APPLIED PHYSICS MATERIAL

GOKARAJU RANGARAJU INSTITUTE OF ENGINEERING AND TECHNOLOGY

(Autonomous)

Bachupally, Hyderabad – 500090

Preface

The main objective of the material entitled "**Applied Physics**" is to make the I B. Tech (CSE(AIML), CSE(DS), CSE, ECE, EEE & IT) students familiar with the basic concepts of physics in a more systematic manner. This material is written according to **GRIET (Autonomous)** syllabus. This book has been prepared to meet the requirements of Applied Physics course as per new AICTE Regulations.

This book is written and verified by the faculty of Department of Physics.

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Gokaraju Rangaraju Institute of Engineering and Technology (Autonomous)

GR20A1003: Applied Physics

(Common to CSE(AIML), CSE(DS), CSE, ECE, EEE & IT)

Syllabus

B. Tech. I Year **L: 3 T: 1 P: 0 C: 4**

Course Objectives:

1. Understand the dualistic nature of radiation and matter waves with experimental validation.
2. Outline the properties of semiconductor materials for specific applications.
3. Develop basic understanding of optoelectronic devices.
4. Discuss the use of lasers as light sources in optical fiber applications.
5. Study the properties of dielectric, magnetic and superconducting materials for various applications.

Course Outcomes:

1. Solve engineering problems involving quantum nature of radiation and matter waves.
2. Comprehend the characteristics of semiconductor devices such as transistors and diodes.
3. Familiarize with operation of optoelectronic devices and its applications.
4. Analyze the properties of Laser and its propagation in different types of optical fibers.
5. Identify dielectric, magnetic and superconducting materials based on their properties for specific applications.

UNIT I

Quantum Mechanics: Introduction, Black body radiation, Planck's law, Photoelectric effect-Einstein's Photoelectric equation, Compton effect (Qualitative), Wave-Particle duality, de Broglie hypothesis, Davisson and Germer experiment, Heisenberg's uncertainty principle, Born's interpretation of the wave function, Schrodinger's time independent wave equation, Particle in one dimensional infinite potential box.

UNIT II

Semiconductor Physics: Intrinsic and extrinsic semiconductors, Estimation of carrier concentration, Dependence of Fermi level on carrier concentration and variation with temperature, Carrier transport: diffusion and drift, Hall Effect, p-n junction diode: I-V Characteristics, Zener diode: I-V Characteristics, Bipolar Junction Transistor (BJT): Construction and principle of operation (n-p-n and p-n-p) in common base configuration.

UNIT III

Optoelectronics: Radiative transitions: Absorption, Spontaneous and Stimulated emission, Non-radiative transitions: Auger recombination, Surface recombination and recombination at defects, Generation and recombination mechanism in semiconductors, LED and Semiconductor lasers: Device structure, Materials, Characteristics, Semiconductor photo-detectors: PIN and Avalanche detectors and their structure, Materials, Working principle and Characteristics, Solar cell: Structure and Characteristics.

UNIT IV

Lasers: Introduction, Characteristics of lasers, Einstein coefficients, Resonating cavity, Active medium-Meta stable state, Pumping, Population inversion, Construction and working of Ruby laser and He-Ne laser, Applications of lasers.

Fiber Optics: Introduction, Principle and Structure of an optical fiber, Basic components in optical fiber communication system, Comparison of optical fibers over conventional cables, Acceptance angle-Numerical aperture, Types of optical fibers, Losses associated with optical fibers, Applications of optical fibers.

UNIT V

Dielectric Materials: Introduction, Types of polarizations (Electronic, Ionic and Orientational Polarizations) and calculation of Electronic and Ionic polarizability.

Magnetic Materials: Introduction, Bohr magneton, classification of dia, para and ferro magnetic materials on the basis of magnetic moment, Hysteresis curve based on domain theory, Soft and hard magnetic materials, Properties of anti-ferro and ferri magnetic materials.

Superconducting materials: Introduction to superconductors, General properties, Meissner effect, Type I and Type II superconductors, Applications of superconducting materials.

