck's radiation law

But $v = c/\lambda$ and $|dv| = -\frac{c}{\lambda^2}d\lambda$

$$\text{ie } E\lambda d\lambda = \frac{8\pi h}{c^3}\left[\frac{c^3}{\lambda^3}\right]\frac{1}{\left\{\exp\left[\frac{ch}{\lambda kT}\right] - 1\right\}}\left[\frac{c}{\lambda^2}d\lambda\right]$$

therefore

$$E\lambda d\lambda = \left[\frac{8\pi hc}{\lambda^5}\right]\left[\frac{1}{\exp\left[\frac{ch}{\lambda kT}\right] - 1}\right]d\lambda$$

This equation of Planck well agrees with the experimental value throughout the whole range of wavelength.

With the help of planck's radiation law, wien's displacement law and Rayleigh-Jeans law can be derived in the following way:

For small temperature , λT is small. Now exp(hc/λkT)>>1 and 1 can be neglected in the denominator or Eqn.

$$E\lambda d\lambda = \frac{8\pi ch}{\lambda^5}\left\{\exp\left(\frac{-ch}{\lambda kT}\right)\right\}d\lambda$$

$$= C_1\lambda^{-5}\left\{exp\left(\frac{C_2}{\lambda T}\right)\right\}d\lambda \quad \text{where } C_1 = 8\pi ch,\ C_2 = \frac{ch}{k}$$

which is **Wein's law**

Rayleigh- Jeans law

For large temperatures λT is large.

$$\text{Now } \exp\left(\frac{ch}{\lambda kT}\right) = 1 + \left(\frac{ch}{\lambda kT}\right) + \tfrac{1}{2}\left(\frac{ch}{\lambda kT}\right)^2 + \ldots\ldots\ldots\ldots$$

$$= 1 + \left(\frac{ch}{\lambda kT}\right)$$

$$E\lambda d\lambda = \frac{8\pi ch}{\lambda^5}\left[\frac{1}{1+\left(\frac{ch}{\lambda kT}\right)-1}\right]d\lambda$$

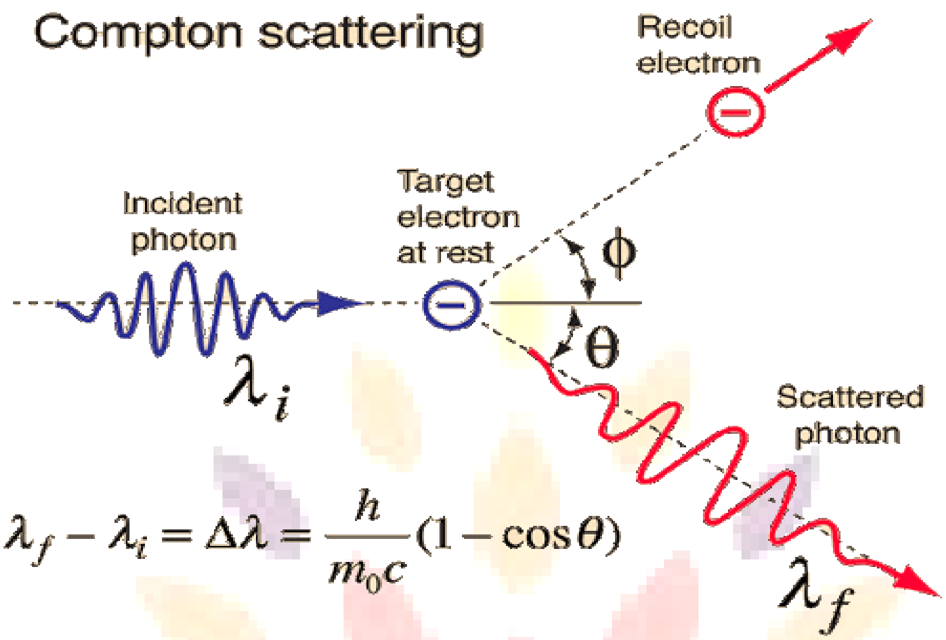
$$\text{i.e.} \quad E\lambda d\lambda = \frac{8\pi ch}{\lambda^5}\times\frac{\lambda kT}{Ch^5}d\lambda = \frac{8\pi KT}{\lambda^4}d\lambda$$

This is **Rayleigh- Jeans law**

where it should be clearly understood that the quantization of energy in the oscillators is not only confined to the atoms of black body but it is a general concept.

1.4 Compton Effect:

Compton effect is the phenomenon in which a collision between a photon and a particle results in an increase in the kinetic energy of the particle and a corresponding increase in the wavelength of the photon. Or An increase in wavelength of X-rays or gamma rays that occurs when they are scattered.



$$\lambda_f - \lambda_i = \Delta\lambda = \frac{h}{m_0 c}(1 - \cos\theta)$$

Where λ_i = wavelength of incident radiation

$\lambda_f = wavelength\ of\ scattered\ photon$

Θ =angle made by the recoiled electron

CASE 1) : When $\theta=0^0$

$$\lambda_f - \lambda_i = \Delta\lambda = \frac{h}{m_0 c}(1 - cos0^0)$$

$$\lambda_f - \lambda_i = \frac{h}{m_0 c}(1 - 1) \quad \text{since } cos0^0 = 1$$

$$\lambda_f - \lambda_i = \frac{h}{m_0 c}(\,0\,)$$

$$\lambda_f - \lambda_i = 0$$

This indicates no scattering along the direction of incidence

CASE 2) : When $\theta=90^0$

$$\lambda_f - \lambda_i = \Delta\lambda = \frac{h}{m_0 c}(1 - cos90^0)$$

$$\lambda_f - \lambda_i = \frac{h}{m_0 c}(1 - 0) \quad \text{since } cos90^0 = 0$$

$$\lambda_f - \lambda_i = \frac{h}{m_0 c}(1)$$

$$\lambda_f - \lambda_i = \frac{h}{m_0 c} = \frac{6.625 * 10^{-34}}{9.1 * 10^{-31} * 3 * 10^{8}} = 0.02445 A^0$$

This difference in wavelength is known as Compton wavelength

CASE 3) : When $\theta = 180^0$

$$\lambda_f - \lambda_i = \Delta\lambda = \frac{h}{m_0 c}(1 - \cos 180^0)$$

$$\lambda_f - \lambda_i = \frac{h}{m_0 c}(1 - (-1)) \text{ since } \cos 180^0 = -1$$

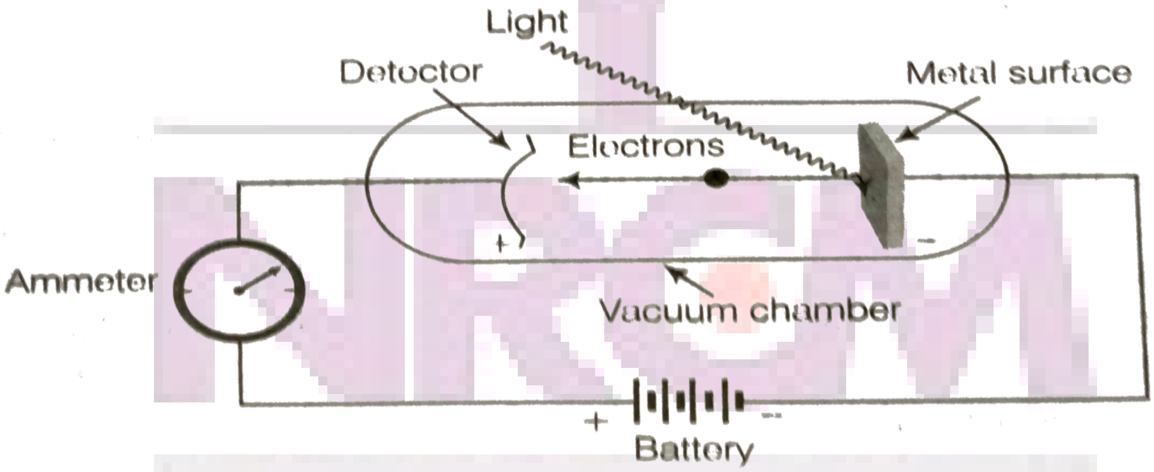
$$\lambda_f - \lambda_i = \frac{h}{m_0 c}(2)$$

$$\lambda_f - \lambda_i = \frac{2h}{m_0 c} = \frac{2 * 6.625 * 10^{-34}}{9.1 * 10^{-31} * 3 * 10^{8}} = 0.4849 A^0$$

Hence as θ varies from 0^0 to 180^0, the wavelength of the scattered radiation increases from λ to $\lambda + \frac{2h}{m_0 c}$

1.5 Photoelectric effect:

The photoelectric effect is the emission of electrons when electromagnetic radiation, such as light, hits a material. Electrons emitted in this manner are called photoelectrons.



The apparatus used to study photo electric effect is shown above.

It consists of an evacuated tube which contains two electrodes. One is connected to the negative terminal of the battery while other is connected to the positive terminal of the battery through ammeter.

In the absence of light there is no flow of current .

When monochromatic light is allowed to fall on the metal surface the electrons are ejected and travel towards the detector. This results a current flow in the circuit.

The no.of ejected electrons and their kinetic energy depends upon the following factors :

1) The potential difference between the two plates.

2) The intensity of incident radiation.

3) The frequency of incident radiation.

4) The photo metal used.

Laws of photoelectric effect:

(i) There is a definite cut off value of frequency below which electrons cannot be ejected by any substance.
(ii) Number of emitted electrons are directly proportional to the intensity of light incident.
(iii) Kinetic energy of emitted electrons depends on the frequency of incident light on substance.
(iv) There is no time logging between the incident of light and emission of electrons.

1.6 Waves and Particles:

De Broglie suggested that the radiation has dual nature i,e both particle as well as wave nature. The concept of particle is easy to grasp. It has mass, velocity, momentum and energy. The concept of wave is a bit more difficult than that of a particle. A wave is spread out over a relatively large region of space, it cannot be said to be located just here and there, and it is hard to think of mass being associated with a wave. A wave is specified by its frequency, wavelength, phase, amplitude, intensity.

Considering the above facts, it appears difficult to accept the conflicting ideas that radiation has dual nature. However this acceptance is essential because radiation sometimes behaves as a wave and at other times as a particle.

(1) Radiations behaves as waves in experiments based on interference, diffraction, polarization etc. this is due to the fact that these phenomena require the presence of two waves at the same position and at the same time. Thus we conclude that radiation behaves like wave.
(2) Plank's quantum theory was successful in explaining blackbody radiation, photoelectric effect, Compton Effect and had established that the radiant energy, in its interaction with the matter, behaves as though it consists of corpuscles. Here radiation interacts with matter in the form of photons or quanta. Thus radiation behaves like particle.

Hence radiation cannot exhibit both particle and wave nature simultaneously.

1.7 de-Broglie hypothesis:

As electromagnetic waves behave like particles and Particles like electrons will behave like waves called **matter waves**. The matter waves thus conceived by de-Broglie are de-Broglie matter waves. He derived an expression for the wavelength of matter waves on the analogy of radiation

Based on the Planck’s theory of radiation, the energy of a photon (Quanta) is given by

$$E = h\nu \qquad since\ \nu = \frac{C}{\lambda}$$

$$E = h\frac{C}{\lambda} \ldots \ldots \ldots \ldots \ldots (1)$$

C→ is velocity of light

λ is wavelength

According to Einstein mass-energy relation

From eqns (1) and (2)

$$\frac{hC}{\lambda} = mC^2$$

$$\lambda = \frac{h}{mC} = \frac{h}{P}$$

Where: $P = mC$ → is momentum of photon

λ → s de-Broglie wavelength associated with a photon.

De-Broglie proposed the concept of matter waves, according to which a material particle of mass ‘m’ moving with velocity ‘v’ should be associated with de-Broglie wavelength ‘λ’ given by

Wavelwngth for particle can be written as

$$\lambda = \frac{h}{mv} = \frac{h}{P}$$

Where: $P = mv$ →momentum associated with particle

De-Broglie suggested that this equation for wavelength is a perfectly general one, applying to, material particles as well as to photons.

If E is the kinetic energy of particle

$$E = \frac{1}{2}mv^2 = \frac{1}{2}\frac{m^2v^2}{m} = \frac{1}{2}\frac{P^2}{m}$$

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

Hence de-Broglie’s wave length is

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

de-Broglie’s wave length of Electron

If m_0 is the rest mass of electron and it is accelerated with a potential V. if v is the velocity attained by electron due to acceleration.

Kinetic energy of electron

$$E = \frac{1}{2} m_0 v^2 \ldots\ldots\ldots\ldots\ldots\ldots\ldots 1$$

Energy of electron due to application of potential

$$E = eV \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots .2$$

From 1 and 2

$$\frac{1}{2} m_0 v^2 = eV$$

$$\frac{1}{2} {m_0}^2 v^2 = m_0 eV$$

$${m_0}^2 v^2 = 2m_0 eV$$

$$P^2 = 2m_0 eV$$

From de-Broglie wave length

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

$$\lambda = \frac{h}{\sqrt{2m_0 eV}}$$

$$\lambda = \frac{h}{\sqrt{2 * V * 9.1 * 10^{-31} * 1.63 * 10^{-19}}}$$

$$\lambda = \frac{12.26}{\sqrt{V}} A^0$$

The above expression is for non relativistic case since relative variation of mass with velocity is not considered. Thus accelerated electrons exhibit wave nature corresponding to wave length of x rays. This concept only helped Davisson & Germer to provide experimental evidence on matter waves when they conducted electron diffraction experiments.

Characteristics of Matter waves:

Since $\lambda = h / m v$

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 waves is associated.
4. Whether the particle is changed or not, matter waves is associated with it.
5. It can be proved that matter waves travel faster than light.

We know that $E = h\nu$ and $E = mc^2$

$h\nu = mc^2$ or $\nu = mc^2 / h$

Wave velocity (ω) is given by

$$\omega = \nu \lambda = m c^2 \lambda / h = (m c^2 / h)(h / m v)$$

⇨ $\omega = c^2 / v$

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

6. No single phenomena exhibit both particle nature and wave nature simultaneously.
7. The wave nature of matter introduces an uncertainty in the location of the particle & the momentum of the particle exists when both are determined simultaneously.

1.8 Davisson and Germer's experiment:

C. J. Davisson and L. H. Germer were studying scattering of electrons by a metal target and measuring the intensity of electrons scattered in different directions.

Experimental Arrangement:

An electron gun, which comprises of a tungsten filament is heated by a low tension battery B1, produces electrons. These electrons are accelerated to desired velocity by applying suitable potential from a high tension source B2. The accelerated electrons are collimated into a fine beam by allowing them to pass through a system of pin holes provided in the cylinder. The whole instrument is kept in an evacuated chamber.

The past moving beam of electrons is made to strike the Nickel target capable of rotating about an axis perpendicular to the plane. The electrons are now scattered in all directions by the atomic planes of crystals. The intensity of the electron beam scattered in a direction can be measured by the electron collector which can be rotated about the same axis as the target. The collector is connected to a galvanometer whose deflection is proportional to the intensity of the electron beam entering the collector.

The electron beam is accelerated by 54 V is made to strike the Nickel crystal and a sharp maximum is occurred at angle of 50^o with the incident beam. The incident beam and the diffracted beam in this experiment make an angle of 65^o with the family of Bragg's planes.

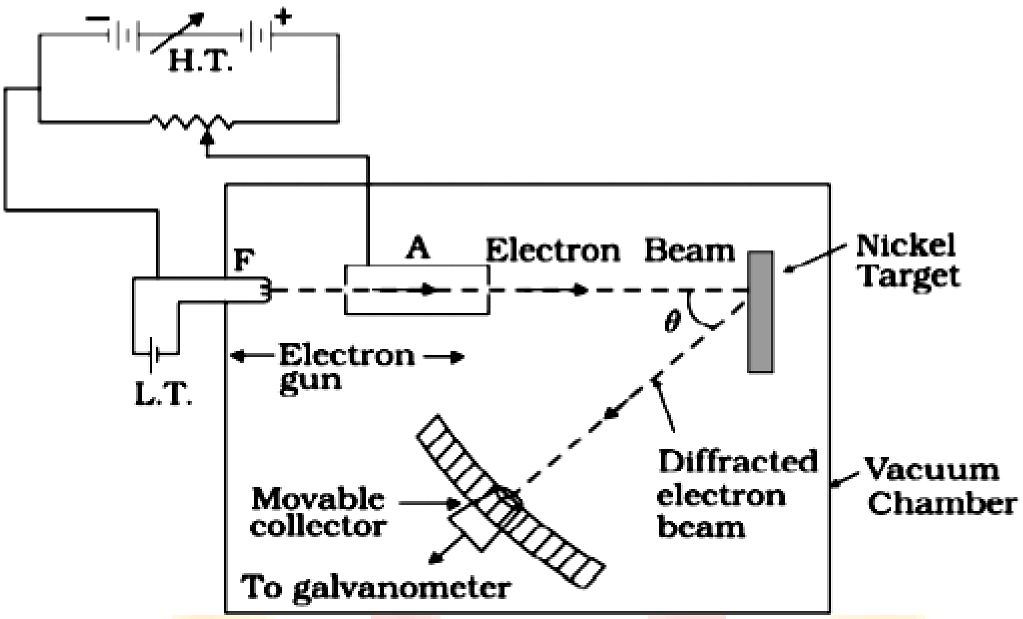


Fig. Davisson and Germer's Apparatus

$$d = 0.091\text{nm} \quad \text{(for Ni crystals)}$$

According to Bragg's law for maxima in diffracted pattern,

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

$$\text{For } n = 1, \quad \lambda = 2d \sin \theta$$

$$= 2 \text{ x}0.91\text{x } 10^{-10}\text{x } \sin 65^{o}$$

$$= 0.165 \text{ nm}$$

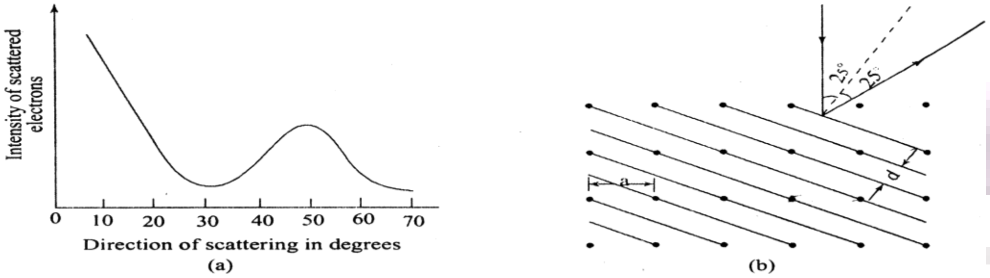


Figure : (a) The variation of the intensity of scatterd electrons with the direction of scattering and (b) nickel crystal acting as a grating

For a 54 V electron, the deBrogllie wavelength associated with the electron is given by

$$= 12.25 / \sqrt{V} = (12.25 / \sqrt{54})\ ^{o}A$$

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

This value is in agreement with the experimental value. This experiment provides a direct verification of deBroglie hypothesis of wave nature of moving particles.

1.9 Heisenberg Uncertainty Principle:

According to classical mechanics, a moving particle at any instant has a fixed position in space and a definite momentum which can be determined simultaneously with any desired accuracy. The classical point of view represents an approximation which is adequate for the objects of appreciable size, but not for the particles of atomic dimensions.

Since a moving particle has to be regarded as a de Broglie group, there is a limit to the accuracy with which we can measure the particle properties. The particle may be found anywhere within the wave group, moving with the group velocity. If the group is narrow, it is easy to locate its position but the uncertainty in calculating its velocity or momentum increases. On the other hand, if the group is wide, its momentum can be estimated satisfactorily, but the uncertainty in finding the location of the particle is great. Heisenberg stated that the simultaneous determination of exact position and momentum of a moving particle is impossible.

If Δx is Error in the measurement of position of the particle along X-axis

Δp is Error in the measurement of momentum

Then $\Delta x . \Delta p = h$-----------(1) where h is Plank's constant

The above relation represents the uncertainty involved in measurement of both the position and momentum of the particle.

To optimize the above error, lower limit is applied to the eqn. (1)

Then $(\Delta x). (\Delta p) \geq \hbar / 2$ where $\hbar = h / 2 \Pi$

A particle can be exactly located ($\Delta x \rightarrow 0$) only at the expense of an infinite momentum ($\Delta p \rightarrow \infty$).

There are uncertainty relations between position and momentum, energy and time, and angular momentum and angle.

If the time during which a system occupies a certain state is not greater than Δt, then the energy of the state cannot be known within ΔE,

i e $(\Delta E)(\Delta t) \geq$ ђ / 2 .

1.10 Schrodinger's Time Independent Wave Equation:

Schrödinger, in 1926, developed wave equation for the moving particles. One of its forms can be derived by simply incorporating the de-Broglie wavelength expression into the classical wave eqn.

If a particle of mass moving with velocity 'v' is associated with a group of waves.

Let ψ be the wave function of the particle. Also let us consider a simple form of progressing wave like the one represented by the following equation,

$$\psi = \psi_0 \sin(\omega t - kx) \ldots\ldots\ldots\ldots (1)$$

Where $\psi = \psi(x, t)$ and ψ_0 is the amplitude.

Differentiating ψ partially w.r.to x,

$$\frac{\partial \psi}{\partial x} = \psi_0 \cos(\omega t - kx)(-k)$$

$$= -k\psi_0 \cos(\omega t - kx)$$

Once again differentiate w.r.to x

$$\frac{\partial^2 \psi}{\partial x^2} = -k\psi_0(-\sin(\omega t - kx))(-k)$$

$$= -k^2\psi_0 \sin(\omega t - kx)$$

$$\frac{\partial^2 \psi}{\partial x^2} = -k^2\psi \qquad from\ eq\ (1)$$

$$\frac{\partial^2 \psi}{\partial x^2} + k^2\psi = 0 \ldots\ldots\ldots\ldots\ldots (2)$$

Since $k = \frac{2\pi}{\lambda}$

$$\frac{\partial^2 \psi}{\partial x^2} + \frac{4\pi^2}{\lambda^2}\psi = 0 \ldots\ldots\ldots\ldots (3)$$

From eqn. (2) or eqn. (3) is the differential form of the classical wave eqn. now we incorporate de-Broglie wavelength expression $\lambda = \frac{h}{mv}$

Thus we obtain

$$\frac{\partial^2\psi}{\partial x^2}+\frac{4\pi^2}{\left(\frac{h}{mv}\right)^2}\psi=0$$

$$\frac{\partial^2\psi}{\partial x^2}+\frac{4\pi^2m^2v^2}{h^2}\psi=0\ldots\ldots\ldots\ldots(4)$$

The total energy E of the particle is the sum of its kinetic energy K and potential energy V

$$E=K.E.+P.E\ldots\ldots\ldots(5)$$

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

$$E-V=\frac{1}{2}mv^2\ldots\ldots(6)$$

$$2(E-V)=mv^2$$

$$2m(E-V)=m^2v^2\ldots\ldots(7)$$

From (4) and (7)

$$\frac{\partial^2\psi}{\partial x^2}+\frac{8\pi^2m(E-V)}{h^2}\psi=0\ldots\ldots\ldots\ldots(8)$$

In quantum mechanics, the value $\frac{h}{2\pi}$ occurs more frequently.

Hence we denote, $\hbar=\frac{h}{2\pi}$

Using this notation, we have

$$\frac{\partial^2\psi}{\partial x^2}+\frac{2m(E-V)}{\hbar^2}\psi=0\ldots\ldots\ldots\ldots(9)$$

For simplicity, we considered only one – dimensional wave. Extending eqn. (9) for a three – dimensional, we have

$$\frac{\partial^2\psi}{\partial x^2}+\frac{\partial^2\psi}{\partial y^2}+\frac{\partial^2\psi}{\partial z^2}+\frac{2m(E-V)}{\hbar^2}\psi=0\ldots\ldots\ldots\ldots(10)$$

Where $\psi=\psi(x,y,z)$

Here, we have considered only stationary states of ψ after separating the time dependence of ψ.

Using the Laplacian operator,

$$\nabla^2=\frac{\partial^2}{\partial x^2}+\frac{\partial^2}{\partial y^2}+\frac{\partial^2}{\partial z^2}\ldots\ldots\ldots\ldots(11)$$

Eqn. (10) can be written as

$$\nabla^2\psi+\frac{2m(E-V)}{\hbar^2}\psi=0\ldots\ldots\ldots\ldots(12)$$

This is the Schrödinger Time Independent Wave Equation.

Physical Significance of Wave Function:

Max Born in 1926 gave a satisfactory interpretation of the wave function ψ associated with a moving particle. He postulated that the square of the magnitude of the wave function $|\psi|^2$(or $\psi\psi^*$), evaluated at a particular point represents the probability of finding the particle at the point. $|\psi|^2$ is called the probability density and ψ is the probability amplitude. Thus the probability of the particle within an element volume $d\tau$ is $|\psi|^2\ d\tau$. Since the particle is certainly somewhere, the integral at $|\psi|^2\ d\tau$ over all space must be unity i.e.

$$\int_{-\infty}^{\infty}|\psi|^2\ .d\tau = 1$$

A wave function that obeys the above equations is said to be normalized. Energy acceptable wave function must be normalizable besides being normalizable; an acceptable wave function should fulfill the following requirements (limitations)

It must be finite everywhere.

It must be single valued.

It must be continuous and have a continuous first derivative everywhere.

Normalization of a wave function:

Since $|\psi(x, y, z)|^2.d\nu$ is the probability that the particle will be found in a volume element $d\nu$. Surrounding the point at position (x, y, z), the total probability that the particle will be somewhere in space must be equal to 1. Thus, we have

$$\int_{-\infty}^{\infty}|\psi(x, y, z)^2|.d\nu = 1$$

Where ψ is a function of the space coordinates (x, y, z) from this ‘normalization condition’ we can find the value of the complaint and its sign. A wave function which satisfies the above condition is said to be normalized (to unity).

The normalizing condition for the wave function for the motion of a particle in one dimension is

$$\int_{-\infty}^{\infty}|\psi(x)|^2.dx = 1$$

From these equations, we see that for one – dimensional case, the dimension of $\psi(x)$ is $L^{-1/2}$ and for the three dimensional case the dimension of $\psi(x, y, z)$ is $L^{-3/2}$.

1.11 Particle in One Dimensional Potential Box:

Consider a particle of mass 'm' placed inside a one-dimensional box of infinite height and width L.

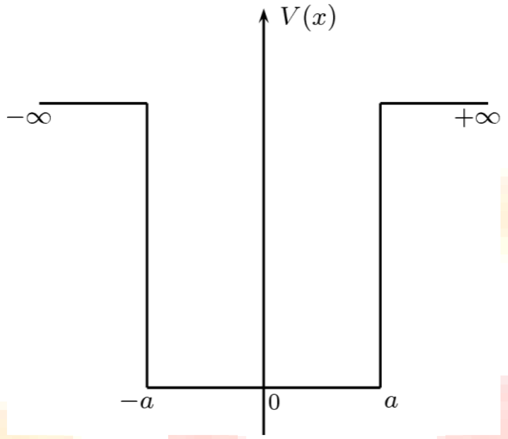


Fig. Particle in a potential well of infinite height.

Assume that the particle is freely moving inside the box. The motion of the particle is restricted by the walls of the box. The particle is bouncing back and forth between the walls of the box at x = 0 and x = a. For a freely moving particle at the bottom of the potential well, the potential energy is very low. Since the potential energy is very low, moving particle energy is assumed to be zero between x =0 and x = a.

The potential energy of the particle outside the walls is infinite due to the infinite P.E.

The particle cannot escape from the box

i.e. $V = 0$ for $0 < x < a$

$V = \infty$ for $0 \geq x \geq a$

Since the particle cannot be present outside the box, its wave function is zero

i e $|\psi| = 0$ for $0 > x > a$

$|\psi| = 0$ for $x = a$ & $x = 0$

The Schrödinger one – dimensional time independent eqn. is

$$\frac{\partial^2\psi}{\partial x^2} + [2\,m\,(E - V) / \hbar^2]\,\psi = 0 \text{----------(1)}$$

For freely moving particle $V = 0$

$$\frac{\partial^2\psi}{\partial x^2} + [\,2\,m\,E\ /\ \hbar^2\,]\,\psi = 0 \text{----------(2)}$$

$$\text{Taking} \quad 2\,m\,E / \hbar^2 = K^2 \text{-----------------------}(3)$$

$$\text{Eqn.(1) becomes} \quad \partial^2 \psi / \partial x^2 + k^2 \Psi = 0 \text{------------- } (4)$$

Eqn. (1) is similar to eq. of harmonic motion and the solution of above eqn. is written as

$$\Psi = A \sin kx + B \cos kx \text{----------- } (5)$$

where A, B and k are unknown quantities and to calculate them it is necessary to construct boundary conditions.

Hence boundary conditions are

When $x = 0$, $\Psi = 0$ => from (5) $0 = 0 + B$ => $B = 0$--------- (6)

When $x = a$, $\Psi = 0$ => from (5) $0 = A \sin ka + B \cos ka$-----------(7)

But from (6) $B = 0$ therefore eqn. (7) may turn as

$$A \sin ka = 0$$

Since the electron is present in the box $a \neq 0$

$$\sin ka = 0$$

$$Ka = n\,\Pi$$

$$k = n\,\Pi / a \text{----------------- } (8)$$

Substituting the value of k in eqn. (3)

$$2\,m\,E / \hbar^2 = (n\,\Pi / a)^2$$

$$E = (n\,\Pi / a)^2 \; (\hbar^2 / 2\,m) = (n\,\Pi / a)^2 \; (h^2 / 8\,m\,\Pi^2)$$

$$E = n^2\, h^2 / 8\,m\,a^2$$

$$E = n^2\, h^2 / 8\,m\,a^2$$

$$\text{In general } E_n = n^2\, h^2 / 8\,m\,a^2 \text{---------------------}(9)$$

The wave eqn. can be written as

$$\Psi = A \sin (n\,\Pi\,x / a) \text{---------- } (10)$$

Let us find the value of A, if an electron is definitely present inside the box, then

$$=> \int_{-\infty}^{\infty} |\psi|^2 \, dx = 1$$

$$=> \int_0^a A^2 \sin^2 (n\,\Pi\,x / a)\, dx = 1$$

$$=> \int_0^a \sin^2 (n\,\Pi\,x / a)\, dx = 1 / A^2$$

$$=> \int_0^a [1 - \cos (2\,\Pi\,n\,(x / a)) / 2]\, dx = 1 / A^2$$

$$A = \sqrt{2/a} \text{-------------} (11)$$

From eqn's. (10) & (11)

$$\Psi n = \sqrt{2/a} \ \sin(n\Pi x/a) \text{----------} (12)$$

Eqn. (9) represents an energy level for each value of n. The wave function for this energy level is given in eqn. (12). Therefore the particle in the box can have discrete values of energies. These values are quantized. Not that the particle cannot have zero energy .The normalized wave functions Ψ1 , Ψ2, Ψ3 given by eqn (12) is plotted. The values corresponding to each E_n value is known as Eigen value and the corresponding wave function is known as Eigen function.

The wave function Ψ_1, has two nodes at x = 0 & x = a

The wave function Ψ_2, has three nodes at x = 0, x = a / 2 & x = a

The wave function Ψ_3, has three nodes at x = 0, x = a / 3, x = 2 a / 3 & at x = a

The wave function Ψ_n, has (n + 1) nodes

Substituting the value of E in (3), we get

For three dimensional potential box, the eigen functions are given by

Ψ_{n2} $\sin k_1 \times \sin k_2 \times \sin k_3$

Where $k_1 = \frac{n_1\pi}{a}, k_2 = \frac{n_2\pi}{a}, k_3 = \frac{n_2\pi}{a},$

Eigen values are given by $E_n = \frac{n^2 h^2 \pi}{8ma^2}$

Eigen values are given by

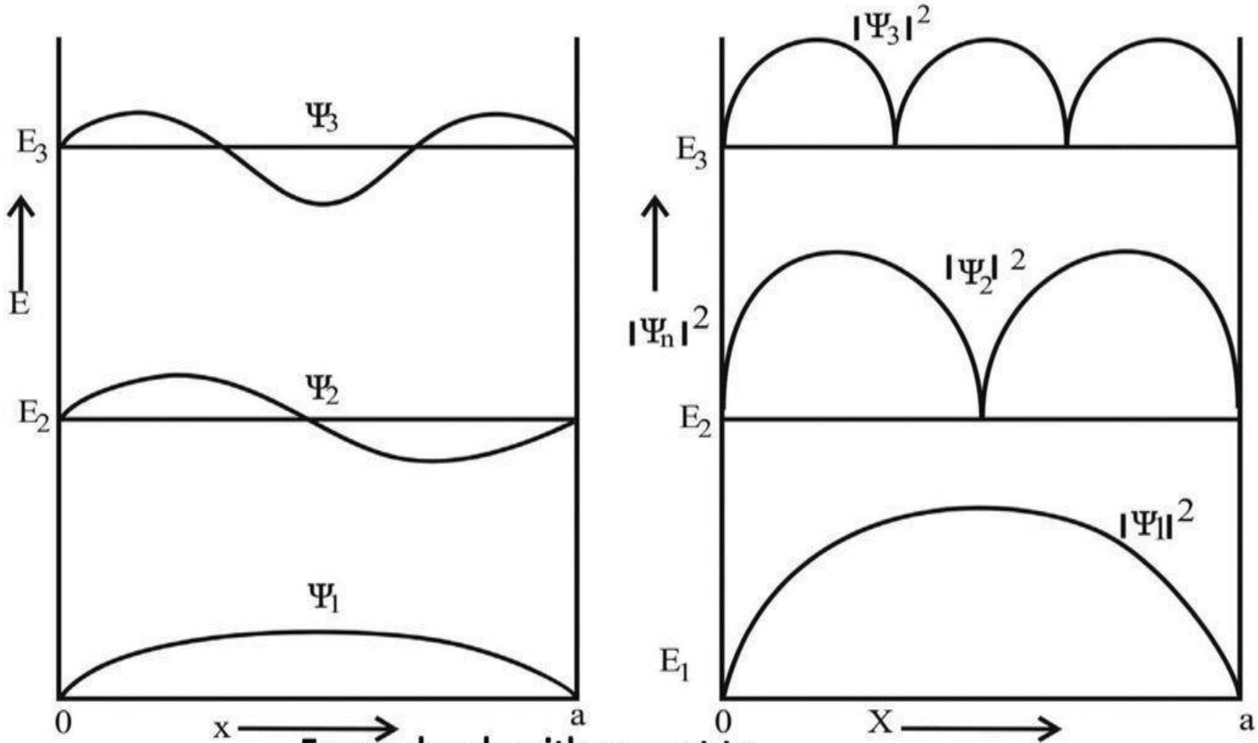
$(2\,m / \hbar^2)\,(p^2 / 2\,m) = k^2$

Where n = $n = n_1^2 + n_2^2 + n_3^2$

$\Rightarrow p^2 / \hbar^2 = k^2$

$k = p / \hbar = p / (h / 2\,\Pi) = 2\,\Pi\,p / h$

$k = 2\,\Pi / \lambda$ where k is known as wave vector.



Energy levels with respect to
(a) wave functions and (b) probability density

Therefore, the normalized wave function is given as,

$$\Psi_n = \sqrt{\frac{2}{a}}\, \sin \frac{n\pi}{a} x$$

1.	Equation for wavelength of a Photon is $\lambda = \frac{h}{mc}$	**6.**	Eigen energy level of a particle is given by $E_n = \frac{n^2h^2}{8mL^2}$
2.	De Broglie's wavelength for a particle associated with some velocity is $\lambda = \frac{h}{mv}$	**7.**	Equation for the particle in a one dimensional box is given by $\psi = (\sqrt{\frac{2}{L}})\sin\frac{n\pi x}{L}$
3.	De Broglie's wavelength for a particle with some energy is $\lambda = \frac{h}{\sqrt{2mE}}$	**8.**	Heisenberg's Uncertainty Principle for position & momentum is given by $\Delta x.\Delta p \geq \frac{h}{4\pi}$
4.	De Broglie's wavelength for a particle associated with T is $\lambda = \frac{h}{\sqrt{3kT}}$	**9.**	Schrodinger wave equation(time independent) is $\nabla^2\psi + \frac{2m}{\hbar^2}(E - v)\psi = 0$
5.	De Broglie's wavelength associated with an electron with potential is $\lambda = \frac{1.226}{\sqrt{v}}nm$	**10**	Compton shift $\lambda_f - \lambda_i = \Delta\lambda = \frac{h}{m_0 c}(1 - cos0^0)$

ELECTRON THEORY OF SOLIDS

1. 12 FREE ELECTRON THEORY

In solids, electrons in outer most orbits of atoms determine its electrical properties. Electron theory is applicable to all solids, both metals and non metals. In addition, it explains the electrical, thermal and magnetic properties of solids. The structure and properties of solids are explained employing their electronic structure by the electron theory of solids.

It has been developed in three main stages:

1. Classical free electron theory
2. Quantum Free Electron Theory.
3. Zone Theory.

Classical free electron theory: The first theory was developed by Drude & Lorentz in 1900. According to this theory, metal contains free electrons which are responsible for the electrical conductivity and metals obey the laws of classical mechanics.

Quantum Free Electron Theory: In 1928 Sommerfield developed the quantum free electron theory. According to Sommerfield, the free electrons move with a constant potential. This theory obeys quantum laws.

Zone Theory: Bloch introduced the band theory in 1928. According to this theory, free electrons move in a periodic potential provided by the lattice. This theory is also called “Band Theory of Solids”. It gives complete informational study of electrons.

Classical free electron theory:

Even though the classical free electron theory is the first theory developed to explain the electrical conduction of metals, it has many practical applications. The advantages and disadvantages of the classical free electron theory are as follows:

Advantages:

1. It explains the electrical conductivity and thermal conductivity of metals.
2. It verifies ohm’s law.
3. It is used to explain the optical properties of metals.
4. Metal composed of atoms in which electrons revolve around the nucleus are many states available for occupation. If the density of states is zero, no states can be occupied at that energy level.
5. The valence electrons are freely moving about the whole volume of the metals like the molecules of perfect gas in a container

6. The free electrons moves in random directions and collide with either positive ions or other free electrons. Collision is independent of charges and is elastic in nature
7. The movements of free electrons obey the laws of classical kinetic theory of gases
8. Potential field remains constant throughout the lattice.
9. In metals, there are large numbers of free electrons moving freely within the metal i.e. the free electrons or valence electrons are free to move in the metal like gaseous molecules, because nuclei occupy only 15% metal space and the remaining 85% space is available for the electrons to move.

Drawbacks:

1. It fails to explain the electric specific heat and the specific heat capacity of metals.
2. It fails to explain superconducting properties of metals.
3. It fails to explain new phenomena like photoelectric effect, Compton effect, black – Body radiation, etc.
4. It fails to explain Electrical conductivity (perfectly) of semiconductors or insulators.
5. The classical free electron model predicts the incorrect temperature dependence of
6. It fails to give a correct mathematical expression for thermal conductivity.
7. Ferromagnetism couldn't be explained by this theory.
8. Susceptibility has greater theoretical value than the experimental value.

Quantum free electron theory:

Advantages:

1. All the electrons are not present in the ground state at 0 K, but the distribution obeys Pauli's exclusion principle. At 0 K, the highest energy level filled is called Fermi- level.
2. The potential remains constant throughout the lattice.
3. Collision of electrons with positive ion cores or other free electrons is independent of charges and is elastic in nature. Energy levels are discrete.
4. It was successful to explain not only conductivity, but also thermionic emission paramagnetism, specific heat.

Drawbacks:

1. It fails to explain classification of solids as conductors, semiconductors and insulators.

1.14 STATISTICAL DISTRIBUTION FUNCTIONS:

The main assumption of Maxwell –Boltzmann statistics are

1. The particles are identical & distinguishable.

2. The volume of each phase space cell chosen is extremely small and hence chosen volume has very large no of cells.

3. Since cells are extremely small, each cell can have either one particle or no particle though there is no limit on the number of particles which can occupy a phase space cell.

4. System is isolated which means both total Energy and total no of particles remain constant.

5. State of each particle is specified either by its cell number in phase. Space or instantaneous position and momentum coordinate.

6. Energy levels are continuous.

7. Maxwell distribution function $F_{MB} = A/\exp(-Ei/kt)$

Where Ei – i_{th} Energy level.

k- Boltzmann constant

T- Absolute temp

8. The particles which obey M-B statistics system consisting of molecules.

Bose - Einstein statistics:

The main assumption of B-E statistics:

1) The particles which obey B-E statistics are called bosons.
2) The Bosons of system are identical & indistinguishable
3) Bosons obey uncertainty principle.
4) Any number of bosons can occupy a single cell in phase space.
5) Bosons do not obey Pauli's Exclusion principle
6) The numbers of phase space cells is comparable with the numbers of bosons .
7) wave functions representing the Bosons are symmetric ie $\psi(2,1) = \psi(1,2)$
8) The wave function s of boson do overlap slightly ie weak interaction exists.
9) Energy states are discrete

i. $$f_{BE}(E) = \frac{1}{\exp\left(\frac{E_F - E_i}{kt}\right) - 1}$$

E_i – i^{th} energy level

E_F- Fermi Energy

T - Absolute temp and k- Boltzmann const.

The particles which obey boson are photons. He_4, π and K- mesons, phonon in a solids, Bosons can have spin of nh/2π where n is integer.

Fermi – Dirac Statistics:

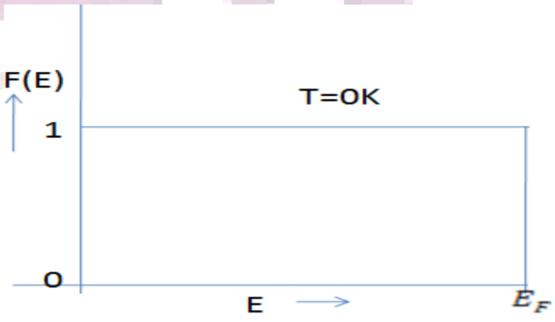
1) The particles which obey F –D statistics are called fermions.
2) Fermions are identical and indistinguishable
3) There cannot be more than one particle in a single cell in phase space i.e they obey Pauli's exclusion principle.
4) Fermions have integral spin
5) Wave function representing fermions are antisymmetric ie $\varphi(1,2) = -\varphi(2,1)$
6) Weak interaction exists between particles
7) Uncertainity principle is applicable.
8) Energy states are discrete.
9) The Fermi Dirac distribution function f(D), is the probability that a fermions occupies a state of energy E and is given by

$$f_{FD}(\varepsilon) = \frac{1}{\exp\left(\alpha + \frac{E}{kt}\right) + 1}$$

α is constant and is dependent on temperature $\alpha = -E_F/k_T$

1.15 Fermi level and Fermi energy

The distribution of energy states in a semiconductor is explained by Fermi-Dirac statistics since it deals with the particles having half integral spin like electrons. Consider that the assembly of electrons as electron gas which behaves like a system of Fermi particles or fermions. The Fermions obeying Fermi–Dirac statistics i.e., Pauli's exclusion principle.



Fermi energy: It is the energy of state at which the

Probability of electron occupation is ½ at any temperature above 0K. It separates filled energy states and unfilled energy states. The highest energy level that can be occupied by an electron at 0 K is called Fermi energy level

Fermi level: It is a level at which the electron probability is ½ at any temp above 0K (or) always it is 1 or 0 at 0K.

Therefore, the probability function F(E) of an electron occupying an energy level E is given by,

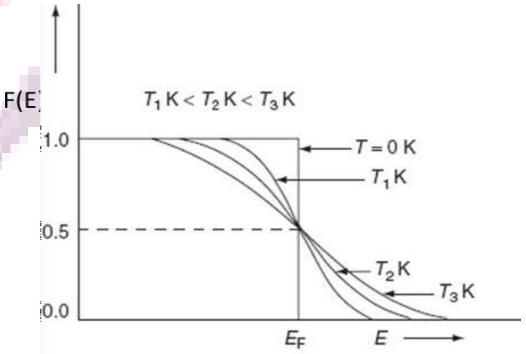
$$f(E)=\frac{1}{1-\exp\left(\frac{E-E_F}{kT}\right)} \quad \text{-------- (1)}$$

Where E_F known as Fermi energy and it is constant for a system,

K is the Boltzmann constant and T is the absolute temperature.

Case I : Probability of occupation at T= 0K,and E < E_F Therefore F(E) =1,as per above ,clearly indicates that at T=0K, the energy level below the Fermi energy level E_F is fully occupied by electrons leaving the upper level vacant.

Therefore, there is 100% probability that the electrons to occupy energy level below Fermi level.



Case II: Probability of occupation at T= 0K, and E > E_F. i.e., all levels below E_F are completely filled and al levels above E_F are completely empty. As the temperature rises F (E).

Case III: Probability of occupation at T= 0K, and E = E_F

$$F(E)=\frac{1}{1+exp^0}=\frac{1}{1+1}=0.5$$

The above condition states that, T=0K, there is a 50% probability for the electrons to occupy Fermi energy.

The probability function F(E) lies between 0 an 1

Hence there are three probabilities namely

1. F(E) =1 100% probability to occupy the energy level by electrons.
2. F(E) =0 No probability to occupy the energy levels by electrons and hence ,it is empty.
3. F(E) =0.5 50% probability of finding the electron in the energy level.

1.16 PERIODIC POTENTIAL AND BLOCH THEOREM:

According to free electron model, a conduction electron in metal experiences constant potential. But in real crystal, there exists a periodic arrangement of positively charged ions through which the electrons move. As a consequence, the potential experienced by electrons is not constant but it varies with the periodicity of the lattice. In zone theory, as per Bloch, potential energy of electrons considered as varying potential with respect to lattice ‘a’.