Teaching methodologies:

- White board and marker
- Power Point Presentations
- Video lectures

Text books:

1. Engineering Physics, B.K. Pandey, S. Chaturvedi - CengageLearing.
2. Halliday and Resnick, Physics - Wiley.
3. Engineering Physics, P.K Palanisamy, Scitech Publishers.
4. A textbook of Engineering Physics, Dr. M. N. Avadhanulu, Dr. P.G. Kshirsagar - S. Chand.
5. Applied Physics, T. Bhīma Sankaram, BSP Publishers.

References:

1. Richard Robinett, Quantum Mechanics

2. Fundamentals of Semiconductor Devices, Second Edition, Anderson and Anderson, McGraw Hill.
3. J. Singh, Semiconductor Optoelectronics: Physics and Technology, McGraw- Hill Inc.(1995)
4. Semiconductor Physics and Devices, 4e, Neamen and Biswas, McGraw Hill.
5. Online Course: “Optoelectronic Materials and Devices” by Monica Katiyar and Deepak Gupthaon NPTEL.

Unit 1: Quantum Mechanics

1). Black body radiation:

- A body that completely absorbs radiation of all wavelengths incident on it is referred as a black body. When such a body is heated, it emits radiations called as black body radiations.
- A cavity is made out of hallow container of any material (preferably iron or copper) with a narrow opening and painted with black in the inside portion gives a close approximation to a perfect black body. When any radiation falls on this hole, it enters the cavity, gets reflected by the wall of the cavity and gets absorbed. If we heat the cavity at various temperatures, it will emit radiations of the all frequencies or wave lengths. So the emitted radiation from a black body is a continuous spectrum, contains radiations of all frequencies or wave lengths.
- The experimental results shows that 1) the distribution of frequencies is a function of temperature of the black body 2) with increase of temperature, the total amount of emitted radiation increases.

2). Planck's quantum theory or hypothesis:

Max Planck 1n 1900 introduced the quantum theory of radiation to explain the distribution of energy in the spectrum of black body radiation i.e. frequency distribution of thermal radiation. Planck assumptions are

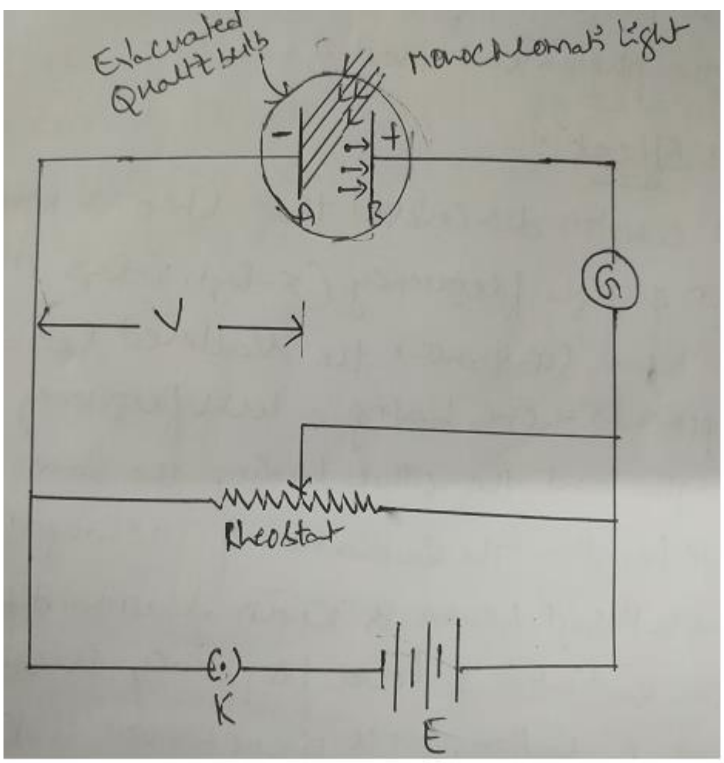
1. The atomic oscillators in a body cannot have any arbitrary amount of energy but can have only discrete units of energy given by $E = nh\nu$. Where n=0, 1, 2…… (Any positive integer), h=Planck's constant and ν= frequency of the oscillator.
2. The oscillator can emit or absorb energy only in the form of wave packets of energy($h\nu$) in indivisible discrete units. The emission or absorption of energy occurs only when the oscillator jumps from one energy state to another along with the energy difference given by $E_2-E_1= (n_2-n_1)h\nu$.