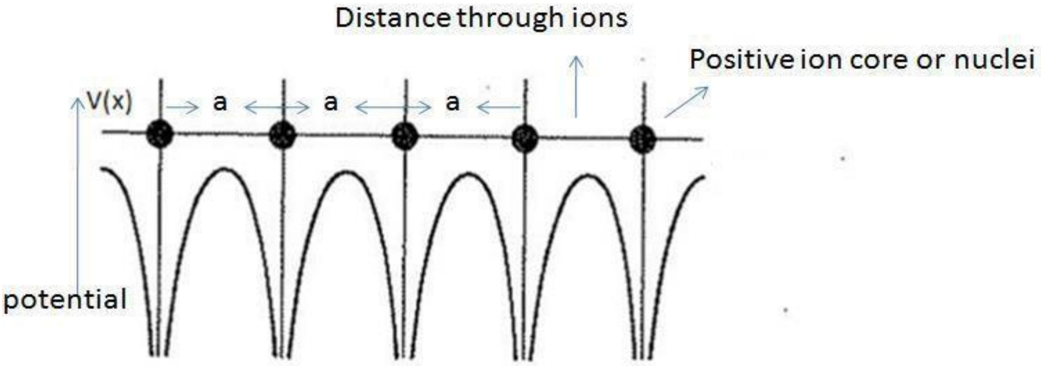
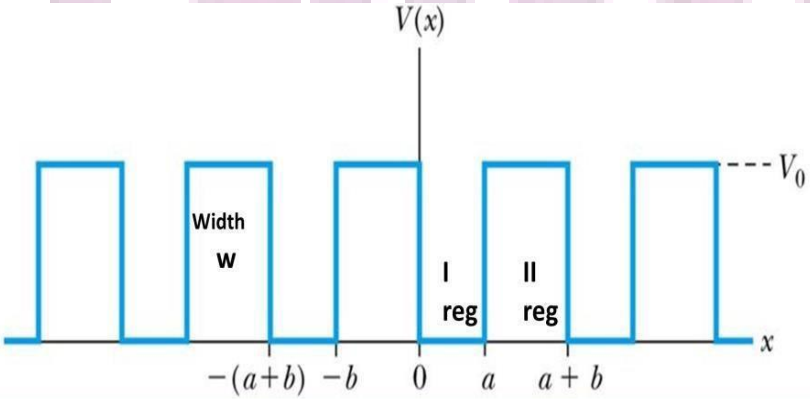


Fig: Variation of potential energy in a periodic lattice

1.17 KRONIG -PENNEY MODEL:

According to this theory, the electrons move in a periodic potential produced by the positive ion cores. The potential of electron varies periodically with periodicity of ion core and potential energy of the electrons is zero near nucleus of the positive ion core. It is maximum when it is lying between the adjacent nuclei which are separated by inter-atomic spacing. The variation of potential of electrons while it is moving through ion core is shown fig.



$V(x) = \{ 0$, for the region $0 < x < a$

$\{ V_0$ for the region $-b < x < a$ ----------------------(1)

Applying the time independent Schrödinger's wave equation for above two regions

$d^2\Psi / dx^2 + 2\,m\,E\,\Psi / \hbar^2 = 0$ for region $0 < x < a$--------------(2)

and $d^2\Psi / dx^2 + 2\,m\,(E - V)\,\Psi / \hbar^2 = 0$ for region $-b < x < a$ ------------(3)

Substituting $\alpha^2 = 2\,m\,E / \hbar^2$-----------------------------(4)

$\beta^2 = 2\,m\,(E - V) / \hbar^2$--------------------(5)

$d^2\Psi / dx^2 + \alpha^2\,\Psi = 0$ for region $0 < x < a$ -------------(6)

$d^2\Psi / dx^2 + \beta^2\,\Psi = 0$ for region $-b < x < a$-------------(7)

The solution for the eqn.s (6) and (7) can be written as

$\Psi(x) = U_k(x)\,e^{ikx}$-------------------------------(8)

The above solution consists of a plane wave e^{ikx} modulated by the periodic function.

$U_k(x)$, where this $U_k(x)$ has the periodicity of the ion such that

$U_k(x) = U_k(x+a)$ --------------------(9)

and where k is propagating vector along x-direction and is given by $k = 2\,\Pi / \lambda$. This k is also known as wave vector.

Differentiating equation (8) twice with respect to x, and substituting in equation (6) and (7), two independent second order linear differential equations can be obtained for the regions $0 < x < a$ and $-b < x < 0$.

Applying the boundary conditions to the solution of above equations, for linear equations in terms of A,B,C and D it can be obtained (where A,B,C,D are constants) the solution for these equations can be determined only if the determinant of the coefficients of A , B , C , and D vanishes, on solving the determinant.

$(\beta^2 - \alpha^2 / 2\,\alpha\,\beta)\sin h\beta b \sin \alpha a + \cos h\beta b \cos \alpha a = \cos k\,(a + b)$--------------- (10)

The above equation is complicated and Kronig and Penney could conclude with the equation. Hence they tried to modify this equation as follows

Let V_o is tending to infinite and b is approaching to zero. Such that $V_o b$ remains finite. Therefore $\sin h\beta b \rightarrow \beta b$ and $\cos h\beta b \rightarrow 1$

$\beta^2 - \alpha^2 = (2\,m / \hbar^2)\,(V_o - E) - (2\,m\,E / \hbar^2)$

$= (2\,m / \hbar^2)\,(V_o - E - E) = (2\,m / \hbar^2)\,(V_o - 2\,E)$

$= 2\, m V_o / \hbar^2$ (since $V_o >> E$)

Substituting all these values in equation (10) it verities as

$$(2\, m V_o / 2\, \hbar^2 \alpha\, \beta)\, \beta b\, .\, \sin \alpha a + \cos \alpha a == \cos\, k a$$

$$(m V_o b\, a / \hbar^2)\ (\sin \alpha a / \alpha a) + \cos \alpha a == \cos\, k a$$

$$(P / \alpha a)\ \sin \alpha a + \cos \alpha a == \cos\, k a \text{------------------------}(11)$$

Where $P = [\ m V_o b\, a / \hbar^2\ ]$ ------------------ (12)

and is a measure of potential barrier strength.

The left hand side of the equation (11) is plotted as a function of α for the value of $P = 3\,\Pi / 2$ which is shown in fig, the right hand side one takes values between -1 to +1 as indicated by the horizontal lines in fig. Therefore the equation (11) is satisfied only for those values of ka for which left hand side between ± 1.

From fig , the following conclusions are drawn.

1) The energy spectrum of the electron consists of a number of allowed and forbidden energy bands.

2) The width of the allowed energy band increases with increase of energy values ie increasing the values of αa. This is because the first term of equation(11) decreases with increase of αa.

$$(P / \alpha a)\ \sin \alpha a + \cos \alpha a == 3\,\Pi / 2$$

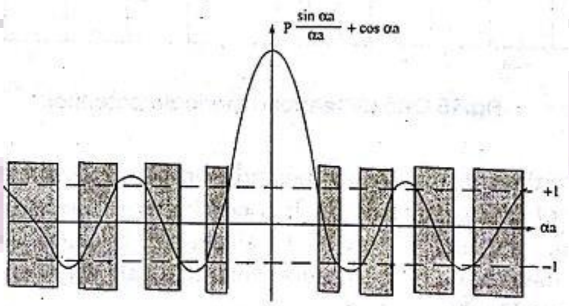


Fig. 16 Plot of $P\dfrac{\sin \alpha a}{\alpha a} + \cos \alpha a$ versus αa.

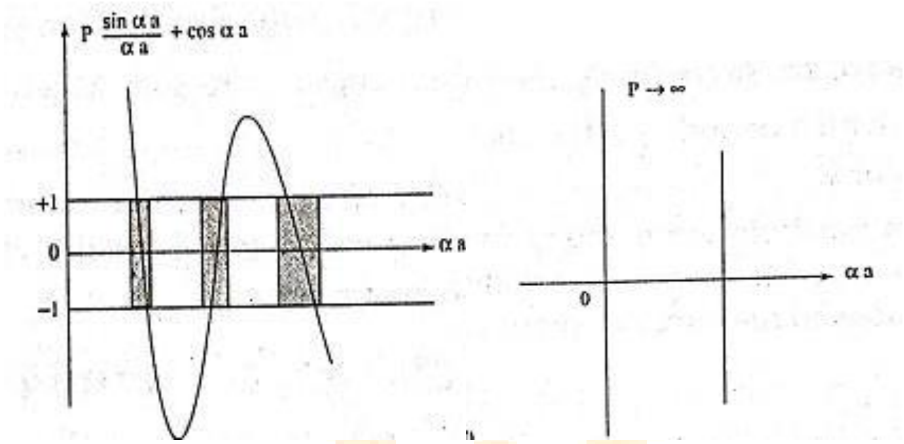


Fig. p--> infinity and p--> 0

3) With increasing P, ie with increasing potential barrier, the width of an allowed band decreases. As P→∞, the allowed energy becomes infinitely narrow and the energy spectrum is a line spectrum as shown in fig.

If P→∞, then the equation (11) has solution ie $\sin \alpha a = 0$

$$\alpha a = \pm n \Pi$$

$$\alpha = \pm n \Pi / a$$

$$\alpha^2 = n^2 \Pi^2 / a^2$$

$$\text{But} \quad \alpha^2 = 2 m E / \hbar^2$$

$$\text{Therefore} \quad 2 m E / \hbar^2 = n^2 \Pi^2 / a^2$$

$$E = [\hbar^2 \Pi^2 / 2 m a^2] n^2$$

$$E = n h^2 / 8 m a^2 \qquad (\text{ since } \hbar = h / 2 \Pi)$$

This expression shows that the energy spectrum of the electron contains discrete energy levels separated by forbidden regions.

4) When P→0 then $\cos \alpha a = \cos ka$

$$\alpha = k , \quad \alpha^2 = k^2$$

$$\text{but} \quad \alpha^2 = 2 m E / \hbar^2$$

$$k^2 = (h^2 / 2 m) (1 / \lambda^2) = (h^2 / 2 m) (P^2 / h^2)$$

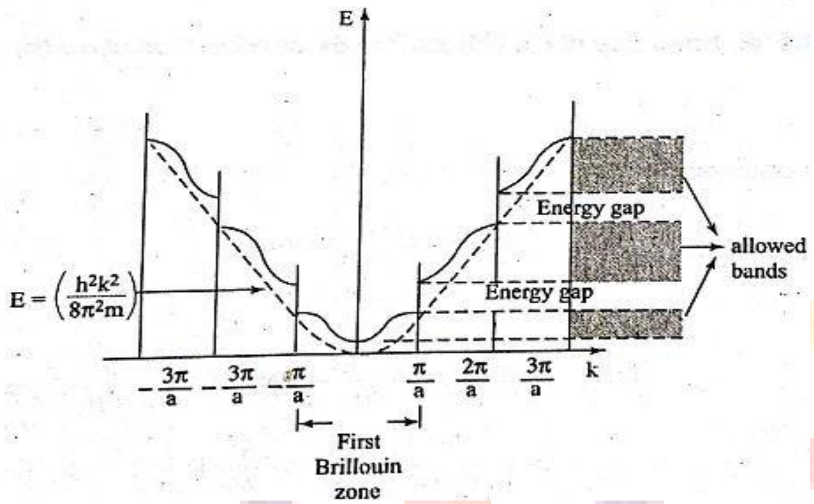
$$E = P^2 / 2 m$$

$$E = 1/2mv^2 \text{ -------------------------- } (14)$$

The equation (11) shows all the electrons are completely free to move in the crystal without any constraints. Hence , no energy level exists ie all the energies are allowed to the electrons and shown in fig(5). This case supports the classical free electrons theory.

$$\left[\left(P / \alpha a \right) \sin \alpha a + \cos \alpha a \right] , P \rightarrow 0$$

1.18 BRILLOUIN ZONE OR E-K DIAGRAM:



The Brillouin zone are the boundaries that are marked by the values of wave vector k,in which electrons can have allowed energy values. These represent the allowed values of k of the electrons in 1D, 2D, &3D.

It is the energy spectrum of an electron moving in presence of a periodic potential field and is divided into allowed energy regions (allowed zones) or forbidden energy gaps (forbidden zones).

Allowed energy values lie in the region k=-π/a to =+π/a. This zone is called the first Brillouin zone. After a break in the energy values, called forbidden energy band, we have another allowed zone spread from k=-π/a to -2π/a and +π/a to +2π/a. This zone is called the second Brillouin zone. Similarly, higher Brillouin zones are formed.

1.19 CONCEPT OF EFFECTIVE MASS OF ELECTRON:

When an electron in a periodic potential of lattice is accelerated by an known electric field or magnetic field, then the mass of the electron is called effective mass and is represented by m*

To explain, let us consider an electron of charge 'e' and mass 'm' moving inside a crystal lattice of electric field E.

acceleration $a = eE / m$ is not a constant in the periodic lattice of the crystal. It can be considered that its variation is caused by the variation of electron's mass when it moves in the crystal lattice.

Therefore Acceleration $a = eE / m^*$

Electrical force on the electron $F = m^* a$ --------------(1)

Considering the free electron as a wave packet, the group velocity v_g corresponding to the particle's velocity can be written as

$$v_g = dw / dk = 2 \Pi \, dv / dk = (2 \Pi / h) \, dE / dk \text{-------------------}(2)$$

where the energy $E = h \upsilon$ and $\hbar = h / 2 \Pi$.

Acceleration $a = d v_g / dt = (1 / \hbar) \, d^2E / dk \, dt = (1 / \hbar)(d^2E / dk^2) \, dk / dt$

Since $\hbar k = p$ and $dp / dt = F$,

$$dk / dt = F / \hbar$$

Therefore $a = (1 / \hbar^2)(d^2E / dk^2) F$

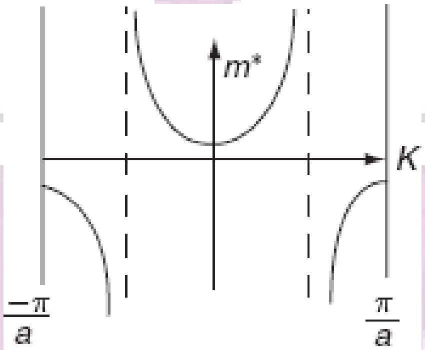
Or $F = (\hbar^2 / (d^2E / dk^2)) \, a \text{-----------------------} (3)$

Comparing eqns . (1) and (3) we get

$$m^* = \hbar^2 / (d^2E / dk^2) \text{-----------------}(4)$$

This eqn indicates that the effective mass is determined by $\mathbf{d^2E / dk^2}$

Variation of effective mass m* with k: The graph shows variation of m* with k. Near k=0,effective mass approaches m. As the k value increases $\boldsymbol{m}$m* increases, reaching its maximum value known as infinite effective mass. Above the point of inflection, m* is negative and as k tends toπ/a, it decreases to a small negative value called negative effective mass in the lower region. The positively charged particle which can be located in the lower region called negative



1.20 ORIGIN OF ENERGY BAND FORMATION IN SOLIDS:

The band theory of solids explains the formation of energy bands and determines whether a solid is a conductor, semiconductor or insulator.

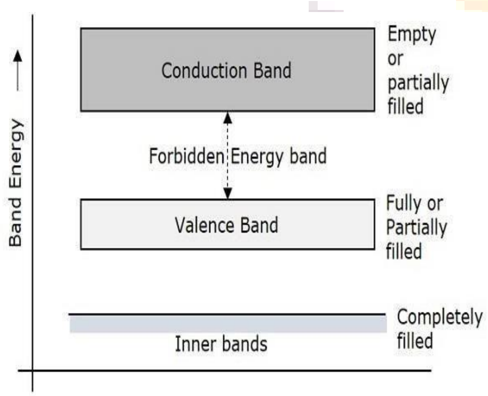
The existence of continuous bands of allowed energies can be understood starting with the atomic scale. The electrons of a single isolated atom occupy atomic orbitals, which form a discrete set of energy levels.

When two identical atoms are brought closer, the outermost orbits of these atoms overlap and interact. When the wave functions of the electrons of different atoms begin to overlap considerably, the energy levels corresponding to those wave functions split.

If more atoms are brought together more levels are formed and for a solid of N atoms, each of the energy levels of an atom splits into N energy levels. These energy levels are so close that they form an almost continuous band. The width of the band depends upon the degree of overlap of electrons of adjacent atoms and is largest for the outermost atomic electrons.

As a result of the finite width of the energy bands, gaps are essentially leftover between the bands called forbidden energy gap.

The electrons first occupy the lower energy levels (and are of no importance) then the electrons in the higher energy levels are of important to explain electrical properties of solids and these are called valence band and conduction band.



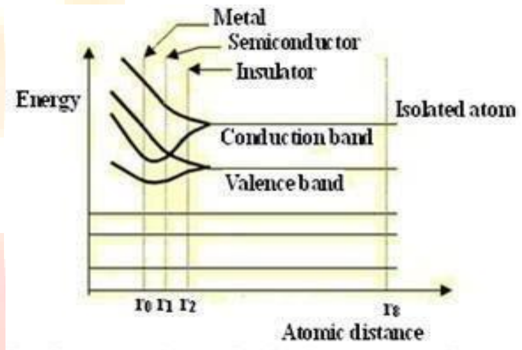


Fig: Formation of energy bands when atoms are closer

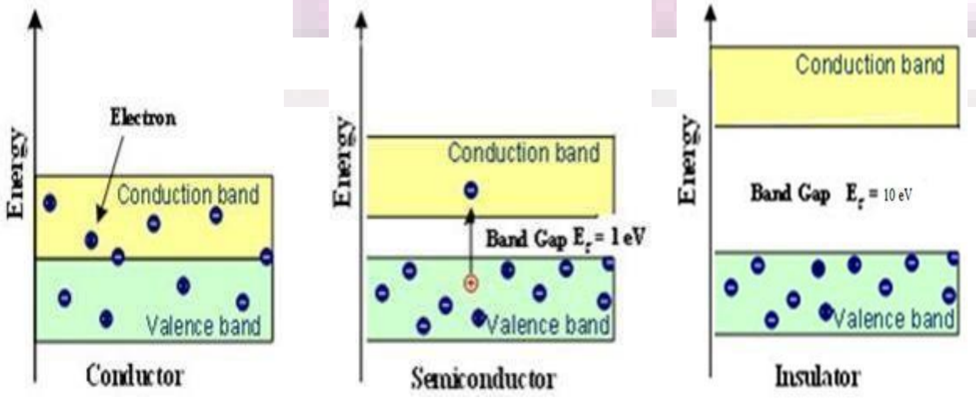
Valence band: A band occupied by valence electrons and is responsible for electrical, thermal and optical properties of solids and it is filled at 0K.

Conduction band: A band corresponding to outer most orbit is called conduction band and is the highest energy band and it is completely empty at 0K.

The **forbidden energy gap** between valence band conduction band is known as the energy band gap. By this solids are classified in to conductors, semiconductors and insulators.

1.21 CLASSIFICATION OF SOLIDS INTO CONDUCTORS , SEMICONDUCTORS & INSULATORS:

Based on the energy band diagram materials or solids are classified as follows:



Conductors: In this kind of materials, there is no forbidden gap between the valence band and conduction band. It is observed that the valence band overlaps with the conduction band in metals as shown in figure. There are sufficient numbers of free electrons, available for electrical conduction and due to the overlapping of the two bands there is an easy transition of electrons from one band to another band takes place, and there no chance for the presence of holes. Resistivity of conductors is very small and it is very few milli ohm meters.(Ω m).

Examples: All metals (Na, Mg, Al, Cu, Ni Cu, Ag, Li, Ar etc)

Semiconductors: In semiconductors, there is a band gap exists between the valence band and conduction band and it is very less and it is the order of -1 to 2 eV are known as semiconductors. It will conduct electricity partially at normal conditions. The electrical resistivity values are 0.5 to 10^3 ohm meter. Due to thermal vibrations within the solid, some electrons gain enough energy to overcome the band gap (or barrier) and behave as conduction electrons. Conductivity exists here due to electronics and holes.

Examples: Silicon, Germanium, Ga As.

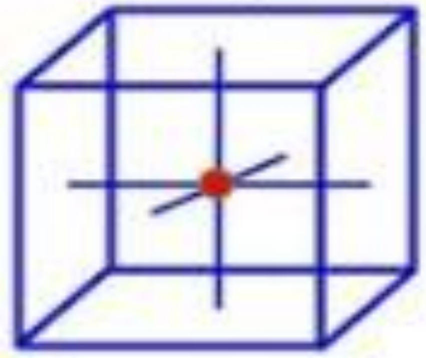
Insulators: In insulators, the width of forbidden energy gap between the valence band and conduction band is very large. Due to large energy gap, electrons cannot jump from V.B to C.B.Energy gap is of the order of ~10 eV and higher than semiconductors. Resistivity values of insulators are 10^7 to 10^{12} ohm-m. Electrons are tightly bound to the nucleus, no valence electrons are available.

Examples: Wood, rubber, glass.

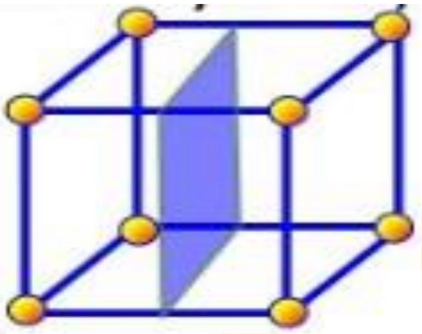
1.22 Symmetry in solids

A Symmetry operation is an operation that can be performed either physically or imaginatively that results in no change in the appearance of an object.

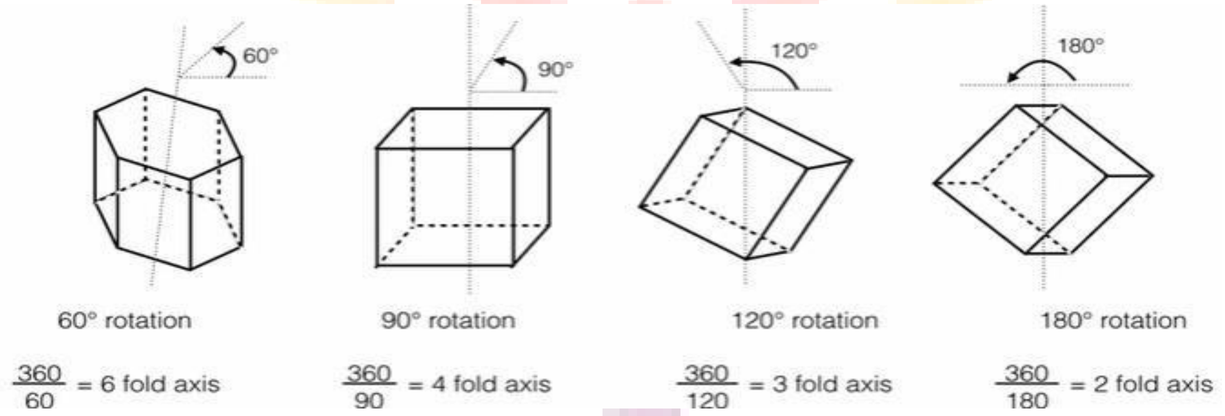
Center of symmetry: If an imaginary straight line can be passed through a crystal from any point on the surface of crystal such that the point of entry is similar to the point of exit, then the crystal has a center of symmetry.

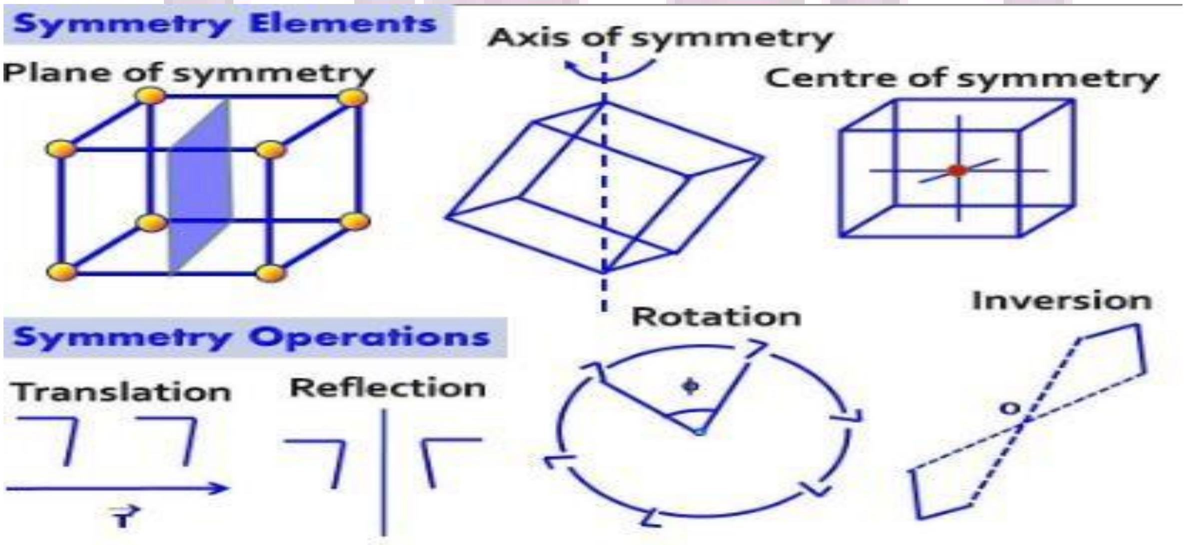


Plane of symmetry: When an imaginary plane is passed through a crystal such that the portion of the crystal on one side of the plane is a reflection, or mirror image, of the portion on the other side of the plane, the plane is a **plane of symmetry** (often called a mirror plane).



Axis of symmetry: When an imaginary line can be passed through a crystal such that the crystal can be rotated 360° about the line to fill the same space two, three, four, or six times, it has an **axis of symmetry.**





Short answer questions

1. What is a block body and explain its construction.
2. Explain about photoelectric effect.
3. Define Compton effect and Compton shift.
4. What are the postulates of Plank's hypothesis?
5. Distinguish between waves and particles.
6. What are matter wave? Explain their properties.
7. State and explain Heisenberg's uncertainty principle.
8. Explain Physical significance of wave function.
9. Write the draw backs of classical free electron theory.
10. Discuss briefly about electron in periodic potential.
11. Write short note on origin of energy band formation in solids.
12. What are the possible symmetries in solids?

Essay questions

1. Derive expression for Plank's radiation law.
2. What is Compton effect? Derive Compton shift relation.
3. Describe experimental verification of matter waves using Davisson-Germer's experiment.
4. Derive time independent Schrodinger's wave equation for a free particle.
5. Derive an expression for energy and wave function of a particle bound to 1-D potential box.
6. Explain the Kronig-Penny model of solids and show that it leads to energy band structure.
7. Derive an expression for effective mass of an electron moving in energy bands of a solid.
8. Distinguish between conductor, semiconductors and insulators.

Multiple answer questions

1. In the spectrum of black body radiation, Wein's law is applicable to [ ]

(A) Longer wavelength region (B) shorter wavelength region (C) any wavelength region (D) none of wavelengths

2. If ΔE and Δt are the uncertainties in the measurement of energy and time of a system, according to Heisenberg's uncertainty principle. [ ]

(A) $\Delta E.\Delta t \geq h/4\pi$ (B) $\Delta E.\Delta t \leq h/4\pi$ (C) $\Delta E.\Delta t \geq h/2\pi$ \(D) $\Delta E.\Delta t \leq h/2\pi$

3. Matter waves are called [ ]

(A) Electromagnetic waves (B)de Broglie waves
(C)ultrasonic waves (D)Planck waves

4. The wave function is [ ]

(A) The quantity associates with all waves

(B) The probability amplitude of finding the particle in space

(C) A mathematical function with four variables

(D) A real function

5. Davisson and Germer experiment supports the concept of ....of matter particles. [ ]

(A) Particle (B) Wave nature (C) Dual nature (D) Both B and C

6. The de Broglie wavelength is infinity when the speed of the matter particle is. [ ]

(A) Infinity (B) Finite (c) Zero (D) no relation

7. In the Davisson and Germer experiment, when 54 volts is applied to electrons, the first order diffraction spectrum is observed at the scattering angle of .... [ ]

(A) 25^0 (B) 50^0 (C) 36^0 (D) 42^0

8. According to ....principle, it is not possible to know position and momentum of a particle at the same time. [ ]
(A) de-Broglie (B) Bragg (C) Schorindiger (D) Heisenberg

10. Schorindiger time independent wave equation is………. [ ]

(A) $\frac{\partial^2\varphi}{\partial x^2}+\frac{\partial^2\varphi}{\partial y^2}+\frac{\partial^2\varphi}{\partial z}+\frac{8\pi^2(E-V)}{h^2}\varphi=0$

(B) $\frac{\partial^2\varphi}{\partial x^2}+\frac{\partial^2\varphi}{\partial y^2}+\frac{\partial^2\varphi}{\partial z}+\frac{8m\pi^2(E-V)}{h^2}\varphi=0$

(C)$\frac{\partial^2\varphi}{\partial x^2}+\frac{\partial^2\varphi}{\partial y^2}+\frac{\partial^2\varphi}{\partial z}+\frac{8m\pi^2(E-V)}{h^2}\varphi=0$

(D)$E\varphi=-\frac{\partial\varphi}{\partial t}$

11. Inside the one dimensional potential box the potential energy of the particle is [ ]

(A)Infinity (B) Depends on the size of box (C) Depends on the size of particle (D) Zero

12. The energy of the particle in one dimensional potential box is [ ]

(A) $E=\frac{n^2h^2}{ml^2}$ (B) $E=\frac{n^2h^2}{8ml^2}$ (C) $E=\frac{nh}{8ml^2}$ (D) E= 0

13. In which of the following de-Briglie wave equation is wrongly interpreted [ ]

(A) $\lambda=\frac{h}{mv}$ (B) $\lambda=\frac{h}{\sqrt{2mE}}$ (C) $\lambda=\frac{h}{p}$ (D) $\lambda=\frac{h}{mv^2}$

14. If an electron is moving under a field of V then the de-Broglie wave equation is given by[ ]

(A) $\lambda=\frac{12.2}{\sqrt{V}}$ (B) $\lambda=\frac{h}{\sqrt{2mV}}$ (C) $\lambda=\frac{h}{pV}$ (D) $\lambda=\frac{h}{mV}$

15. If an electron is moving under potential field of 100V the wave length is [ ]

(A) 12.2A^0 (B) 12.2cm (C) 1.22A^0 (D)12.2m

16. Mater waves and electromagnetic waves are [ ]

(A) Same (B) Different (C) in some times both are similar (D) None.

17. Heisenberg's uncertainty principle is a consequence of [ ]

(A) de-Broglie (B) Bragg (C) Schorindiger (D) Davisson and Germer

18. A combination of position space and momentum space is called [ ]

(A)Macrostate (B)Microstate (C)Phase space (D)Whole space

19. Quantum theory successfully explains [ ]

a. Interference
b. Polarization and blockbody radiation
c. Photoelectric effect
d. All

20. Dual nature of matter was proposed by [ ]

a. De Broglie
b. Plnck
c. Newton
d. None

21. The target material in Davisson and Germer's Experiment [ ]

a. Ni,
b. Au

c. Na
d. Cl

22. Diffraction angle for nickel in Davisson and Germer’s Experiment [ ]

(a).50°, (b).60°, (c).25°, (d).70°

23. Compton effect proves [ ]

(a) light have particle nature, (b) light have wave nature, (c) a & b, (d) none of them

24. Davisson-Germer’s experiment proves [ ]

(a) light have particle nature, (b) light have wave nature, (c) a & b, (d) none of them

25. Matter waves are called [ ]

(A)Electromagnetic waves (B)de Broglie waves
(C)ultrasonic waves (D)Planck waves

UNIT-II

Semiconductor Physics and Devices

Introduction:

The materials which allow electricity partially to pass through them are known as semiconductors. From last two decades the use of solid state devises has become prominent. Most of these solid state devices use Semi conductor crystals. From the point of band theory of electrical conductivity, semiconductors differ from conductors and insulators. In metals addition of impurities and rise of temperature result in decrease in the electrical conductivity where as in semi conductors the electrical conductivity increases in contrary to conductors. Germanium and Silicon are most important semiconductors which are widely used in the manufacturing of diodes and transistors.

2.1 Types of Semi Conductors:

Semiconductors are mainly classified into two types.

1. Intrinsic (or) Pure Semi conductor
2. Extrinsic (or) Impure semiconductor.

Intrinsic Semiconductor:

A semiconductor in its pure form is known as intrinsic semiconductor.

- The Silicon crystal which contains all of Si atoms is known as intrinsic semiconductor.
- In the Si (or) Ge the number of valence electrons is four. Each atom will complete '4' covalent bonds with four similar neighboring atoms.
- At the room temperature due to the thermal agitation some electrons in the valence band are shifted into the conduction band. Then electron vacancies created in the valence band. These are known as holes.
- The number of holes in the valence band and number of electrons in conduction band are equal.
- The average energy of holes and the electrons are represented by the Fermi energy level. It lies at the middle of forbidden gap.

Ex: - Ge, Si.

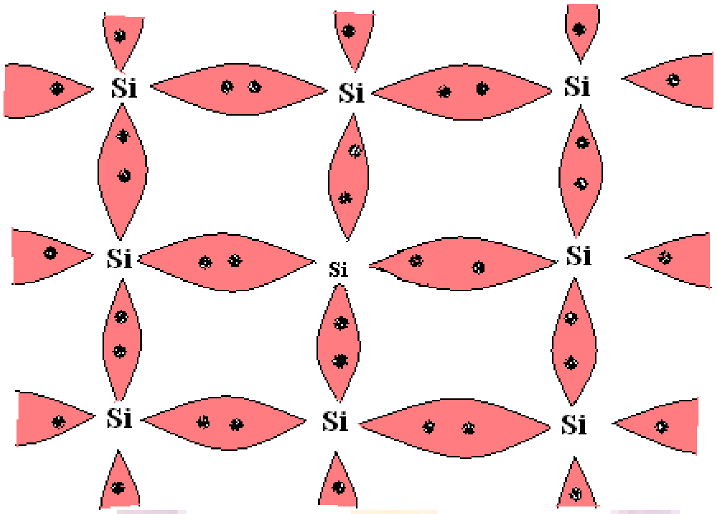


Fig: Pure Silicon

Extrinsic Semiconductor:

A doped semiconductor is called extrinsic semiconductor. The prices of adding impurities to a substance are called doping. On basis of doping Extrinsic semiconductors are again divided into two types.

1. N-type extrinsic semiconductor

2. P- type extrinsic semiconductor

1. N-type Extrinsic Semiconductor:

When we add the pentavalent impurity to a pure semiconductor then it is called N-type extrinsic semiconductor.

- This semiconductor is generated by doping pentavalent impurity to the intrinsic semiconductor.
- The phosphorous (p) atom is substituting in the place of ‘Si’ atom then it will complete four covalent bonds with four neighboring Si atoms. But one electron is left free without forming the band. This electron goes into the conduction band with out creating hole in the valence band.
- A small quantity of pentavalent impurity is added to the crystal then large number of electrons is produced in conduction band. Due to thermal agitation some electrons in the valence band are shifted into the conduction band by creating the holes in the valence band.
- The impurity atom is donating an electron to the conduction band. So this impurity is known as donor impurity.
- The majority charge carriers are electrons and the minority carriers are holes.

- The majority carriers are the negative charge carriers. So this semiconductor is known as N-type extrinsic semiconductor.
- The Fermi energy level is shifted towards the conduction band.

Ex: Pentavalent impurities are P, As, etc.

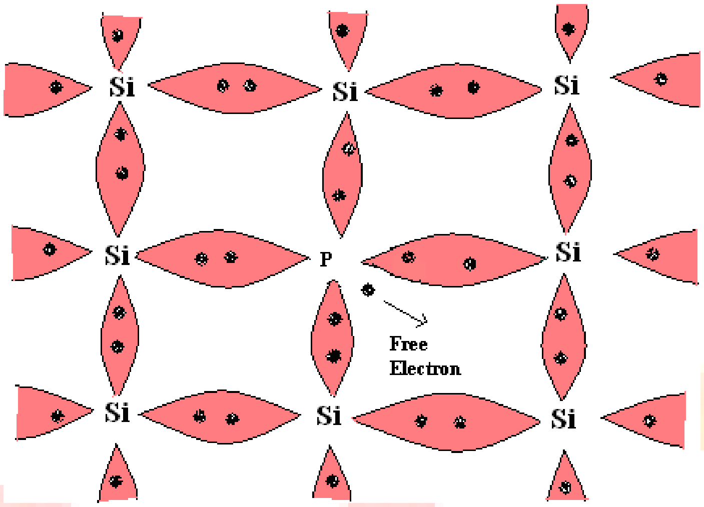


Fig: Pentavalent impurity (P) doped into intrinsic semiconductor (Si)

2. P-type Extrinsic Semiconductor:

When we add trivalent impurity to a pure semiconductor then it is called a P-type extrinsic semiconductor.

- This semiconductor is generated by doping trivalent impurity to the intrinsic semiconductor.
- If an ‘Al’ atom is substituted in place of ‘Si’ atom then it will complete three covalent bonds with three neighboring ‘Si’ atoms. But one more electron should be required to complete the fourth covalent bond. In the absence of fourth electron a hole is generated which lies in valence band. In this process no electron is shifted to the conduction bond.
- A small quantity trivalent impurity is added to the crystal then large number of holes in the valence band. Due to thermal agitation some more electrons in valence band are shifted to conduction band by creating the holes in valence band.
- The impurity atom is in a position to get an electron. So this impurity atom is known as acceptor impurity..
- In this semiconductor majority carriers are holes and minority carriers are electrons.
- The majority carriers have positive charge, so this semi conductor is known as P-type extrinsic semiconductor.

- The Fermi energy level shifted towards the valence band.

Ex: - B, Al, Ga, etc.

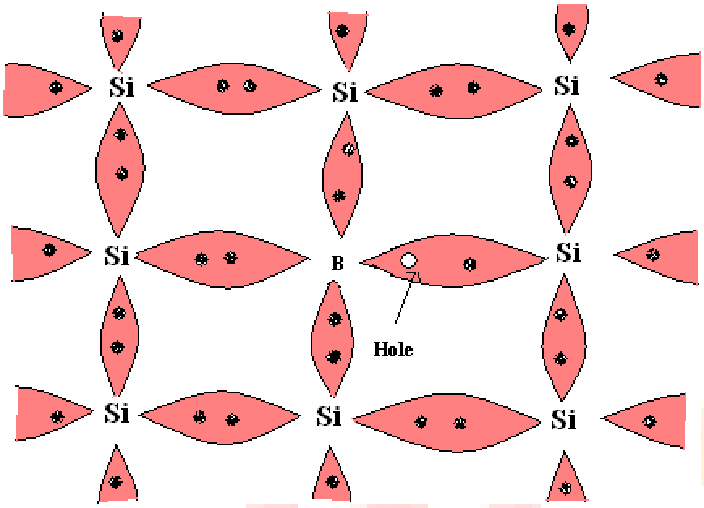


Fig: Trivalent impurity (B) doped into intrinsic semiconductor (Si)

2.2 Carrier Concentration in Semiconductors

The number of charge carriers per unit volume is defined as carrier concentration.

Units: Number of electrons/m^3.

Intrinsic Carrier Concentrations:

In intrinsic semi conductors, as the temperature is increased electron-hole passes will be generated. Hence the electron concentration, n_i, in the conduction band will be equal to the hole concentration p_i in the valence band.

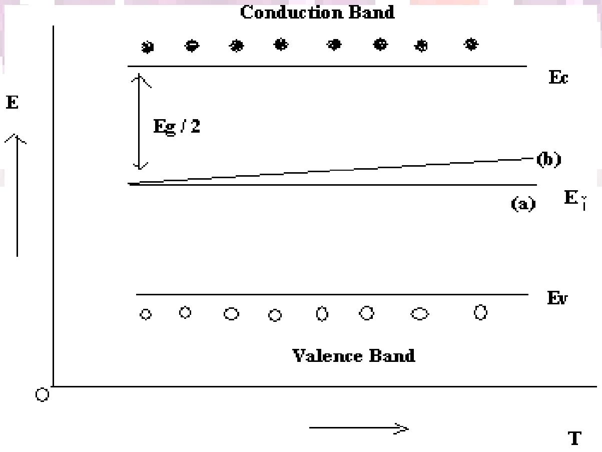


Fig: Fermi level at (a) T = 0 (b) As temperature increases $m_h^* > m_e^*$

Let E_i be the Fermi level of the intrinsic semiconductor in equilibrium, then the number of electrons per unit volume in the conduction band.

$$n_i = 2\left(\frac{2m_e \pi k_B T}{h^2}\right)^{\frac{3}{2}} \exp\left(\frac{E_i - E_c}{k_B T}\right)$$

And the number of holes per unit volume in the valence band

$$p_i = 2\left(\frac{2m_h \pi k_B T}{h^2}\right)^{\frac{3}{2}} \exp\left(\frac{E_v - E_i}{k_B T}\right)$$

But in intrinsic semiconductors $n_i = p_i$

Hence, $$2\left(\frac{2m_e \pi k_B T}{h^2}\right)^{\frac{3}{2}} \exp\left(\frac{E_i - E_c}{k_B T}\right) = 2\left(\frac{2m_h \pi K_B T}{h^2}\right)^{\frac{3}{2}} \exp\left(\frac{E_v - E_i}{k_B T}\right)$$

$$m_e^{\frac{3}{2}} \exp\left(\frac{E_i - E_c}{k_B T}\right) = m_h^{\frac{3}{2}} \exp\left(\frac{E_v - E_i}{k_B T}\right)$$

$$\text{Exp}\left(\frac{E_i - E_c - E_v + E_i}{k_B T}\right) = \left(\frac{m_h}{m_e}\right)^{\frac{3}{2}}$$

$$2E_i - E_c - E_v = K_B T \ln\left(\frac{m_h}{m_e}\right) K_B T$$

$$E_i = \frac{1}{2}\left(E_c + E_v\right) + \frac{3}{4}\ln\left(\frac{m_h}{m_e}\right) k_B T.$$

If the effective masses $m_e = m_h$, then

$$E_i = \frac{E_c + E_v}{2} \left[\because \ln 1 = 0\right]$$

i.e. E_i lies mid way between E_c and E_v, which happens to be the centre of the bond gap at any temperature.

Combining n_i and p_i values,

$$n_i p_i = 4\left(\frac{2\pi m_e kT}{h^2}\right)^{\frac{3}{2}}\left[\frac{2\pi m_h k_B T}{h^2}\right]^{\frac{3}{2}} \exp\left(\frac{E_i - E_C}{KT}\right)\exp\left(\frac{E_v - E_i}{KT}\right)$$

$$n_i^2 = 4\left(\frac{2\pi k}{h^2}\right)^3 (m_e m_h)^{\frac{3}{2}} T^3 \exp\left(\frac{E_v - E_c}{KT}\right)\left(\because n_i = P_i\right)$$

$$n^2 = AT^3 \exp\left(\frac{-E_g}{KT}\right)$$

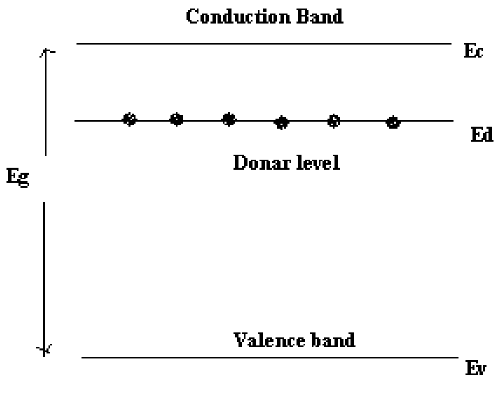
Where $A = 4\left(\frac{2\pi k}{h}\right)^3 (m_h m_e)^{\frac{3}{2}}$ a constant value of semiconductor and $E_g = E_c - E_v$ is energy gap of the semiconductor.

It is to be noted that A and E_g are constants for a given semiconductor and n_i- is called the intrinsic concentration which indicates thermally generated electrons and holes. It is a strong function of temperature 'T'.

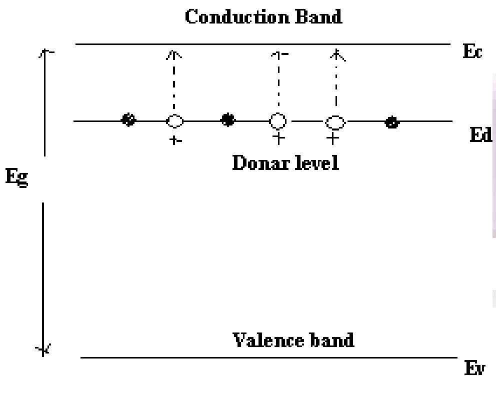
2.3 Electron Concentration in Extrinsic Semiconductor

1. **Carrier Concentration in N-Type Semiconductors**:

The energy level diagram of a N-type semiconductor shown in figure



At T = O K



At T > 0K

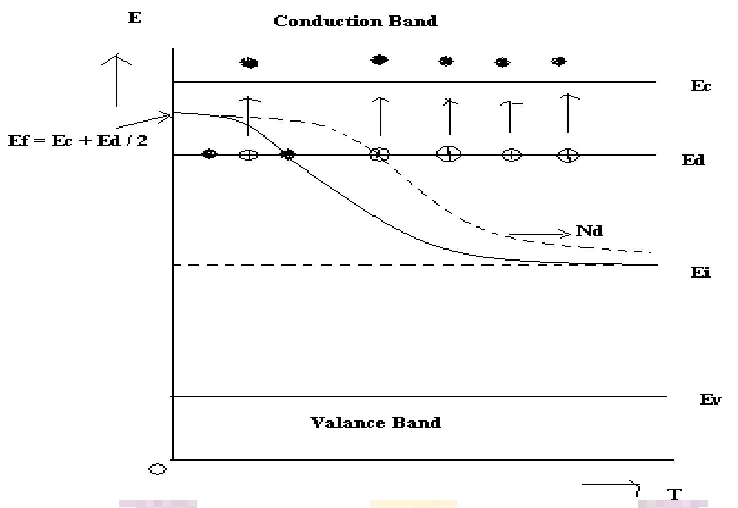


Fig: Variation of Fermi Level with Temperature

N_d is the donor concentration and E_d is the donor energy level. At very low temperatures all donor levels are filled with electrons. With increase of temperature more and more donor atoms get ionized and the density of electrons in the conduction band increases.

Density of electrons in conduction band is given by

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

If we assume that E_F lies more than a few KT above the donor level then the density of ionized donors is given by

$$N_d\left[1 - F\left(E_d\right)\right] \cong N_d \exp\left(\frac{E_d - E_F}{KT}\right)$$

At very low temperatures, when electron-hole pairs not generated due to breaking of covalent bonds. The number of electrons in the conduction band must be equal to the number of ionized donors.

$$\text{i.e. } 2\left(\frac{2\pi m_e^* KT}{h^2}\right)^{3/2} \exp\left(\frac{E_F - E_C}{KT}\right) = N_d \exp\left(\frac{E_d - E_F}{KT}\right)$$

Taking logarithm and rearranging we get

$$\left(\frac{E_F - E_C}{KT}\right) - \left(\frac{E_d - E_F}{KT}\right) = \log N_d - \log 2\left(\frac{2\pi m_e^* KT}{h^2}\right)^{\frac{3}{2}}$$

$$2E_F - \left(E_d + E_C\right) = KT \log \frac{N_d}{2\left(\frac{2\pi m_e^* KT}{h^2}\right)^{\frac{3}{2}}}$$

$$E_F = \left(\frac{E_d + E_c}{2}\right) + \frac{kT}{2}\log \frac{N_d}{2\left(\frac{2\pi m_e^* kT}{h^2}\right)^{\frac{3}{2}}} \text{------}(2)$$

$$\text{At O K. } E_F = \frac{E_d + E_c}{2}$$

i.e. at 0 k, Fermi level lies exactly at the middle of the donor level E_d and the bottom of the conduction band E_c

Density of Electrons in the Conduction Band:

The density of electrons in the conduction band is given by

$$n = 2\left(\frac{2\pi m_e^* KT}{h^2}\right)^{\frac{3}{2}} \exp\left(\frac{E_F - E_C}{KT}\right) \text{----}(3)$$

Substitute 'E_F' value in equation (2) in the above equation.

$$\exp\left(\frac{E_F - E_c}{KT}\right) = \exp\left\{\left(\frac{E_d - E_c}{2KT}\right) + \frac{1}{2}\log \frac{N_d}{2\left(\frac{2\pi m_e^* KT}{h^2}\right)^{\frac{3}{2}}}\right\}$$

$$\text{Exp}\left(\frac{E_F - E_C}{KT}\right) = \exp\left\{\left(\frac{E_d - E_c}{2KT}\right) + \log \left[\frac{N_d^{\frac{1}{2}}}{2\left(\frac{2\pi m_e^* KT}{h^2}\right)^{\frac{3}{2}}}\right]^{\frac{1}{2}}\right\} \left(\because \frac{1}{2} logx = \log x^{\frac{1}{2}}\right)$$

$$= \left[\exp\left(\frac{E_d - E_C}{2KT}\right)\right]\frac{N_d^{\frac{1}{2}}}{\left\{2\left(\frac{2\pi m_e^* KT}{h^2}\right)^{\frac{3}{2}}\right\}^{\frac{1}{2}}} \quad \left[\because \exp(a+b) = e^a.e^b\right]$$

Hence

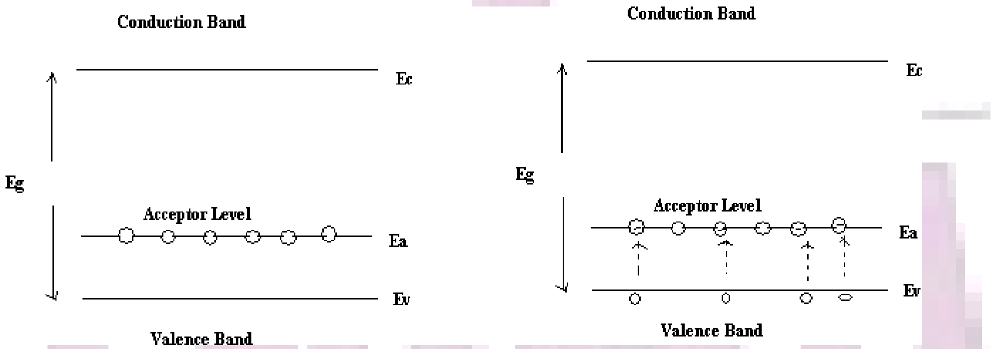
$$n = 2\left(\frac{2\pi m_e^* KT}{h^2}\right)^{\frac{3}{2}}\frac{N_d^{\frac{1}{2}}}{\left[2\left(\frac{2\pi m_e^* KT}{h^2}\right)^{\frac{3}{2}}\right]^{\frac{1}{2}}}\exp\left(\frac{E_d - E_C}{2KT}\right)$$

$$n = (2N_d)^{\frac{1}{2}}\left(\frac{2\pi m_e^* KT}{h^2}\right)^{\frac{3}{4}}\exp\left(\frac{E_d - E_C}{KT}\right)$$

Thus we find that the density of electrons in the conduction band is proportional to the square root of the donor concentration at moderately low temperatures.

2. Carrier Concentration in P-type Semiconductor:

The energy level diagram of a P-type semiconductor is as shown in figure below.



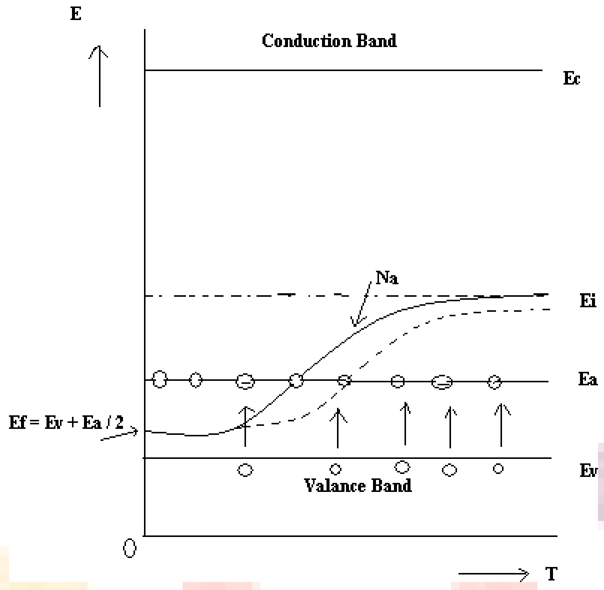


Fig: Variation of Fermi Level with Temperature

N_a is the acceptor concentration i.e. the number of acceptor atoms per unit volume of the material and E_a is the acceptor energy level.

At very low temperatures all the acceptor levels are empty. With increase of temperature acceptor atoms get ionized i.e. the electrons move from valence band and occupy the vacant sites in the acceptor energy level there by leaving holes in the valence band.

Density of holes in the valence band is given by

$$p = 2\left(\frac{2\pi m_h^* KT}{h^2}\right)^{\frac{3}{2}} \exp\left(\frac{E_V - E_F}{KT}\right)$$

Since E_F lies below acceptor level, the density of ionized acceptor is given by

$$N_a F(E_a) = N_a \exp\left(\frac{E_F - E_a}{KT}\right)$$

Since the density of holes in the valence band is equal to the density of ionized acceptors

$$2\left(\frac{2\pi m_h^{*}KT}{h^{2}}\right)^{3/2}\exp\left(\frac{E_V-E_F}{KT}\right)=N_a\exp\left(\frac{E_F-E_a}{KT}\right)$$

$$\text{i.e. }\exp\left(\frac{E_V+E_a-2E_F}{KT}\right)=\frac{N_a}{2\left(\frac{2\pi m_h^{*}KT}{h^{2}}\right)^{3/2}}$$

Taking logarithm

$$\left(\frac{E_V+E_a-2E_F}{KT}\right)=\log\frac{N_a}{2\left(\frac{2\pi n_h^{*}KT}{h^{2}}\right)^{3/2}}$$

$$\text{i.e. }E_F=\frac{E_V+E_a}{2}-\frac{KT}{2}\log\frac{N_a}{2\left(\frac{2\pi m_h^{*}KT}{h^{2}}\right)^{3/2}}----(1)$$

$$\text{AT O K }E_F=\frac{E_V+E_d}{2}$$

At Ok, Fermi level lies exactly at the middle of the acceptor level and the top of the valence band as shown in above fig

Density of Holes in Valence Band:

The density of holes in the valence band is given by

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

Substitute equation (1) value in equation (2)

$$\text{Exp}\left(\frac{E_V - E_F}{KT}\right) = \exp\left\{\frac{E_V}{KT} - \frac{E_V + E_d}{2KT} + \frac{1}{2}\log\frac{N_a}{2\left(\frac{2\pi m^* KT}{h^2}\right)^{\frac{3}{2}}}\right\}$$

$$=\exp\left\{\left(\frac{E_V - E_a}{2KT}\right) + \log\frac{N_a^{\frac{1}{2}}}{\left(2\left(\frac{2\pi m^* KT}{h^2}\right)^{\frac{3}{2}}\right)^{\frac{1}{2}}}\right\}$$

$$\text{Hence } \; p = 2\left(\frac{2\pi m^* kT}{h^2}\right)^{\frac{3}{2}}\left\{\exp\left(\frac{E_V - E_a}{2KT}\right)\right\}\frac{N_a^{\frac{1}{2}}}{\left[2\left(\frac{2\pi m^* kT}{h^2}\right)^{\frac{3}{2}}\right]^{\frac{1}{2}}}$$

$$p = \left(2N_a\right)^{\frac{1}{2}}\left(\frac{2\pi m^* KT}{h^2}\right)^{\frac{3}{4}}\exp\left(\frac{E_V - E_a}{2KT}\right).$$

Thus we find that the density of holes in the valence band is proportional to the square root of the acceptor concentration at moderately low temperature.

2.4 Drift Current and Conductivity in Semiconductors

In the presence of electric field, the drift velocities V_{de} *and* V_{dh} carriers on the thermal velocities v_{te} and v_{th}. But the flow of charge carriers result in an electric current in the semiconductor crystal known as the drift currents. Let an electric field E be applied in the positive X-direction creating drift currents Jn_d and J_{pd} of electrons and holes respectively.

In the absence of electric field, the drift velocities reduce to zero. Thus current density will also be zero.Consider the free electrons in a semiconductor moving with a uniform velocity $v_{de.}$ In the negative X-direction due to the application of the electric field E in the positive X-direction. Suppose AB, a small rectangular box element of length v_{de} and unit sides of the square end faces A and B in the semiconductor shown in fig

{Total change in the box AB}**Q=** {Volume of the box AB} X {Density of Particles} X {Charge on each particle}

$$Q = \left(V_{de} \times 1 \times 1\right) \times n \times -q$$
$$\therefore Q = -qnV_{de} - - - (1)$$

The current density J_{nd} due to the free electrons at the face B will be

$$J = \frac{charge}{time \times area} - - - - (2)$$

From (1) & (2) the current density of electrons J_{nd} = -qnv$_{de}$ ----------(3)

Similarly current density of holes, J_{pd} = qpV$_{dh}$ ---------- (4)

But drift velocities in terms of mobilities are

$$V_{de} = -\mu_n E - - - - (5)$$

$$V_{dp} = \mu_p E - - - - - (6)$$

Hence substituting equations (5) & (6) in (3) & (4)

$$J_{nd} = nq\mu_n E$$
$$J_{pd} = nq\mu_p E$$

Total current density due to both electrons and holes will be

$$J_d = J_{nd} + J_{pd}$$
$$J_d = (nq\mu_n + nq\mu_p)E$$

According to ohm's law, the current density

$$J_d = \sigma E$$
$$\sigma = nq\mu_n + nq\mu_p$$
$$\sigma = \sigma_n + \sigma_p$$

Where $\sigma_n = nq\mu_n \; and \sigma_p = nq\mu_p$ the electrical conductivities due to electrons and holes respectively.

Diffusion Currents: A directed movement of charge carriers constitutes an electric current diffusion takes place due to the existence of a non-uniform concentration of carriers. Fick's states that the diffusion flux F i.e. the particle current are proportional to and in a direction opposite to the gradient of the particles.

It can be written as

$$F\alpha \frac{-\partial N}{\partial x}.$$

$$F = \frac{-D\partial N}{\partial x}$$

Where ‘D’ is diffusion current.

If ‘n’ and ‘p’ are the electron and hole concentrations, then the flux densities of electrons and holes J_e *and* J_P *canbe written as*

$$J_e = -D_n \frac{\partial n}{\partial x}$$

$$J_p = J_h = -D_p \frac{\partial p}{\partial x}$$

Where D_n and D_p are diffusion constants of the electrons and holes respectively.

Then diffusion current densities become.

$$J_{ndiff} = qD_n . \frac{\partial n}{dx}.$$

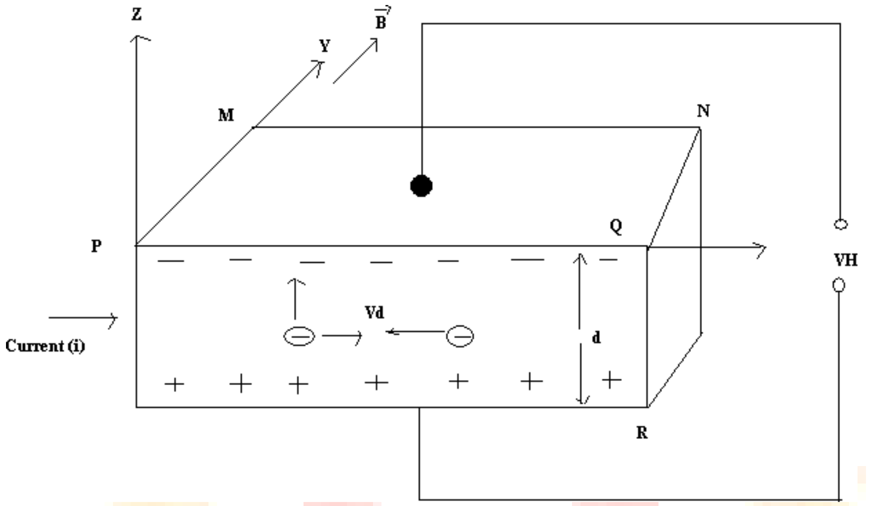
$$J_{Pdiff} = -qD_p \frac{dp}{dx}$$

Where +q and –q are charges of the hole and electron respectively.

2.5 Hall Effect

When a magnetic field is applied perpendicular to a current carrying conductor or semiconductor, a voltage is developed across the specimen in a direction perpendicular to both the current and the magnetic field. This phenomenon is called the Hall Effect and the voltage developed is called the Hall voltage.

Consider a uniform thick metal strip placed with its length parallel to x-axis. Let a current ‘i’ is passed in the conductor along x-Axis and magnetic field B is established along y-axis. Due to the magnetic field charge carriers experience a force F_D perpendicular to x-y plane. i.e. along z-axis. This force direction is given by Fleming left hand rule.



The nature of charge carriers can be found by determining the sign of Hall e.m f which can be measured by potentiometers. Experiments showed that the charge carriers in metal are electrons while the charge carriers in p-type semiconductors are holes.

Magnetic deflecting force $F_D = q(v_\alpha \times \beta)$------(1)

Hall electric deflecting force $F_H = qE_H$ -------------------------(2)

When equilibrium is reached, the magnetic deflecting forces on the charge carriers are balanced by the electric forces due to electric field.

Hence net farce on the charge carriers becomes zero.

From (1) & (2)

$$q(v_d \times B) + qE_H = 0$$
$$E_H = -(V_d \times B)$$

Interms of magnitude $E_H = V_d.B$----(3)

Where V_d is drift velocity of electrons.

The relation b/w current density and drift velocity is $J = V_d ne$

$$V_d = \frac{J}{ne} = \frac{J}{nq} \text{------}(4)$$

Where ‘n’ is the number of charge carriers per unit volume

Substitute Eq’n (4) in equation (3)

$$E_H = \left(\frac{J}{nq}\right) B \text{----}(5)$$

If V_{H-} be the Hall voltage in equilibrium.

$$\therefore \text{ Hall electric field, } E_H = \left(\frac{V_H}{d}\right) \text{------}(6) \left(\because E = \frac{v}{d}\right)$$

Where‘d’ is width of the metal strip.

By measuring the current in the slab, the current density J can be calculated. $\left(J = \frac{i}{A}\right)$

Where ‘A’ is the area of cross section of the slab.

The magnetic field ‘B’ can be measured by Gauss-meter.

On substituting E_H,J and B in Equation (5) the value of $\frac{1}{nq}$ can be calculated

$$\therefore \textit{Hall coefficient } R_H = \frac{E_H}{JB}$$

$$\frac{E_H}{JB} = \frac{1}{nq} \therefore \therefore R_H = \frac{1}{nq}$$

The Hall coefficient is negative when the charge carriers are electrons and positive when the charge carriers are holes.

Applications of Hall Effect:

1. The sign (electrons or holes) of charge carriers is determined.
2. The carrier concentration can be determined.
3. The mobility of charge carriers is measured directly.
4. Electrical conductivity of the material can be determined

5. It can be used to determine whether the given material is metal, insulator or semiconductor.
6. We can measure the unknown magnetic field by using the measured Hall voltage and the Hall coefficient for the slab.

2.6 PN JUNCTION DIODE

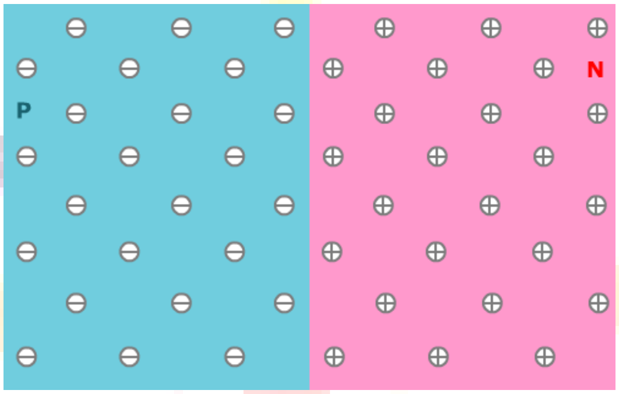


Fig: P- type material is joined with N-type material

Carrier Movement in Equilibrium:

A p-n junction with no external inputs represents equilibrium between carrier generation, recombination, diffusion and drift in the presence of the electric field in the depletion region. Despite the presence of the electric field, which creates an impediment to the diffusion of carriers across the electric field, some carriers still cross the junction by diffusion.

In the Figure below, most majority carriers which enter the **depletion region** move back towards the region from which they originated. However, statistically some carriers will have a high velocity and travel in a sufficient net direction such that they cross the junction. Once a majority carrier crosses the junction, it becomes a minority carrier. It will continue to diffuse away from the junction and can travel a distance on average equal to the diffusion length before it recombines.

The current caused by the diffusion of carriers across the junction is called diffusion current. In the figure below, watch the carriers in the depletion region and wait for carriers which cross the junction. Remember that in an actual p-n junction the number and velocity of the carriers is much greater and that the number of carriers crossing the junction is much larger.

Minority carriers which reach the edge of the diffusion region are swept across it by the electric field in the depletion region. This current is called the drift current. In equilibrium the drift current is limited by the number of minority carriers which are thermally generated within a diffusion length of the junction.

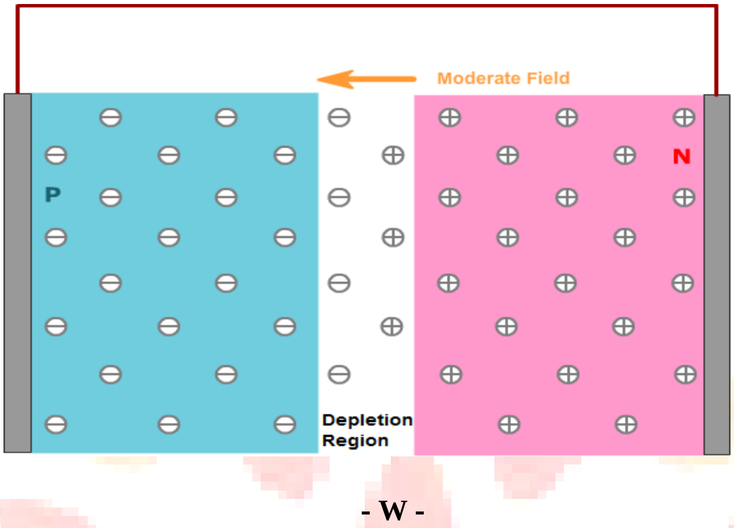
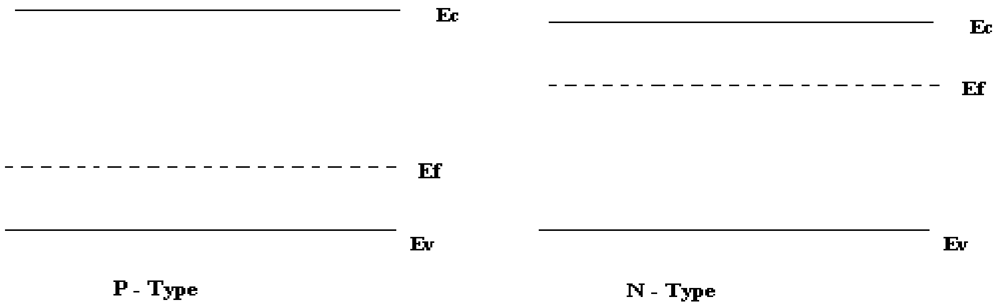


Fig: Formation of PN junction

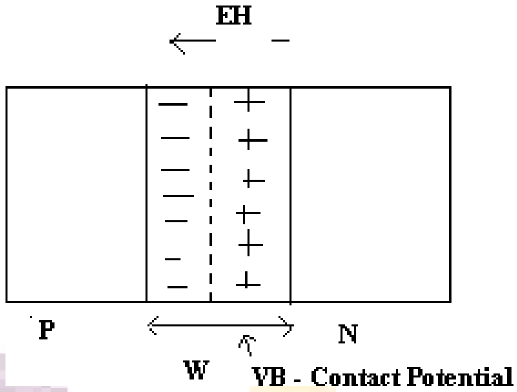
In equilibrium, the net current from the device is zero. The electron drift current and the electron diffusion current exactly balance out (if they did not there would be a net buildup of electrons on either one side or the other of the device). Similarly, the hole drift current and the hole diffusion current also balance each other out.

Energy Diagrams of PN Diode:

1. Before the formation of PN junction, the Fermi level lies to valence band in P type and near to conduction band in N type.

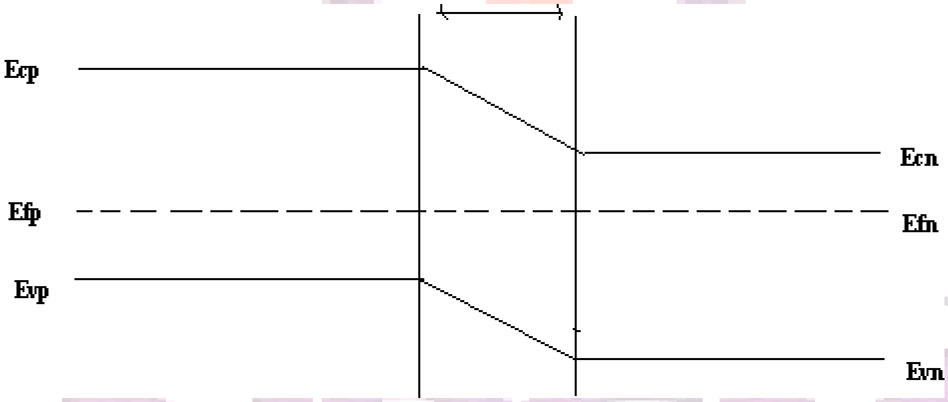


2. When a P type material is brought closer to N type material, a contact potential V_B is developed which is due to potentials of depletion regions on n- side p- side respectively.



3. The contact or barrier potential due to n- type is Vn and p-type is Vp. There fore at the junction $V_B = Vn – Vp$

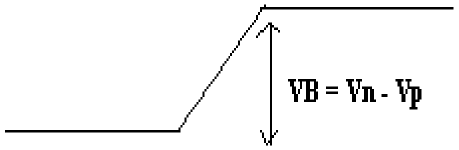
4. After the junction formation, the Fermi level becomes common for both types.



The electric field E_B = E vp – E vn

= Ecp – Ecn

= eV_B



There are three biasing conditions for the standard junction diodes. They are,

1. Zero Bias
2. Forward Bias
3. Reverse Bias

1. Zero Bias: When a diode is said to be zero biased, no external voltage is applied to the PN Junction.

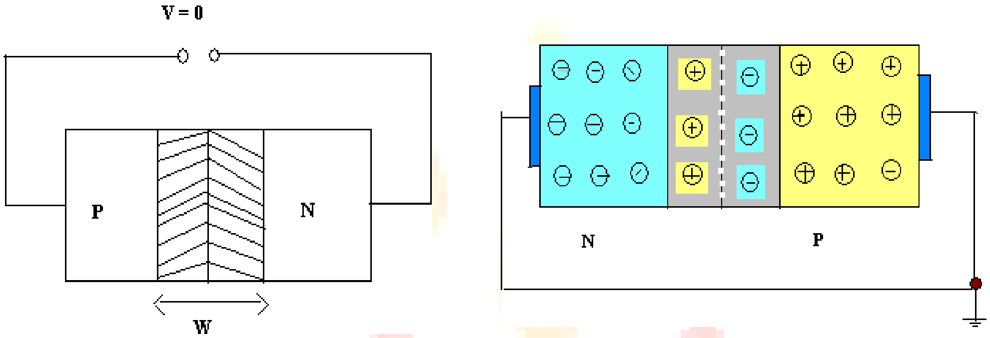


Fig: Zero biased PN junction

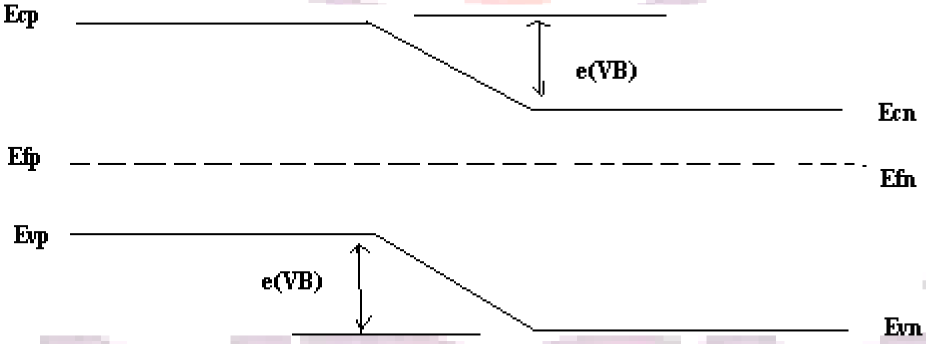


Fig: Energy level diagram

2. Forward Bias: When the positive terminal of the battery is connected to the P side and negative terminal to the N side, then the PN junction is known as Forward Biased.

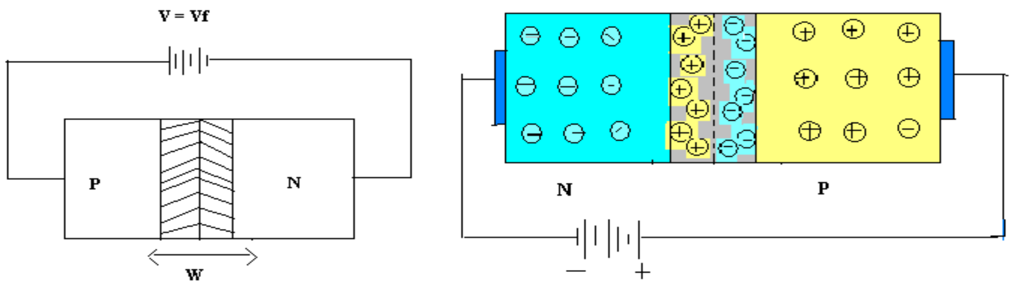


Fig: Forward biased PN junction

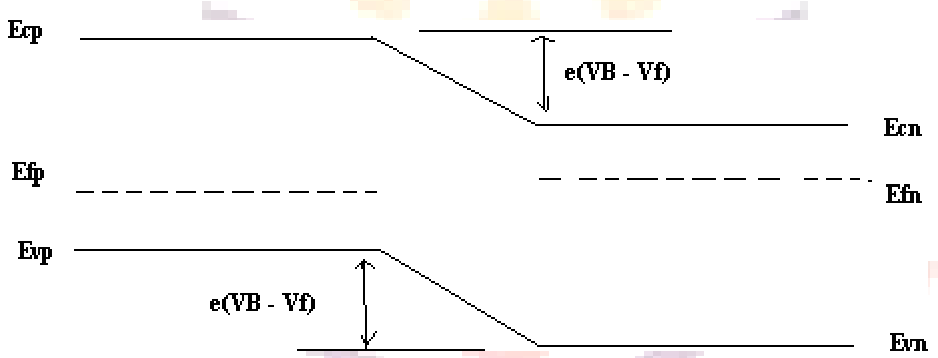


Fig: Energy level diagram

3. Reverse Bias: When the positive terminal of the battery is connected to the N side and negative terminal is to the P side then the PN junction is known as Reverse Biased.

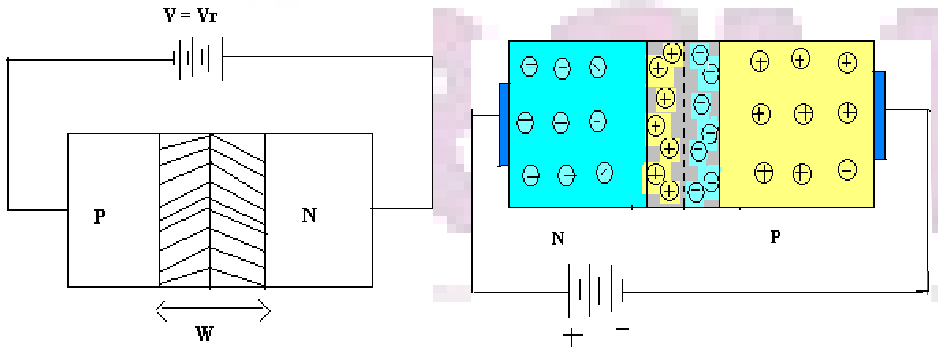


Fig: Reverse biased PN junction

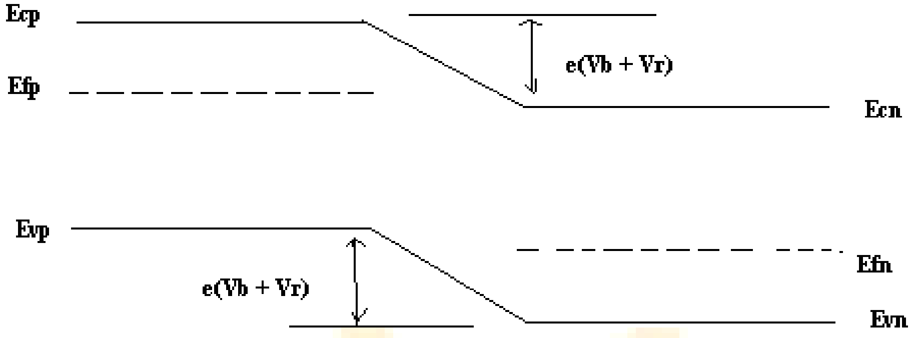


Fig: Energy level diagram

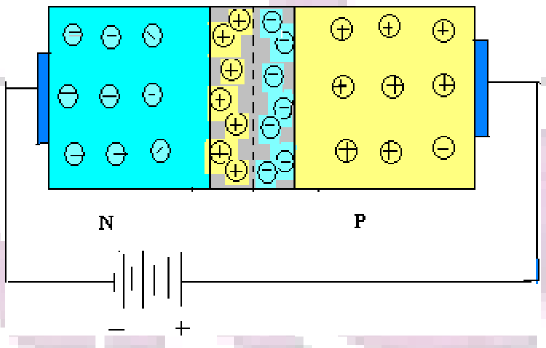
I-V Characteristics of PN Junction:

To understand how a diode responds when it is connected in an electrical circuit, its V – I characteristics should be studied.

It ca be understand simply by plotting a graph between the voltage applied across the terminals of the diode and the current that flows through the diode.

Forward Characteristics:

1. When a diode is connected in a forward bias condition the current through the diode is small for the low voltage. i.e. for first few tenths of volts.

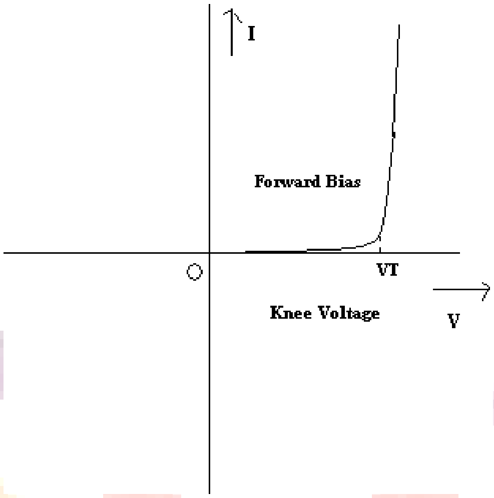


2. The external voltage applied reduces the barrier potential at the junction, but the diode does not conduct well until the applied external voltage overcomes the barrier potential.

3. When this happens, large number of electrons from n- side and holes from p-side start crossing the junction.

4. Now, even small increase in applied voltage produces a sharp increase in current.

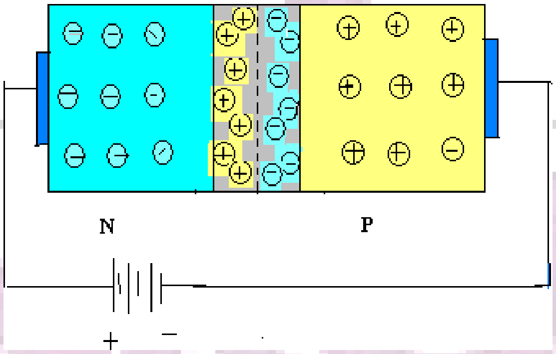
5. The voltage beyond which the current increases rapidly is called **Knee voltage or Threshold voltage.**



6. Since the diode can conduct infinite current above this knee point as if effectively becomes a short circuit, resistors are used in series with the device limit its current flow.

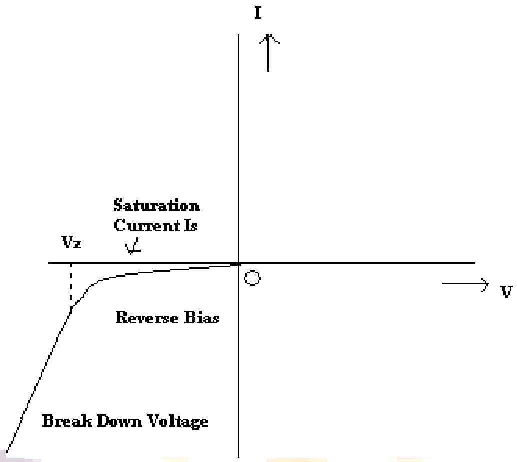
Reverse Characteristics:

1. Under Reverse bias condition, the conduction through the diode is almost negligible.



2. A very small current flows through the diode due to minority carriers crossing the junction.

3. This current remains constant for all voltages less than the break down voltage Vz. This current is called **reverse saturation current.**



4. When the applied reverse bias voltage becomes more than the break down voltage Vz, the current increases at a rapid rate.

5. An ordinary PN junction should not be operated in this voltage, because the diode becomes overheat and failed due to the “avalanche effect” around the junction.

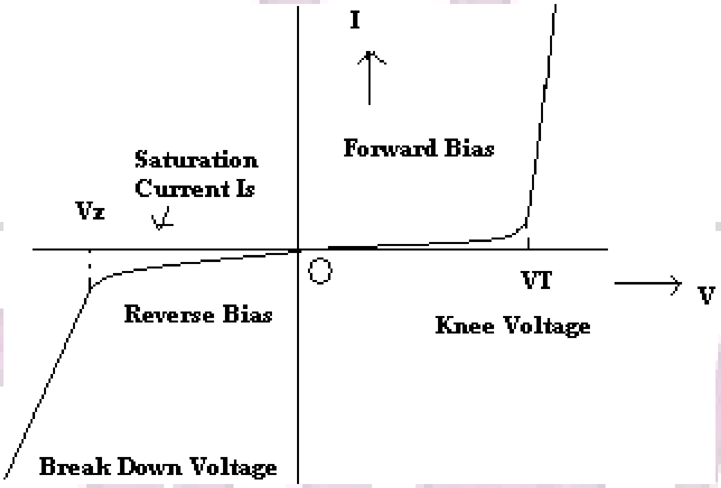


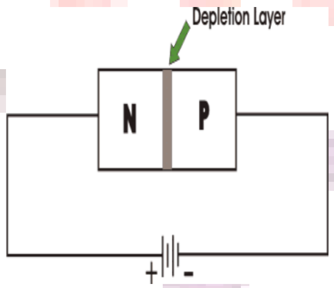
Fig: I – V Characteristics of PN junction diode

2.7 Zener diode:

A zener diode is a special type of device designed to operate in the zener breakdown region. Zener diodes acts like normal p-n junction diodes under forward biased condition. The breakdown voltage of a zener diode is carefully set by controlling the doping level during manufacture. Zener diodes are mainly used to protect electronic circuits from over voltage.

Zener diode is heavily doped than that of the normal p-n junction diode. Hence, it has very thin depletion region. Therefore, zener diodes allow more electric current than the normal p-n junction diodes. Zener diode allows electric current in forward direction like a normal diode but also allows electric current in the reverse direction if the applied reverse voltage is greater than the zener voltage. Zener diode is always connected in reverse direction because it is specifically designed to work in reverse direction.

The name zener diode was named after the American physicist Clarance Melvin Zener who discovered the zener effect. Zener diodes are the basic building blocks of electronic circuits. They are widely used in all kinds of electronic equipments.



Breakdown in zener diode

There are two types of reverse breakdown regions in a zener diode: avalanche breakdown and zener breakdown.

Avalanche breakdown: The avalanche breakdown occurs in both normal diodes and zener diodes at high reverse voltage. When high reverse voltage is applied to the p-n junction diode, the free electrons (minority carriers) gains large amount of energy and accelerated to greater velocities.

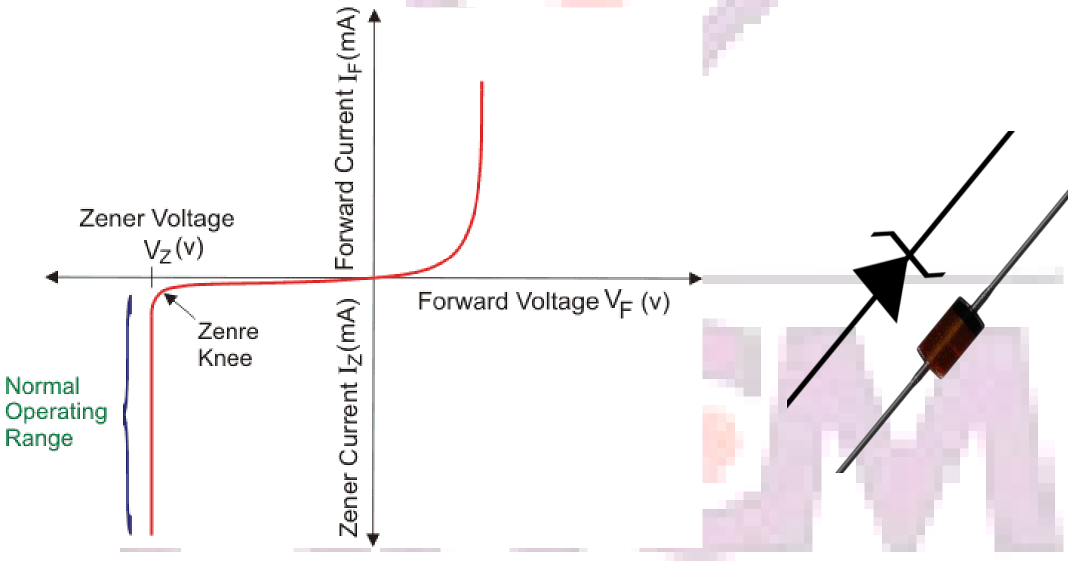
The free electrons moving at high speed will collides with the atoms and knock off more electrons. These electrons are again accelerated and collide with other atoms. Because of this continuous collision with the atoms, a large number of free electrons are generated. As a result, electric current in the diode increases rapidly. This sudden increase in electric current may permanently destroys the normal diode. However, avalanche diodes may not be destroyed because they are carefully designed to operate in avalanche breakdown region. Avalanche breakdown occurs in zener diodes with zener voltage (Vz) greater than 6V.

Zener breakdown: The zener breakdown occurs in heavily doped p-n junction diodes because of their narrow depletion region. When reverse biased voltage applied to the diode is increased, the narrow depletion region generates.

When reverse biased voltage applied to the diode reaches close to zener voltage, the electric field in the depletion region is strong enough to pull electrons from their valance band. The valence electrons which gains sufficient energy from the strong electric field of depletion region will breaks bonding with the parent atom will become free electrons. This free electrons carry electric current from one place to another place. At zener breakdown region, a small increase in voltage will rapidly increases the electric current.

- Zener breakdown occurs at low reverse voltage whereas avalanche breakdown occurs at high reverse voltage.
- Zener breakdown occurs in zener diodes because they have very thin depletion region.
- Breakdown region is the normal operating region for a zener diode.
- Zener breakdown occurs in zener voltage (Vz) less than 6V.Now, discussing about the diode circuits we should look through the graphical representation of the operation of the **zener diode**. Normally, it is called the V-I characteristics of a Zener diode.

V-I Characteristics of zener diode



The VI characteristics of a zener diode are shown in the above figure and its symbol. When forward biased voltage is applied to the zener diode, it works like a normal diode. However, when reverse biased voltage is applied to the zener diode, it works in different manner. When reverse biased voltage is applied to a zener diode, it allows only a small amount of leakage current until the voltage is less than zener voltage. When reverse biased voltage applied to the zener diode reaches zener voltage, it starts allowing large amount of electric current. At this point, a small increase in reverse voltage will rapidly increases the electric current. Because of this sudden rise in electric current, breakdown occurs called zener breakdown. However, zener diode exhibits a controlled breakdown that does damage the device. The zener breakdown voltae of the zener diode is depends on the amount of doping applied. If the diode is heavily doped, zener breakdown occurs low reverse voltages.

On the other hand, if the diode is lightly doped, the zener breakdown occurs at high reverse voltages.

Zener diodes are available with zener voltages in the range of 1.8V to 400V.

Advantages of zener diode:

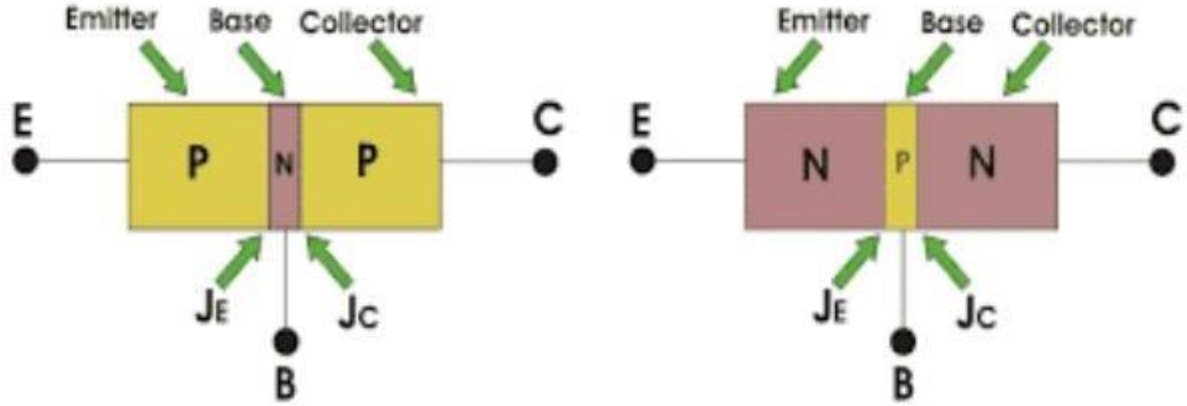
- Power dissipation capacity is very high
- High accuracy
- Small size
- Low cost

Applications of zener diode:

- It is normally used as voltage reference
- Zener diodes are used in voltage stabilizers or shunt regulators.
- Zener diodes are used in switching operations
- Zener dioes are used in clipping and clamping circuits.
- Zener dioes are used in various protection circuits.

2.8 Bipolar Junction Transistor (BJT) Construction:

A Bipolar Junction Transistor (BJT) has three terminals connected to three doped semiconductor regions. In an NPN transistor, a thin and lightly doped P-type base is sandwiched between a heavily doped N-type emitter and another N=type collector while in a PNP transistor, a thin and lightly doped N-type base is sandwiched between a heavily doped P-type emitter and another P-type collector. In the following we will only consider NPN BJTs.



1. Emitter: Emitter terminal is the heavily doped region as compared two base and collector. This is because the work of the emitter is to supply charge carrier to the collector via the base. The size of the emitter is more than base but less than the collector.

2. Base: The size of base region is extremely small, it is less than emitter as well as the collector. The size of the base is always kept small so that charge carriers coming from the emitter and entering base will not recombine in the base region and will be directed towards the collector region. The doping intensity of base is also less than emitter and collector for the same reason mentioned above.

3. Collector: The collector terminal is moderately doped, and the size of the collector region is slightly more than emitter region because all the charge carriers coming from the emitter recombine at base and heat is released in this process. Thus, it is necessary for the collector terminal to be large enough so that it can be dissipate the heat and the device may not burn out.

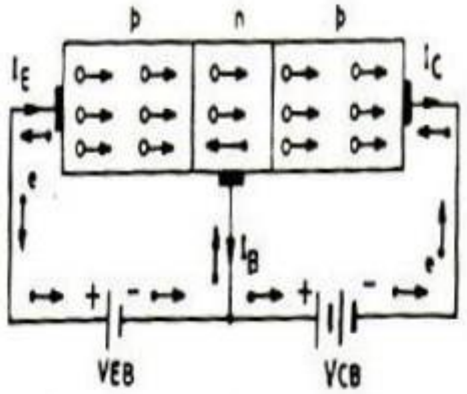
Principle of operation:

In many schematics of transistor circuits (especially when there exist a large number of transistors in the circuit), the circle in the symbol of a transistor is omitted. The figures below show the cross section of two NPN transistors. Note that although both the collector and emitter of a transistor are made of N-type semiconductor material, they have totally different geometry and therefore cannot be interchanged. All previously considered components (resistor, capacitor, inductor, and diode have two terminals (leads) and can therefore be characterized by the single relationship between the current going through and the voltage across the two leads. Differently, a transistor is a three-terminal component, which could be considered as a two-port network with an input-port and an output-port, each formed by two of the three terminals, and characterized by the relationships of both input and output currents and voltages. Depending on which of the three terminals is used as common terminal, there can be three possible

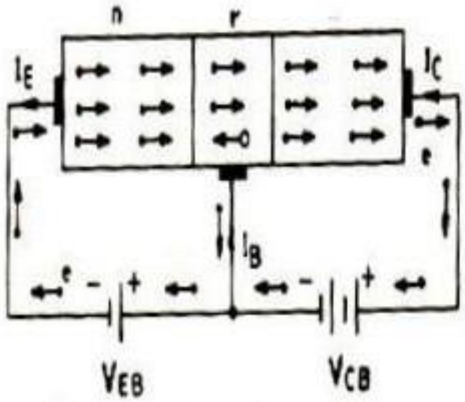
Configuration for the two-part network formed by a transistor:

- Common emitter (CE)

- Common base (CB)
- Common Collector (CC)



Basic Connections of p-n-p Transistor
(a)



Basic Connections of n-p-n Transistor
(b)

- Common-Base (CB) configuration

Two voltages VBE and VCB are applied respectively to the emitter E and collector C, with respect to the common base B, so that the BE junction forward biased while the CB junction is reversed biased. Note that the polarity of VBE and direction of IB associated with the PN-junction between E and B are the same as those associated with a diode, voltage polarity; positive on P, negative on N, current direction: from P to N, but VCB and the direction of IC associated with the PN-junction between the base and collector are defined oppositely.