The energy of each quantum is a minimum amount of energy that cannot be further sub divided. The radiation of energy emitted or absorbed in a discontinuous manner and in the form of quantum is called the Planck's quantum hypothesis.

3). Photoelectric Effect:

- The emission of electrons from a metal plate when illuminated by light radiation of suitable wave length or frequency is called photoelectric effect. The emitted electrons are called photo electrons. This effect was discovered by Hertz, when ultraviolet light falls on zinc plate.
- This phenomenon was experimentally verified by the scientists, discovered that alkali metals like Li, Na, K etc. eject electrons when visible light falls on them.
- Millikan investigated this effect with a number of alkali metals over a wide range of light frequencies and was awarded Noble prize in 1923.

The experimental arrangement to study the photoelectric effect is shown in figure.



- It consists of two photosensitive surfaces **A** and **B** enclosed in an evacuated quartz bulb. The plate **A** is connected to negative terminal of a potential device and plate **B** is connected to positive terminal through a galvanometer **G** or a micro ammeter. In the absence of light, there is no flow of current and hence there is no deflection in the galvanometer. When monochromatic light is allowed to incident on plate **A**, a current starts flowing in the circuit shown by galvanometer. The current is known as photo current. This shows that when light falls on the metal plate, electrons are ejected.
- The number of electrons emitted and their kinetic energy depends on 1) the potential difference between two electrodes i.e. between plate **A** and **B** 2) the intensity of incident radiation 3) the frequency of incident radiation 4) the photo metal used.

Einstein's Photoelectric equation:

Following Planck's idea that light consists of photons. Einstein proposed an explanation of photoelectric effect as early as 1905. According to Einstein's explanation, in photoelectric effect one photon is completely absorbed by one electron, which thereby gains the quantum of energy and may be emitted from the metal. The photons energy is used in the following two parts:

(i) Apart of its energy is used to free the electron from the atom and away from the metal surface. This energy is known as photoelectric work function of the metal. This is denoted by W_0.

(ii) The other part is used in giving kinetic energy ($\frac{1}{2}mv^2$) to the electron.

Thus, $h\nu = W_0 + \frac{1}{2}mv^2$ ---------- (1)

Where v is the velocity of emitted electron. Eq. (1) is known as Einstein's photoelectric equation.

When the photon's energy is of such a value that it can only liberate the electron from metal, then the kinetic energy of the electron will be zero. Eq. (1) now reduces to

$h\nu_0 = W_0$ ----------- (2)

Where ν_0 is called the threshold frequency.

Threshold frequency is defined as the minimum frequency which can cause photoelectric emission.

If the frequency of the photon is below threshold frequency no emission of electrons will take place. Corresponding to threshold frequency, we define long wavelength limit (λ_0) . It represents the upper limit of wavelength for photoelectric effect. Its physical significance is that radiations having wavelength longer than λ_0 would not be able to eject electrons from a given metal surface whereas those having $\lambda < \lambda_0$, will. The value of λ_0 is given by

$$c = \nu_0\lambda_0$$

$$\lambda_0 = \frac{C}{\vartheta_0} = \frac{\text{ch}}{w_0}$$

$$\lambda_0 = \frac{3\times10^{8}\times6\cdot625\times10^{-34}}{w_0}$$

$$= \frac{19.875\times10^{-26}}{w_0}\ \text{metre.}$$

Here w_0 is expressed in joules. If w_0 is expressed in eV, then

$$\lambda_0 = \frac{19.875\times10^{-26}}{1.602\times10^{-19}w_0}$$

$$= \frac{12400}{w_0}\ A^0 \text{ ---------------- (3)}$$

From eq. (3), the value of photoelectric work function is given by

$$w_0 = \frac{12400}{\lambda_0}\ \text{eV where } \lambda_0 \text{ is in } A^0. \text{ --------------- (4)}$$

Substituting the value of $w_0 = h\nu_0$ in equation (1), we have

$$h\nu = h\nu_0 + \frac{1}{2}mv^2$$

$$\frac{1}{2}mv^2 = (h\nu - h\nu_0) = h(\nu - \nu_0) \text{ ---------------------(5)}$$

This is another form of Einstein’s Photoelectric equation.

The Einstein’s Photoelectric equation predicts all the experimental results.

From eq. (1), we have

$$\frac{1}{2}mv^2 = h\nu - W_0$$

For a particular emitter, work function W_0 is constant and hence

$$K.E. = \frac{1}{2}mv^2 \propto h\nu$$

$$v^2 \propto \nu$$

Thus, the increase in frequency ν of incident light causes increase in velocity of photoelectrons provided intensity of incident light is constant.

An increase in the intensity of radiation is equivalent to an increase in the number of photons falling on the emitting surface. If the frequency of the incident radiation is above the threshold frequency $\nu > \nu_0$, then the number of emitted electrons will increase. In this way the intensity of emitted electrons is directly proportional to the intensity of incident radiation.

From Eq. (5), we have

$$\frac{1}{2}mv^2 = h\nu - h\nu_0$$

If V_0 be the stopping potential, then

$$eV_0 = h\nu - h\nu_0$$

$$V_0 = \frac{h\vartheta}{e} - \frac{h}{e}\vartheta_0 \text{ ------------(7)}$$

As h and e are constant ϑ_0 is also constant for a given photo cathode, eq.(7) shows that graph between stopping potential V_0 and frequency ν would be straight line of slope h/e.

Fundamental Laws of Photo-Electric Emission:

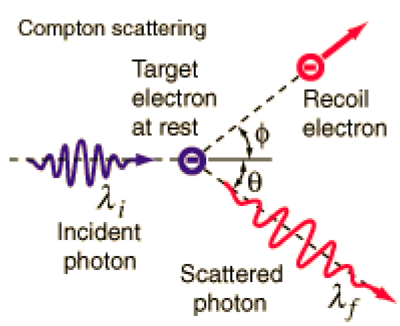
- There is no time lag between incident radiation (photon) and ejected photoelectron.
- The rate of photo-emission is directly proportional to intensity of incident radiation (light).

- The velocity and hence the kinetic energy of photo-electrons is independent of intensity of incident light.
- The velocity and hence the kinetic energy of photo-electrons is directly proportional to frequency of incident radiation.
- The emission of electron take place above a certain frequency known as threshold frequency. This frequency is characteristic frequency of photo-metal used.

4). Compton Effect:

In 1921 Compton discovered that when a monochromatic radiation of high frequency (X-Rays, γ-Rays etc.) is scattered by a substance, the scattered radiation contains two components, one is having a lower frequency or higher wave length and the other is having same frequency or wave length. The radiation of unchanged frequency in the scattered beam is known as unmodified radiation while the radiation of lower frequency is called as modified radiation. This phenomenon is known as Compton Effect.

This Compton scattering results are 1) modified frequencies 2) unmodified frequencies 3) recoil-electrons.



On the basis of quantum theory of radiation, the radiation consists of energy packets called photons. These photons strike the electrons of a scattering substance. According to Compton phenomenon of scattering, collision between two particles i.e. the photon of incident radiation and the electron of scatterer take place. The photon collides with the electron of the scatterer at rest, it transfers some energy to the electron i.e. it loses energy. The scattered photon will therefore have a smaller energy and consequently a lower frequency or greater wave length than the incident photon. The observed change in frequency or wave length of the scattered radiation is known as

Compton Effect. In the scattering process, the electron gain kinetic energy and thus recoils with certain velocity.

5). Wave-particle Duality: De-Broglie Hypothesis:

An electromagnetic wave behaves like particles, particles like electrons behave like waves called matter waves, also called de-Broglie matter waves. The wave length of matter waves is derived on the analogy of radiation.