The behaviour of the NPN-transistor is determined by its two PN-junctions:

- The forward biased base-emitter (BE) PN-junction allows the free electrons in emitter to go through the PN-junction to arrive at the base, forming the emitter current IE.

- As the P-type base is thin and lightly doped, only a small number of the electrons from the emitter are combined with the holes in base to form the base current IB.

- Most of the electrons coming from the emitter become minority carrier in the P-type base, and they go through the reverse biased collector-base PN junction to arrive at the collector.

- The percentage of those electrons that arrive at the collector out of the electrons from the emitter is defined as α (e.g. 99%, depending on the doping and geometry of the material). The total collector current IC is therefore IC= αIE. The current gain or current transfer ratio is defined as the ratio between the emitter (input) current IE and the collector (output) IC.

Formulas:

01	Fermi level in P-type semiconductor is $E_f = \frac{E_v + E_a}{2}$	5	Density of electrons in the conduction band is $n = (2N_d)^{1/2}\left(\frac{2\pi m_e^* KT}{h^2}\right)^{3/4} \exp\left(\frac{E_d - E_c}{2KT}\right)$
02	The diode equation is given by $I = I_0\left[\exp\left(\frac{eV}{\beta KT}\right) - 1\right]$	6	Fermi level in N-type semiconductor is $E_f = \frac{E_d + E_c}{2}$
03	Density of electrons in a semiconductors is given by $n = 2\left(\frac{2\pi m_e^* kT}{h^2}\right)^{\frac{3}{2}} \exp\left(\frac{E_f - E_c}{KT}\right)$	7	**Fermi level in intrinsic semiconductor is** **$E_f = E_g/2$**
04	Density of holes in a semiconductor is given by $p = 2\left(\frac{2\pi m_h^* KT}{h^2}\right)^{\frac{3}{2}} \exp\left(\frac{E_v - E_f}{KT}\right)$	8	Intrinsic carrier concentration is given by $n_i = 2\left(\frac{2\pi Kt}{h^2}\right)^{\frac{3}{2}} (m_e^* m_h^*)^{3/4} \exp -\left(\frac{E_g}{2KT}\right)$

SEMICODUCTOR DEVICES

2.9 Direct and Indirect Band Gap Semiconductors:

Semiconductors are available in elemental form (Ge,Si) and compound form (GaAs,Inp) Further they can further subdivided into direct band gap and indirect band gap semiconductors.

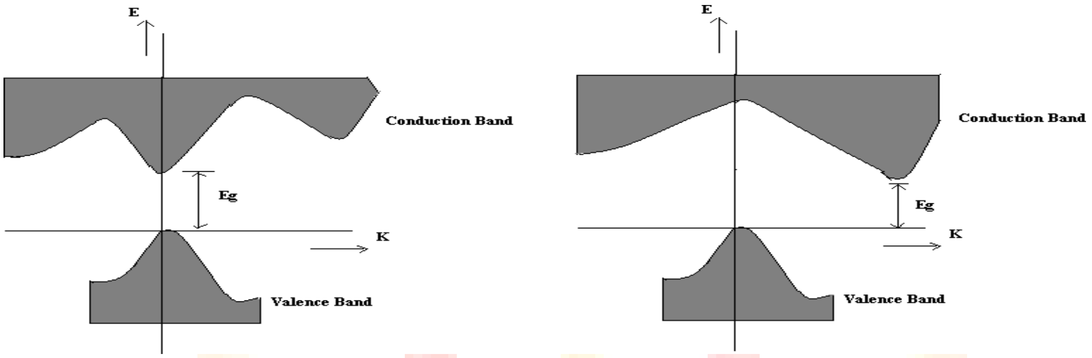


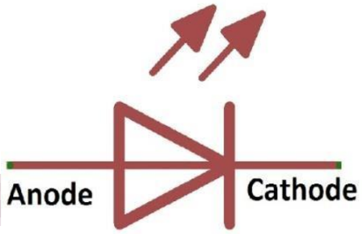
Fig: (a) Band diagram of direct band gap and indirect band gap semiconductors

Direct band gap Semiconductor	Indirect band gap Semiconductor
1. Fig(a) shows the energy band diagram drawn between energy ‘E’ and wave vector ‘k’ of a direct band gap semi conductor. 2. As shown in the band diagram, the minimum energy of conduction band and maximum energy of valence band are having the same value of wave vector. 3. An electron from the conduction band can recombine with a hole the valence band directly emitting a light photon of energy $h\upsilon$. 4. Life time (i.e. recombination time) of charge carriers is very less. 5. Due to emission of light photon during recombination of charge carriers, these are used to fabricate LEDS and laser diodes. 6. These are mostly from the	1. Fig (b) shows the energy band diagram drawn between ‘E’ and wave vector ‘k’ of an indirect band gap semiconductor 2. In this band diagram the minimum energy of conduction band and maximum energy of valence band are having the different values of wave vector. 3. An electron from the conduction band can recombine with a hole in valence band indirectly through traps. Here there is no emission of light photon. 4. Life time of charge carriers is more 5. Due to longer life time of charge Carriers, these are used to amplify the signals, as in the case of diodes and transistors. 6. These are mostly from the elemental semiconductors

compound semiconductors. 7. Ex: - In P, GaAs. 8. Band gap energy of InP =1.35eV And GaAs =1.42eV	7. Ex: - Si, Ge. 8. Band gap energy of Si=0.7eV and Ge=1.12eV.

2.10 LIGHT EMITTING DIODE(LED):

The LED is a PN-junction diode which emits light when an electric current passes through it in the forward direction. In the LED, the recombination of charge carrier takes place. The electron from the N-side and the hole from the P-side are combined and gives the energy in the form of heat and light.



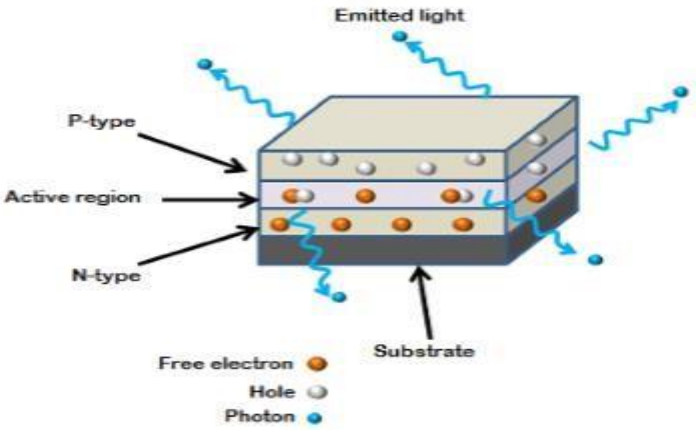
Construction of LED: The recombination of the charge carrier occurs in the P-type material, and hence P-material is the surface of the LED. For the maximum emission of light, the anode is deposited at the edge of the P-type material. The cathode is made of gold film, and it is usually placed at the bottom of the N-region. This gold layer of cathode helps in reflecting the light to the surface.

The gallium arsenide phosphide is used for the manufacturing of LED which emits red or yellow light for emission. The LED are also available in green, yellow amber and red in colour.

Working of LED:

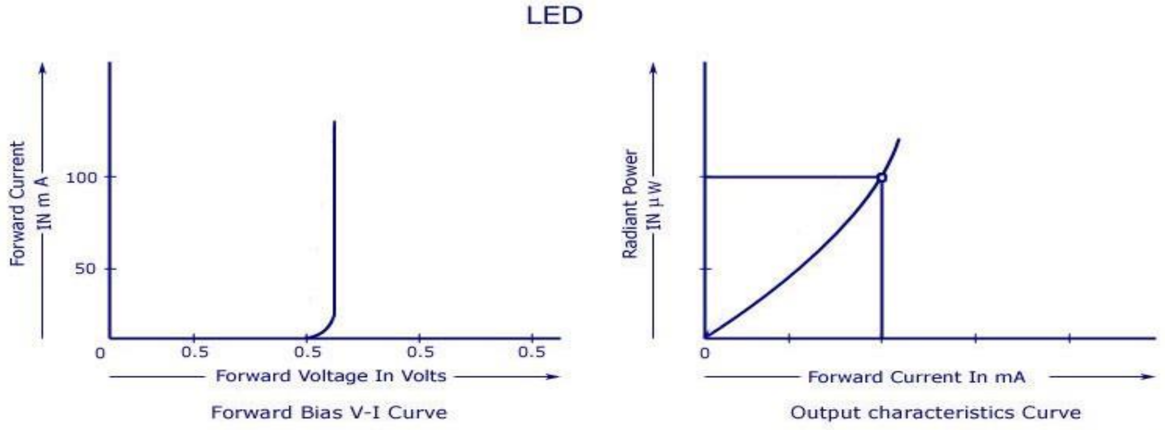
The working of the LED depends on the quantum theory. The quantum theory states that when the energy of electrons decreases from the higher level to lower level, it emits energy in the form of photons. The energy of the photons is equal to the gap between the higher and lower level.

The LED is connected in the forward biased, which allows the current to flows in the forward direction. The flow of current is because of the movement of electrons in the opposite direction. The recombination shows that the electrons move from the conduction band to valence band and they emits electromagnetic energy in the form of photons. The energy of photons is equal to the gap between the valence and the conduction band.



The gallium arsenide phosphide is used for the manufacturing of LED which emits red or yellow light for emission. The LED are also available in green, yellow amber and red in colour.

V –I Characteristics of LED:



Forward Bias V-I Curve

Output characteristics Curve

www.CircuitsToday.com

The output characteristics curve shows that radiant power of LED is directly proportional the forward current in LED.

Applications of LEDs

- Electronic displays such as OLEDs, micro-LEDs, quantum dots etc.
- As an LED indicator.
- In remote controls.
- Lightings.
- Opto-isolators.

2.12 SEMICONDUCTOR LASER

A ***semiconductor diode laser*** is a specifically made p-n junction diode that emits coherent light under forward bias. R.N. Hall and his coworkers made the first semiconductor laser in 1962. P-N junction lasers are emits light almost anywhere in the spectrum from UV to IR.

The **laser diode** (light amplification by stimulated emission of radiation) produces a monochromatic (single Color) light. Laser diodes in conjunction with photodiodes are used to retrieve date from-compact discs.

Diode lasers are remarkably small in size (0.1 mm long). They have high efficiency of the order of 40%. In spite of their small size and low power requirements, they produce power outputs equivalent to that of He-Ne lasers. Diode lasers are useful in optical fibre communications, in CD players, CD-ROM drives, optical reading and high speed laser printing etc wide.

a) Semiconductor Materials

i) Semiconductors are two different groups, direct band gap semiconductors and indirect band gap semiconductors.

ii) Direct band gap semiconductors are formed by group III_V elements and group IV-VI elements. Most of the compound semiconductors belong to this group.

iii) Leasers are made using direct band gap semiconductors. Gallium Arsenide (GaAs) diode is an example of semiconductor diode laser.

iv) Direct band gap semiconductor is the one in which a conduction band electron can recombine directly with a hole in the valence band. The recombination process lead to emission of light.

b) Principle

i) The energy hand structure of a semiconductor consists of a valence band and a conduction band separated by an energy gap, E_g. The conduction band contains electrons and the valence band contains holes and electrons.

ii) When an electron from the conduction band jumps into a hole in the valence band, the excess energy E_g is given out in the form of a photon.

iii) Electron-hole recombination is the basic mechanism responsible for emission of light.

Iv) The wavelength of the light is given by the relation $\lambda = hc/E_g$.

v) Semiconductors having a suitable value of E_g emit light in the optical region.

c) Types of Semiconductor Diode Lasers

Broadly there are two types of semiconductor diode lasers. They are known as *homojunction semiconductor laser and heterojunction semiconductor lasers.*

i) Homojunction Semiconductor Laser

ii) Heetrojunction Semiconductor Laser

Homojunction Semiconductor Laser

A Simple diode laser which makes use of the same semiconductor material on both sides of the junction is known as a homojunction diode laser. Example: Gallium arsenide (GaAs) laser.

a) Construction: Fig. shows the schematic of a homojuncation diode laser. Starting with a heavily doped n-type GaAs material, a p-region is formed on its top by diffusing zinc atoms into it. A heavily zinc doped layer constitutes the heavily doped p-region.

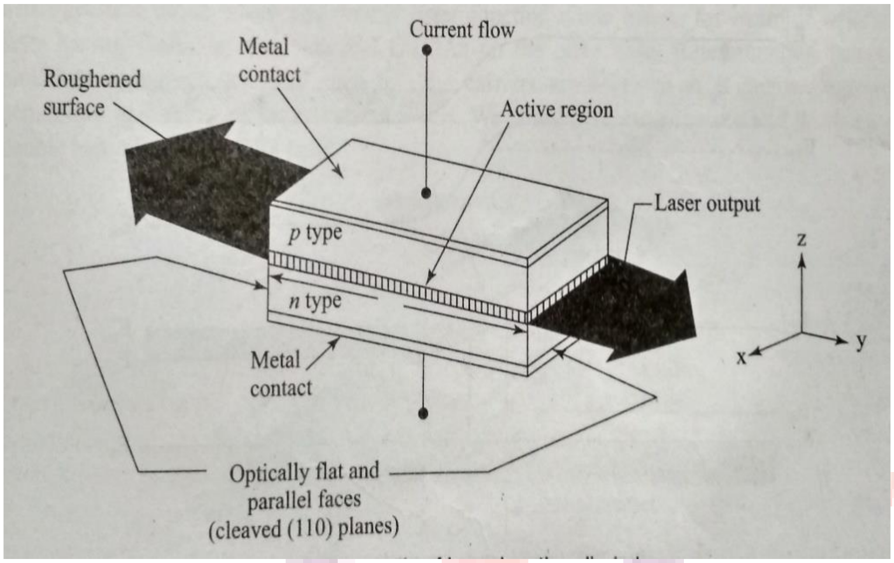


Fig: Homojunction diode laser

The diode is extremely small in size. Typical diode chips are 500 μm long and about 100 μm wide and thick. The top and bottom faces are metalized and metal contacts are provided to pass current through the diode. A pair of parallel planes cleaved at the two ends of the PN junction provides required reflection to from the cavity. The two remaining sides of the diode are roughened to remove lasing action in that direction. The entire structure is packaged in small case which looks like the metal case used for discrete transistors.

b) Working:

i) Heavily doped p- and n- regions are used. Because of very high doping on n-side, the donor levels are broadened and extend into the conduction band.

ii) The Fermi level is pushed into the conduction band and electrons occupy the levels lying below the Fermi level.

iii) Similarly, on the heavily doped p-side the Fermi level lies within the valence band and holes occupy the portion of the valence band that lies above the Fermi Level.

iv) At thermal equilibrium, the Fermi level is uniform across the junction.

2.13 Photo Detectors

A photo detector is an optoelectronic device which absorbs light and converts the optical energy into measurable electric current.

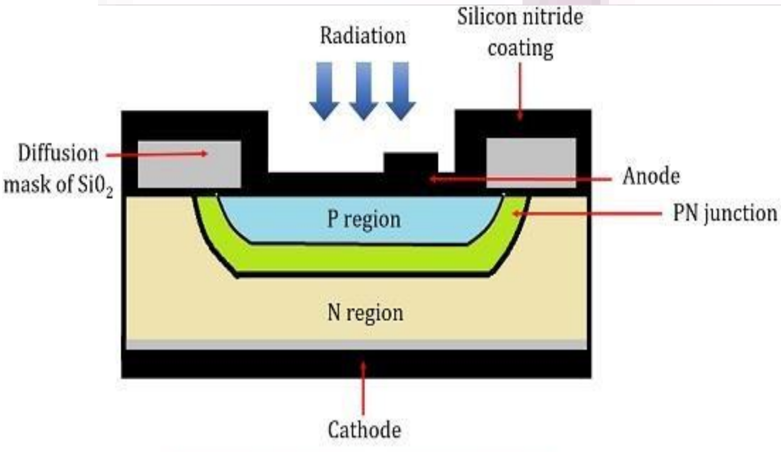
Photodiode: A photodiode is a p-n junction diode, used to convert the light into current or voltage by operating in reverse biased mode.

Working Principle:

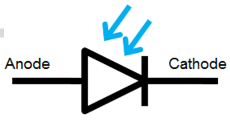
The working principle of a photodiode is, when a photon of ample energy strikes the diode, it makes a couple of an electron-hole pairs. Therefore, holes in the region move toward the anode, and electrons move toward the cathode, and a photocurrent will be generated.

Construction: The photodiode is made up of two layers of P-type and N-type semiconductor. In this, the P-type material is formed from diffusion of the lightly doped P-type substrate. Thus, the layer of P+ ions is formed due to the diffusion process. And N-type epitaxial layer is grown on N-type substrate. The contacts are made up of metals to form two terminal cathode and anode. The front area of the diode is divided into two types that are active surface and non-active surface. The non-active surface is made up of SiO_2 (Silicon di Oxide) and the active surface is coated with anti-reflection material. The active surface is called so because the light rays are incident on it.

While on the non-active surface the light rays do not strike. The active layer is coated with anti-reflection material so that the light energy is not lost and the maximum of it can be converted into current.

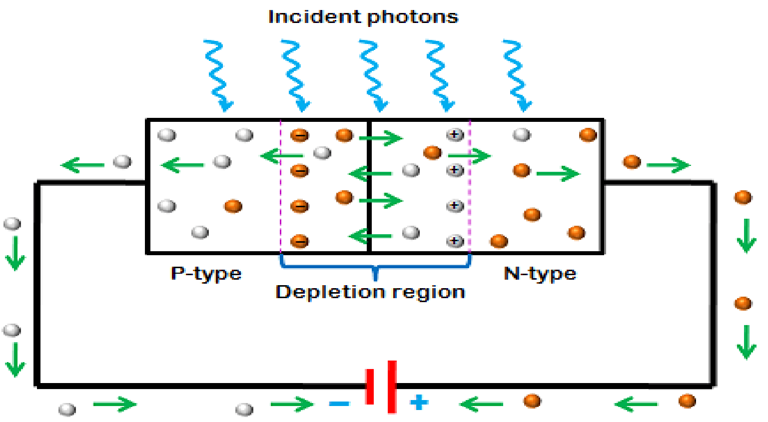


Structure of Photodiode



Photodiode symbol

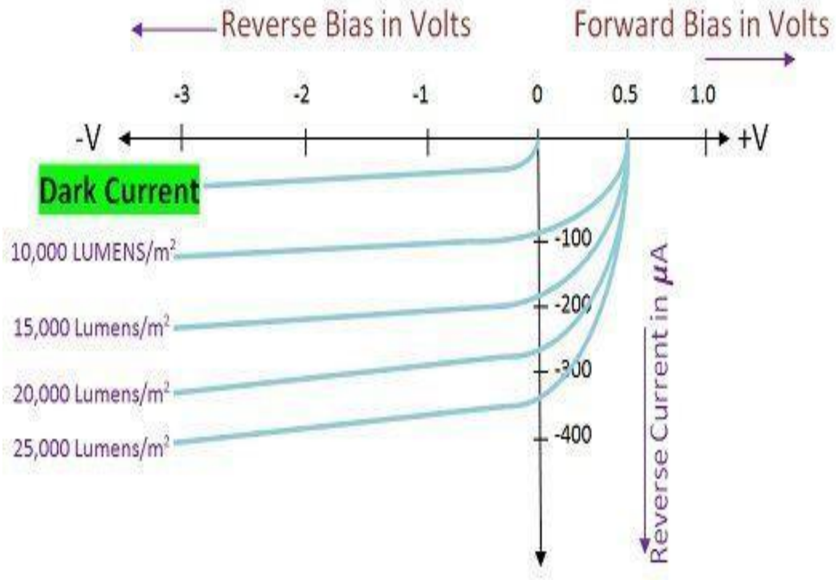
Working: When a light is made to illuminate the PN junction, the photon enters the depletion region of diode and hits the atom with high energy. This results electron - hole pairs. In general, an electron will have negative charge and holes will have a positive charge. The depletion energy will have built in electric filed. Due to that electric filed, electron hole pairs moves away from the junction. Hence, holes move to anode and electrons move to cathode to produce photo current.



PN Junction photodiode

V-I Characteristics of Photodiode

Photodiode operates in reverse bias condition. Reverse voltages are plotted along X axis in volts and reverse current are plotted along Y-axis in microampere. Reverse current does not depend on reverse voltage. When there is no light illumination, reverse current will be almost zero. The minimum amount of current present is called as **Dark Current**. Once when the light illumination increases, reverse current also increases linearly as shown in below figure.



Applications of photodiodes

Photodiodes are used in

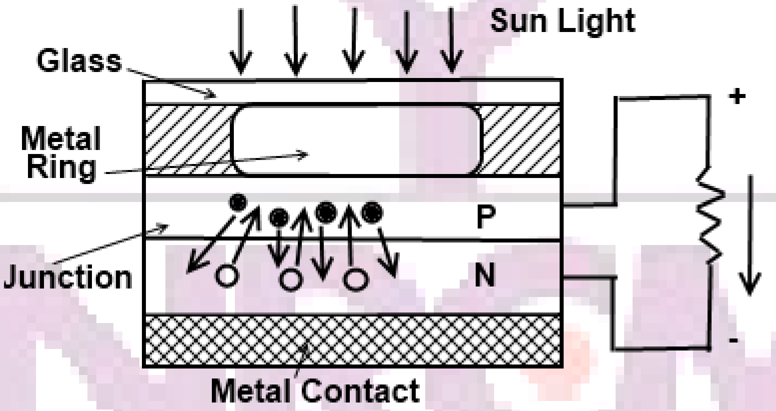
- Consumer electronics devices such as compact disc players,
- Smoke detectors,
- Medical devices
- Receivers for infrared remote control devices used to control equipment from televisions to air conditioners.

2.14 Solar Cell or Photovoltaic

A **solar cell** (also known as a photovoltaic cell or PV cell) is defined as an electrical device that converts light energy into electrical energy through the photovoltaic effect.

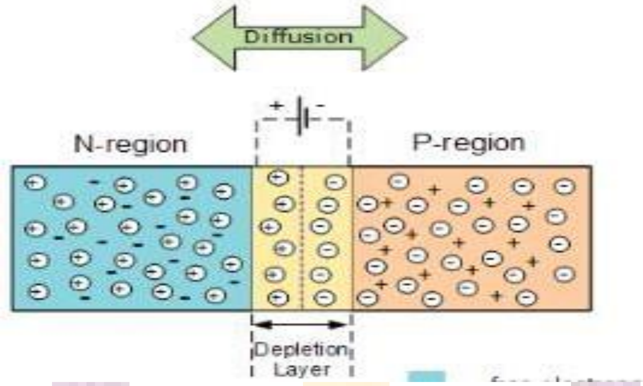
Construction: Consider the figure below shows the constructions of the silicon photovoltaic cell. The upper surface of the cell is made of the thin layer of the p-type material so that the light can easily enter into the material. The metal rings are placed around p-type and n-type material which acts as their positive and negative output terminals respectively.

Working Principle: When light reaches the p-n junction, the light photons can easily enter in the junction, through very thin p-type layer. The light energy, in the form of photons, supplies sufficient energy to the junction to create a number of electron-hole pairs. The free electrons in the depletion region can quickly come to the n-type side of the junction. Similarly, the holes in the depletion can quickly come to the p-type side of the junction.



Once, the newly created free electrons come to the n-type side, cannot further cross the junction because of barrier potential of the junction. Similarly, the newly created holes once come to the p-type side cannot further cross the junction became of same barrier potential of the junction.

As the concentration of electrons becomes higher in one side, i.e. n-type side of the junction and concentration of holes becomes more in another side, i.e. the p-type side of the junction, the p-n junction will behave like a small battery cell. A voltage is set up which is known as photo voltage. If we connect a small load across the junction, there will be a tiny current flowing through it.



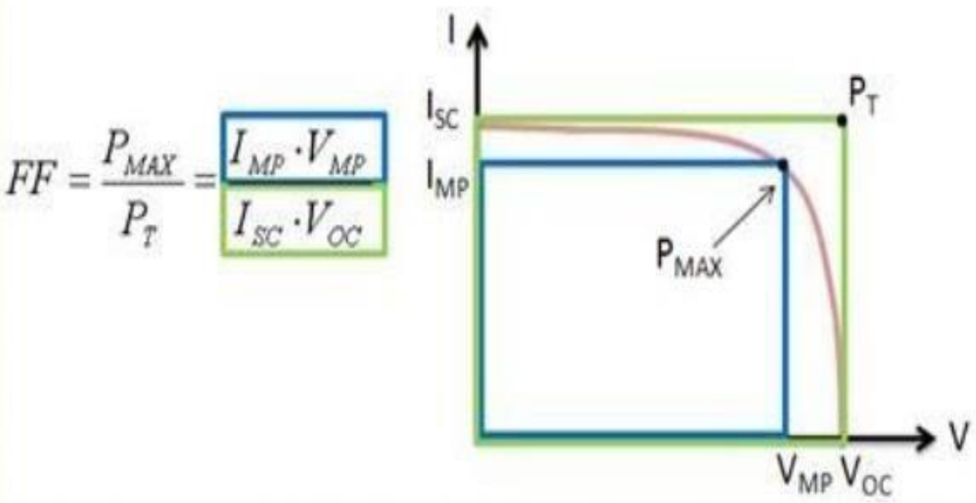
V-I Characteristics of a solar Cell:

The voltage - current characteristics of solar cell is shown in below figure.

From the graph it is clear that the maximum current occurs in the solar cell when the voltage is zero is known as **short circuit current I_{sc}**.

The maximum voltage that occurs in the solar cell when the current is zero is known as **open circuit voltage V_{oc}**.

The **fill factor** is the ratio of the actual maximum obtainable power to the product of the open circuit voltage and short circuit current.



The efficiency of a solar cell is determined as the fraction of incident power which is converted to electricity and is defined as:

$$P_{max} = V_{OC} I_{SC} FF$$

$$\eta = \frac{V_{OC} I_{SC} FF}{P_{in}}$$

Materials Used in Solar Cell:

The materials which are used for this purpose must have band gap close to 1.5ev. Commonly used materials are-

1. Silicon.
2. GaAs.
3. CdTe.
4. $CuInSe_2$

Criteria for Materials to be Used in Solar Cell

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

Advantages of Solar Cell

1. No pollution associated with it.
2. It must last for a long time.
3. No maintenance cost.

Disadvantages of Solar Cell

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

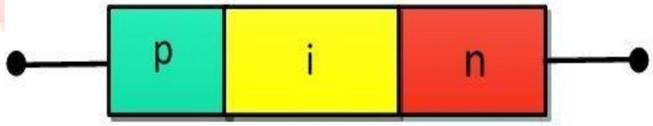
Applications

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

2.15 PIN Diode

The diode in which the intrinsic layer of high resistivity is sandwiched between the P and N-region of semiconductor material such type of diode is known as the PIN diode. The PIN diode is a type of photodetector used for converting the light energy into the electrical energy.

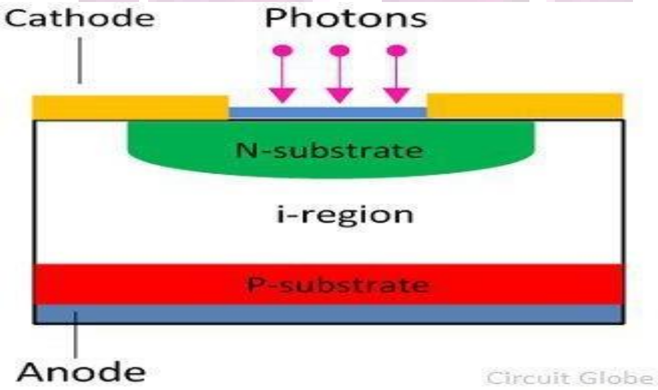
Construction: The diode consists the P-region and N-region which is separated by the intrinsic semiconductor material. The intrinsic region has no free charge carrier. It acts as an insulator between n and the p-type region. The i-region has the high resistance which obstructs the flow of electrons to pass through it.



PIN Diode

Circuit Globe

Working: The working of the PIN diode is similar to the ordinary diode. When the diode is unbiased, their charge carrier will diffuse. The process of diffusion occurs continue until the charges become equilibrium in the depletion region.



Let the N and I-layer make the depletion region. The diffusion of the hole and electron across the region generates the depletion layer across the NI-region. The thin depletion layer induces across n-region, and thick depletion region of opposite polarity induces across the I-region.

When the diode is kept forward biased, the charges are continuously injected into the I-region from the P and N-region. This reduces the forward resistance of the diode, and it behaves like a variable resistance.

When the reverse voltage is applied across the diode, the width of the depletion region increases. The thickness of the region increases until the entire mobile charge carrier of the I-region swept away from it. The reverse voltage requires for removing the complete charge carrier from the I-region is known as the **swept voltage**. In reverse bias, the diode behaves like a capacitor. The P and N region acts as the positive and negative plates of the capacitor, and the intrinsic region is the insulator between the plates.

Characteristics of PIN diode

- **Low Capacitance**: As we already discussed that a PIN diode offers a lower value of capacitance due to the larger distance between p and n region.
- **High breakdown voltage**: Due to the presence of intrinsic region, PIN diode exhibits a higher value of breakdown voltage.
- **High Sensitive to photodetection**: The depletion region is responsible for generating energy when radiation falls on its surface. The existence of an intrinsic region enhances the area for radiation absorption.
- **High Storage of carriers**: This is the important characteristic of PIN diode. The intrinsic region enhances the area for storage of carriers. The stored charge in the depletion region is responsible for the amount of current flowing through the circuit.

Applications of PIN diode

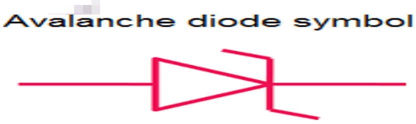
1. **As a Photodetector**: A PIN diode can change the absorbed light into electrical energy. The placement of intrinsic region between the p and n region increases the region for radiation absorption. With the increased radiation absorption region, the efficiency of the device to produce electrical energy also increases. Thus, it can be used as a photodiode.
2. **As a radio frequency switch**: The intrinsic region isolates the p and n region of the diode due to which capacitance decreases. The capacitance of the device should almost negligible in order to operate it as a switch.
3. **As a voltage rectifier**: PIN diode is able to bear high reverse voltage due to the intrinsic layer. This leads to an increase in the breakdown voltage of the diode. Hence, due to this, the device allows the rectification of high input voltage.

2.16 Avalanche Diode

An avalanche diode is a special type of semiconductor device designed to operate in reverse breakdown region.

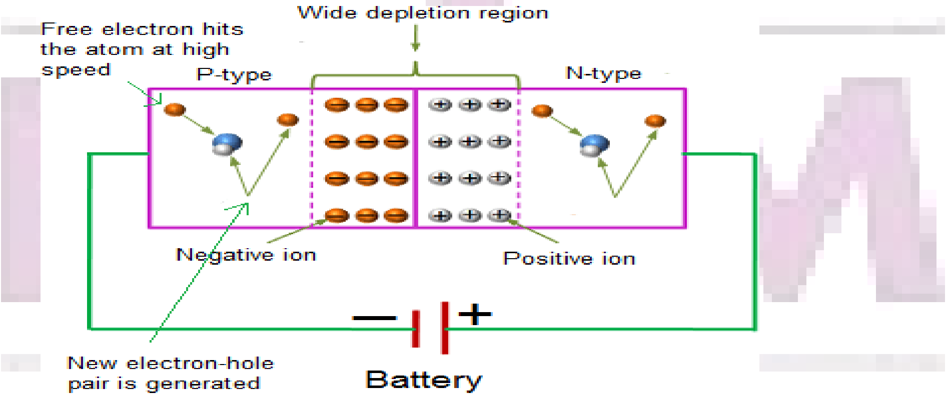
Construction: Avalanche diodes are generally made from silicon or other semiconductor materials. The construction of avalanche diode is similar to zener diode but the doping level in avalanche diode differs from zener diode.

Zener diodes are heavily doped. Therefore, the width of depletion region in zener diode is very thin. Because of this thin depletion layer or region, reverse breakdown occurs at lower voltages in zener diode. On the other hand, avalanche diodes are lightly doped. Therefore, the width of depletion layer in avalanche diode is very wide compared to the zener diode. Because of this wide depletion region, reverse breakdown occurs at higher voltages in avalanche diode. The breakdown voltage of avalanche diode is carefully set by controlling the doping level during manufacture.


Avalanche diode symbol

The symbol of avalanche diode is similar to the normal diode but with the bend edges on the vertical bar.

Working: When reverse bias voltage is applied to the avalanche diode, the free electrons (majority carriers) in the n-type semiconductor and the holes (majority carriers) in the p-type semiconductor are moved away from the junction. As a result, the width of depletion region increases. Therefore, the majority carriers will not carry electric current. However, the minority carriers (free electrons in p-type and holes in n-type) experience a repulsive force from external voltage.

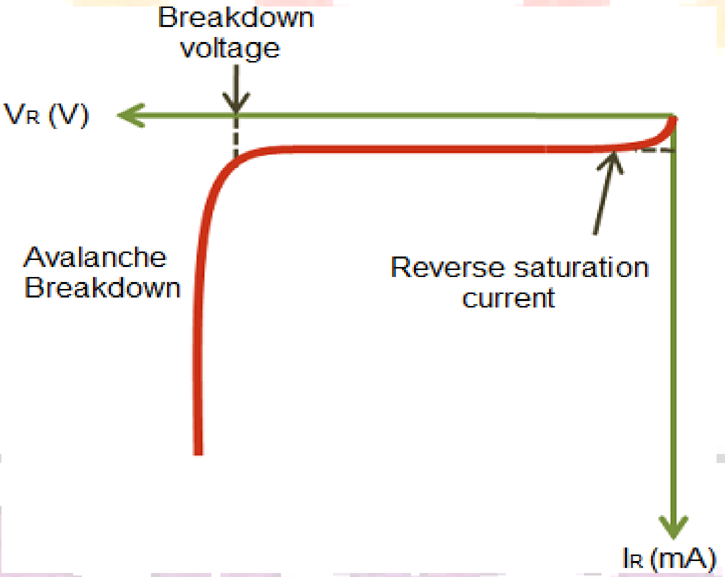


As a result, the minority carriers flow from p-type to n-type and n-type to p-type by carrying the electric current. However, electric current carried by minority carriers is very small. This small electric current carried by minority carriers is called reverse leakage current.

If the reverse bias voltage applied to the avalanche diode is further increased, the minority carriers (free electrons or holes) will gain large amount of energy and accelerated to greater velocities. The free electrons moving at high speed will collide with the atoms and transfer their energy to the valence electrons.

The valance electrons which gains enough energy from the high-speed electrons will be detached from the parent atom and become free electrons. These free electrons are again accelerated. When these free electrons again collide with other atoms, they knock off more electrons. Because of this continuous collision with the atoms, a large number of minority carriers (free electrons or holes) are generated. These large numbers of free electrons carry excess current in the diode.

When the reverse voltage applied to the avalanche diode continuously increases, at some point the junction breakdown or avalanche breakdown occurs. At this point, a small increase in voltage will suddenly increases the electric current. This sudden increase of electric current may permanently destroys the normal p-n junction diode. However, avalanche diodes may not be destroyed because they are carefully designed to operate in avalanche breakdown region.



The breakdown voltage of the avalanche diode depends on the doping density. Increasing the doping density will decreases the breakdown voltage of the avalanche diode.

Applications of avalanche diodes

- Avalanche diodes can be used as white noise generators.
- Avalanche diodes are used in protecting circuits.
- This makes the diode to start performing current without injuring itself, and switches the extreme power away from the electrical circuits to its ground terminal.

Short answer questions

1. What are intrinsic semiconductors? Give examples.
2. What are extrinsic semiconductors? Give examples.
3. Distinguish between intrinsic and extrinsic semiconductors.
4. Define Fermi level and mention its position in intrinsic and extrinsic semiconductors at 0K.
5. Explain about carrier generation and recombination mechanism.
6. Write the applications of Hall effect.
7. Write short note on Zener diode.
8. Explain V-I characteristics of p-n junction.

Essay questions

1. Derive an expression for concentration of electrons and holes in intrinsic semiconductor.
2. Derive an expression for carrier concentration in n-type and p-type semiconductor.
3. Explain drift and diffusion mechanism in semiconductors.
4. What is Hall effect? Derive expression for Hall coefficient.
5. Explain how a p-n junction is formed and explain with neat energy level diagram of p-n junction.
6. Explain construction and working of BJT.
7. Explain construction and working of avalanche diode.
8. Explain construction and working of PIN diode.
9. Explain construction and working of LED.
10. Explain construction and working of solarcell.

Multiple answer questions

1. At 0K pure silicon is [ ]

(a) an intrinsic semiconductor (b) extrinsic semiconductor

(c) insulator (d) superconductor

2. The majority carriers in p- type Ge are [ ]

(a) free electrons (b) holes (c) ions (d) conductions electrons

3. The electric current in a pure semiconductor when voltage is applied is due to [ ]

(a) Electrons (b) holes (c) ions (d) holes and electrons

4. In an intrinsic semiconductor at 0 K, the Fermi level lies [ ]

(a) at the centre of top of the valence band and bottom of the conduction band

(b) at the centre of donor level and intrinsic Fermi level

(c) at the centre of donor level and bottom of the conduction band

(d) at the centre of acceptor level and top of the valence band

5. The density of charge cxarriers in a pure semiconductor is proportional to [ ]

(a) $\exp(- Eg/kT)$(b) $\exp(2Eg/kT)$ (c) $\exp(- Eg/kT^2)$(d) $\exp(-Eg/2kT)$

6. Life time of LEDs is about [ ]
(a) 10^2 hours (b) 10^3 hours (c) 10^4 hours (d) 10^5 hours

7. The thickness of depletion region is in the order of [ ]
(a) 6 X 10^{-3} cm (b) 6 X 10^{-9} cm (c) 6 X 10^{-6} cm (d) 6 X 10^{-12} cm

8. In a LED, if Eg is the band gap, the wavelength of emission is given by [ ]
(a) $\lambda = Eg / h\upsilon$ (b) $\lambda = h\upsilon / Eg$ (c) $\lambda = Eg / hc$ (d) $\lambda = hc / Eg$

9. Response time of LEDs in the order of [ ]
(a) 10^{-3} s (b) 10^{-6} s (c) 10^{-9} s (d) 10^{-12} s

10. Intrinsic semiconductor atom possesses--- valance electrons [ ]
(a) 3 (b) 5 (c) 4 (d) 7

11. Which of the following a semiconductor material [ ]
(a) Aluminium (b) Rubber (c) Silicon (d) Phosporous

12. At 0 K pure silicon is [ ]
(a) Insulator (b) conductor
(c) Semiconductor (d) super conductor

13. At room temperature , semiconductor possesses—co-efficient of resistivity [ ]
(a) Positive (b) negative (c) zero (d) neutral

14. Selenium is [ ]
(a) Intrinsic semiconductor (b) Extrinsic semiconductor
(c) p-type semiconductor (d) n-type semiconductor

15. Electron- hole recombination results [ ]
(a) Release of energy (b) Absorption of energy (c) Both a&b (d) None

16. In a reverse bias diode the depletion layer is [ ]
(a)Thick (b) thin (c) negligible (d) very large

17. In intrinsic semiconductor the carrier concentration varies [ ]
(a) 1/T (b) $T^{3/2}$(c) T^2 (d) T

18. The resistivity of pure silicon 0^0C is 300Ωm. The intrinsic scarier concentration per cubic meter is (μ_e-0.14 and $\mu_h=0.05m^3V^{-1}s^{-1}$) [ ]
(a) 1.095×10^{17} (b) 2.19 x 10^{17} (c) 10^{17} (d) zero

19. In conductors energy gap is [ ]
(a) 0.6 (b) 0.7 (c) 0 (d) 1.1

20. Hall coefficient for n type material [ ]

(a)negative (b)positive (c)neutral (d)none

21. Hall coefficient for p type material [ ]

(a)negative (b)positive (c)neutral (d)none

22. The energy gap for Germanium -----Ev [ ]

(a)0.75 (b)1.1 (c)1.5 (d)2

23. The energy gap for Silicon ----- eV [ ]

(a) 0.75 (b) 1.1 (c) 1.5 (d) 2

24.The Charge carriers in intrinsic semi conductor [ ]

(a)electrons (b)holes (c)both a&b (d)none

25. Majority chrge carriers in P- type semiconductor [ ]

(a) Holes (b) Electrons
(c) Protons (d) Photons

Fill in the blanks

1. Solar is a --------- device

2. LEDs are made up of --------semiconductors

3. PIN diode consists of……

4. Photo voltalic cell works on the principle of---------

5. when reverse baised, PIN diode act like a ---------

Choose the Correct Alternative

1. Photovoltaic cell works on the principle of……. [ ]
a)forward bias b photovoltaic effect c)reverse bias d)none

2.PIN diode consists of…… [ ]
a) 1operating regions b 2operatin regions c)3operating regionsd) none

3. Photo diode is normally…….. [ ]
a) forward biased b) reverse biased c)none d)emitting light

4. photo conductivity increases with addition of [ ]
A)impurity b)nickel c)iron d)none

5. A solar cell is simply photodiode which is operated at [ ]

a) zero baised voltage b)constsnt baised voltage c)forward baised voltage

d)reverse baised voltage

UNIT-III

Dielectric, Magnetic and Energy of Materials

Dielectrics materials

Introduction: Dielectrics are insulating materials so there are no free charge carriers in them.

Ex : Mica, plastic glass and wood.

The dielectrics are of two types they are,

1)**Non-polar dielectrics :**

In case of non–polar dielectrics the centre of gravity of positive charge is coincide with the center of gravity of negative charge.

They have symmetric in nature.

Their dipole moment is zero.

Ex: methane, benzene etc.

2)**Polar-dielectrics :**

In case of polar dielectrics the center of gravity of positive charge is not coincide with the center of gravity of negative charge.

They have asymmetric in nature.

Their dipole moment is not zero.

Ex: NH_3, Hcl, water etc.

3.1 Basic definitions

Electric dipole: A system consisting of two equal and opposite charge separated by a small distance is called as electric dipole.

Length of dipole is denoted by 2l (or) d.

$$q\ \text{O}\text{------------}\text{O}\ -q$$
$$\leftarrow\ 2l\ \rightarrow$$

Electric dipole moment: The product of magnitude of charge and the distance between two charges is called as electric dipole moment It is denoted by P (or) μ

Dipole moment(μ) = charge × distance between them

$$(\mu) = q \times 2l$$

Units are coulomb-metre

<u>Dielectric constant</u>(or) <u>relative permittivity</u> (ϵ_r): Ratio between the permittivity of the medium to the permittivity of free space is called as relative permittivity.

That is (ϵ_r) = permittivity of medium / permittivity of free space

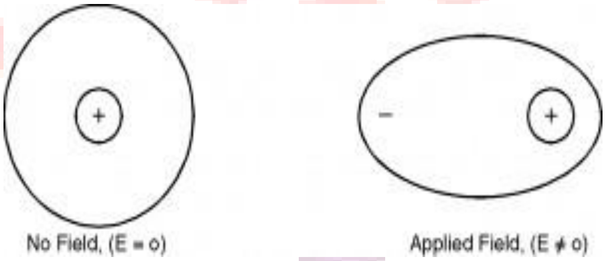
(ϵ_r) = ϵ / ϵ_o = capacitance of capacitor with dielectric / capacitance of capacitor without dielectric

= c / c_o

It has no units

Electric polarization

The process of producing electric dipoles which are oriented along the field direction is called as polarization in dielectrics. It is denoted by P



Polarizability(α):

The induced dipole moment is directly proportional to the intensity of the electric field.

That is μ proportional E

$\mu = \alpha E$ where α is called proportionality constant of polarizablity

Induced dipole moment per unit electric field is called as polarizability

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

Polarization vector ($\overline{P}$): The dipole moment per unit volume of the dielectric material is called as polarization vector P.

$$\overline{P} = N \mu$$

Where μ = average dipole moment per molecule

N = no. of molecules per unit volume

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

Electric displacement at a point in a material is given by $D = \epsilon E$

We know that $\epsilon = \epsilon_o \epsilon_r$

$$D = \epsilon_o \epsilon_r E$$

As the polarization measures the additional flux density rising from the presence of the material as compared to free space is given by

$$D = \epsilon_o E + P$$

We know that $D = \epsilon_o \epsilon_r E$

$$\epsilon_o \epsilon_r E = \epsilon_o E + P$$

$$P = \epsilon_o \epsilon_r E - \epsilon_o E$$

$$P = \epsilon_o (\epsilon_r - 1)E$$

Electric susceptibility(χ_e):

The polarization vector is proportional to the total electric flux density(E)

$$\text{i.e.,} \quad P = \epsilon_o \chi_e E$$

$$\chi_e = P / \epsilon_o E$$

$$\chi_e = \epsilon_o (\epsilon_r - 1)E / \epsilon_o E$$

$$\chi_e = (\epsilon_r - 1)$$

3.2 Types of polarization

They are four types of polarizations

1) Electronic polarization

2) Ionic polarization

3) Orientation polarization and

4) Space charge polarization

3.2.1 Electronic polarization:

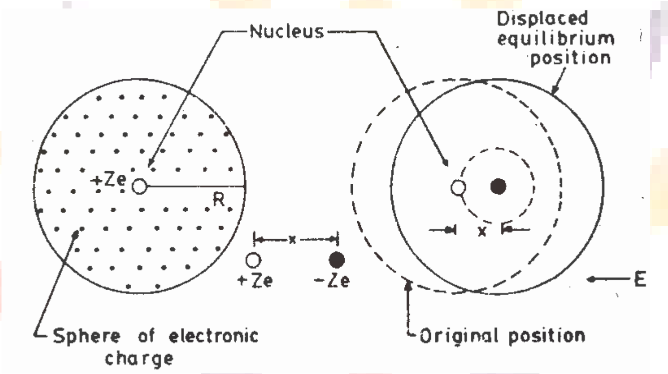
The displacement of the positively charged nucleus and the electrons of an atom in opposite directions, on application of an electric field, result in electronic polarization.

Induced dipole moment μ proportional E

$$\mu = \alpha_e E$$

where α_e is the electronic polarizability. It is independent of temperature.

<u>Calculation of electronic polarizability:</u>



A simplified classical modal of an atom is shown in above figure. 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

$$\rho = \frac{-Ze}{4\pi R^3/3}$$

$$= -3Ze / 4\pi R^3$$

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 developed between them, which tends to opposite the displacement. When these forces namely Lorentz force and coulomb force are equal and opposite, equilibrium is reached and let x be the displacement under that condition.

Lorentz force = - ZeE

Coulomb force = Ze(charge enclosed in the sphere of radius x) / $4\pi\epsilon_o x^2$

The charge enclosed in the sphere = $4\pi x^3 \rho / 3$

$$= (4\pi x^3 / 3)\ (-\ 3Ze / 4\pi R^3\ )$$

$$= -\ Zex^3 / R^3$$

Hence coulomb force $=(Ze /4\pi\epsilon_o x^2)\ (-Zex^3 / R^3) = -\ Z^2 e^2 x / 4\pi\epsilon_o R^3$

In the equilibrium position, Lorentz force = coulomb force

$$-\ ZeE = -\ z^2 e^2 x /4\pi\epsilon_o R^3$$

$$X = 4\pi\epsilon_o R^3 E / Ze$$

The two electric charges Ze and –Ze are separated by a distance x under the action of the applied field thus constituting induced electric dipoles.

Induced electric dipole moment $\mu_e = Zex$

$$= Ze4\pi\epsilon_o R^3 E / Ze$$

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

i.e., $\mu_e = \alpha_e E$

Where $\alpha_e = 4\pi\epsilon_o R^3$ is called electronic polarizability.

The dipole moment per unit volume is called electronic polarization. It is independent of temperature.

$\mathbf{P} = N\ \boldsymbol{\mu e} = N\ \boldsymbol{\alpha e}\ E$ where N is Number of atoms / m^3

$\mathbf{P_e} = N\ (4\ \Pi\ \varepsilon_0\ R^3 E\ ) = 4\ \Pi\ \varepsilon_0\ R^3\ N\ E$ where

R is radius of atom

3.2.2 Ionic Polarization

It is due to the displacement of cat ions and anions in opposite directions and occurs in an ionic solid .

Consider a NaCl molecule. Suppose an electric field is applied in the positive direction . The positive ion moves by x1 and the negative ion moves by x2

Let M is mass of positive ion

m is mass of negative ion

Total displacement x = x1 + x2 ----------------------(1)

Lorentz force on positive ion = + e E ----------(2) Lorentz force on negative ion = - e E ----------(3) Restoring force on positive ion = -k1 x1 ----------(2 a)

Restoring force on negative ion = +k2 x2 ---------(3 a) where k1 , k2 Restoring force constants

At equilibrium, Lorentz force and restoring force are equal and opposite

For positive ion, e E = k1x1

$X_1 = Ee / k_1$

For negative ion, $e E = k2\ x_2$

$X_2 = Ee / k_2$

Where $k_1 = M\ \omega_0^2$ & $k_2 = m\ \omega_0^2$ where ω_0 is angular velocity of ions

Therefore $x = x1 + x2 = (e E / \omega_0^2) [1/M + 1/m]$------- (4)

From definition of dipole moment

μ = charge x distance of separation

$\boldsymbol{\mu} = \mathbf{e}\ x = (e^2 E / \omega_0^2) [1/M + 1/m]$

But $\boldsymbol{\mu \alpha}$ E or $\boldsymbol{\mu = \alpha_i}E$

Therefore $\boldsymbol{\alpha_i} = (e^2 / \omega_0^2) [1/M + 1/m]$ -- (5)

This is ionic polarization

3.2.3 Orientational Polarization:

In methane molecule, the centre of negative and positive charges coincides, so that there is no permanent dipole moment. On the other hand, in certain molecules such as Ch3Cl, the positive and negative charges do not coincide.Even in the absence of an electric field, this molecule carries a dipole moment, they tend to align themselves in the direction of applied field. The polarization due to such alignment is called orientation polarization. It is dependent on temperature. With increase of temperature the thermal energy tends to randomize the alignment.

Orientational polarization $P_o = N\boldsymbol{\mu} = N\mu^2 E / 3KT$

$$= N\,\boldsymbol{\alpha_0} E$$

Therefore Orientational polarizability $\boldsymbol{\alpha_0} = P_o / NE$

$= \mu^2 / 3kT$

Thusorintational polarizability $\boldsymbol{\alpha_0}$ is proportional to absolute temperature material.

3.2.4 Space-charge polarization:

Space-charge polarization occurs due to the accumulation of charge at the electrodes or at the interfaces in a multiphase material.

The total polarization of a material is the sum of the contribution from the various sources seen above.

$P_{total} = P_e + P_i + P_o + P_s$

Since the space-charge polarizability is very small when compared to other types of polarizabilities, the total polarizability of a gas can be written as

$$\alpha = \alpha_e + \alpha_i + \alpha_o$$

$$= 4\pi\epsilon_o R^3 + (e^2 / \omega_0^2)\,[1/M + 1/m] + \mu^2 / 3kT$$

Hence total polarization is given by

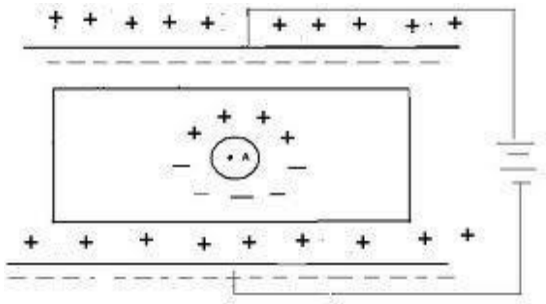
$$P = N\alpha E$$

$$P = NE\,\{4\pi\epsilon_o R^3 + (e^2 / \omega_0^2)\,[1/M + 1/m] + \mu^2 / 3kT\}$$

This equation is known as Langevin-Debye equation

3.3 Internal fields in solids: (Lorentz method):

Let a dielectric be placed between the plates of a parallel plates capacitor and let there be an imaginary spherical cavity around the atom A inside the dielectric. It is also assumed that the radius of the cavity is large compared to the radius of the atom.



CALCULATION OF LOCAL FIELD

The internal fields at the atom site A can be considered to be made up of the following four components namely E_1, E_2, E_3, and E_4.

$$E_{int} = E_1 + E_2 + E_3 + E_4 \text{ ------------------------ (1)}$$

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

$E_1 = D / \epsilon_o$ we know that $D = P + \epsilon_o E$

$$E_1 = P + \epsilon_o E / \epsilon_o = E + \frac{P}{\epsilon_o} \text{ ------------------------ (2)}$$

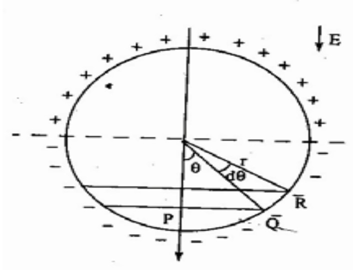
E_2 is the field intensity at A due to the charge density induced on the two sides of the dielectric.

Therefore $E_2 = - P / \epsilon_o$ ------------------------ (3)

E_3 is the field intensity at A due to other atoms contained in the cavity. We are assuming a cubic structure, because of symmetry

$E_3 = o$ ------------------------ (4)

Calculation of E_4:



If dA is the surface area of the sphere of radius r lying between θ and $\theta + d\theta$, where θ is the direction with reference to the direction of the applied force,

then $dA = 2\pi(PQ)\,(QR)$

but $\sin\theta = PQ / r$, $PQ = r \sin\theta$

and $d\theta = QR / r$, $QR = r d\theta$

Hence $dA = 2\pi r \sin\theta r d\theta = 2\pi r^2 \sin\theta d\theta$

The charge dq on the surface dA is equal to the normal component of the polarizarion multiplied by the surface area.

Therefore $dq = P \cos\theta dA = P\,(2\pi r^2 \sin\theta \cos\theta d\theta)$

The field due to this charge at A, denoted by dE_4 in the direction $\theta = o$ is

$$dE_4 = dq\cos\theta / 4\pi\epsilon_o r^2$$

$$= P\cos\theta 2\pi r^2 \sin\theta\cos\theta d\theta / 4\pi\epsilon_o r^2$$

$$= P \cos^2\theta \sin\theta d\theta / 2\epsilon_o$$

Thus the total field E_4 due to the charges on the surface of the entire cavity is obtained by integrating

$$E_4 = \int dE_4 = \frac{P}{2\epsilon_o} \int_0^{\Pi} \cos^2\theta \sin\theta\, d\theta$$

let $\cos\theta = x$

$\sin\theta\, d\theta = -dx$

limits are, when $\theta = 0^o$, $x = 1$ and $\theta = 180^o$, $x = -1$

$$E_4 = \frac{P}{2\epsilon_o} \int_1^{-1} x^2(-dx)$$

$$E_4 = \frac{P}{2\epsilon_o} \int_{-1}^{1} x^2\, dx$$

$$E_4 = \frac{P}{2\epsilon_o} \left[x^3/3 \right]_1^{-1}$$

$$E_4 = \frac{P}{2\epsilon_o} [1/3 - (-1/3)]$$

$$E_4 = \frac{P}{2\epsilon_o} (2/3)$$

$$E_4 = \frac{P}{3\epsilon_o} \text{ --------------- } (5)$$

Substituting the equations (2),(3),(4) and (5) in equation (1)

We get $E_{int} = E + \frac{P}{\epsilon_o} - \frac{P}{\epsilon_o} + \frac{P}{3\epsilon_o}$

$E_{int} = E + \frac{P}{3\epsilon_o}$ this is the equation for internal field

3.4 Clausius – Mosotti Relation:

Let us consider the elemental dielectric having cubic structure. Since there are no ions and fermanent dipoles in these materials, them ionic polarizability αi and orientational polarizability $\boldsymbol{\alpha 0}$ are zero.

i.e. $\alpha i = \alpha_0 = 0$

Hence polarization $P = N \alpha_e Ei$

$= N \alpha_e \ (E + P / 3\varepsilon_0)$

i.e. $P [1 - N \alpha_e / 3 \varepsilon_0] = N \alpha_e E$

$P = N \alpha_e E / [1 - N \alpha_e / 3 \varepsilon_0]$ ---(1)

We know that

$D = P + \varepsilon_0 E$

$P = D - \varepsilon_0 E$

Dividing on both sides by E

$P / E = D / E - \varepsilon_0 = \varepsilon - \varepsilon_0 = \varepsilon_0 \varepsilon_r - \varepsilon_0$

$P = E \varepsilon_0 (\varepsilon_r - 1)$ --------(2)

From eqn**1** and **2**, we get

$P = E \varepsilon_0 (\varepsilon_r - 1) = N \alpha_e E / [1 - N \alpha_e / 3 \varepsilon_0]$

$[1 - N \alpha_e / 3 \varepsilon_0] = N \alpha_e / [\varepsilon_0 (\varepsilon_r - 1)]$

$1 = N \alpha e / 3 \varepsilon_0 + N \alpha_e / \varepsilon_0 (\varepsilon_r - 1)$

$1 = (N \alpha_e / 3 \varepsilon_0) (1 + 3 / (\varepsilon_r - 1))$

$1 = (N \alpha_e / 3 \varepsilon_0)[(\varepsilon_r - 1 + 3) / (\varepsilon_r - 1)]$

$1 = (N \alpha e / 3 \varepsilon_0)[(\varepsilon_r + 2) / (\varepsilon_r - 1)]$

$$(\varepsilon_r + 2) / (\varepsilon_r - 1) = N \alpha e / 3 \varepsilon_0$$

Where N – no of molecules per unit volume

This is Clausius – Mosotti Relation.

3.5 Piezo – Electricity:

These materials have the property of becoming electrically polarized when mechanical stress is applied. This property is known as Piezo – electric effect has an inverse

.According to inverse piezo electric effect, when an electric stress or voltage is applied, the material becomes strained. The strain is directly proportional to the applied field E.

When piezo electric crystals are subjected to compression or tension, opposite kinds of charges are developed at the opposite faces perpendicular to the direction of applied force. The charges produced are proportional to the applied force.

Piezo – Electric Materials and Their Applications: Single crystal of quartz is used for filter, resonator and delay line applications. Natural quartz is now being replaced by synthetic material.

Rochelle salt is used as transducer in gramophone pickups, ear phones,

hearing aids, microphones etc. the commercial ceramic materials are based on barium titanate, lead zirconate and lead titanate. They are used for high voltage generation (gas lighters),

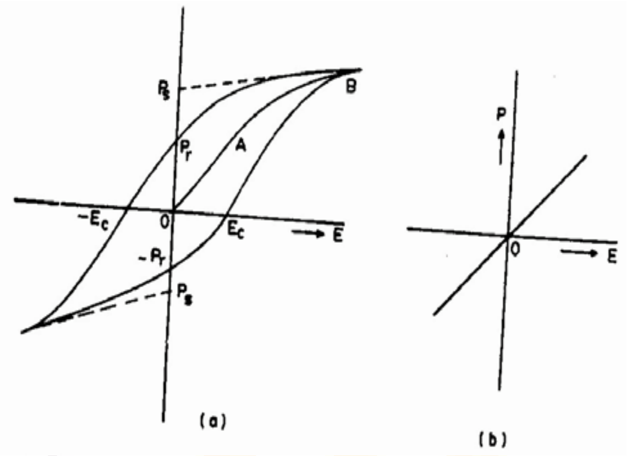
accelerometers, transducers etc.

3.6 Ferro electricity:

Ferro electric materials are an important group not only because of intrinsic Ferro electric property, but because many possess useful piezo electric, birefringent and electro optical properties.

The intrinsic Ferro electric property is the possibility of reversal or change of orientation of the polarization direction by an electric field. This leads to hysteresis in the polarization P, electric field E relation , similar to magnetic hysteresis. Above a critical

temperature, the Curie point Tc , the spontaneous polarization is destroyed by thermal disorder. The permittivity shows a characteristic peak at Tc.



3.7 PYRO ELECTRICITY

Pyroelectric effect is the charge in spontaneous polarization when the temp. of the specimen is changed. The pyro electric co-efficient λ is defined as the change in polarization per unit temperature change of the specimen.

$$\lambda = \frac{dp}{dT}$$

Change in polarization results in change in external filed and hence charge on the surface. As the possible to detect a change of 16 10− with a suitable electrometer temp. changes as small as 6 0 10 c − can be measured using the pyro electric effect.

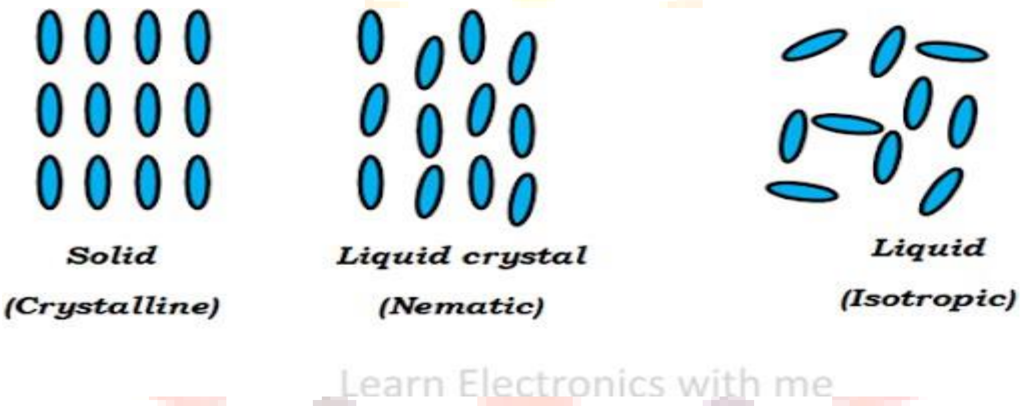
Applications

The pyro electric materials such as BaTiO3 , LiNibO3 etc are used to make very good instead detectors which can operator at room temp. materials such as TGS , NaNO2 and PZT ceramics are used in polarizing and construction of pyro electric image tubes.

3.8 Liquid Crystal Display

Liquid Crystal Display (LCD) is an flat display screen used in electronic devices such as laptop, computer, TV, cellphones and portable video games. As the name says liquid crystal is a material which flows like a liquid and shows some properties of solid. These LCD are vey thin displays and it consumes less power than LEDs.

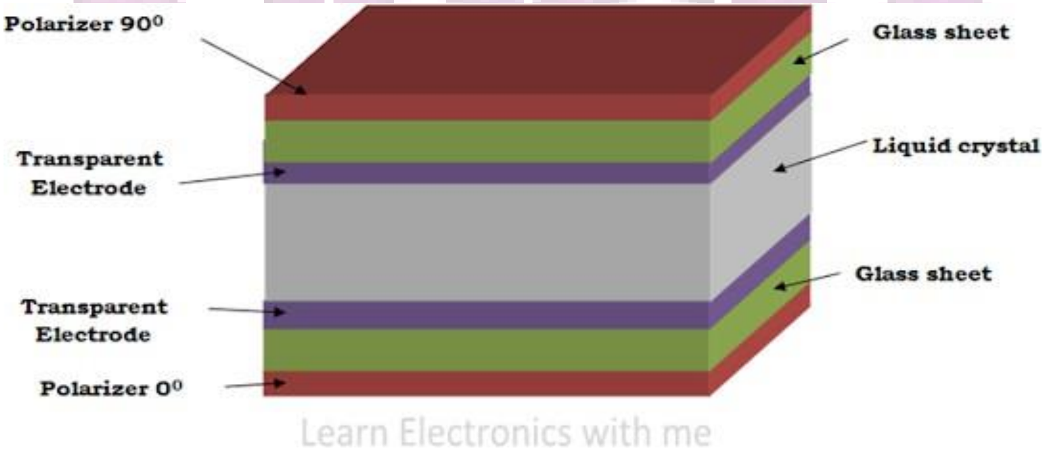
Molecular arrangement of Liquid Crystal:



Molecular arrangement of liquid crystal

As the name says the molecular structure of liquid crystal is in between solid crystal and liquid isotropic. In Liquid crystal display (LCD) nematic type of liquid cyrstal molecular arrangement is used in which molecules are oriented in some degree of alignment. For example when we increase the temperature the ice cube melts and liquid crystal is like the state in between ice cube and water

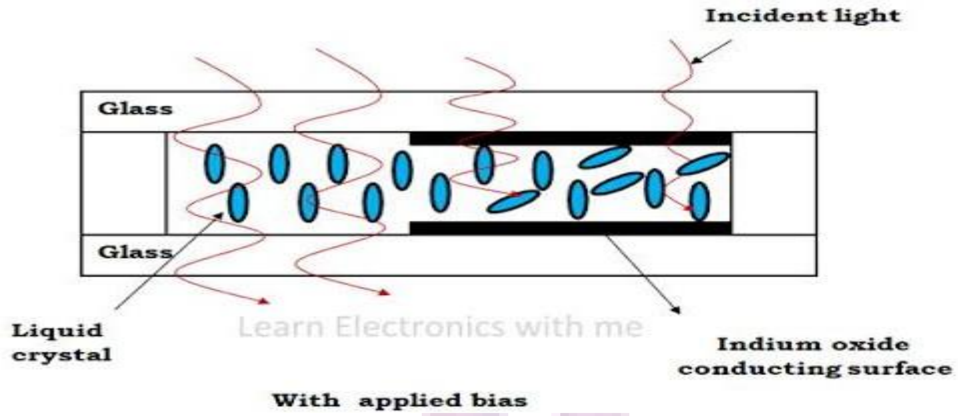
Construction of Liquid Crystal Display:



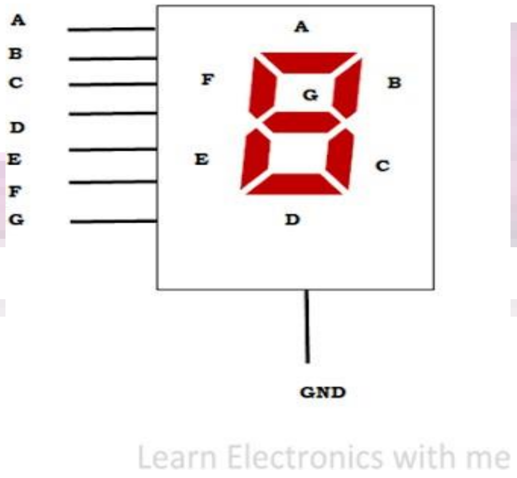
Construction of LCD consists of two polarized glass pieces. Two electrodes are used, one is positive and the other one is negative. External potential is applied to LCD through this electrodes and it is made up of indium-tin-oxide. Liquid crystal layer of about 10µm- 20µm is placed between two glass sheets. The light is passed or blocked by changing the polarization.

Working of Liquid Crystal Display

The basic working principle of LCD is blocking of light. It does not produce light on its own. So external light source is used. When the external light passes from one polarizer to the next polarizer, external supply is given to the liquid crystal ,the polarized light aligns itself so that the image is produced in the screen.



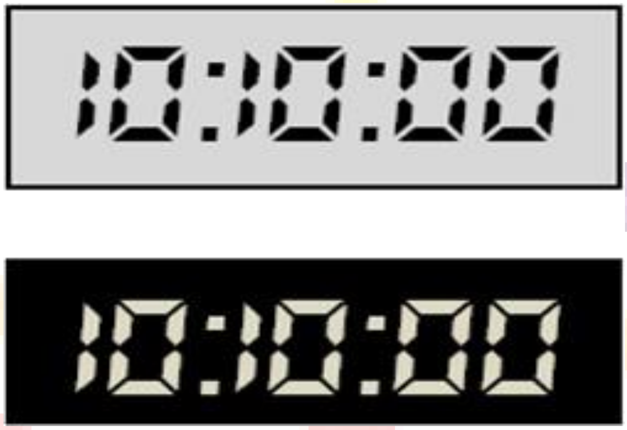
The indium oxide conducting surface is a transparent layer which is placed on both the sides of the sealed thick layer of liquid crystal . When no external bias is applied the molecular arrangement is not disturbed.



When the external bias is applied the molecular arrangement is disturbed and it and that area looks dark and the other area looks clear.

In the segment arrangement, the conducting segment looks dark and the other segment looks clear. To display number 2 , the segments A,B,G,E,D are energized.

Positive and Negative LCDs:



In positive LCD display the segments are dark and the background is white and the polarizers are placed perpendicular to each other. In the negative LCD display the segments are white in the dark background and the polarizers are aligned to each other.

Advantages:

- It is thin and compact
- Low power consumption
- Less heat is emitted during operation
- Low cost

Disadvantages:

- Speed of operation is low
- Lifespan is less
- Restricted viewing angles

Applications:

- Used in digital wrist watch
- Display images in digital cameras
- Used in numerical counters
- Display screen in calculators
- Mainly used in television
- Used in mobile screens

- Used in video players
- Used in image sensing circuits

Magnetic materials

The basic aim in the study of the subject of magnetic materials is to understand the effect of an external magnetic field on a bulk material ,and also to account for its specific behaviour. A dipole is an object that a magnetic pole is on one end and a equal and opposite second magnetic dipole is on the other end.

A bar magnet can be considered as a dipole with a north pole at one end and South Pole at the other. If a magnet is cut into two, two magnets or dipoles are created out of one. This sectioning and creation of dipoles can continue to the atomic level. Therefore, the source of magnetism lies in the basic building block of all the matter i.e. the atom.

Consider electric current flowing through a conductor. When the electrons are flowing through the conductor, a magnetic field is forms around the conductor. A magnetic field is produced whenever an electric charge is in motion. The strength of the field is called the **magnetic moment.**

Magnetic materials are those which can be easily magnetized as they have permanent magnetic moment in the presence of applied magnetic field. Magnetism arises from the magnetic dipole moments. It is responsible for producing magnetic influence of attraction or repulsion.

3.9 Basic definitions

Magnetic dipole :it is a system consisting of two equal and opposite magnetic poles separated by a small distance of ‘2l’metre.

Magnetic Moment (μm) :It is defined as the product of the pole strength (m) and the distance between the two poles (2l) of the magnet.

i .e . . $\mu m = (2l)\, m$

Units: Ampere – metre^2

Magnetic Flux Density or Magnetic Induction (B): It is defined as the number of magnetic lines of force passing perpendicularly through unit area.

i .e . . **B** = magnetic flux / area = Φ / A Units: Weber / metre2 or Tesla.

Permeability:

Magnetic Field Intensity (H): The magnetic field intensity at any point in the magnetic field is the force experienced by a unit north pole placed at that point.

Units: Ampere / meter

The magnetic induction B due to magnetic field intensity H applied in vacuum is related by

B proportional

$$HB = \mu_0 H$$

where μ_0 is permeability of free space = 4 Π x 10-7 H / m

If the field is applied in a medium, the magnetic induction in the solid is given by

$$B = \mu H$$

where μ is permeability of the material in the medium

$$\mu = B / H$$

Hence magnetic Permeability μ of any material is the ratio of the magnetic induction to the applied magnetic field intensity. The ratio of μ / μ_0 is called the relative permeability (μ_r).

$$\mu_r = \mu / \mu_0$$

Therefore $B = \mu_0 \mu_r H$

Magnetization: It is the process of converting a non – magnetic material into a magnetic material. The intensity of magnetization (M) of a material is the magnetic moment per unit volume.

intensity of magnetization (M) = magnetic moment / volume

The intensity of magnetization is directly related to the applied field H through the susceptibility of the medium (χ) by

$$\chi = M / H \text{--------------} (1)$$

The magnetic susceptibility of a material is the ratio of the intensity of magnetization produced to the magnetic field intensity which produces the magnetization. It has no units.

We know

$$B = \mu H$$

$$= \mu_0 \mu_r H$$

i.e $B = \mu_0 \mu_r H + \mu_0 H - \mu_0 H$

$$= \mu_0 H + \mu_0 H (\mu_r - 1)$$

$= \mu_0 H + \mu_0 M$ where M is magnetization = $H(\mu_r - 1)$

$$\textbf{i.e} \qquad \mathbf{B} = \mu\mathbf{0} \ \ (\mathbf{H} + \mathbf{M}) \text{---------} (2)$$

The first term on the right side of eqn (2) is due to external field. The second term is due to the magnetization.

$$\text{Hence } \mu\mathbf{0} \ = \mathbf{B} / \mathbf{H} + \mathbf{M}$$

Relative Permeability ,

$$\mu\mathbf{r} = \mu / \ \mu\mathbf{0} = (\mathbf{B} / \mathbf{H}) \ / (\mathbf{B} / \mathbf{H} + \mathbf{M}) = \mathbf{H} + \mathbf{M} / \mathbf{H} \ = \mathbf{1} + \mathbf{M} / \mathbf{H}$$

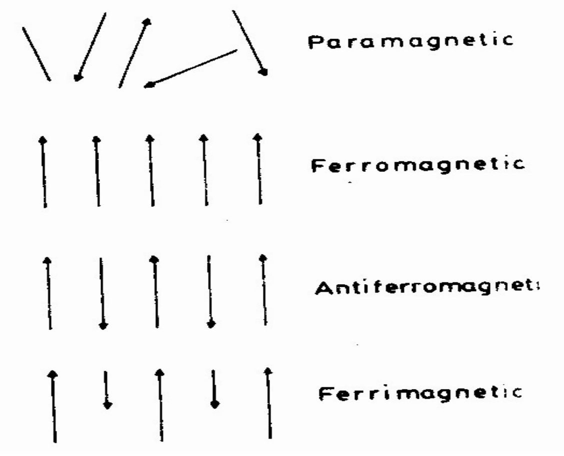
$$\mu\mathbf{r} = \ \mathbf{1} + \chi \text{---------} \mathbf{(3)}$$

The magnetic properties of all substances are associated with the orbital and spin motions of the electrons in their atoms. Due to this motion, the electrons become elementary magnets of the substance. In few materials these elementary magnets are able to strengthen the applied magnetic field , while in few others , they orient themselves such that the applied magnetic field is weakened.

3.10 Classification Of Magnetic Materials:

All matter respond in one way or the other when subjected to the influence of a magnetic field. The response could be strong or weak, but there is none with zero response ie, there is no matter which is non magnetic in the absolute sense. Depending upon the magnitude and sign of response to the applied field , and also on the basis of effect of temperature on the magnetic properties, all materials are classified broadly under 5 categories.

1. Diamagnetic materials
2. Paramagnetic materials,
3. Ferromagnetic materials
4. Antiferromagnetic materials and
5. Ferrimagnetic materials.



1. Diamagnetic materials: Diamagnetic materials are those which experience a repelling force when brought near the pole of a strong magnet. In a non uniform magnetic field they are repelled away from stronger parts of the field.

In the absence of an external magnetic field , the net magnetic dipole moment over each atom or molecule of a diamagnetic material is zero.

Ex: Cu, Bi , Pb .Zn and rare gases.

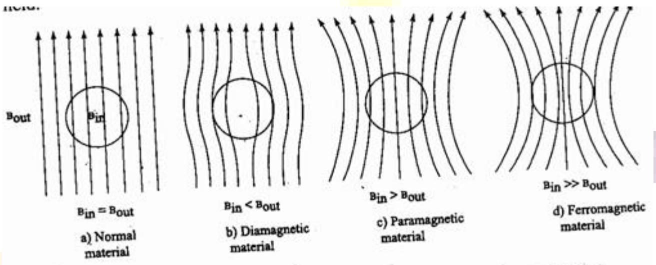


Fig. The behaviour of magnetic materials in the presence of magnetic field.

Paramagnetic materials: Paramagnetic materials are those which experience a feeble attractive force when brought near the pole of a magnet. They are attracted towards the stronger parts of magnetic field. Due to the spin and orbital motion of the electrons, the atoms of paramagnetic material posses a net intrinsic permanent moment.

Susceptibility χ is positive and small for these materials. The susceptibility is inversely proportional to the temperature T.

$\chi \ \alpha \ 1/T$

$\chi = C/T$ where C is Curie's temperature.

Below superconducting transition temperatures, these materials exhibit the Para magnetism. Examples: Al, Mn, Pt, CuCl2 .

Ferromagnetic Materials: Ferromagnetic materials are those which experience a very

strong attractive force when brought near the pole of a magnet. These materials, apart from getting magnetized parallel to the direction of the applied field, will continue to retain the magnetic property even after the magnetizing field removed. The atoms of ferromagnetic materials also have a net intrinsic magnetic dipole moment which is due to the spin of the electrons.

Susceptibility is always positive and large and it depends upon temperature.

$\chi = C / (T- \theta)$ (only in paramagnetic region i.e., $T > \theta$)

θ is Curie's temperature.

When the temperature of the material is greater than its Curie temperature then it converts into paramagnetic material.

Examples: Fe, Ni, Co, MnO.

Antiferromagnetic matériels : These are the ferromagnetic materials in which equal no of opposite spins with same magnitude such that the orientation of neighbouring spins is in antiparallel manner are present.

Susceptibility is small and positive and it is inversely proportional to the temperature.

$\chi = C/(T+\theta)$

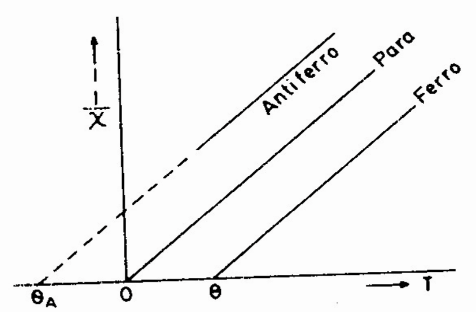
the temperature at which anti ferromagnetic material converts into paramagnetic material is known as Neel's temperature.

Examples: FeO, Cr2 O3 .

Ferrimagnetic materials: These are the ferromagnetic materials in which equal no of opposite spins with different magnitudes such that the orientation of neighbouring spins is in antiparallel manner are present.

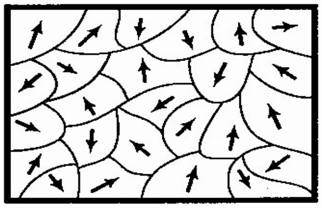
Susceptibility positive and large, it is inversely proportional to temperature

$\chi = C/(T \pm \theta)$ T> TN (Neel's temperature) Examples : ZnFe2 O4 , CuFe2 O4

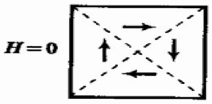


3.11 Domain theory of ferromagnetism:

According to Weiss, a virgin specimen of ferromagnetic material consists of a no of regions or domains (≈ 10-6 m or larger) which are spontaneously magnetized. In each domain spontaneous magnetization is due to parallel alignment of all magnetic dipoles. The direction of spontaneous magnetization varies from domain to domain. The resultant magnetization may hence be zero or nearly zero. When an external field is applied there are two possible ways of alignment fo a random domain.

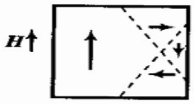


RANDOM ORIENTATION OF MAGNETIC MOMENTS OF THE DOMAINS



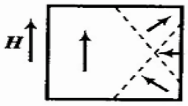
DOMAIN ORIENTATION IN THE ABSENCE OF MAGNETIC FIELD

(a)



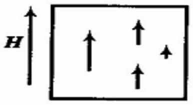
DOMAIN EMLARGEMENT / SRINKAGE DUE TO WEAK FIELDS

(b)



DOMAIN ROTATION DUE TO STRONG FIELDS

(c)



SATURATION DUE TO VERY HIGH FIELDS

(d)

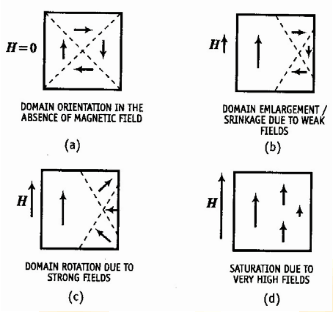
i). **By motion of domain walls:** The volume of the domains that are favourably oriented with respect to the magnetizing field increases at the cost of those that are unfavourably oriented

ii) **By rotation of domains**: When the applied magnetic field is strong, rotation of the direction of magnetization occurs in the direction of the field.

3.12 Hysteresis curve (study of B-H curve):

The hysteresis of ferromagnetic materials refers to the lag of magnetization behind the magnetization field. when the temperature of the ferromagnetic substance is less than the ferromagnetic Curie temperature ,the substance exhibits hysteresis. The domain concept is well suited to explain the phenomenon of hysteresis. The increase in the value of the resultant magnetic moment of the specimen by the application of the applied field , it attributes to the 1. motion of the domain walls and 2. rotation of domains.

When a weak magnetic field is applied, the domains that are aligned parallel to the field and in the easy direction of magnetization, grow in size at the expense of less favorably oriented ones. These results in Bloch wall movement and when the weak field is removed, the domains reverse back to their original state. This reverse wall displacement is indicated by OA of the magnetization curve. When the field becomes stronger, the Bloch wall movement continues and it is mostly irreversible movement. This is indicated by the path AB of the graph. The phenomenon of hysteresis is due to this irreversibility.



DOMAIN ORIENTATION IN THE ABSENCE OF MAGNETIC FIELD
(a)

DOMAIN EMLARGEMENT / SRINKAGE DUE TO WEAK FIELDS
(b)

DOMAIN ROTATION DUE TO STRONG FIELDS
(c)

SATURATION DUE TO VERY HIGH FIELDS
(d)

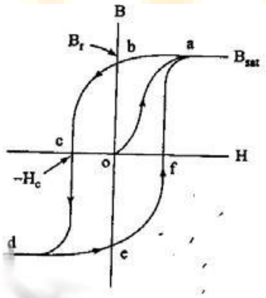


Fig. [redacted] Schematic representation of the hysteresis loop for a ferromagnetic material.

At the point B all domains have got magnetized along their easy directions. Application of still higher fields rotates the domains into the field direction which may be away from the easy direction. Once the domain rotation is complete the specimen is saturated denoted by C. on removal of the field the specimen tends to attain the original configuration by the movement of Bloch walls. But this movement is hampered by the impurities, lattice imperfections etc, and so more energy must be supplied to overcome the opposing forces. This means that a coercive field is required to reduce the magnetization of the specimen to zero. The amount of energy spent in this regard is a loss. Hysteresis loss is the loss of energy in taking a ferromagnetic body through a complete cycle of magnetization and this loss is represented by the area enclosed by the hysteresis loop.

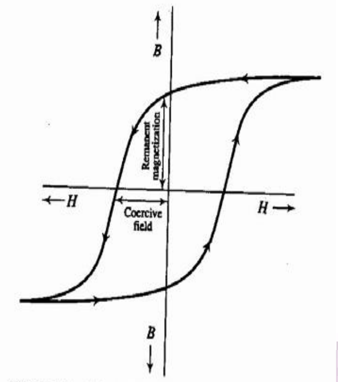
A hysteresis curve shows the relationship between the magnetic flux density B and applied magnetic field H. It is also referred to as the B-H curve(loop).

3.13 Hard and Soft Magnetic Materials:

Hysteresis loop of the ferromagnetic materials vary in size and shape. This variation in hysteresis loops leads to a broad classification of all the magnetic materials into hard type and soft type.

Hard Magnetic Materials:

Hard magnetic materials are those which are characterized by large hysteresis loop because of which they retain a considerable amount of their magnetic energy after the external magnetic field is switched off. These materials are subjected to a magnetic field of increasing intensity, the domain walls movements are impeded due to certain factors. The cause for such a nature is attributed to the presence of impurities or non-magnetic materials, or the lattice imperfections. Such defects attract the domain walls thereby reducing the wall energy. It results in a stable state for the domain walls and gives mechanical hardness to the material which increases the electrical resistivity. The increase in electrical resisitivity brings down the eddy current loss if used in a.c conditions. The hard magnetic materials can neither be easily magnetized nor easily demagnetized.



HYSTERESIS CURVE FOR HARD MAGNETIC MATERIAL

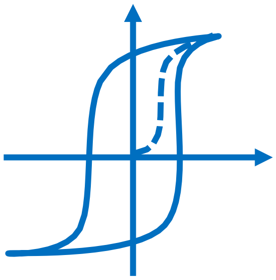
Properties:

1. High remanent magnetization
2. High coercivity
3. High saturation flux density
4. Low initial permeability
5. High hysteresis energy loss
6. High permeability
7. The eddy current loss is low for ceramic type and large for metallic type.

Examples of hard magnetic materials are, i) Iron- nickel- aluminum alloys with certain amount of cobalt called Alnico alloy. ii) Copper nickel iron alloys. iii) Platinum cobalt alloy.

Applications of hard magnetic materials: For production of permanent magnets, used in magnetic detectors, microphones, flux meters, voltage regulators, damping devices and magnetic separators.

SOFT MAGNETIC MATERIALS



- Soft Magnetic materials have low hysteresis loss due to small hysteresis loop area.
- The curve is tall and thin.
- The coercivity and retentivity are small, hence these materials can be easily magnetized and demagnetized.
- These materials have large values of permeability and susceptibility.
- **Ex: Iron silicon alloys, Ferrous nickel alloy, soft iron etc.,**
- These are used to make electromagnets and mainly used in electro-magnetic machinery and transformer cores and also used in switching circuits , microwave isolators and matrix storage of computers.

3.14 Bubble Memory Devices

It is invented by Andrew Bobeck in 1970s at Bell Labs. Bubble Memory is the storage technology in which thin layer of magnetic material are used to store the information These magnetic materials will contain small magnetized areas known as bubbles or domains. Each such bubble or domain will store one bit of data. The magnetic material is arranged into parallel tracks so that the bubbles can move along under the application of the external magnetic field. The bubble memory is non-volatile storage technology i.e. the information will retain even after power is switched off

Advantages

1. Low power consumption

2. High functional packing density .

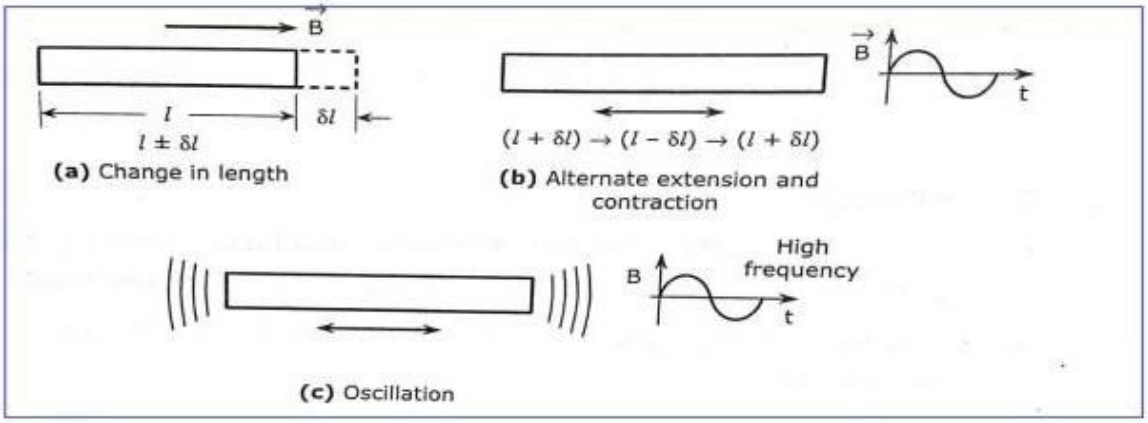
3. More durable than disc memory since it has no moving parts.

4. Rugged in nature which made it important in military applications even though it is not successful in commercial market

5. It is resistant to extreme temperatures, dust, humidity and radiation.

3.15 Magnetostriction (James Joule, 1842)

When a ferromagnetic rod like iron, nickel is kept in the strong magnetic field parallel to it length, it is subjected to a change in dimensions. This is called magnetostriction effect. If the rod is placed in a rapidly varying magnetic field alternately expands and contracts with twice the frequency of the applied magnetic field. This change in length of the ferromagnetic material is independent of the polarity of applied magnetic field. The longitudinal expansion and contraction in ferromagnetic rod produces ultrasonic sound waves in the medium surrounding the nickel rod. The frequency range of the waves depend on the mode of vibration of the ferromagnetic material and may vary from few hundred to 3,00,000 Hz. Since, the rod vibrates longitudinally; the frequency of the fundamental mode of vibration can be usedas



(a) Change in length

(b) Alternate extension and contraction

(c) Oscillation

$$f = \frac{m}{2l}\sqrt{\frac{Y}{\rho}}$$

where Y is the Young's modulus of the material and ρ its density and m is mode of vibration. m=1 fundamental frequency, m=2 first over tone Similarly the frequency of LC oscillatory circuit is

$$f = \frac{\omega}{2\pi} = \frac{1}{2\pi\sqrt{LC}}$$

3.16 Magnetoresistance

It was discovered by William Thomson in 1856

The change in the electrical resistance of certain materials under the application of external magnetic field is known as magneroresistance. The materials which exhibit this nature are known as the magnetoresistors. The resistance of the magnetoresistors are directly proportional to the magnetic field.

Working Principle: In the absence of the magnetic field, the charge carriers of the magneto resistor move in the straight path. But when the field is applied, the electrons will experience a force, which will increases the path length and the collisions of electrons. This will result in increase in the resistance of the material. These magnetoresistors are classified into three categories.

1.Giant magnetoresistors (GMR): In these magnetoresistors, the resistance will becomes small when their ferromagnetic layers are parallel to each other and vice versa.

2. Extraordinary magnetoresistors: In these magnetoresistors, the resistance of the material is high in the absence of magnetic field and low in the presence of a field.

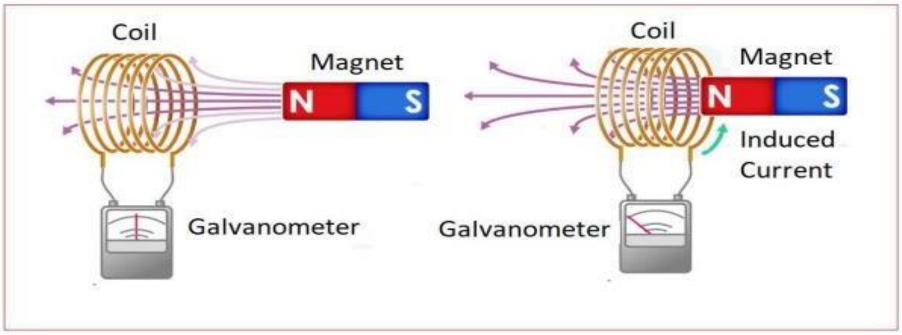
3. Tunnel magnetoresistors: In these magnetoresistors, the heavy current flows if the magnetisation of the electrodes is parallel to each other. The antiparallel arrangement increases the resistance between the layer.

3.17 Magnetic Field Sensors

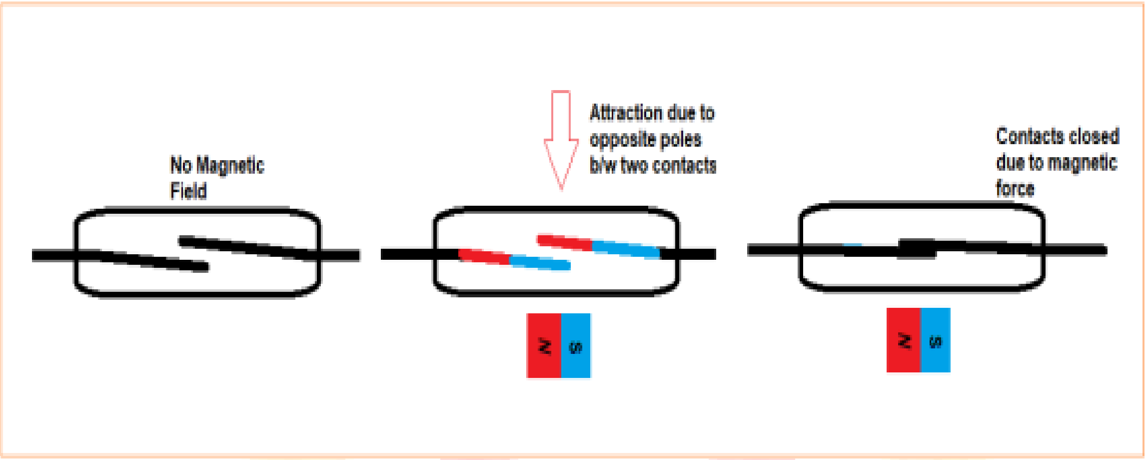
Magnetic field sensors are the devices that detect and measure magnetic fields around permanent magnets, current conductors, and electrical devices. These devices are very accurate, space efficient and operate with little power. These magnetic sensor works by converting the variations of a magnetic field and its magnitude into electric signals.