Based on Planck's theory of radiation, the energy of a photon is given by

$E = h\nu = \frac{hc}{\lambda}$….. (1)

$c =$ Velocity of light, $\lambda =$ Wavelength of the photon, h= Planck's constant

According to Einstein's mass energy relation, $E = mc^2$…… (2)

m= mass of the photon

Equating equations (1) and (2), $mc^2 = \frac{hc}{\lambda}$

$\lambda = \frac{hc}{mc^2} = \frac{h}{mc} = \frac{h}{p}$…… (3), P = momentum of photon

De-Broglie proposed the concept of matter waves, according to which a material particle of mass 'm', moving with a velocity 'v' should have an associated wavelength 'λ' called de-Broglie wavelength.

$\lambda = \frac{h}{mv} = \frac{h}{p}$… (4) is called de-Broglie's wave equation.

Wavelength is associated with moving particle and independent of charge of the particles.

Greater the mass and velocity of the particle, lesser will be the wavelength.

De-Broglie wavelength associated with an electron:

If a velocity 'v' is given to an electron by accelerating it through a potential difference 'V', then the work done on the electron is 'Ve', and the work done is converted into the kinetic energy of an electron.

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

$v = \sqrt{\frac{2eV}{m}}$

$mv = \sqrt{2meV}$…. (5) in (4)

$\lambda = \frac{h}{\sqrt{2meV}}$...... (6)

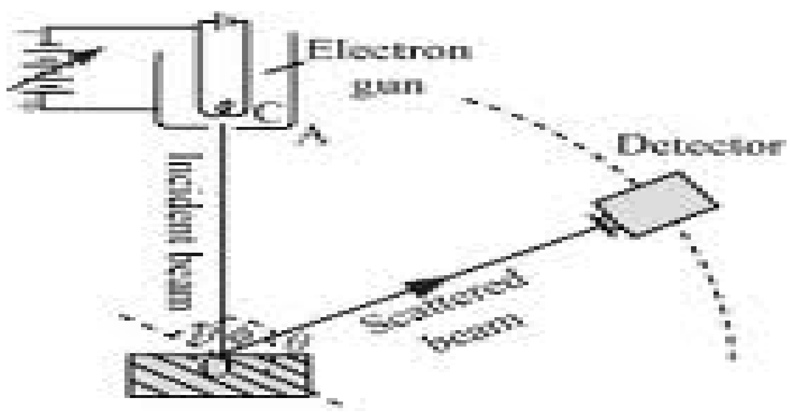
By substituting the values of h = $6.625\times 10^{-34} Jsec$, m = $9.1\times 10^{-31} Kg$ and e = charge of electron=1.6×10^{-19}C

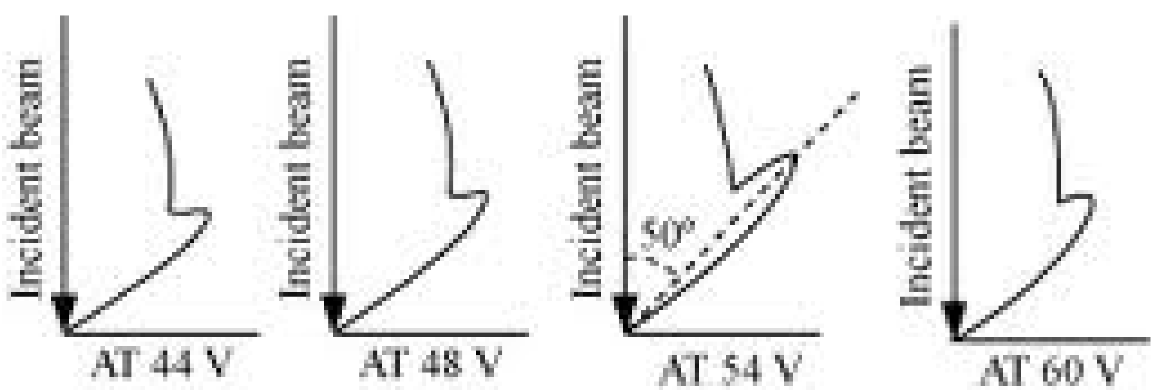
$\lambda = \frac{12.27}{\sqrt{V}} A^0$...... (8), Where V= in volt and $\lambda =$ in A^0

6). Davison and Germer Experiment: Experimental validity for De-Broglie hypothesis:

The first experimental evidence of the wave nature of particles was provided by C.J Davison and L.H Germer in 1927.