Typical magnetic sensors and their application

a) Coils: The coil is used detect the variations in a magnetic field. when a magnet is moved towards a coil , the magnetic flux density in the coil will increases. This increase in magnetic flux density in the coil result in the induced electromotive force and induced current. The measurement of the induced electromotive force and current will allow you to detect the ratio of change in magnetic flux density and its direction. These coils will become a highly sensitive magnetic sensors when combined with other coils or magnetic materials. The typical examples for the coil sensors are search coils, rotation angle sensors (resolvers), fluxgate sensors.



b) Reed switches: The device consist of a glass tube filled with inert gas to prevent the activation (deterioration) of the contacts.



These glass tube consist two reeds (contacts), made of nickel or other magnetic material and come from the right and left ends of the tube. The role of the inert gas is to prevent the deterioration of the contacts. In the absence of the field, the reed switch is open. But under the application of magnetic field, the magnetic material is magnetized and the contacts are attracted to each other closing the circuit (conduction state).

Unlike semiconductor sensors such as MR sensor elements or Hall elements, the reed switch operates without a power supply and is therefore often used in automobiles or other locations where power is difficult to supply.

c) MR (Magnetoresistance) sensor elements: These sensors works on the principle of magnetoresistance effect. There are a number of MR sensor types using different operating principles.

d) Anisotropic Magneto-Resistance (AMR) sensor elements: It is discovered by William Thomson in 1956. Anisotropic Magneto-Resistance effect is exhibited by the ferromagnetic material when placed in an external magnetic field. When the direction of magnetization in a ferromagnetic material is parallel to the current, the electron orbital becomes perpendicular to the current. This will increases the spin-dependent scattering of electrons and the resistance of the material will increases.

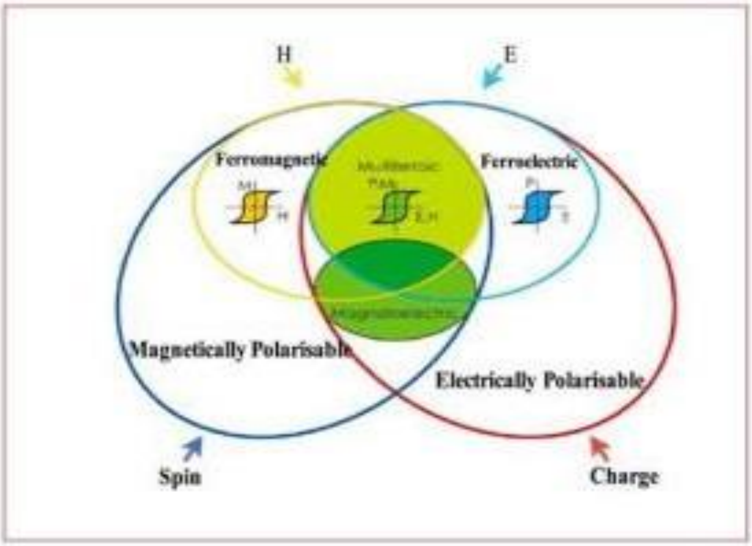
Similarly when the direction of magnetization is perpendicular to the current, the electron orbital becomes horizontal to the current. This will reducing the spin-dependent scattering and the resistance of the material will decreases. The rate of change in resistance caused by the state of the magnetic field is called magnetoresistive ratio (MR ratio). The MR ratio for an AMR sensor element is about 5%. The AMR sensor element is often used in magnetic switches and rotation sensors because of its simple structure.

3.18 Multiferroics (MFs)

There three fundamental ferroic behaviours in nature, namely

- Ferromagnetism
- Ferroelectricity
- Ferroelasiticity

Multiferroics are those materials which will exhibit more than one ferroic behaviour simultaneously. However the multiferroics which will exhibit ferromagnetism and ferroelectricity are more popular and have vast appliations. In these materials the intensity of magnaitazation can be controlled by the electric field intensity and polaraization can be controlled by the magnetic field. These multiferroics are classified in two categories i.e. type-I multiferroics and type-II multiferroics



Type-I multiferroics: These materials show a linear magnetoelectric response, as well as changes in dielectric susceptibility at the magnetic phase transition. In these materials the ferroelectricity and ferromagnetism will occur at different temperatures. The ferroelectricity (which requires the structural distortion) occurs at high temperature but the magnetic ordering (usually anti ferromagnetic) occurs at low temperature.
Ex: BeFO3 (Beryllium Fluorate)

Type-II multiferroics: These are the materials in which the magnetic ordering breaks the inversion symmetry and directly causes the ferroelectricity. In these materials the ferroelectricity and ferromagnetism will occur at same temperatures.
Ex: TbMn2O5 (Terbium Manganes Pentoxolane)
Applications : Multiferroics have potential for applications as actuators, switches, magnetic field sensors and new types of electronic memory devices.

ENERGY MATERIALS

Introduction

Energy materials are the class of materials, which will store the energy, convert the energy in one form to another form. The energy martials with dual conversion capacity i.e. electrical energy to chemical energy and chemical energy to electrical energy have striking applications in electronics and automobile industry.

3.19 Electrolytes

Liquid Electrolytes: These class of electrolites conducts electricity when dissolved in water. These electrolytes, when dissolved in a solvent, dissociate into cations (positive ions) and the anions (negative ions). The conductance of electrolytes is due to ions and termed as ionic conductivity. Conductivity (or specific conductance) of an electrolyte solution is a measure of its ability to conduct electricity.

$$Resistance, R = \rho \frac{l}{A}$$

L is the length between the electrodes, A is the cross-sectional area of the sample and ρ is the specific resistance.

In practice, the conductivity cell is calibrated by using solutions of known specific resistance, ρ*, and the cell-constant, defined as the ratio of l and A is derived.

$$Resistance, R = \rho C, where\ C = \frac{l}{A}, cell\ constant.$$

Hence we can write the specific conductance, the reciprocal of specific resistance (resistivity) as

$$\kappa = \frac{1}{\rho} = \frac{C}{R}$$

Sometimes the conductance (reciprocal of the resistance) is denoted as G= I/R

Hence, the specific conductance can be written as κ= CG

The specific conductance of a solution containing one electrolyte depends on the concentration of the electrolyte. The molar conductivity is defined as the ratio between the specific conductance (κ) and concentration of the electrolyte(c).

$$\text{molar conductivity}, \Lambda_m = \frac{\kappa}{c}$$

Factors affecting Electrolytic Conductance

1. Concentration of ions: The conductivity of electrolytes is proportional to concentration of ions but molar conductivity increases with a decrease in the concentration of the solution.

2. Nature of electrolyte: The electrolytes which fully dissolve in solution are termed as strong electrolytes. Materials such as KNO3, with a higher degree of separation, will fully dissolve in solvents, will have more number of ions in the solution and hence will have higher conductivity. The electrolytes which partially dissolve in solution are termed as week electrolytes. Materials such as CH3COOH, with a small degree of separation, will partially dissolve in solvents, will have less number of ions in the solution hence will have lower conductivity.

3. Temperature: The solubility of a electrolyte there by the concentration increases with increase in temperature.

Solid Electrolytes

Solid ionic conductors that can be used in electrochemical cells as an electrolyte are called solid electrolytes. Only one ion is mobile in solid ionic conductors. The transference number is defined as the ratio of the electric current derived from the cation to the total electric current. According Patterson, the solids with a transference number > 0.99 termed as solid electrolytes.

A large transference number can reduce concentration polarization of electrolytes during charge–discharge steps, and thus produce higher power density. Solid electrolytes possess a much higher thermal stability, and this makes the solid-state battery (SSB) one of the best choices for the next generation of batteries. Moreover, inorganic solid electrolytes can work in hostile environments, such as in the temperature range from −50◦C to 200◦C or even higher. The solid-state batteries based on solid-state electrolytes could also significantly increase the energy density and the power density, which are the critical features for large energy storage systems.

Based on their components, the solid-state electrolytes can be divided into three categories

- Inorganic electrolytes,
- Organic polymer electrolytes
- Composite electrolytes

1. Inorganic electrolytes: Inorganic electrolytes usually exhibit high ion conductivity, in the range of 10^{-4} Scm^{-1} . The inorganic electrolyte is more suitable for rigid battery design, as it possesses better thermal/chemical stabilities, higher mechanical strength and exhibits an obvious conductivity advantage over a wide temperature range. Some of the reported inorganic electrolytes show ionic conductivity that is competitive with or even higher than commercial liquid electrolytes. However, performance of solid state batteries with inorganic electrolytes is limited due the poor interfacial contact between electrolyte and electrode

2. Organic polymers electrolytes: Organic polymers electrolytes are different from inorganic ceramics in their chemical and mechanical properties, which enforces a different battery designs. Organic polymer electrolytes have several advantages over the inorganic solid electrolyte, such as its high flexibility, the ability to easily form intimate electrode-electrolyte contact and the simple process ability. However, these materials face other issues, such as low Li^+ conductivity ($<10^{-5}$ Scm^{-2} at room temperature), large ionic transfer resistance, and oxidation at high voltages. The polymer electrolyte materials are further classified in to

1 Gel polymer electrolyte and

2 Solvent-free solid polymer electrolyte

Gel polymer electrolyte exhibits weaker mechanical properties but higher ionic conductivity. Its conduction mechanism is similar to the liquid electrolyte.

The Solvent-free solid polymer electrolyte exhibits stronger mechanical properties and could be prepared into free-standing electrolyte membranes without adding other mechanical supports. In these materials, Na-salts are dissolved in the polymer host and these Na ions could transport within the polymer hosts via the segmental motion of the polymer chains

3. Composite electrolytes: A composite material is made from two or more constituent materials which have dissimilar chemical or physical properties. The composite material will exhibit the properties different from the individual elements. However, the individual elements remain separate and distinct, distinguishing composites from mixtures and solid solutions. Ceramic/polymer composite electrolytes may solve the ionic conductivity and interfacial contact issues consistently by combining the advantages of two different types of electrolytes.

Requirements of a good solid state electrolyte:

(i) High ionic conductivity (>10^{-4} Scm^{-2})

(ii) Good mechanical strength and enough structural defects to prevent lithium dendrite penetration;

(iii) Low-cost raw material and low cost preparation techniques

(iv) Low activation energy for lithium-ion diffusion.

Experimental studies showed that the ceramic materials can exhibit higher ionic conductivity than polymers. Besides, the electrochemical stability window of polymeric electrolytes is relatively low compared to that of inorganic electrolytes. Hence the researchers are paying much attention to inorganic electrolytes for application in all solid-state batteries. In a crystalline solid electrolyte, thermal energy drives the migration of lithium ions through cationic vacancies or interstitials.

If q the charge of transfer ions, n is the concentration of electrolytes, and mobility of charge carriers of the crystal , ionic conductivity, σ is given as

18.5

The above equation is referred as modified Archimedes equation where is known as activation energy is pre -factor. The typical value of m =1. The above equation shows that increasing the concentration of electrolytes (n) increase the ionic conductivity in the solid. Hence for a specific battery operating temperature, concentration of electrolytes (n) highly related to the mobile defect formation energy (Ef).

Advantages of Solid-state electrolytes over the conventional organic liquid electrolytes

1. Solid-state electrolytes possess higher thermal stability.
2. They will ensures higher safety due to their lower flammability.
3. Durability of Solid-state electrolytes is more.
4. Their battery design is simple.

Disadvantages of Solid-state electrolytes over the conventional organic liquid electrolytes

The room-temperature ionic conductivity in solid electrolytes is lower than that in liquid electrolytes.

3.20 Superionic conductors

Superionic conductors are a class of solid materials which show an unusual high ionic conductivity. Their structure is characterized by strong disorder in the sub-lattice of conducting ions. These solids will have high ionic conductivity and negligible electronic conductivity. The ionic conductivity occurs due to the motion of ions, whereas the electronic conductivity results from the flow of electrons.

Super ionic conductors conductivity (σ) will be usually more than $10^{-2}\ \Omega^{-1}\ cm^{-1}$.

Few ionic conductors attain high electrical conductivity only above a certain temperature. This is due to results in the generation of anion Frenkel disorder and it appears that both vacancies and interstitials are mobile in the superionic phase.

The Process of ionic conduction: The conduction in the ionic conductors' may due to the presence of crystal defects in solids (Normal Ionic Conductors) or may be due to molten defects (Super ionic conductors).

Normal Ionic Conductors: In normal ionic conductors, the ion transportation is due Frenkel defects are schottky defects. As these defect concentration increases with temperature, the ionic conductivity of these solids increases with temperature.

Super ionic conductors: In the solids with molten defects, all the ions are available for conduction. The number of defect or void sites in these solids is more than the number of ions. This will allow the ions to move freely with low activation energy which will results in high conductivity. These are called superionic conductors (SICs)

The differences between the normal ionic conductors and super ionic conductors

1. Normal Ionic conductors

1. low ionic conductivity and may have appreciable electronic conductivity
2. Conductivity increases with temperature just below melting point.
3. Number of charge carriers are low and conductivity is strongly temperature dependent
4. The activation energy for ion migration is high.
5. The conduction is due to the thermal generated defects and the activation processes involves both energy of defect formation and defect migration

2. Super Ionic conductors

1. High ionic conductivity and negligible electronic conductivity
2. High ionic conductivity even well below the melting point
3. Number of charge carriers are high and conductivity is temperature independent
4. The activation energy for ion migration is low
5. The conduction is due to high carrier concentration and the enthalpy of formation is almost zero

Classification of Fast Ionic Conductors

1. Cationic conductors: In cationic conductors, the high ionic conduction is due to the positively charged mobile ions. The cationic conductors usually contain monovalent cations such as Ag+ , Na^+ , Li^+ , K^+ or H^+ or divalent cations such as Ca^{2+}, Ba^{2+}, Cd^{2+}, trivalent cations are Nd^{3+} , Eu^{3+} , Er^{3+} , etc. However, it is observed that monovalent ions exhibit high conductivity. The conductivity changes with temperature as the structure of crystal changes with temperature. For example, the Ag+ conductivity in AgI is low At room temperature because I^- ions adopt either hexagonal or cubic-close-packed structure. When the temperatures is raised above 146° C, AgI transforms into a polymorph in which I^- ions adopt an open body-centered-cubic packed structure containing disordered Ag+ ions and the conductivity of AgI increases sharply to about 1 S cm^{-1} .

2. Anionic conductors: In the anionic conductors, the high ionic conduction is due to the negatively charged mobile ions. Anionic conductors are classified in to oxide (O^{2-}) and fluoride (F^-) groups. Conductors, such as stabilized zirconias and PbF2, require high temperatures for fast ion conductivity. These conductors usually have the fluorite (CaF2) type structure in which anions (O^{2-} or F^-) are arranged at corners of a cube and cations occupy body centers of alternative cubes.

3. Amorphous conductors: In addition to crystalline inorganic solids, superionic conductivity can also be found in amorphous inorganic materials. Glassy electrolytes based on sulfides and halides have much higher conductivity than oxides at ambient temperatures. Many Li+ and Ag+ conducting glasses are known prepared and had vast applications. Even though oxide-based glasses have low conductivity, they are more stable than sulfides or halides at high temperatures

4. Polymer-based conductors: Superionic conductivity is also known in polymer based solids. The polymer electrolytes are classified in to two types.

1. Polymer-salt complexes
2. Polyelectrolytes.

- Polymer-salt complexes are prepared by dissolving a salt such as LiClO4 in a polymer such as poly ethylene oxide. Both cations and anions in polymer-salt electrolytes can be mobile.
- In polyelectrolytes, the polymer backbone contains covalently attached charged (positive or negative) groups and the charge-balancing counter ions are able to make long-range migration. The best-known polyelectrolyte is Nafion perfluorocarbon sulfonic acid polymer, which is a proton conductor under wet conditions.

Applications of Superionic conductors

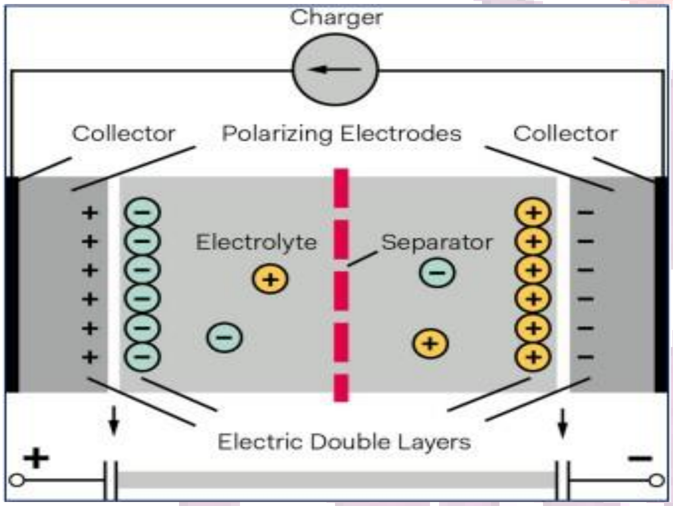
- Energy storage and generation (electrolyzers, batteries, and fuel cells),Membranes in ion selective electrodes
- For the development of all-solid-state electrochemical devices, which have many advantages over those based on liquid electrolytes including ease of miniaturization and high-temperature stability.

- Gas Sensors: Oxygen gas sensors based on oxide conductors are being widely used to monitor automobile exhaust gases. Oxide conductors are also being studied for the construction of solid oxide fuel cells (SOFC).
- Nafion and related sulfonated polymers are under investigation as proton conductors in polymer electrolyte membrane (PEM) fuel cells
- Electrochromic display capacitors,
- Analog memory devices,
- Miniature cells,
- Power storage devices

3.21 Materials and electrolytes for super capacitors

The super capacitors (SCs) are the class of capacitor with capacitance value much higher than other capacitors, but with lower voltage limits. These super capcitors bridges the gap between electrolytic capacitors and rechargeable batteries. The various electrode material used for making the supercapacitors are Graphene, polymer, metal oxides, carbon etc. Different electrolytes like Li, Na, Na2SO4, sulphuric acid and phosphoric acid used in super capacitors.

Construction and working of a supercapacitor



A supercapacitor cell consists of two electrodes, a separator, and an electrolyte. The collectros are made with the metals of high conductivity. A membrane is kept between the two electrodes which allow only the ionic conductivity, but stops electrical conductivity. An active material, made up of metal oxides, carbon and graphite is used an electrolyte. The system is impregnated with an electrolyte. The geometrical size of the two carbon sheets and of the separators is designed to have huge surface area. Due to its structure, the highly porous carbon can store more energy than any other electrolytic capacitor. Under the application of voltage, the positive plate attracts negative ions from the electrolyte, and negative plate attracts positive ions. This will form the ion layers to the either side of the plate (termed as double layer formation), resulting in the ions being stored near the surface of the carbon. This mechanism gives supercapacitors the ability to store and restore high energy in a very short time period.

The advantages of supercapacitors

- Their storage capacity is about 10 to 100 times more per unit volume compared to electrolytic capacitors.
- They also have the advantage of fast charging and discharging
- Higher charging and discharging cycles compared to rechargeable batteries.

Applications of Supercapacitors

- Used in applications requiring many rapid charge/discharge cycles, rather than long-term compact energy storage.
- In automobiles, buses, trains, cranes and elevators, where they are used for regenerative braking ¬ Short-term energy storage
- burst-mode power delivery
- As power backup for static random-access memory (SRAM).

Unlike ordinary capacitors, supercapacitors do not use the conventional solid dielectric. The two storage principles by which the electrical energy is stored in the supercapacitors are

- Electrostatic double-layer capacitance
- Electrochemical pseudocapacitance

The distribution of the two types of capacitance depends on the material and structure of the electrodes.

1. Electrostatic double-layer capacitors (EDLCs): Electrostatic double-layer capacitors (EDLCs) use carbon electrodes or derivatives with much higher electrostatic double-layer capacitance than electrochemical pseudocapacitance, achieving separation of charge in a Helmholtz double layer at the interface between the surface of a conductive electrode and an electrolyte. The separation of charge is of the order of a few ångströms (0.3–0.8 nm), much smaller than in a conventional capacitor.

2. Electrochemical pseudocapacitors: Electrochemical pseudocapacitors use metal oxide or conducting polymer electrodes with a high amount of electrochemical pseudocapacitance additional to the double-layer capacitance. Pseudocapacitance is achieved by Faradaic electron charge-transfer with redox reactions, intercalation or electrosorption. Hybrid capacitors, such as the lithium-ion capacitor, use electrodes with differing characteristics: one exhibiting mostly electrostatic capacitance and the other mostly electrochemical capacitance. The electrolyte forms an ionic conductive connection between the two electrodes which distinguishes them from conventional electrolytic capacitors where a dielectric layer always exists, and the so-called electrolyte, e.g., MnO2 or conducting polymer, is in fact part of the second electrode (the cathode, or more correctly the positive electrode). Supercapacitors are polarized by design with asymmetric electrodes, or, for symmetric electrodes, by a potential applied during manufacturing.

3.22 Rechargeable ion batteries

A rechargeable battery is a type of electrical battery which can be charged, discharged into a load, and recharged many times. The three most popular rechargeable batteries are

- Nickel-Cadmium (Ni-Cd)
- Nickel Metal-Hydride (Ni-MH)
- Lithium-Ion (Li-Ion)

Energy Density of a battery

1. The gravimetric energy density: This is the total energy of a battery in comparison to its weight. Units Watt-hours/kilogram (W-hr/kg).

2. The volumetric energy density: This is the total energy of a battery in comparison to its volume. Units: Watt-hours/liter (W-hr/l). The Amp-hour capacity: It is defined as the amount of current that a battery can deliver for 1 hour before the battery voltage reaches the end-of-life point.

Types of lithium-ion batteries

1. Lithium Cobalt Oxide batteries: Lithium cobalt oxide batteries are made up of lithium carbonate and cobalt. They have a cobalt oxide cathode and a graphite carbon anode. The lithium ions migrate from the anode to the cathode during discharge, with the flow reversing when the battery is charged. These batteries are used in cell phones, laptops, and electronic cameras because of their high specific energy. These batteries has a few disadvantages, including short battery life and low specific power.

2. Lithium Manganese Oxide Batteries: These batteries have high-temperature stability compared to the others which makes them safer than other lithium-ion battery types. Due to this property, they are used in medical equipment and devices, power tools, electric motorcycles, and other applications.

3. Lithium Iron Phosphate (LFP) Batteries: Phosphate is used as a cathode in lithium ion phosphate batteries. They have low resistance qualities, which improve their thermal stability and safety. They have high durability and a long lifecycle. Fully charged batteries can be kept with no effect on the battery's overall charge life. Due to the lengthy battery life, Li-phosphate batteries are cost-effective. However, due to the lower voltage of the lithium-phosphate battery, they have less energy in comparision with other lithium batteries. As a result, these batteries are frequently used in electric bikes and other applications requiring a long lifecycle and high levels of safety. These batteries are also commonly used in electric vehicles. These batteries are frequently used in electric vehicles and other applications requiring a long lifecycle and high levels of safety.

4. Lithium Nickel Manganese Cobalt Oxide (NMC) batteries: Lithium Nickel manganese Cobalt Oxide batteries are constructed with a variety of materials. A cathode constructed of a mix 60% nickel, 20% manganese, and 20% cobalt. These batteries are cost effective as nickel is cheaper. These batteries can have a high specific energy density or a high specific power (but can’t have both features). Because of their low self-heating rate, they are most commonly seen in power tools, electric vehicles.

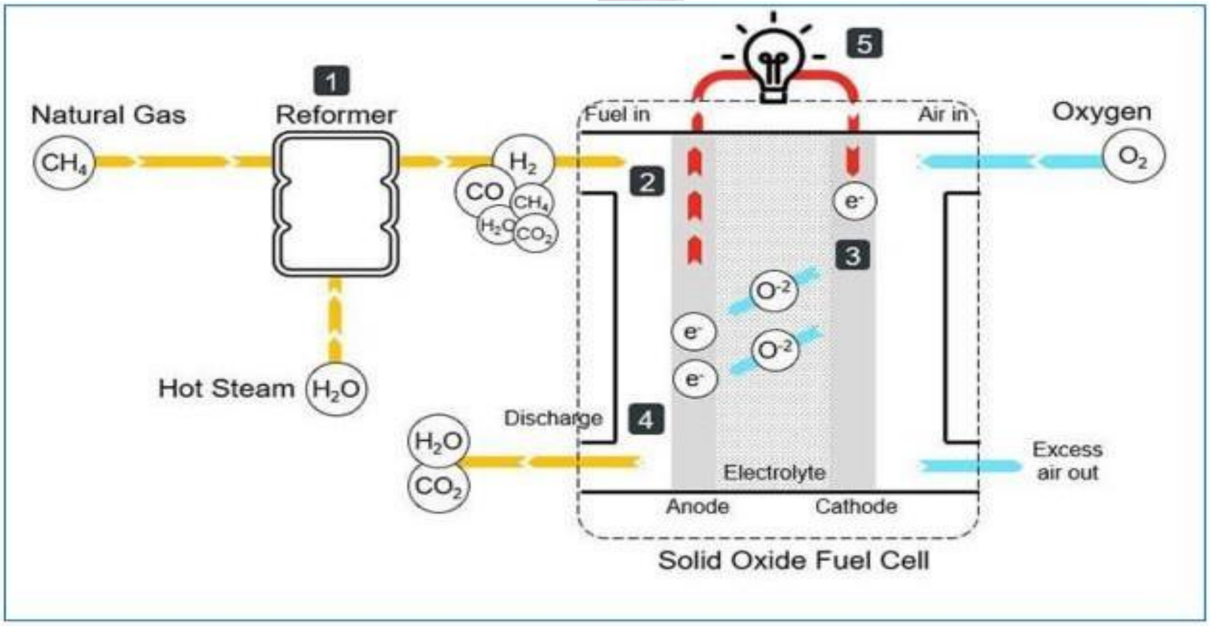
5. Lithium Nickel Cobalt Aluminum Oxide batteries: These batteries offer a high-energy density with a long lifespan. However they are less safe than other lithium-ion battery types and are rather expensive. Hence, while these batteries are used in electrical vehicles, they must be accompanied by monitoring systems to ensure driver safety. These batteries have little applications in consumer electronics, but have great potential in the automobile industry. Given the widespread use of NCA batteries in electric vehicles, demand for these batteries may increase as the number of electric vehicles grows.

6. Lithium Titanate Batteries: These batteries are made using the nanotechnology and have an extremely rapid recharge time. However, their lower energy density than other lithium-ion battery types (but more than non-lithium-ion batteries) is the disadvantage while using them in power automobiles. Li-titanate batteries are being used in electric vehicles and bicycles. The researchers are working to increase their power density to extend their applications in public transportation.

3.23 Solid Oxide Fuel Cells (SOFC)

Fuel cells convert the chemical energy stored in the fuel to electric and thermal energy without the need for combustion. This makes them different from engines and power plants, which may have the same applications but rely on combustion, reducing the efficiency of the energy conversion.

Working Principle of a Solid Oxide Fuel Cell:



Natural gas goes through a steam-reforming process. This chemical reaction produces hydrogen (H_2), carbon monoxide (CO), carbon dioxide (CO_2) and steam (H_2O). This mix of elements enters the fuel cell at the anode side while the air enters the fuel cell at the cathode side. The oxygen in the air combines with free electrons to form oxide ions at the cathode. These oxide ions along with the free electrons travel from the cathode to the anode through the electrolyte. At the anode, oxide ions react with hydrogen forming water (steam) and with carbon monoxide (CO) forming carbon dioxide (CO2). This reaction will release release free electrons, which travel to cathode through the external electrical circuit, producing electricity.

Applications of Solid Oxide Fuel Cells.

1. High efficiency delivers financial benefits
2. Electrical efficiency of solid oxide fuel cells is close to 60% which is much higher than the efficiencies of coal power plants.
3. As the fuel cells are located locally, the distribution losses will be minimum, unlike the central power plants.
4. This high efficiency delivers financial benefits and minimizes the environmental footprint, since
5. The solid oxide fuel cells are environmental friendly as they use natural gas as fuel in comparison to traditional power plants using coal as fuel.
6. Solid oxide fuel cells also don’t emit sulphur oxides and particulate matter.
7. Modular design brings scalability: The individual fuel cells are bundled together to form a stack. These stacks are then combined with other equipment to form modules. These individual power generation modules can be paralleled to form the fuel cell power system. You can add more fuel cell modules to the overall system as you need. This provides financial flexibility for the user to align the power generation investments with business needs.

Short questions

1. Define the terms: dielectric constant, electric displacement, polarizability and electric susceptibility.
2. Deduce Clausius-Mositti relation.
3. Explain ferroelectricity.
4. Explain piezoelectricity.
5. Define the terms: magnetic field strength, magnetic flux density, magnetization and magnetic susceptibility.
6. Derive relation between χ_m and μ_r.
7. Why diamagnetic materials have negative susceptibility?
8. What are soft and hard magnetic materials?
9. What are the applications of ferrites?
10. Write about the hysteresis curve?
11. What is electrolyte?
12. How the electrolytes are classified?
13. Mention the advantages of Solid electrolytes over the liquid electrolytes
14. Mention the requirements of a good electrolyte
15. Differentiate between the normal ionic conductors and super ionic conductors
16. What are supercapacitors? Write few applications of supercapacitors

Essay type questions

1. Define current and current density and derive continuity equation.
2. What are Maxwell's equations? Write Maxwell's equations and explain their significance.
3. What is internal field of a dielectric and how it is calculated for a dielectric?
4. Classify and explain the properties of different types of magnetic materials.
5. What is domain? Explain ferromagnetic hysteresis on the basis of domains.
6. What are anti-ferro and ferri magnetic materials? Explain their properties.
7. Write a detail notes on solid and liquid electrolytes
8. Write a detail note on superionic conductors.
9. Write a detail notes on recharble batteries
10. What are Solid Oxide Fuel Cells? With neat diagram, explain the working principle of Solid Oxide Fuel Cells

Multiple answer questions

1. The expression for local field (E_{local}) of a dielectric material is given by [ ]

(A) $E_i = P + \left(\frac{E}{3\varepsilon_0}\right)$ (B) $E_i = E + \left(\frac{E}{3\varepsilon_0}\right)$

(C) $E_i = P + \left(\frac{3\varepsilon_0}{E}\right)$ (D) $E_i = E + \left(\frac{P}{3\varepsilon_0}\right)$

2. Orientational polarizability [ ]

(A) increases with increase of temperature (B) decreases with increase of temperat

(C) is independent of temperature (D) becomes zero with increase or decrease of temp.

3. The Classius-Mosotti equation is [ ]

(A) $\frac{(\varepsilon_r-1)}{(\varepsilon_r+2)} = \frac{3\varepsilon_0}{N\alpha}$ (B) $\frac{(\varepsilon_r-1)}{(\varepsilon_r+2)} = \frac{N\alpha}{3\varepsilon_0}$ (C) $\frac{(\varepsilon_r+2)}{(\varepsilon_r-1)} = \frac{N\alpha}{3\varepsilon_0}$

(D) $\frac{(\varepsilon_r+2)}{(\varepsilon_r-1)} = \frac{3\varepsilon_0}{N\alpha}$

4. In the absence of external electric field, the electric dipoles in a dipole substance are [ ]

(A) Parallel (B) Anti Parallel

(C) Randomly Orented (D) Perpendicular to each other

5. Dielectrics are [ ]

(A) Solids (B) Metals (C) Semiconductors (D) Insulators

6. The dipole moment per uint volume is .... [ ]

(A) Polarization (B) Electric flux density (C) polarization Vector (D) polarizability

7. Choose the correct relation for ionic polarization [ ]

(A) $\alpha_i = \frac{e^2}{\omega^2{}_0}\left(\frac{1}{M}+\frac{1}{m}\right)$ (B) $\alpha_i = \frac{e^2}{\omega^2{}_0}\left(\frac{1}{M}-\frac{1}{m}\right)$

(C) $\alpha_i = \frac{e^2}{\omega^2{}_0}(M+m)$ (D) $\alpha_i = \frac{e^2}{\omega^2{}_0}(M-m)$

8. Material which lack permanent dipoles are called .... [ ]

(A)Ferrimagnetic (B) Antiferromagnetic (C) Diamagnetic (D) Paramagnetic

9. The value of permitivity of free space is equal to............................ [ ]

(A) $4\pi X10^{-7}Hm^{-1}$ (B)$8.85X10^{-12}Fm^{-1}$ (C)$1.68X10^{-19}C$ (D)$2.54X10^{-23}J$

10. Choose the correct Relation [ ]

(A) $E = \varepsilon_0(\varepsilon_r - 1)P$ (B) D= $\varepsilon_0(\varepsilon_r - 1)E$ (C) $P = \varepsilon_0(\varepsilon_r - 1)E$ (D) $\varepsilon_r = (\chi - 1)$

11. Hystersisi in polarization-electric field relation is exhibited by [ ]

(A) Piezo electric materials (B) Ferro electric materials

(C) Pyro elec tric materials (D) Electro optic materials

12. The polarizations which are dependent of temperature are [ ]

(A) Orentation and Space Charge (B) Electronic and Ionic

(C) Orentation and Ionic (D) Electronic and Space Charge

13. In the case of pyroelectric materials .... changes with temperature. [ ]

(A) Current (B) Dielectric constant (C)Polarization (D)Optical property

14. The dielectric constant of solids [ ]

(A) ε_r >1 (B) ε_r <1 (C) ε_r =1 (D) ε_r = 0

15. Using inverse Piezo-electric effect, ...can be produced. [ ]

(A) Voltage (B) Electric field (C) Current (D) Stress

16. Polarization per unit applied electric field is called [ ]

(A)electric susceptibility (B) magnetic susceptibility
(C) electric polarizability (D) dielectric constant

17. Equal number of opposite spins with different magnitudes present in................... materials[ ]

(A)Ferrimagnetic (B) Antiferromagnetic (C) Diamagnetic (D) Paramagnetic

18. Magnetization per unit magnetic field intensity is called [ ]

(A)magnetic induction (B) magnetic susceptibility

(C) magnetic permeability (D) magnetic flux density

19. Among the following materials, which exhibits ferro-magnetic property? [ ]

(A) Al (B) Gold (C) Nickel (D) Silver

20. The MKS unit of............ is weber per square metre. [ ]

(A) Hm^{-1} (B) Tesla (C)$kg\ s^{-2}\ A^{-1}$

21. Diamagnetic susceptibility is [ ]

(A) Large, negative (B) Small, positive (C) Small, negative (D) Large, positive

22. The unit of magnetic field intensity is [ ]

(A) Am^{-1} (B) Hm^{-1} (C) Wb^{-2} (D) No units

23. The nuclear magnetic momentum is expressed in the unit of nuclear magneton its value is................ [ ]

(A)5.05×10^{-29} A-m^2 (B) 5.05×10^{-29}A-m (C) 5.5×10^{-29} A-m (D) 5.05×10^{-29} w-m2

24. Super conductors can be called as [ ]

(A) Perfect Diamagnetic (B) Perfect Ferro magnetic
(C) para magnetic (D) Non magnetic material

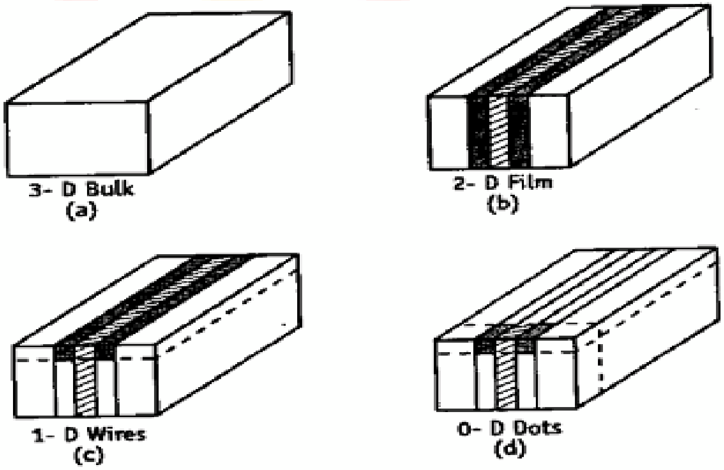
UNIT-IV

NANOTECHNOLOGY

Introduction

In 1959, Richard Feynman made a statement ‘there is plenty of room at the bottom’. Based on his study he manipulated smaller units of matter. He prophesied that “we can arrange the atoms the way we want, the very atoms, all the way down”. The term ‘nanotechnology’ was coined by Norio Taniguchi at the University of Tokyo. Nano means $10^{-9.}$ A nano metre is one thousand millionth of a metre (i.e. 10^{-9} m).

Nanomaterials could be defined as those materials which have structured components with size less than 100nm at least in one dimension. Any bulk material we take, its size can express in 3-dimensions. Any planer material, its area can be expressed in 2-dimension. Any linear material, its length can be expressed in 1-dimension.



SCHEMATIC DIAGRAM OF QUANTUM STRUCTURES

Materials that are nano scale in 1-dimension or layers, such as thin films or surface coatings.
Materials that are nano scale in 2-dimensions include nanowires and nanotubes.
Materials that are nano scale in 3- dimensions are particles like precipitates, colloids and quantum dots.

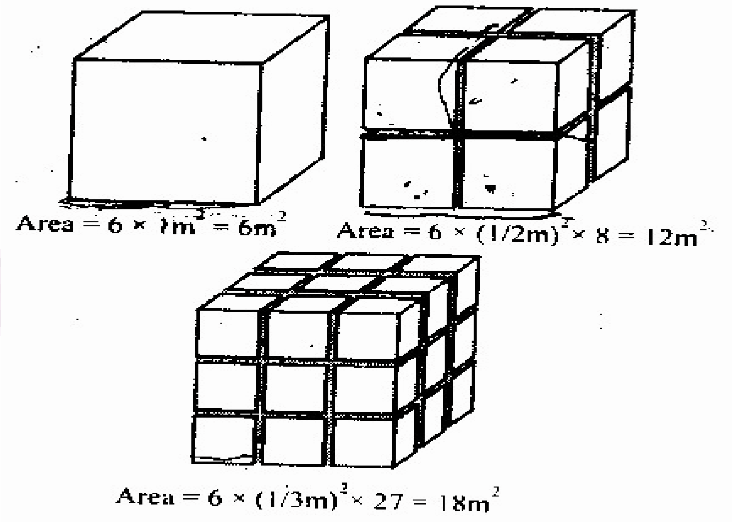
Nanoscience: it can be defined as the study of phenomena and manipulation of materials at atomic, molecular and macromolecular scales, where properties differ significantly from those at a larger scale.

Nanotechnology: It can be defined as the design, characterization, production and application of structures, devices and systems by controlling shape and size at the nano metre scale. It is also defined as “A branch of engineering that deals with the design and manufacture of extremely small electronic circuits and mechanical devices built at molecular level of matter. Now nanotechnology crosses and unites academic fields such as Physics, Chemistry and

Computer science.

4.1 Increase in surface area to volume ratio

Nano materials have relatively larger surface area when compared to the volume of the bulk material.



Consider a sphere of radius r
Its surface area $=4\Pi r^2$
Its volume $= 4\Pi r^3 /3$

$$\frac{\text{Surface area}}{\text{Volume}} = \frac{4\Pi r^2}{4\Pi r^3 /3} = \frac{3}{r}$$

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

EX: For a cubic volume,

Surface area = $6x1m^2 = 6m^2$

When it is divided it 8 pieces
It surface area = $6x\ (1/2m)^{2x8} = 12m^2$
When the sane volume id divided into 27 pieces,

It surface area = $6x\ (1/3m)^{2x27} = 18m^2$
Therefore, when the given volume is divided into smaller pieces, the surface area increases. Hence as particle size decreases, greater proportions of atoms are found at the surface compared to those inside. Thus nano particles have much greater surface to volume ratio. It makes material more chemically reactive.

As growth and catalytic chemical reaction occur at surfaces, then given mass of material in nano particulate form will be much more reactive than the same mass of bulk material. This affects there strength or electrical properties.

4.2 Quantum confinement effects

When the size or dimension of a material is continuously reduced from a large or macroscope size (such as centimeter) to a very small size, then it is observed that the properties of the matter remains same in the beginning but small changes occur.

afterwards. If the size drops below 100 nm (in nano range) then drastic changes occur in the properties. A progressive generation of diminishing size of rectangular nanostructures takes place in the following way.

If one dimension is reduced to the nano range while the third remains the same, then the structure so formed is known as quantum well as in fig (b).

If the two dimensions are reduced to nan orange while the third remains the same, then the structure so formed is known as quantum wire as shown in fig (1).

When all the 3-dimensions of the material are reduced to nano-range, then it is called as quantum dot as shown in fig (d).

It is important to mention here that the word quantum is associated with all the three structures. This is because the changes in properties arise from quantum mechanical nature.

When the dimensions of potential box is order of de-Broglie wave length of electron, the energy levels of electrons change. This effect is called Quantum configuration.

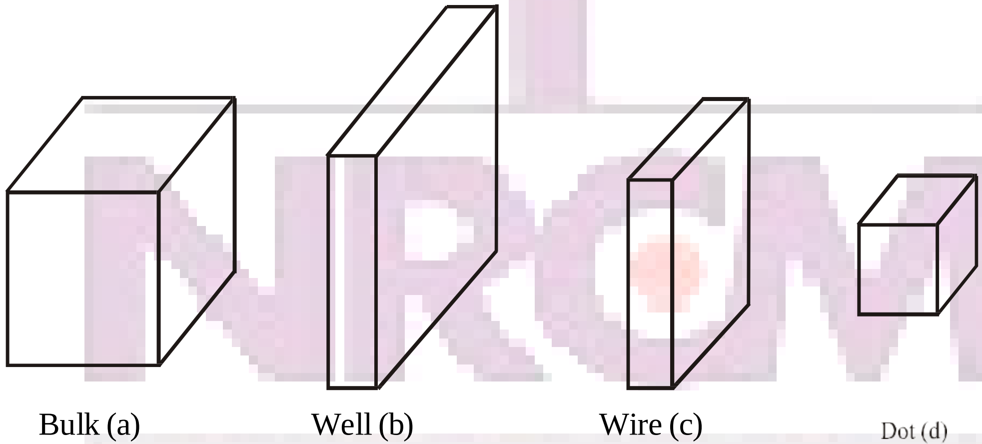


Fig: Progressive generation of rectangular nano structures

4.3 Synthesis of nanoparticles

The following two main techniques are used for the preparation of quantum dots.

1. Bottom-up Technique

2. Top-down Technique

Bottom-up Technique: This is a technique in which materials and devices are built up atom by atom i.e, technique to collect, consolidate and fashion of individual atoms and molecules into the structure. There is carried out by a sequence of chemical reactions controlled by series of catalysts. This process is used widely in biology. For examples, catalysts called enzymes assemble amino acids to construct living tissues that forms and supports the organs of the body.

Top-Down Technique: This is a technique in which materials are synthesized or constructed by removing existing materials from larger entities. Therefore in this technique, a large scale object or pattern is gradually reduced in dimensions or dimensions to mono scale pattern. This can be accomplished by a technique called lithography. Lithography is an image that is produced by making a pattern on the stone, inking the stone and then pushing the inked stone onto the paper. The lithography used may be a nano scale lithography of dip-pen lithography or an E-bean lithography. The lithography shines radiation through a tip to the surface coated with radiation - sensitive resist. The resist is then removed and the surface is chemically treated to produce the nanostructure.

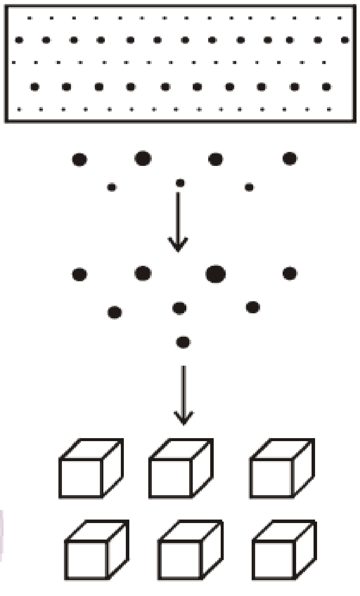


Fig: Nano particles

Nano materials can be synthesized by two techniques.

Bottom-up technique: In this technique, the nano structured materials are synthesized by assembling the atoms or molecules together to form the nano materials.

- Sol-Gel method
- Precipitation method
- Combustion method

Top-Down technique: In this technique, the bulk solids are dis-assembled (broken) into finer pieces until the particles are in the order of nanometer.

- Ball milling (Mechanical Griding) method
- Chemical vapour deposition (CVD) method
- Physical vapour deposition (PVD) method

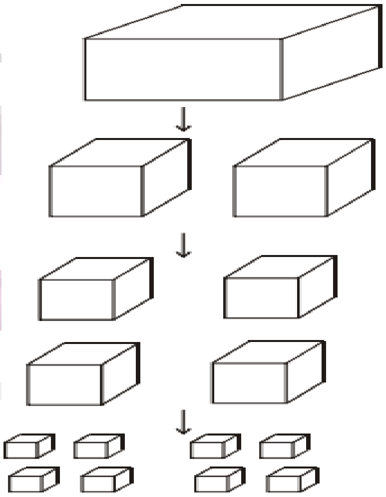


Fig.: Nano Structure

4.3.1 Sol-Gel Method

Sol-Gel is a chemical process used to make ceramic and glass materials in the form of thin films, fibers or powders.

A sol is a colloidal or molecular suspension of solid particles of ions in a solvent and a Gel is a semi-rigid mass that forms when the solvent form the sol begins to evaporate.

The precursors for synthesizing the colloids are metal alkoxides and metal chlorides [Ex: Tetramethoxy (TMOs) and Tetra ethoxy, silane (TEOs)]. The starting material is processed with water or dilute acid in an alkaline solvent. The material undergoes hydrolysis and poly condensation reaction which leads to the form of colloids. The colloid system composed of solid particles dispersed in a solveril. The sol is then evolved to form an inorganic network containing liquid phase (gel). The schematic representation of the synthesis of nano particles using sol. Gel method is shown in below figure.

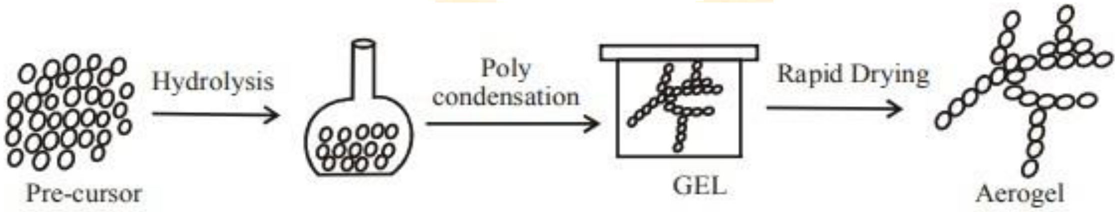


Fig.

Advantages:

- This method is low cost and low temperatures technique.
- One can get a highly porous material like glass and glass ceramics.
- One can get monetized nano particles.

Disadvantages:

- Controlling the growth of particle is different difficult.
- Slopping the newly formed particles from agglomeration is also difficult.

Note:

A precursor is a compound that participates in a chemical reaction and produces another compound.

Allotropy is the property of some chemical element to exist in two or more different forms in the same physical state.

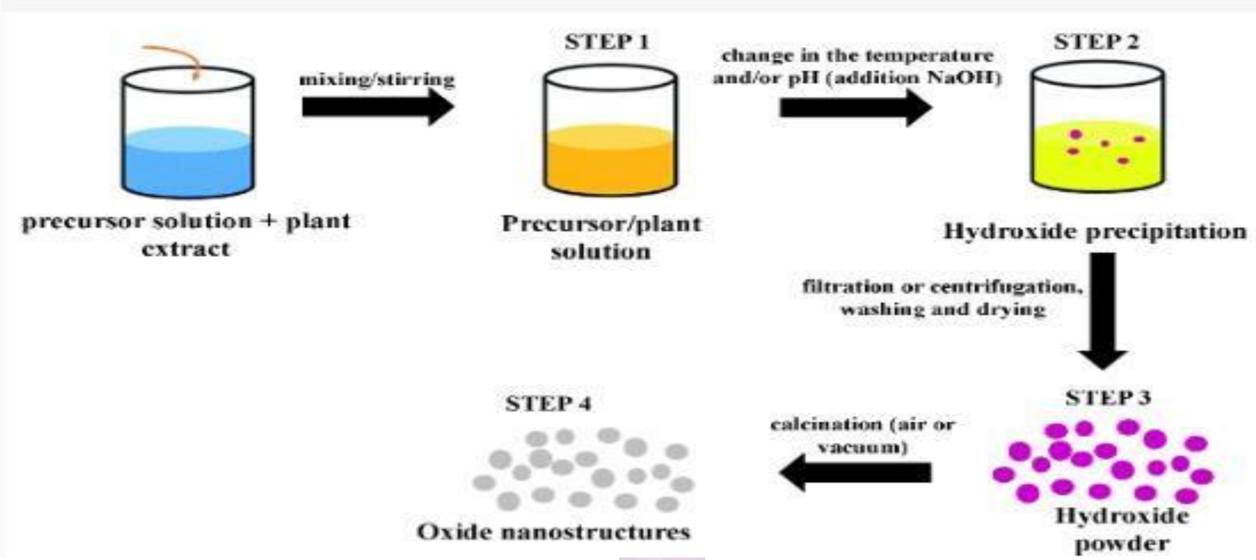
4.3.2 Chemical Precipitation and Co-precipitation

A chemical precipitation process consists of three main steps:

- chemical reaction
- nucleation
- crystal growth

Chemical precipitation is generally not a controlled process in terms of reaction kinetics and the solid phase nucleation and growth processes. Therefore, solids obtained by chemical precipitation have a wide particle size distribution plus uncontrolled particle morphology, along with agglomeration. To obtain nanoparticles with a narrow size distribution, the necessary requirements are (i) a high degree of supersaturation, (ii) a uniform spatial concentration distribution inside a reactor and (iii) a uniform growth time for all particles or crystals.

The other commonly used solution method for the synthesis of multi component oxide ceramics is co-precipitation method, which produces a "mixed" precipitate comprising two or more insoluble species that are simultaneously removed from solution. The precursors used in this method are mostly inorganic salts (nitrate, chloride, sulfate, etc.) that are dissolved in water or any other suitable medium to form a homogeneous solution with clusters of ions. The solution is then subjected to pH adjustment or evaporation to force those salts to precipitate as hydroxides, hydrous oxides, or oxalates. The crystal growth and their aggregation are influenced by the concentration of salt, temperature, the actual pH and the rate of pH change. After precipitation, the solid mass is collected, washed and gradually dried by heating to the boiling point of the medium.



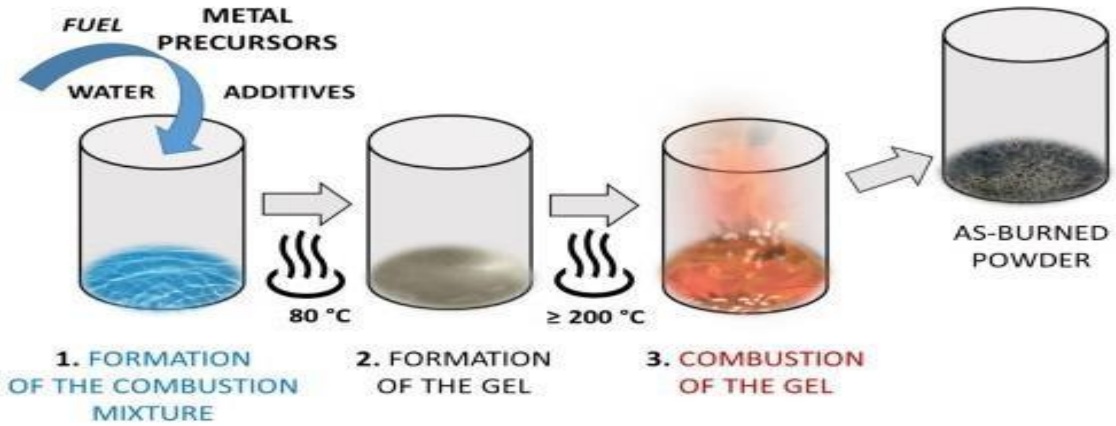
4.3.3 Combustion method

Combustion reaction: when a substance reacts with oxygen, forming light and heat in the form of fire.

Combustion is a high-temperature exothermic (heat releasing) redox (oxygen adding) chemical reaction between a fuel and an oxidant.

For example, when methane burns in oxygen, it releases carbon dioxide and water. The formation of carbon dioxide shows the carbon present in the methane has undergone oxidation.

For the combustion process, fuel and oxidizer are required; metal nitrate acts as an oxidizing reactant and urea acts as a reducing reactant. The synthesis process involves weighing solid precursors, then grinding and mixing generally in an aqueous solution of distilled water in which the ingredients are dissolved.



4.3.4 Chemical vapour deposition(CVD) method

In this method, nano particles are deposited from gas phase. Material is heated to form a gas and then allowed to deposit on an solid surface. Usually under high vacuum. In deposition by chemical reaction new products are formed.

In this method a metal organic precursor is introduced into the hot zone of the reactor using mass flow controller. The precursor is vaporized either by resistive or inductive healing. The carrier gas such as Ar (or) Ne carries the hot atoms to the reaction chamber. The hot atoms collide with cold atoms and undergo condensation through nucleation and form small clusters inside reaction chamber other reactants are added to control the reaction rate. Then these clusters are added to condense on a moving bell arrangement with scrapper to collect the nano particles. The particle size can be controlled by rate of evaporation, rate of cluster formation and rate of condensation (cluster removed from the reaction chamber).

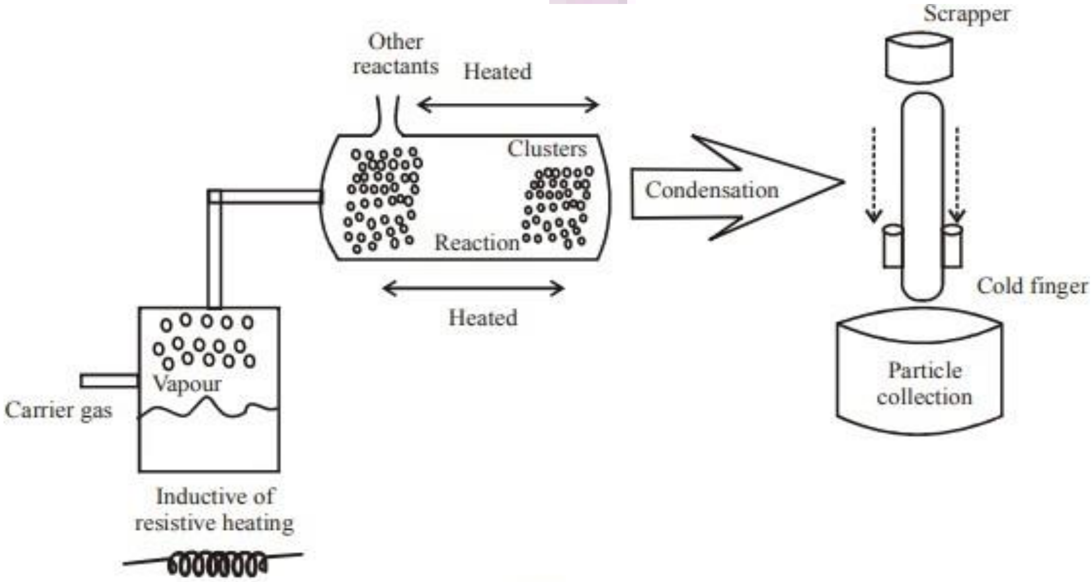


Fig.

Advantages:

- Wide range of ceramics including nitrides and carbides can be synthesized.
- More complex oxides such as BaTiO3 or composite structures can be formed.
- Controlling growth of particles is easy.

Disadvantages:

- High cost and high temperature technique.

4.3.5 Physical Vapour Deposition (PVD) method

In this method the experimental set up consists of a bell jar in which an inert gasor reactive gas is filled after vacuum. The materials to be evaporated are placed in the crucible and are heated either his resistance or an electron bombardment until sufficient vapour develops. The evaporated atoms (or) molecular are allowed condensing on a cold finger which is externally cooled by liquid N2. The nano particles on the cold finger is scraped by the scraper and then collected to the piston anvil through a funnel. The piston anvil is used to obtain the compacted nano powders. The desired purity of the nano powder is obtained since the evaporation is done at the vacuum chamber with the pressure of an inert or reactive gas. This method is more suitable for non- conductive or high melting materials.

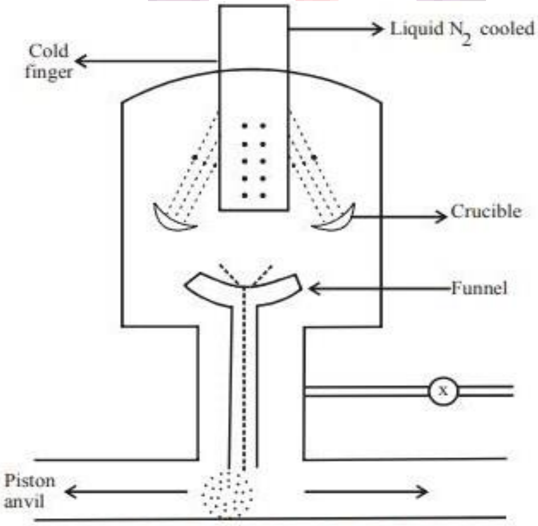


Fig. Physical Vapour Deposition

4.3.6 Ball milling method

In ball milling, also called mechanical crushing, small balls are allowed to rotate around the inside of a drum and then fall on a solid with gravity force and crush the solid into nano crystallites. Ball milling can be used to prepare a wide range of elemental and oxide powders. For example iron with grain sizes of 10-30 nm can be formed. Other crystallites such as iron nitriles can be made using ammonia gas. A variety of intermetallic compounds based on nickel and aluminum can be formed. Ball milling is the preferred method for preparing metal oxides.

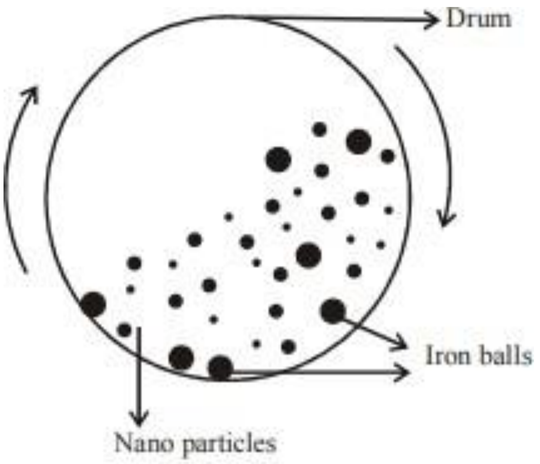


Fig. Ball Moulding

4.4. Characterization Techniques

4.4.1 Transmission Electron Microscope (TEM)Principle:

The transmission electron microscope works on the some basic principle as that of a light microscope except that an electron beam is used instead of light beam. Due to much lower wavelength associated with electrons. It is possible to get a resolution which is thousand times more in comparison as obtained with light microscope. Therefore, an enlarged version of the image of the specimen appears on the florescent screen (or) photographic plate. We can also consider the working principle of TEM likea slide projector.

Working: At the top of the microscope, there is electron gun which produces a stream of monochromatic electrons. The beam travels through vacuum int eh column of microscope.

The beam strikes the condenser lenses instead of glass lenses focusing, the microscope user electromagnetic lenses which focus the electrons into a very fine beam.

The beam strikes the specimen which we want to study. Depending on the density of the material present, some of the electrons are scattered and disappear from the beam. The other are transmitted through the specimen.

The transmitted electrons are focused by the objective lens into an image. The image is passed through the projector lenses.

The beam then hits a fluor's fluorescent screen. The screen shows a shadow like image of the specimen allowing the user to see the image.

It is observed that transmission of unscattered electrons is inversely proportional to the specimen thickness i.e., the thicker areas will have less transmitted light and thus will appear dark. On the other hand, the thinner areas will have more transmitted light and thus will appear brighter.

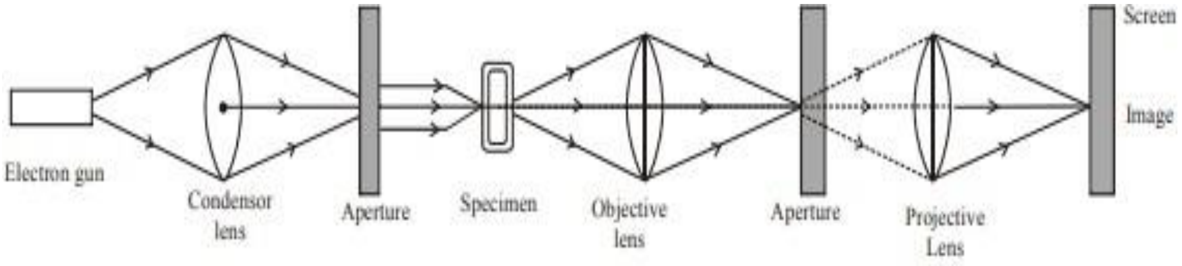


Fig. Transmission Electron Microscope

Uses:

The high magnification range and resolution has made the TEM as a valuable tool in medical, biological and material research.
The object of the order of 0.2 nm be viewed.
This allows the visualization of viruses and bacteria's.

4.4.2 Characterisation of Nano Particles by XRD

The analysis of crystalline materials semi crystalline materials and amorphous materials at the nano scale are possible with x-ray diffraction. XRD provides an adaptable method for measuring crystalline phases, degree of crystallinity and structures.
Measurements by XRD help to understand what really happens during processing. For characterization of nano particles X-ray differentiation (XRD) is the most widely used technique.
Typical XRD pattern of silver particles prepared by the chemical as shown in the below figure.
The X-RD study indicates the formation of silver (Ag) nano particles.
From this study considering the peak of diffraction angle at 450, average particle size has estimated by using Debye Scherrer formula.

$$D=(k\lambda/\beta \cos \theta)$$

'λ' is the wavelength of X-Ray (0.1541 nm)
' β ' is FWHM (full width at half maximum) (0.011 radian),
'θ' is the diffraction angle (450)
D is the particle diameter (size)
The average particle size is calculated to be around 14 nm.
Thus using XRD pattern we are able to calculate the particle size.
To 'see' the particle, we have to use TEM or SEM.

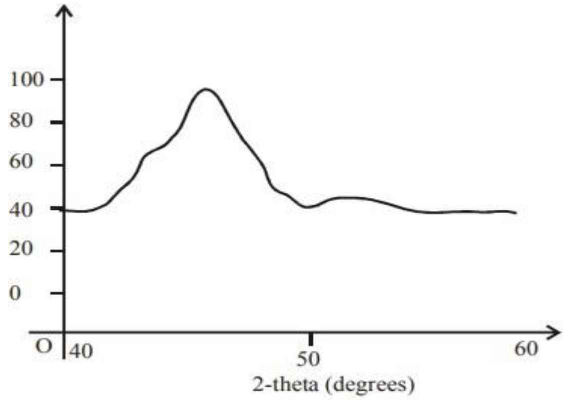


Fig.: X-ray diffraction of Ag nano particles

4.4.3 SCANNING ELECTRON MICROSCOPE (SEM)

The image is scanning electron microscopy (SEM) is produced by scanning the sample with a focused electron and detecting the secondary and / or back scattered electrons.

A schematic representation of a SEM is shown in the below figure.

The electron gun produces a stream of monochromatic electrons

The electron stream is condensed by the first condenser lens. It works inconjunction lens forms the electrons into a thin, light coherent beam.

The second condenser lens forms the electrons into a thin, light coherent beam.

Objective aperture further eliminates high angle electrons from the beam.

A set of coils acting as electrostatic lens scans and sweeps the beam in a grid fashion (as in television). The beam (dwells) on the points for a period of a time determined by the scan speed. Dwell time is usually in microsound range.

The objective lens focuses the scanning beam onto the part of the specimen.

When a beam strikes the sample interaction occurs. Before the beam moves to the next dwell point, the various instruments housed to measure various interactions count the number of interactions and display a pixel on a CRT.

The intensity of display is determined by the interaction number. More interactions give a brighter pixel.

This process is repeated, until the grid scan is finished and then repeated. The entire pattern can be scanned 30 times per second.

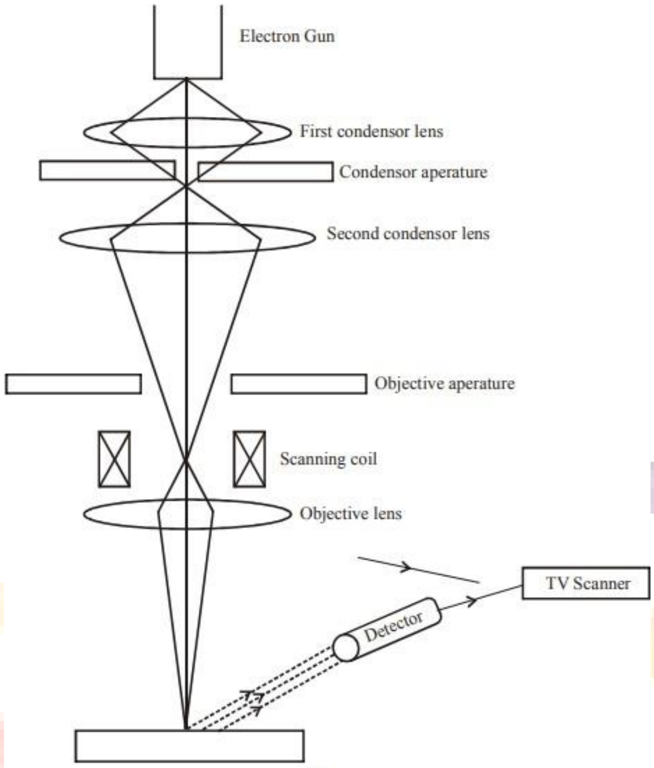


Fig.

Note: This method is only useful to single crystal particles of size more than 20 n.

4.5. DOMINANCE OF ELECTROMAGNETIC FORCES

Then particle size is downsized to nanoscale, gravitational forces become negligible and electromagnetic forces dominate.

Gravitational force between any two particles is a function of mass and distance, whereas electromagnetic force is a function of charge and distance and is independent of mass. Since the mass of a nanoscale object very small, the gravitational force is negligible. Since electromagnetic force is not influenced by the mass of the particles, there are strong electromagnetic forces between nanoscale particles. For example, the electromagnetic force between two protons is 1036 times stronger than the gravitational force.

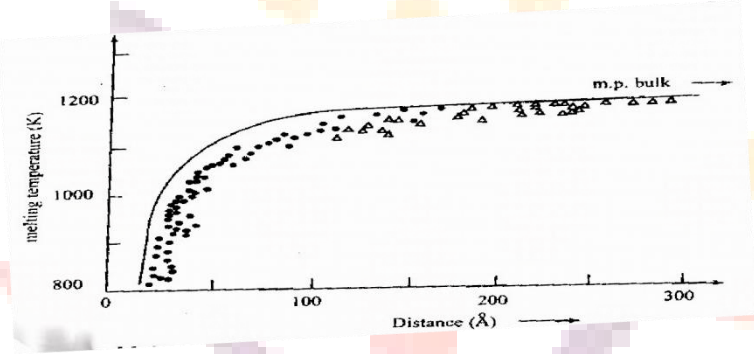
4.6. RANDOM MOLECULAR MOTION

Nano-sized materials, there exists random molecular motion which is also a size- dependent property. As long as the material is above absolute zero temperature, molecules in it move because of kinetic energy, this is called random molecular motion and it ceases at absolute zero. In case of bulk materials, this random motion of macroparticles is negligible as compared to the size of the particles. Hence, this random motion (which is also called the Brownian motion) is not affected by the motion of the particle. However, at nanolevel, these random motions are comparable with the size of the particles and influence the behaviour of the particles. The melting point of various nanomaterials with varying particle size will have different melting points. The melting point decreases with decrease in particle size.

4.7. Properties of nano materials

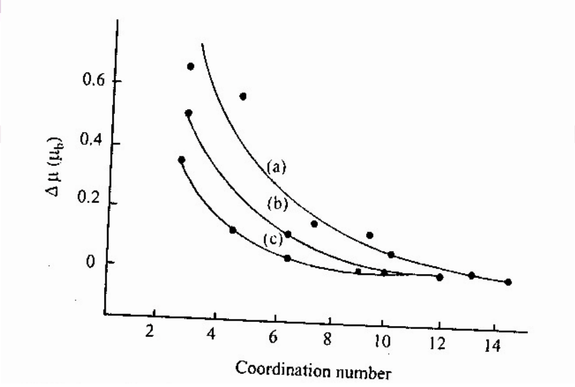
The physical, electronic, magnetic and chemical properties of materials depend on size. Small particles behave differently from those of individual atoms or bulk.

Physical properties: The effect of reducing the bulk into particle size is to create more surface sites i.e. to increase the surface to volume ratio. This changes the surface pressure and results in a change in the inter particle spacing. Thus the inter atomic spacing decreases with size.
The change in the inter particle spacing and the large surface to volume ratio in particle have a combined effect on material properties. Variation in the surface free energy changes the chemical potential. This affects the thermodynamic properties like melting point. The melting point decreases with size and at very small sizes the decrease is faster.



Chemical properties: the large surface to volume ratio, the variations in geometry and electronic structure has a strong effect on catalytic properties. The reactivity of small clusters increases rapidly even when the magnitude of the cluster size is changed only by a few atoms.

Another important application is hydrogen storage in metals. Most metals do not absorb, hydrogen is typically absorbed dissociatively on surfaces with hydrogen- to- metal atom ratio of one. This limit is significantly enhanced in small sizes. The small positively charged clusters of Ni, Pd and Pt and containing between 2 and 60 atoms decreases with increasing cluster size. This shows that small particles may be very useful in hydrogen storage devices in metals.



Electrical properties: The ionization potential at small sizes is higher than that for the bulk and show marked fluctuations as function of size. Due to quantum confinement the electronic bands in metals become narrower. The delocalized electronic states are transformed to more localized molecular bands and these bands can be altered by the passage of current through these materials or by the application of an electric field.

In nano ceramics and magnetic nano composites the electrical conductivity increases with reduction in particle size where as in metals, electrical conductivity decreases.

Optical properties: Depending on the particle size, different colours are same. Gold nano spheres of 100nm appear orange in colour while 50nm nano spheres appear green in colour. If semiconductor particles are made small enough, quantum effects come into play, which limits the energies at which electrons and holes can exist in the particles. As energy is related to wavelength or colour, the optical properties of the particles can be finely tuned depending on its size. Thus particles can be made to emit or absorb specific wavelength of light, merely by controlling their size.

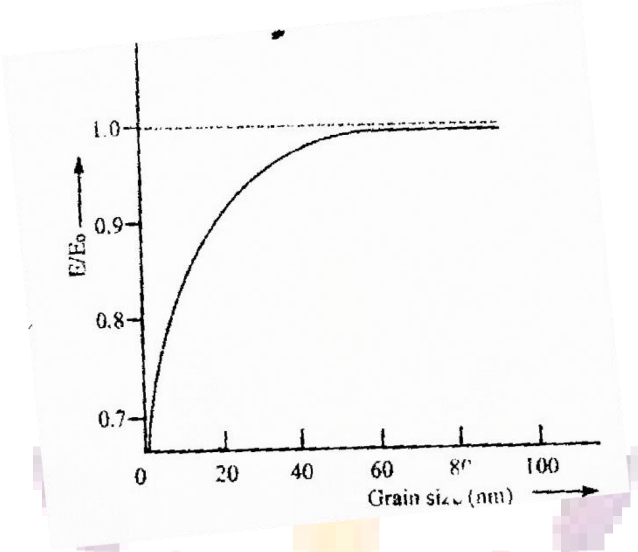
An electro chromic device consist of materials in which an optical absorption band can be introduced or existing band can be altered by the passage of current through the materials, or by the application of an electric field. They are similar to liquid crystal displays (LCD) commonly used in calculator and watches. The resolution, brightness and contrast of these devices depend on tungstic acid gel’s grain size.

Magnetic properties: The strength of a magnet is measured in terms of coercivity and saturation magnetization values. These values increase with a decrease in the grain size and an increase in the specific surface area (surface area per unit volume) of the grains.

In small particle a large number or fraction of the atoms reside at the surface. These atoms have lower coordination number than the interior atoms. As the coordination number decreases, the moment increases towards the atomic value there is small particles are more magnetic than the bulk material.

Nano particle of even non magnetic solids are found to be magnetic. It has been found theoretically and experimentally that the magnetism special to small sizes and disappears in clusters. At small sizes, the clusters become spontaneously magnetic.

Mechanical properties: If the grains are nano scale in size, the interface area within the material greatly increases, which enhances its strength. Because of the nano size many mechanical properties like hardness, elastic modulus, fracture toughness, scratch resistance, fatigue strength are modified.



The presence of extrinsic defects such as pores and cracks may be responsible for low values of E (young's modulus) in nano crystalline materials. The intrinsic elastic modulli of nano structured materials are essentially the same as those for conventional grain size material until the grain size becomes very small. At lower grain size, the no. of atoms associated with the grain boundaries and triple junctions become very large. The hardness, strength and deformation behaviour of nano crystalline materials is unique and not yet well understood.

Super plasticity is the capability of some polycrystalline materials to exhibit very large texture deformations without fracture. Super plasticity has been observed occurs at somewhat low temperatures and at higher strain rates in nano crystalline material.

4.8 APPLICATION OF NANOMATERIALS:

1. **Engineering:** i).Wear protection for tools and machines (anti blocking coatings, scratch resistant coatings on plastic parts). ii) Lubricant – free bearings.
2. **Electronic industry:** Data memory (MRAM,GMR-HD), Displays(OLED,FED), Laser diodes, Glass fibres
3. **Automotive industry:** Light weight construction, Painting (fillers, base coat, clear coat), Sensors, Coating for wind screen and car bodies.
4. **Construction:** Construction materials, Thermal insulation, Flame retardants.

5. **Chemical industry:** Fillers for painting systems, Coating systems based on nano Composites. Impregnation of papers, Magnetic Fluids.
6. **Medicine:** Drug delivery systems, Agents in cancer therapy, Anti microbial agents And coatings, Medical rapid tests Active agents.
7. **Energy:** Fuel cells, Solar cells, batteries, Capacitors.
8. **Cosmetics:** Sun protection, Skin creams, Tooth paste, Lipsticks.

Short Questions

1. What are nano materials?
2. Write about origin of nanotechnology.
3. Why do nanomaterials exhibit different properties?
4. Explain about surface area to volume ratio.
5. What is meant by quantum confinement?
6. Discuss about sol-gel technique.
7. Give the applications of nanotechnology.
8. Write the advantages of TEM.
9. What are the applications of XRD?

Long Questions

1. Explain the fabrication of nanoparticles by CVD method.
2. Explain the fabrication of nanoparticles by Sol-Gel.
3. Explain the fabrication of nanoparticles by PVD method.
4. Discuss about TEM technique to characterize nanoparticles.
5. Explain how SEM can be used to characterize nanoparticles.
6. Discuss about XRD technique to characterize nanoparticles

UNIT-V

Lasers and Fibre Optics

Introduction

Laser is a light source which amplifies intensity of light to produce highly directional, coherent and monochromatic beam of light. Lasers are now days used in different fields like medical, industrial, communication and military etc. The acronym (or) short form for LASER is "Light amplification by Stimulated Emission of Radiation" and laser is a specialized light source which is different from conventional light such as tube light (or) electric bulb.

5.1 Characteristics of Lasers:

Lasers when compared with conventional light, it possesses a few outstanding characteristics.

They are

(1) Laser is highly monochromatic

(2) Laser is highly directional

(3) Laser is highly coherent

(4) The intensity of laser is very high

Monochromaticity: The light emitted by a laser is more monochromatic than that of any conventional monochromatic source. The monochromaticity of a light source is measured by its degree of non-monochromaticity. For a good laser the degree of non-monochromaticity is of the order of 10^{-13} .where as the degree of non-monochromaticity for a conventional monochromatic light source is of the order 10^{-3} .Therefore by comparing these two values, it is clear that laser is highly monochromatic.

Directionality: Laser emits light in a single direction. The directionality of the laser beam is measured in terms of divergence, hence for getting high directionality there should be low divergence.

Coherence: The light rays emitting from the laser are in phase with each other, therefore the laser is highly coherent.

Intensity: Due to the concentration of energy over a small region laser beam becomes more intense. The intensity of a laser beam is measured in terms of number of photons emitted per unit area per sec.

The number of photons emitted by a good laser is in the range of 10^{22} to 10^{34} photons per m^2-sec.But the no.of photons emitted by any other light source is in the range of 10^{16} photons/ m^2-sec.So by comparision it is clear that laser is highly intense.

5.2 Interaction of Radiation with matter

Before knowing about spontaneous emission we need to know some fundamental concepts which are explained below:

Absorption:

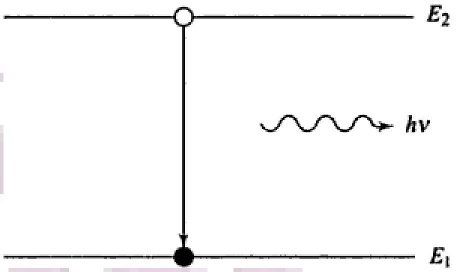
The process of absorption of energy when a particle transfers from it's ground state to higher energy state is called as absorption.

Life time:

The duration of time spent by an atom in the excited state is known as life time of that energy state.

Spontaneous Emission:

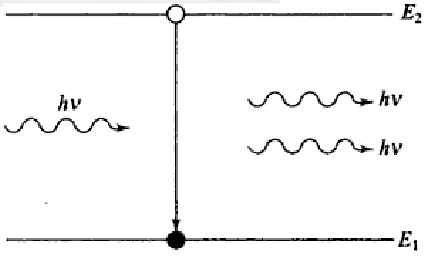
The emission of light photon after the lifetime without any inducement during the transition of atoms from higher energy level to lower energy level is called as spontaneous emission.



Here frequency of emitted photon, $\upsilon = \frac{E_2 - E_1}{h}$

The photons in this case have various wavelengths and they are out of phase. Therefore the photons are incoherent.

Stimulated Emission:



Emission of light photon by the inducement of a photon having energy equal to the emitted photon's energy or the energy difference between the transmission energy levels is called as stimulated emission.

In stimulated emission, the two emitted photons will have same energy and phase. So therefore they are coherent and they have single wavelength.

Metastable State:

The excited state which has long lifetime is known as metastable state.

5.3 Einstein's Coefficients or Einstein's relation

Einstein coefficients explain about the transmissions of electrons among the energy levels in terms of probability.

Absorption:

If we consider a two level energy system, the rate of probability to occur absorption process from energy level 1to energy level 2 depends on properties of energy level 1 and 2 and is proportional to incident energy density U(v) of the radiation of frequency υ incident on the atom.

$$\therefore \quad P_{12} \alpha U(v)$$

$$\Rightarrow \quad P_{12} = B_{12} U(v) \text{ ------------------------- >(1)}$$

Where B_{12} is proportionality constant represents properties of energy levels known as Einstien's coefficient of absorption.

Spontaneous Emission:

The rate of probability to occur spontaneous emission process from energy level 2 to energy level 1 depends only on the properties of energy levels 1 and 2.This process is independent of energy density $U(v)$.

$$\therefore \quad (P_{21})_{spontaneous} = A_{21} \text{ ----------------------- >(2)}$$

Where A_{21} is proportionality constant, represents properties of energy levels known as Einstein's coefficient of spontaneous emission.

Stimulated emission:

The rate of probability to occur stimulated emission process from energy level 2 to energy level 1 depends on properties of energy levels 1 and 2 as well as proportional to stimulated energy density $U(v)$ of frequency ϑ incident on the atom.

$$\therefore \quad (P_{21})_{stimulated} \propto U(v)$$

$$(P_{21})_{stimulated} = B_{12}U(v) \text{ ---------------------- >(3)}$$

Where B_{12} is proportionality constant, represents properties of energy levels known as Einstien's coefficient of Stimulated emission.

The total transition probability of atoms from energy level 2 to energy level 1 can be written as

$$P_{21} = (P_{21})_{spontaneous} + (P_{21})_{stimulated}$$

$$P_{21} = A_{21} + B_{12}U(v) \text{ ------------------ >(4)}$$

<u>Relation between Einstein Coefficients</u>:

Let us consider N_1 and N_2 be populations in the energy level 1 and 2 respectively in a system of atoms, which is at thermal equilibrium at a temperature T.

The no. of atoms that take transitions per unit volume from energy level 1 to energy level 2 in unit time can be written as

$$N_1P_{12} = N_1B_{12}U(v) \text{ -------------------------- >(5)}$$

The no. of atoms that take transitions per unit volume from energy level 2 to energy level 1 in unit time can be written a

$$N_2P_{21} = N_2[A_{21} + B_{12}U(v)] \text{ ---------------- >(6)}$$

At equilibrium, the no. of transitions from energy level 1 to energy level 2 will be equal to the no. of transitions from energy level 2 to energy level 1.

$$\therefore \quad N_1P_{12} = N_2P_{21} \text{ ---------------------- >(7)}$$

From eq^{n}s (5) & (6)

We have,

$$N_1B_{12}U(v) = N_2[A_{21} + B_{12}U(v)]$$

$$\Rightarrow \quad N_1B_{12}U(v) - N_2\,B_{12}U(v) = N_2A_{21}$$

$$\Rightarrow [N_1B_{12} - N_2\,B_{12}]\,B_{12}U(v) = N_2A_{21}$$

$$\Rightarrow \quad U(v) = \frac{N_2A_{21}}{N_1B_{12} - N_2\,B_{12}}$$

$$\Rightarrow U(v) = \frac{N_2A_{21}}{B_{21}\left[\frac{N_1}{N_2}\left(\frac{B_{12}}{B_{21}}\right) - 1\right]}$$

$$\Rightarrow \qquad U(v) = \frac{A_{21}}{B_{21}} \cdot \frac{1}{\left[\frac{N_1}{N_2}\left(\frac{B_{12}}{B_{21}}\right) - 1\right]} \text{ -------------- >(8)}$$

But we know that, according to Boltzmann's distribution law

$$N_1 = N_0 exp\left[\frac{-E_1}{k_B T}\right] \text{ ----------------- >(10)}$$

Where N_0 **is population in the ground state and** k_B is Boltzmann's constant

$$\frac{N_1}{N_2} = exp\left[\frac{E_2 - E_1}{k_B T}\right]$$

$$\frac{N_1}{N_2} = exp\left[\frac{h\vartheta}{k_B T}\right] \ (\because E_\downarrow 2 - E_\downarrow 1 = h\vartheta) \text{ ---------------- >(11)}$$

Substitute eq^n (11) in eq^n (8)

$$U(v) = \frac{A_{21}}{B_{21}} \frac{.1}{\left\{exp\left[\frac{h\vartheta}{k_B T}\right]\left(\frac{B_{12}}{B_{21}}\right) - 1\right\}} \text{ --------------------- >(12)}$$

But according to Planck's radiation law,

$$U(v) = \frac{8\pi h\vartheta^3}{C^3} \cdot \frac{1}{\left\{exp\left[\frac{h\vartheta}{k_B T}\right] - 1\right\}} \text{ ---------------- >(13)}$$

By comparing eq^n.s (12) & (13)

$$\left.\begin{array}{ll} \frac{A_{21}}{B_{21}} = \frac{8\pi h\vartheta^3}{C^3} & \frac{B_{12}}{B_{21}} = 1 \\ \frac{A_{21}}{B_{21}} \propto \vartheta^3 & B_{12} = B_{21} \end{array}\right\} \text{ ---------------- >(14)}$$

Eq^n (14) shows the relations between Einstein's coefficients B_{12}, B_{21} and A_{21} .

The first relation shows that the ratio of Einstein's coefficients of A_{21} and B_{21} is proportional to cube of the frequency of incident photon. The second relation shows the rate of probability of induced emission and absorption are equal when the system is in equilibrium.

5.4 Population inversion:

The no of atoms per unit volume in an energy level is known as population of that energy level.

If N is the no of atoms per unit volume in an energy state E then the expression for population can be written as

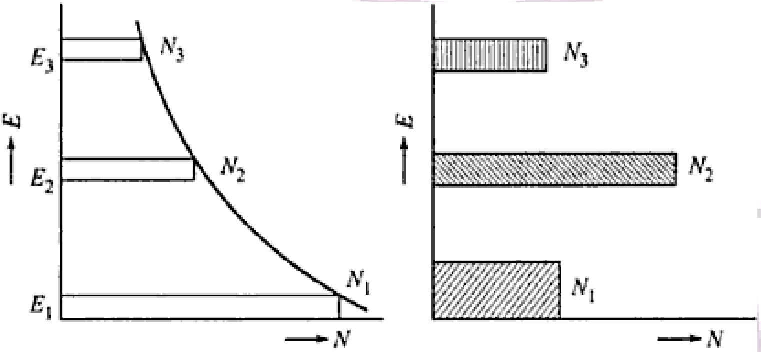
$$N = N_0 exp\left[\frac{E}{k_0 B}\right]$$

From the equation of population, population is maximum in the ground state and decreases exponentially as energy level increases.

So population inversion is a process in which the population of a particular higher energy state is made more populated than that of a lower energy state.

In order to understand the concept of population inversion consider three level system in which there are three energy levels E_1, E_2 and E_3 ,population in those energy levels are N_1, N_2 and N_3 respectively.In normal conditions $E_1 < E_2 < E_3$ and $N_1 > N_2 > N_3$.

We know that E_1 is the ground state and its lifetime is unlimited and E_3 is highest energy state and it is most unstable state and its lifetime is very less. Whereas E_2 is an excited state and has more lifetime compared to E_3 .Therefore here E_2 is metastable state.When some energy is supplied to the system, the atoms excite from ground state (E_1) to excited states (E_2 &$E_1$3) .Due to unstability, excited atoms will come back to ground state after the lifetime of the respective energy states E_2 and E_3 .If this process is continued then atoms will excite continuously to E_2 and E_3 .Because E_3 is the most unstable state,atoms will fall into E_2 immediately.At a particular point,the population in E_2 will become more than the population in ground state.



(a) Normal population of a system ($N_1 > N_2$)

(b) Inverted population of a system ($N_2 > N_1$)

Population of atoms

5.5 Block Diagram of a Laser System

The block diagram of a laser system contains three components. They are

(1) Source of energy
(2) Active medium
(3) Optical cavity

Source of Energy:

It supplies energy to the active medium to achieve population inversion i.e., it performs pumping process.

Active medium:

It is a place where the metastable state is achieved. In metastable state only the population inversion takes place. It can be a liquid, solid, gas or PN-junction.

Optical Cavity:

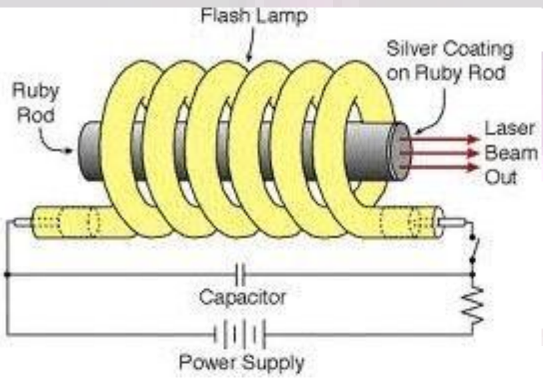
It is an enclosure of active medium and consists of two mirrors. Here one mirror is fully reflective and the other one is partially transparent. Due to mirrors arrangement emitted laser takes back and forth reflections until it gains sufficient energy to come out. The output laser beam is emitted from partially transparent mirror.

5.6 Laser systems

5.6.1 Ruby Laser

Ruby Laser is constructed by Maiman in 1960.It is a pulsed laser. The duration of each pulse is about 10 nanoseconds.

Construction: Ruby laser is made up of a cylindrical ruby crystal rod of composition Al_2O_3 which is doped with 0.05% of Cr_2O_3.The ends of the Ruby rod are silvered such that one end is fully reflecting and the other end is partially reflecting. A Xenon flash tube is arranged around the Ruby rod as shown in the below figure, which supplies flash light of wave length $5600A^0$ to the active medium to achieve population inversion.But here only a part of the flash light is used for pumping of chromium atoms while the rest heats up the apparatus. Therefore a cooling arrangement is provided to keep the experimental set up at normal temperature.



Therefore here,

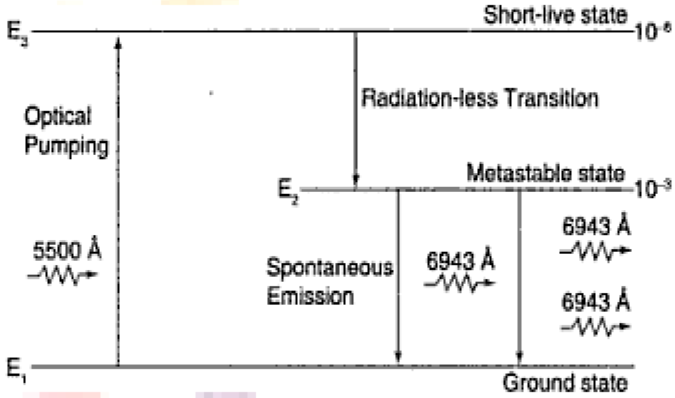
Source of Energy → Xenon flash light

Active medium → Ruby Crystal rod

Optical Cavity → Arrangement of Silver polished surfaces on either sides of Ruby rod

Working: In ruby crystal, chromium atoms are responsible for the population inversion. So here chromium atoms have three active energy levels, they are named as Ground state(G), Metastable state(M) and Higher energy state(H).Due to supply of Xenon flash light to Ruby rod, chromium atoms are excited to H energy state.

From higher energy state all of them do not return to the ground state , but some will return to state G and some will move to state M. Now here the transitions from level H to M are non-radiative i.e. the chromium atoms gives part of the energy to crystal lattice in the form of heat. The atoms which are present in this state M have a little chance to go to the ground energy state because it's lifetime is more. Due to continuous process of excitation of atoms to the higher levels, the population in state M will become more, at this stage, the transition occurs from M to G level emitting out photons. Now stimulated emission starts and photons are emitted in different directions. But only those photons will come out of the laser which travel parallel to the axis of the tube while the photons that travel in other directions will pass out of the Ruby. Now this photon beam which is parallel to the axis of the crystal rod grows in strength and comes through the partial reflector and serves as output laser beam. The wavelength of this beam is 6943A^{0}



Drawbacks:

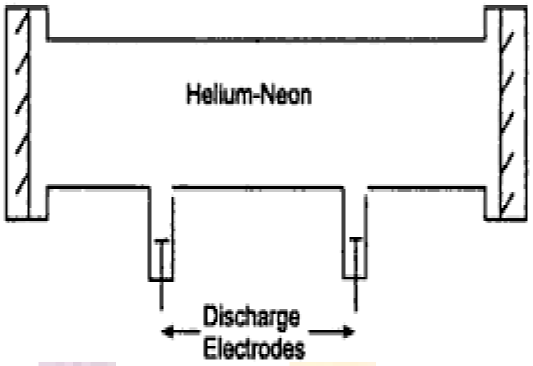
(1) Photons of 6943A^{0} are absorbed by the ground state atoms from the laser beam.

(2) The output laser beam is discontinuous.

5.6.2 He-Ne Laser

It is a gas laser and is a four level laser system. Here electric discharge is used as an efficient method for producing population inversion.

Construction: This laser system consists of a gas discharge tube and it is filled with a mixture of Neon (Ne) and Helium (He).The ratio of He-Ne mixture is about 10:1.The gas mixture of Helium and Neon forms the lasing medium and this mixture is enclosed between a set of parallel mirrors forming an optical cavity. One of the mirrors is completely reflecting and the other is partially reflecting in order to amplify the output laser beam.



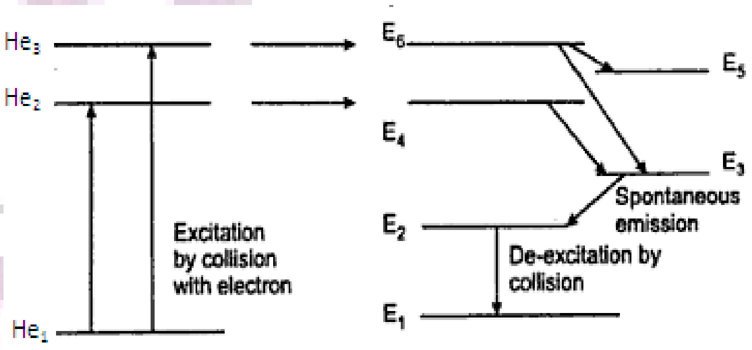
Therefore, here

Source of Energy → Discharge tube

Active medium → He-Ne gas mixture

Optical Cavity → arrangement of reflector

Working: In this laser, the lasing action is due to the Neon atoms. Here Helium atoms are used for pumping of Neon atoms to upper energy levels. When fast moving electrons collide with Helium atoms, then they are excited to the upper states.



Energy Level Diagram.

Here Helium atoms have three active energy levels He_1,He_2& He_3 and Neon atoms have six active energy levels Ne_1-------Ne_6.When He atoms collide with electrons they are excited to upper states He_2 and He_3.These are metastable states. So these atoms which are present in He_2 and He_3 states interact with neon atoms which are in the ground state. The interaction excite the neon atoms to their metastable states (Ne_4 and Ne_6).As the energy exchange continues, the population of neon atoms in the excited states increases more and more. So after reaching metastable state, stimulated emission starts emitting out photons and the excited neon atoms deexcite to the ground state in three different ways. They are

(1) Transition from Ne_6 level to Ne_5 level gives rise to radiation of wavelength $3.39\mu m$.

(2) Transition from Ne_6 level to Ne_3 level gives rise to visible radiation of wavelength $6328 A^{o}$ this lies in red region.

(3) The transition from Ne_4 level to Ne_3 level gives rise to a wavelength of 1.15 μm ,this again lies in infrared region.

The atoms in Ne_5 and Ne_3 level undergo spontaneous transitions to Ne_2 level, finally Ne atoms comes to ground state through collisions with the walls of the tube. This transition is radiationless. The gas lasers are found to emit light which is more directional and monochromatic. Gas lasers are capable of operation continuously without need of cooling.

5.6.4 Semiconductor laser

A semiconductor diode laser is a specifically made p-n junction diode that emits coherent light under forward bias. R.N. Hall and his coworkers made the first semiconductor laser in 1962. P-N junction lasers are emits light almost anywhere in the spectrum from UV to IR.

The laser diode (light amplification by stimulated emission of radiation) produces a monochromatic (single Color) light. Laser diodes in conjunction with photodiodes are used to retrieve date from-compact discs.

Diode lasers are remarkably small in size (0.1 mm long). They have high efficiency of the order of 40%. In spite of their small size and low power requirements, they produce power outputs equivalent to that of He-Ne lasers. Diode lasers are useful in optical fibre communications, in CD players, CD-ROM drives, optical reading and high speed laser printing etc wide.

Semiconductor Materials

vi) Semiconductors are two different groups, direct band gap semiconductors and indirect band gap semiconductors.

vii) Direct band gap semiconductors are formed by group III_V elements and group IV-VI elements. Most of the compound semiconductors belong to this group.

viii) Leasers are made using direct band gap semiconductors. Gallium Arsenide (GaAs) diode is an example of semiconductor diode laser.

ix) Direct band gap semiconductor is the one in which a conduction band electron can recombine directly with a hole in the valence band. The recombination process lead to emission of light.

Principle

i) The energy hand structure of a semiconductor consists of a valence band and a conduction band separated by an energy gap, E_g. The conduction band contains electrons and the valence band contains holes and electrons.

ii) When an electron from the conduction band jumps into a hole in the valence band, the excess energy E_g is given out in the form of a photon.

iii) Electron-hole recombination is the basic mechanism responsible for emission of light.

Iv) The wavelength of the light is given by the relation $\lambda = hc/E_g$.

x) Semiconductors having a suitable value of E_g emit light in the optical region.

Types of Semiconductor Diode Lasers

Broadly there are two types of semiconductor diode lasers. They are known as *homojunction semiconductor laser and heterojunction semiconductor lasers.*

Homojunction Semiconductor Laser
Heetrojunction Semiconductor Laser

Homojunction Semiconductor Laser

A Simple diode laser which makes use of the same semiconductor material on both sides of the junction is known as a homojunction diode laser. Example: Gallium arsenide (GaAs) laser.

Construction: Fig. shows the schematic of a homojuncation diode laser. Starting with a heavily doped n-type GaAs material, a p-region is formed on its top by diffusing zinc atoms into it. A heavily zinc doped layer constitutes the heavily doped p-region.

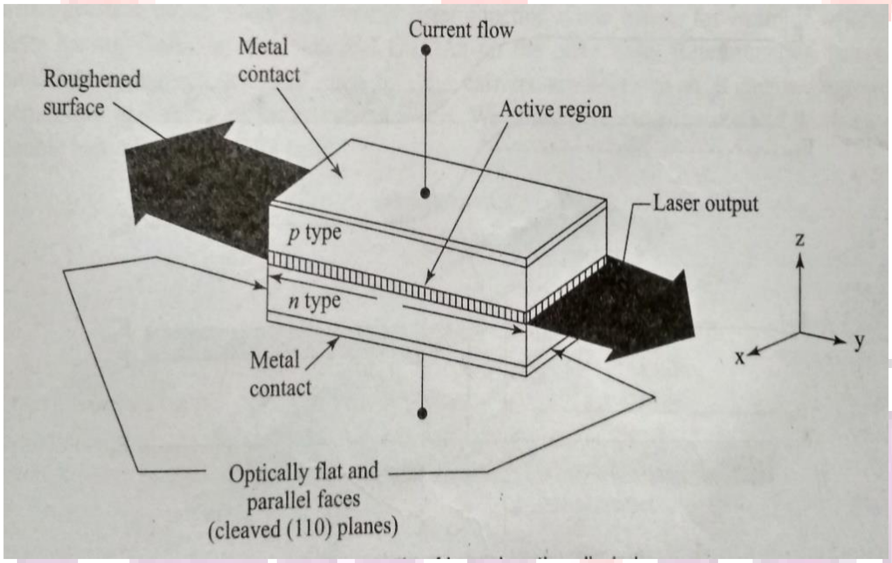


Fig: Homojunction diode laser

The diode is extremely small in size. Typical diode chips are 500 μm long and about 100 μm wide and thick. The top and bottom faces are metalized and metal contacts are provided to pass current through the diode. A pair of parallel planes cleaved at the two ends of the PN junction provides required reflection to from the cavity. The two remaining sides of the diode are roughened to remove lasing action in that direction. The entire structure is packaged in small case which looks like the metal case used for discrete transistors.

Working:

i) Heavily doped p- and n- regions are used. Because of very high doping on n-side, the donor levels are broadened and extend into the conduction band.

ii) The Fermi level is pushed into the conduction band and electrons occupy the levels lying below the Fermi level.

v) Similarly, on the heavily doped p-side the Fermi level lies within the valence band and holes occupy the portion of the valence band that lies above the Fermi Level.

vi) At thermal equilibrium, the Fermi level is uniform across the junction.

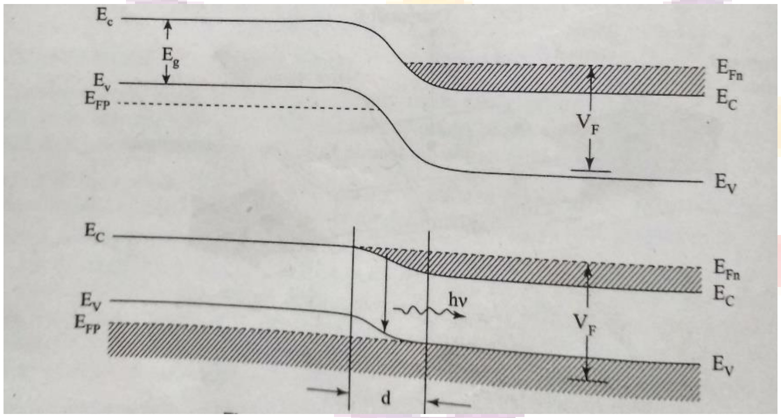


Fig. Laser diode under forward bias

Pumping Mechanism

i) When the junction is forward-biased, electrons and holes are injected into the junction region in high concentrations.

ii) When the diode current reaches a threshold value (see Fig.) , the carrier concentration in the junction region will rise to a very high value.

Population inversion

i) The region d as shown in Fig. contains a large concentration of electrons within the conduction band and simultaneously a large number of holes within the valence band.

ii) The upper energy levels in the narrow region are having a high electron population while the lower energy levels in the same region are vacant. It creates the condition of population inversion and is called an inversion region or active region.

Lasing action

i) Chance recombination leads to emission of spontaneous photons which stimulate the conduction electrons to jump into the vacant states of valence band.

ii) This stimulated electron-hole recombination produces coherent radiation.

iii) GaAs laser emits light at a wavelength of 9000 A in IR region.

Drawbacks of homojunction lasers

i) The active region is not well defined due to the diffusion length of the carriers.

ii) The semiconductor has nearly uniform refractive index throughout. Therefore, light can diffuse from active layer into the surrounding medium. As a result the cavity losses increase.

iii) High threshold currents are required and the laser cannot be operated continuously at room temperature.

5.6.5 CO2 Molecular gas laser

It was the first molecular gas laser developed by Indian born American scientist Prof.C.K.N.Pillai.

It is a four level laser and it operates at 10.6 μm in the far IR region. It is a very efficient laser.

Energy states of CO2 molecules.

A carbon dioxide molecule has a carbon atom at the center with two oxygen atoms attached, one at both sides. Such a molecule exhibits three independent modes of vibrations. They are

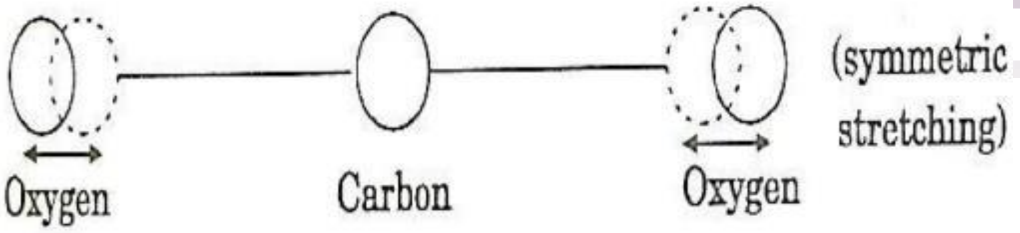
a) Symmetric stretching mode.

b) Bending mode

c) Asymmetric stretching mode.

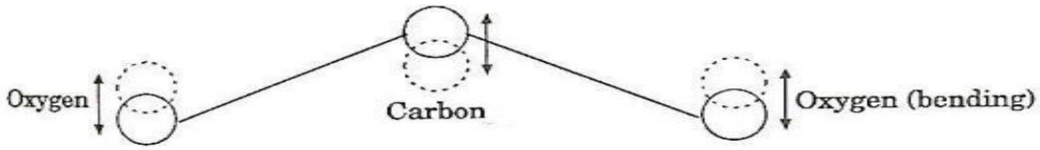
a. **Symmetric stretching mode**

In this mode of vibration, carbon atoms are at rest and both oxygen atoms vibrate simultaneously along the axis of the molecule departing or approaching the fixed carbon atoms.

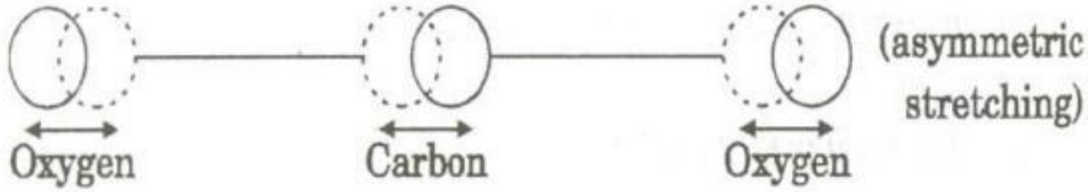


b. **Bending mode:**

In this mode of vibration, oxygen atoms and carbon atoms vibrate perpendicular to molecular axis.



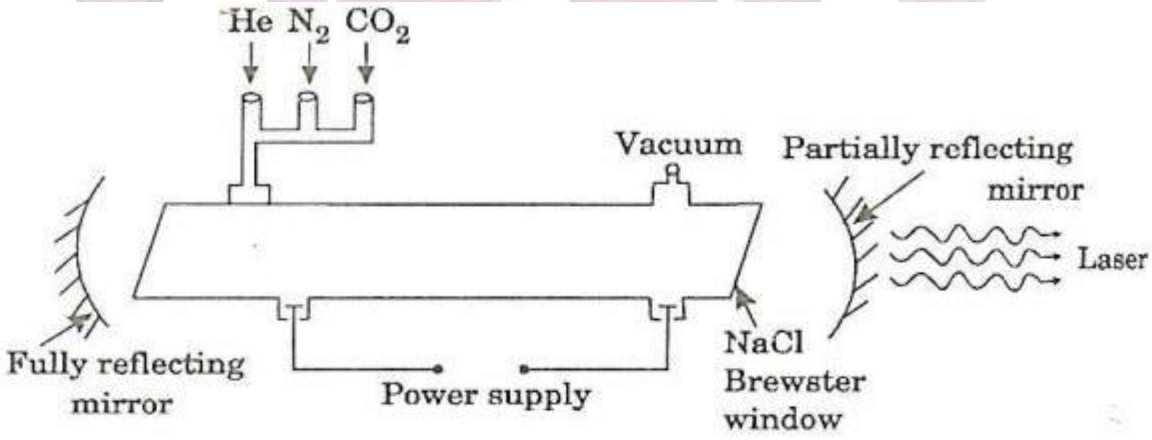
c. **Asymmetric stretching mode**:



In this mode of vibration, oxygen atoms and carbon atoms vibrate asymmetrically, i.e., oxygen atoms move in one direction while carbon atoms in the other direction.

Principle:

The active medium is a gas mixture of CO2, N2 and He. The laser transition takes place between the vibrational states of CO2molecules.



Construction:

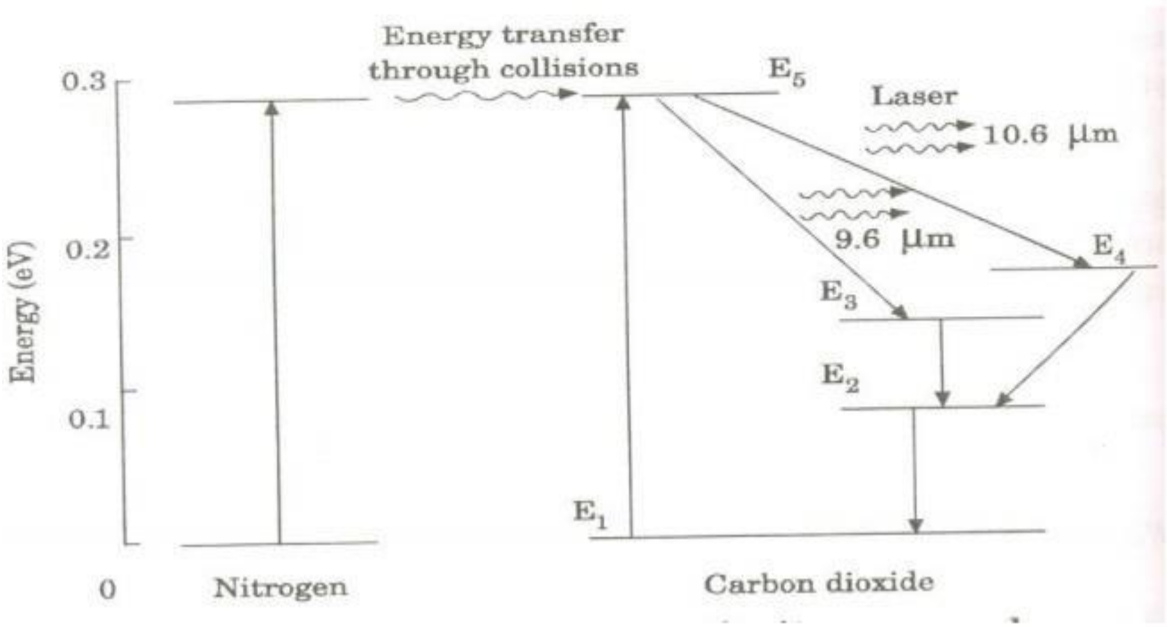
It consists of a quartz tube 5 m long and 2.5 cm in the diameter. This discharge tube is filled with gaseous mixture of CO2(active medium), helium and nitrogen with suitable partial pressures.

The terminals of the discharge tubes are connected to a D.C power supply. The ends of the discharge tube are fitted with NaCl Brewster windows so that the laser light generated will be polarized.

Two concave mirrors one fully reflecting and the other partially form an optical resonator.

Working:

Figure shows energy levels of nitrogen and carbon dioxide molecules.



When an electric discharge occurs in the gas, the electrons collide with nitrogen molecules and they are raised to excited states. This process is represented by the equation

N2 + e* = N2* + e

N2 = Nitrogen molecule in ground state e* = electron with kinetic energy
N2* = nitrogen molecule in excited state e= same electron with lesser energy
Now N2 molecules in the excited state collide with CO2 atoms in ground state and excite to higher electronic, vibrational and rotational levels.
This process is represented by the equation N2* + CO2 = CO2* + N2

N2* = Nitrogen molecule in excited state. CO2 = Carbon dioxide atoms in ground state CO2* = Carbon dioxide atoms in excited state N2 = Nitrogen molecule in ground state.

Since the excited level of nitrogen is very close to the E5 level of CO2 atom, population in E5 level increases.

As soon as population inversion is reached, any of the spontaneously emitted photon will trigger laser action in the tube. There are two types of laser transition possible.

1. Transition E5 to E4 :

This will produce a laser beam of wavelength 10.6μm

2. Transition E5 to E3

This transition will produce a laser beam of wavelength 9.6μm. Normally 10.6μm transition is more intense than 9.6μm transition. The power output from this laser is 10kW.

Characteristics:

1. Type: It is a molecular gas laser.
2. Active medium: A mixture of CO2 , N2 and helium or water vapour is used as active medium
3. Pumping method: Electrical discharge method is used for Pumping action
4. Optical resonator: Two concave mirrors form a resonant cavity
5. Power output: The power output from this laser is about 10kW.
6. Nature of output: The nature of output may be continuous wave or pulsed wave.
7. Wavelength of output: The wavelength of output is 0.6μm and 10.6μm.

Advantages:

1. The construction of CO2 laser is simple
2. The output of this laser is continuous.
3. It has high efficiency
4. It has very high output power.
5. The output power can be increased by extending the length of the gas tube.

Disadvantages:

1. The contamination of oxygen by carbon monoxide will have some effect on laser action
2. The operating temperature plays an important role in determining the output power of laser.
3. The corrosion may occur at the reflecting plates.
4. Accidental exposure may damage our eyes, since it is invisible (infra red region) to our eyes.

Applications:

1. High power CO2 laser finds applications in material processing, welding, drilling, cutting soldering etc.
2. The low atmospheric attenuation (10.6µm makes CO2 laser suitable for open air communication.
3. It is used for remote sensing
4. It is used for treatment of liver and lung diseases.
5. It is mostly used in neuro surgery and general surgery.
6. It is used to perform microsurgery and bloodless operations.

5.7 Applications of Lasers

Lasers are widely used in the fields of

(1)Communication

(2)Computers

(3)Industry

(4)Scientific Research

(5)Military Operation

(6)Medicine

Lasers in Communication:

(1) In case of optical fiber communication, semiconductor laser diodes are used as optical sources and it's band width is very high compared to the radio and microwave communications.

(2) Laser is highly directional and has less divergence, hence it has greater potential use in space crafts and submarines.

(3) Lasers are also used in other communication devices, including high speed photo copiers and printers.

Lasers in Computers:

(1) In local area network (LAN), data can be transferred or transmitted from the memory storage of one computer to other computer using laser for short time.

(2) Lasers are used in CD-Rom's during recording and reading the data.

Lasers in industry:

(1) Lasers can be used to make holes in diamonds and hard steel.

(2) Lasers are used to cut teeth saws, drill eyes in surgical needles, guide bulldozers and test the quality of a fabric.

(3) They are used as a source of intense heat.

(4) Lasers range finder is used to measure distance to make map by surveyors.

(5) Lasers can cut, drill, weld, remove metal from surfaces and perform these operations even at surfaces inaccessible by mechanical methods.

Lasers in Scientific Research:

(1) Scientists are working on separating isotopes of uranium using laser.

(2) Lasers are used in the field of 3D-photography called holography.

(3) Lasers are used to produce certain chemical reactions.

(4) Using lasers, the internal structure of microorganisms and cells are studied very accurately.

(5) The laser has been used in Michelson-Morle experiment, which showed that the velocity of light was constant and thus showed the way for Einstein's theory of relativity.

Lasers in Military Applications:

(1) High energy lasers are used to destroy enemy air crafts and missiles.

(2) Lasers can serve as a war weapon.

(3) Laser can be used for detection and ranging like RADAR. The only difference is it uses light instead of radio waves. Hence it is called as Light Detecting and Ranging(LIDAR).

Lasers in medicine:

(1) Doctors use the heating action of a laser beam to remove diseased body tissue.

(2) Laser beam is used to correct a condition called retinal detachment by eye-specialist.

(3) Lasers are used in opening blocked arteries, reconnecting several nerves, removing warts and treating bleeding ulcers.

(4) Argon and CO_2 lasers are used in treatment of liver and lungs.

(5) Lasers are used for elimination of moles and tumors which are developing in the skin tissue.

Fiber Optics

Introduction:

The optical fiber is a cylindrical wave-guide system through which optical signals can be transmitted over long distances. It is playing an important role in the field of communication to transmit voice, television and digital data signals from one place to another. Fiber optics is important because they have

(1) High information carrying capacity.

(2) Light in weight and small in size.

(3) No possibility of internal noise and cross talk generation.

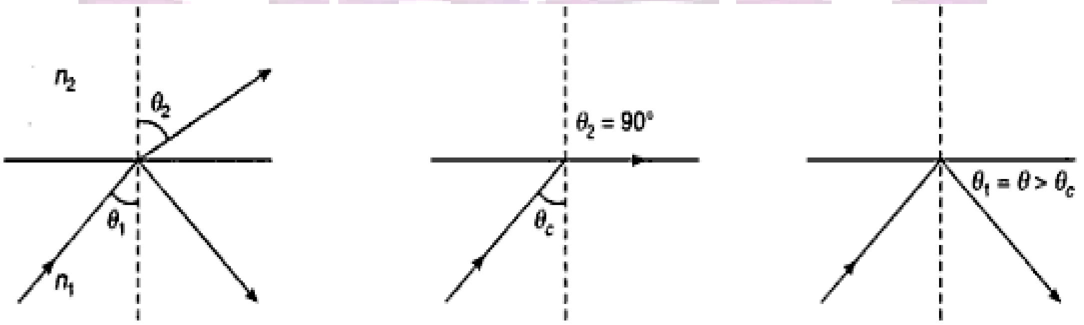
(4) No possibility of short circuits.

(5) Low cost of cables.

5.8 Principle of Optical Fiber

Total Internal Reflection:

The transmission of light in an optical fiber is based on the phenomenon of total internal reflection. According to total internal reflection, when a ray of light travels from a denser medium into a rarer medium and if the angle of incidence is greater than the critical angle then the light gets totally reflected. That is if the light ray is incident at an angle greater than the critical angle for the two media, the ray is totally reflected back into the medium by obeying the laws of reflection. This phenomenon is known as total internal reflection.



(a) Some part of the incident beam is transmitted through n_2, when $\theta_1 < \theta_c$

(b) Refracted ray passes through the core-cladding interface, when $\theta_1 = \theta_c$

(c) Total internal reflection occurs when $\theta_1 > \theta_c$

So according to law of reflection,

$$n_1 sin\theta_1 = n_2 sin\theta_2$$

Here, $\theta_1 = \theta_c \quad , \theta_c \; = 90^0$

$$\therefore n_1 sin\theta_c = n_2 \sin 90^0$$

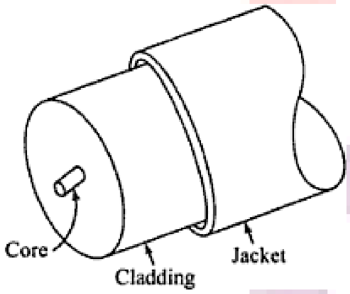
$$\Rightarrow \qquad sin\theta_c = \frac{n_2}{n_1}$$

$$\Rightarrow \qquad \theta_c = sin^{-1}\left(\frac{n_2}{n_1}\right) \text{ ---------------- >(I)}$$

Here eq^n. (I) is the condition for total internal reflection.

5.9 Construction of Optical Fiber

Optical fiber is a very thin and flexible medium having a cylindrical shape consisting of three sections. They are



(1) The core material

(2) The cladding material

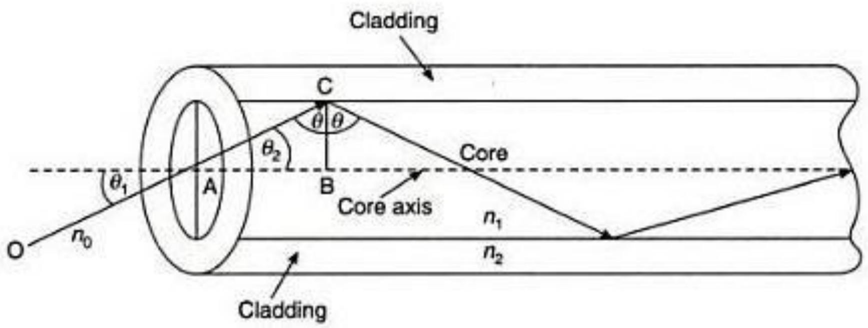
(3) The outer protective jacket

The fiber has a core surrounded by a cladding material. The refractive index is slightly less than that of core material, to satisfy the condition of total internal reflection. To protect the fiber material and also to give mechanical support there is a protective cover called as outer jacket.

5.10 Acceptance angle and Numerical Aperture

Acceptance angle:

Acceptance angle is defined as the angle at which we have to launch the light beam at one end of the fiber optic cable so that the entire light is propagated through the core.



Now in order to calculate an expression for the acceptance angle, consider the above figure which shows a cross section of a fiber with a light ray entering it. The light ray entered from a medium of refractive index n_o into core of refractive index n_1 .Here the ray (OA) enters with an angle of incidence α_i i.e,the incident ray makes an angle α_i with fiber axis.Let the refractive index of core be n_1 and the refractive index of cladding be n_2 .Here $n_1 > n_2$ and the light ray refracts at an angle α_r and strikes the core-cladding interface at angle θ .If the angle is greater than it's critical angle θ_c ,the light ray undergoes total internal reflection at the interface.

∴ According to Snell's Law, $n_o sin\alpha_i = n_1 sin\alpha_r$ ---------------- >(1)

From the right angled triangle ABC,

$$\alpha_r + \theta = 90^0$$

$$\Rightarrow \quad \alpha_r = 90^0 - \theta \quad \text{---------------- >(2)}$$

Substitute (2) in (1)

$$\Rightarrow \quad n_o sin\alpha_i = n_1 \sin(90^0 - \theta)$$

$$\Rightarrow \quad sin\alpha_i = \frac{n_1}{n_0} cos\theta \quad \text{- - - - - - - - - >(3)}$$

When $\theta = \theta_c$, $\alpha_i = \alpha_m$ (maximum α value) i.e, maximum possible value of α_i for which $\theta = \theta_c$

$$\therefore \quad sin\alpha_m = \frac{n_1}{n_0} \cos\theta_c \quad \text{------------------ >(4)}$$

From eq^n of total internal reflection,

$$\Rightarrow \quad \sin\theta_c = \frac{n_2}{n_1}$$

$$\Rightarrow \quad \cos\theta_c = \sqrt{1 - sin^2\theta_c}$$

$$= \sqrt{1-\left({}^{n_2}/_{n_1}\right)^2}$$

$$= \frac{\sqrt{n_1^2-n_2^2}}{n_1} \quad \text{------------------------} >(5)$$

From eq^{n}s. (4) & (5)

$$\sin\alpha_m = \frac{\sqrt{n_1^2-n_2^2}}{n_1} \cdot \frac{n_1}{n_0} = \frac{\sqrt{n_1^2-n_2^2}}{n_0}$$

For air $n_0 = 1$

$$\therefore \quad \sin\alpha_m = \sqrt{n_1^2-n_2^2}$$

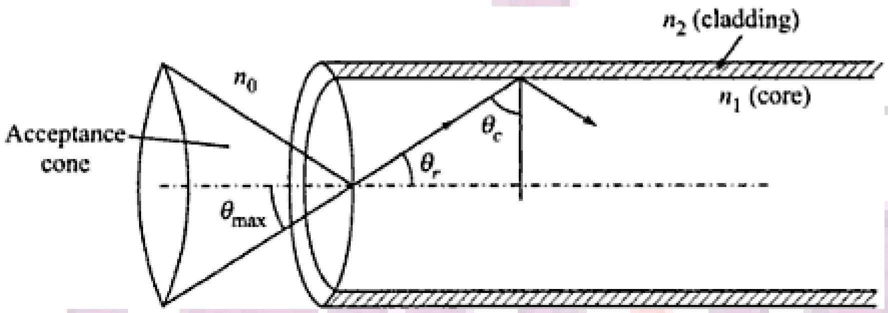
$$\Rightarrow \quad \alpha_m = \sin^{-1}\sqrt{n_1^2-n_2^2} \quad \text{------------------------} >(6)$$

Here the angle α_m is called the acceptance angle.

Acceptance Cone:

It is the cone of light incident at the entrance end of the fiber which will be guided through the fiber, provided the semi vertical angle of the cone is less than or equal to α_m.

Diagrammatically it is shown in the below figure:



Numerical Aperture:

It is defined as the light gathering capacity of an optical fiber and is proportional to acceptance angle. Numerically it is equal to sine of acceptance angle.

Numerical Aperture, NA= $\sin\alpha_m = \dfrac{\sqrt{n_1^2-n_2^2}}{n_0}$

If the medium is air, then $n_0 = 1$

$$\therefore \quad NA = \sqrt{n_1^2 - n_2^2}$$

$$= \sqrt{(n_1 + n_2)(n_1 - n_2)}$$

$$= \sqrt{(n_1 + n_2) n_1 \Delta}$$

Where $\Delta = \frac{(n_1 - n_2)}{n_1}$ called as fractional difference in refractive indices n_1 and n_2

For most of the fibers $n_1 \approx n_2$

So we can take $n_1 + n_2 = 2n_1$

$$\therefore \quad NA = \sqrt{2n_1^2\Delta} = n_1\sqrt{2\Delta}$$

Therefore the numerical aperture is a measure of the amount of light that can be accepted by a fiber. It depends only on the refractive indices of core and cladding materials and is independent of fiber dimensions and generally this value ranges from 0.1 to 0.5.

5.11 Classification of fibers:

Depending upon the refractive index profile of the core, optical fibers are classified into two categories, they are

(1) Step-index fibers

(2) Graded-index fibers

Step-index fibers:

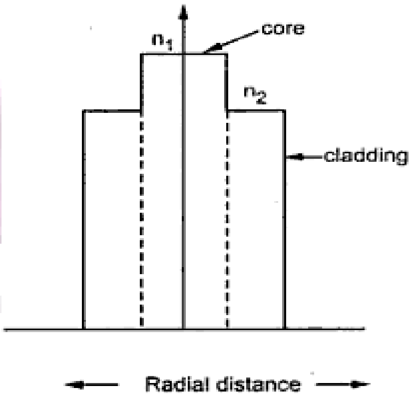
In step-index fibers, the refractive index of the core medium is uniform through out and undergoes a sudden change at the interface of core and cladding medium.

There are two types of step-index fibers, they are

(1) Single-mode step index fibers

(2) Multi-mode step index fibers

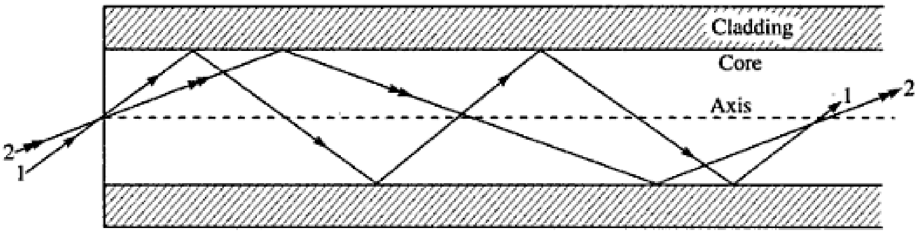
The diameter of the core for a single mode step index fiber is very small of the order



10µm and it propagates the light in only one mode, whereas the diameter of the core for a multimode fiber is of the order 50-200 μm , and it propagates the light in multiple modes.

Transmission of signal in step-index fibers:

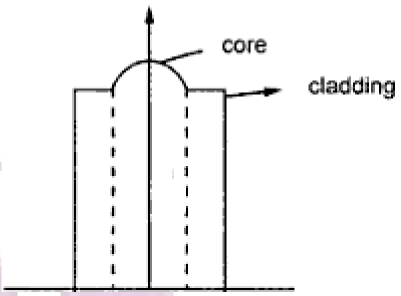
In digital communication systems, information is transmitted in the form of pulses. Light pulses transmitted through the fiber are to be decoded at the receiving end to receive the information.



Two rays entering a step-index fibre at different angles.

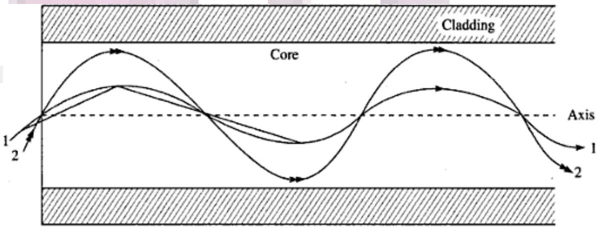
As shown in the above figure, there are three such pulses travelling through the fiber striking the core-cladding interface at different angles and they travel along the fiber by multiple reflections. They have different paths and reach the other end of the fiber at different points i.e., the three rays reach the received end at different times. The pulsed signal received at the other end will be broadened and this is called intermodal dispersion. This reduces the transmission rate and capacity. So smaller the pulse dispersion greater will be the information transmission capacity of the system.

Graded-index fibers: In graded-index fibers, the refractive index of the core medium is made to vary in a parabolic manner such that the maximum refractive index is present at the centre of the core. The diameter of the core is about 50 μm , therefore only multimode propagation is possible in graded index fibers.



Transmission of signal in Graded-index fiber:

In graded index fibers, optical signals travel through core medium in the form of skew rays or helical rays. As shown in the below figure, though different rays travel through the fiber but all come to focus at the same point i.e., all the rays arrive at the other end of the fiber at the same time. This is possible because the velocity is inversely proportional to refractive index.



Two rays entering a GRIN fibre at different angles.

5.12 Attenuation in Optical fibers

Different mechanisms are responsible for the signal attenuation of the fiber and these mechanisms are influenced by material compositions, purification level, wave guide structure.

The attenuation of signal is measured in decibel/km. Signal attenuation is defined as the ratio of the input optical power P_i into the fiber to the output received optical power P_o from the fiber.then the attenuation coefficient of the signal per unit length is given as

$$\alpha = \frac{\frac{10}{L}\log P_i}{P_o}\frac{db}{km}$$

Where $L \rightarrow$ length of fiber

The mechanism of attenuation of signal may be classified broadly into two categories, they are

(1)Absorption losses

(2)Scattering losses

Absorption losses:

It is a material property i.e., it is a characteristic possessed by all the materials. Every material in the universe absorbs few suitable wavelengths as they incident on the material or passed through the material. In the same way core material of a fiber absorbs few wavelengths as the optical pulses or wavelengths pass though it.

Scattering losses:

The core medium of fibers is made of glass or Silica crystalline materials. Since there is no ideal crystal in the Universe, this medium possess few crystal defects. So in the passage of optical signals in the core medium if crystal defects are encountered, they deviate from the path and the total internal reflection is discontinued. Hence such signals will be destroyed by entering into the cladding.

Bending Losses:

The distortion of the fiber from the ideal straight line configuration may also result in losses in fibers. Tight bands cause some of the light to not to be internally reflected but to propagate into the cladding and be lost. The optical power scattered out of fiber at a major bends depends exponentially on the bend radius(R).The loss coefficient can be represented as

$$\alpha_B = C\ exp\left(-\frac{R}{R_c}\right)$$

Where ‘C’ is a constant and $R_c = \frac{a}{(NA)^2}$

Where ‘a’ is the radius of fiber.

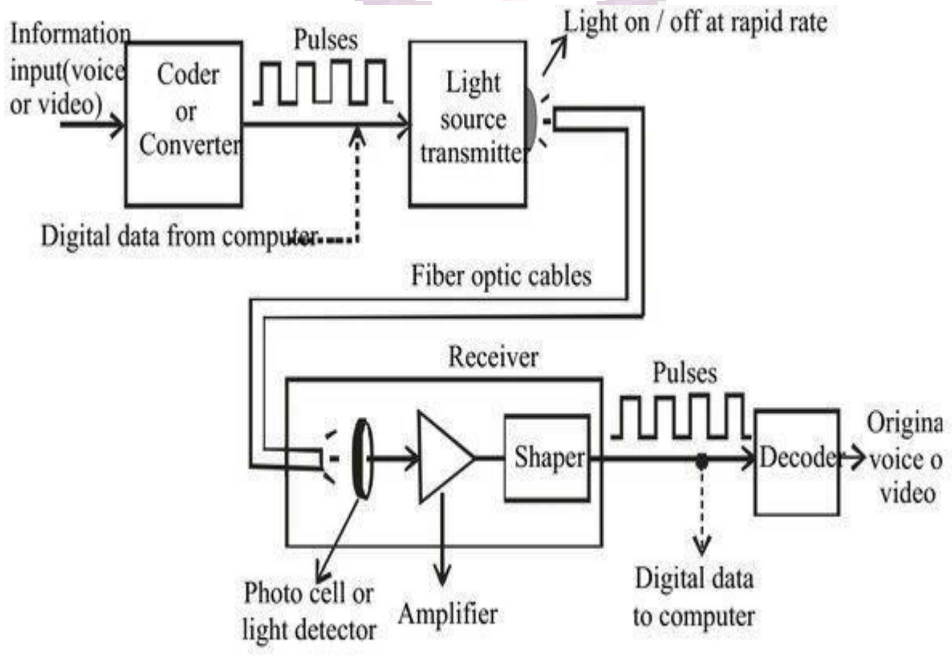
Micro bending and Waveguide losses:

In fiber optical cables a continuous succession of very small bends may cause a very significant rise in fiber attenuation. This effect is known as micro bending loss. Continuous small variation in core diameter or circularity which can easily arise during manufacture if sufficient care is not taken, gives rise to a similar scattering mechanism and cases losses which are called as wave guide losses.

By taking proper precaution all these losses can be minimized and they are largely wavelength independent.

5.13 Optical Fiber Communications

The communication system of fiber optics is well understood by studying the parts and sections of it. The major elements of an optical fiber communication system are shown in the following figure.



Itessentially consists of following parts.

1.Encoder 2.Transmitter 3.Waveguide 4.Receiver 5.Decoder

Encoder: It converts electric signal corresponding to analog information such as voice, figures, objects etc into a binary data This binary data comes out in the form of stream of electrical pulses.

Transmitter: It mainly consists of drive circuit and a light source Drive circuit supplies the

electric pulses to the light source from the encoder LED or diode laser is used as light source and it converts electrical signals are infected into optical signals These optical signals are injected into wave guide.

Wave Guide: It carries the information through the desired distance in the form of optical signal.

Receiver: It consists of photo detector, amplifier, signal restorer

Photo Detector: It converts optical signal into electrical signal This signal may become weak since it travels through very long distance

Amplifier: Such weak signal from photo detector is amplified This is allowed into signal restorer

Signal Restorer: The function of signal restorer is to put the signals In order which are received from wave guide subsequently from photo detector

Decoder: Finally, signals will be decoded and sent in the original form

5.14 Applications of Optical Fiber

Fiber optic cables find many uses in a wide variety of industries and applications. Some uses of fiber optic cables include:

- **Medical**

Used as light guides, imaging tools and also as lasers for surgeries

- **Defense/Government**

Used as hydrophones for seismic waves and SONAR , as wiring in aircraft, submarines and other vehicles and also for field networking

- **Data Storage**

Used for data transmission

- **Telecommunications**

Fiber is laid and used for transmitting and receiving purposes

- **Networking**

Used to connect users and servers in a variety of network settings and help increase the speed and accuracy of data transmission

- **Industrial/Commercial**

Used for imaging in hard to reach areas, as wiring where EMI is an issue, as sensory devices to make temperature, pressure and other measurements, and as wiring in automobiles and in industrial settings

- Broadcast/CATV

Broadcast/cable companies are using fiber optic cables for wiring CATV, HDTV, internet, video on-demand and other applications

Short Questions

1. What is LASER? Explain the characteristics of LASER's.
2. Explain the phenomenon of Absorption, Spontaneous emission and stimulated emission.
3. Explain different pumping mechanisms in laser.
4. Explain working principle of laser.
5. What are the main components of laser.
6. What is population and population inversion?
7. What is optical fiber? Explain the principle of optical fibres.
8. Explain construction of optical fibre.
9. What are step index and graded index optical fibres?
10. What are single mode and multi mode optical fibres?
11. Explain the Attenuation in Optical Fibers
12. What are radiative and nonradiative recombinationmechanism?
13. Write short note on solar cell.
14. Explain construction and working of LED.
15. Write the applications of solar cell

Essay type Questions

1. What are Einstein's coefficients of radiation? Give Einstein relation of radiation.
2. Describe the construction and working principle of ruby laser.
3. Describe the construction and working principle of He-Ne laser.
4. Describe the construction and working principle of CO2 laser.
5. Explain in detail acceptance angle, acceptance cone and numerical aperture of optical fibre.
6. Classify and explain different types of optical fibres with neat light ray diagrams.
7. Explain the applications of optical fibres.
8. Explain construction and working of semiconductor laser.
9. Explain PIN diode in detail.
10. Discuss avalanche photo diode in detail.

Multiple answer questions

1. The wavelength emitted by He-Ne laser is [ ]

(A) 623.8 nm (B) 632.8 nm (C) 682.3 nm (D) 683.2 nm

2. If N_1 and N_2 are the population densities of lower energy state E_1 and higher energy state E_2 respectively, the laser emission is possible only when [ ]

(A) $N_2 > N_1$ (B) $N_2 < N_1$ (C) $N_2 = N_1$ (D) no relation between N_1 and N_2

3. Brewster law is [ ]

A) $\mu = \tan\theta_p$ C) $\mu > \tan\theta_p$
B) $\mu < \tan\theta_p$ D) None of these

4. The active element in ________________laser is chromium. [ ]

A) ruby B) He-Ne C) Co2 D) Semi conductor

5. Propagation of light through fiber core is because of _______________. [ ]

A) Reflection B) refraction C) Total internal reflection D) None

6. The condition for lasing action is [ ]

(A) Excitation (B) meta-stable state(C) population inversion (D) emission

7. In the absence of degeneracy, Einstein coefficients B_{12} and B_{21} are related as [ ]

(A) $B_{12} / B_{21} = h$ (B) $B_{12} = B_{21}$

(C) B_{12} / B_{21} = constant (D) $B_{21} / B_{12} = h$

8. The refractive index of core is 1.5. The refractive index of cladding can be [ ]
(A) 1.52 (B) 1.55 (C) 1.60 (D) 1.45

9. In an optical fibre, meridinal rays propagate [ ]
(A) along the walls of the fiber (B) along the axis of the fiber

(C) into the cladding material (D) along the cladding of the fiber

10. The active medium in He-Ne laser is ______________ [ ]
A) Ne B) Cr C) GaAs D) None of these
11. In semiconductor laser, the population inversion is achieved by heavily doped [ ]
A) Ne B) Cr C) GaAs D) None of these
12. The acceptance angle of an optical fibre having numerical aperture 0.5, is_ [ ]
A) 30^0 B) 60^0 C) 90^0 D) None
13. The ratio of Einstein's coefficient A_{21}/ B_{21} [ ]

a) $\frac{8\pi h\nu 3}{c3}$ b) $\frac{8\pi h\nu 3}{c2}$ c) $\frac{8\pi h\nu 3}{c}$ d) $\frac{2\pi h\nu 3}{c}$

14.The source of excitation in ruby laser is [ ]

a) Sodium vapor lamp b) Xenon flash lamp c) Mercury vapor lamp

d) Incandescent lamp

15.The attenuation in an optical fiber is a function of [ ]

a) Fiber material only b) Wavelength of light only

c) Length of the fiber only d) All the above

16. ___________Laser is used in optical communications [ ]

A) Ruby B) He-Ne C) Co2 D) Semi conductor

17. The population of the various energy levels of a system in thermal equilibrium is given by [ ]

(a) Boltzmann distribution law (b) Einstein relations

(c) Planck's law (d) Beer's law

18 . T.Maiman invented [ ]

(a) He-Ne laser (b) CO2 laser

(c) Ruby laser (d) Nd: YAG laser

19. The colour of the laser output from a Ruby laser is [ ]

(a) green (b) blue (c) red (d) violet

20.. In He-Ne lasers, the ratio of He-Ne is in the order [ ]

(a) 1:10 (b) 1:1 (c) 100:1 (d) 10:1

21 Laser radiation is [ ]

(a) monochromatic (b) highly directional

(c) coherent and stimulated (d) All

22. Propagation of light through fiber core is due to [ ]

(a) diffraction (b) interference (c) refraction

(d) total internal reflection

23. Step index fiber can be a [ ]

(a) monomode fiber only b) multimode fiber only

(c) monomode as well as multimode fiber

(d) either monomode or multimode

24. The process of mixing the signal with the carrier is called [ ]

(a) dispersion (b) attenuation (c) modulation

(d) demodulation

25. To overcome the problem of inter model dispersion one has to use [ ]

(a) multimode fiber (b) step index fiber

(c) graded index fiber (d) plastic fiber