They were studying scattering of electrons by a metal target and measuring the density of electrons scattered in different directions.





From fig, the electron beam from electron gun which consists of a tungsten filament 'F' heated by a low tension battery 'B_1' are accelerated to a desired velocity by applying suitable potential from a high tension battery 'B_2'.

The accelerated electrons are collimated into a fine beam by allowing them to pass thorough a system of pinholes in the cylinder ‘C’.

The fast moving electron beam is made to strike the target (nickel crystal) capable of rotating about an axis perpendicular to the plane of diagram.

The electrons are scattered in all directions by atomic planes of a crystal and intensity of scattered electron beam in all directions can be measured by the electron collector and can be rotated about the same axis as the target.

The collector is connected to a sensitive galvanometer whose deflection is proportional to the intensity of electron beam entering the collector.

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

The incident beam and the diffracted beam make an angle of 65^0 with the family of Bragg’s planes.

The whole instrument is kept in an evacuated chamber.

The spacing of planes in Nickel crystal as determined by x-ray diffraction is 0.091nm

From Bragg’s law 2dsinθ = n λ i.e$2 \times 0.091 \times 10^{-9} \times sin65^{\circ} = 1 \times \lambda$

$\lambda = 0.1648$ nm

Therefore, for a 54 V electron beam, the de-Broglie wavelength associated with the electron is given by $\lambda. = \frac{12.27}{\sqrt{54}}$ A°= 0.1668 nm

This wavelength agrees well with the experimental value. Thus, Davison and Germer experiment provides a direct verification of de-Broglie hypothesis of wave nature of moving particles.

7). Heisenberg’s uncertainty principle:

Heisenberg a German scientist in 1927 gave uncertainty principle which states that “The determination of exact position and momentum of a moving particle simultaneously is impossible’’.

In general, if $\triangle$x represents the error in measurement of position of particle along x-axis, and $\triangle$p represents error in measurement of momentum, then

$$\triangle x.\triangle p = h$$

Or limitation to find the position and momentum of a particle is $(\triangle x).(\triangle p) \geq \frac{h}{4\pi}$i.e. Heisenberg uncertainty principle states that both the position and momentum cannot be measured simultaneously with perfect accuracy.

According to Classical mechanics, a moving particle at any instant has fixed position in space and definite momentum which can be determined simultaneously with any desired accuracy. This assumption is true for objects of appreciable size, but fails in particles of atomic dimensions.

Since a moving atomic particle has to be regarded as a de-Broglie wave group, there is a limit to measure particle properties.

According to Born probability interpretation, the particle may be found anywhere within the wave group moving with group velocity.

If the group is considered to be narrow, it is easier to locate its position, but the uncertainty in calculating its velocity and momentum increases.

If the group is wide, its momentum is estimated easily, but there is great uncertainty about the exact location of the particle.

8). Physical significance of $\boldsymbol{\psi}(\mathbf{wavefunction})$: Born's interpretation:

The wave function $\boldsymbol{\psi}$ is unable to give all possible information about the particle. $\boldsymbol{\psi}$is a complex quantity and has no direct physical meaning. It is only a mathematical tool in order to represent the variable physical quantities in quantum mechanics.

Born suggested that, the value of wave function associated with a moving particle at the position co-ordinates (x,y,z) in space, and at the time instant 't' is related in finding the particle at certain location and certain period of time 't'.

If $\boldsymbol{\psi}$ represents the probability of finding the particle, then it can have two cases.

Case 1: certainty of its Presence: +ve probability

Case 2: certainty of its absence: - ve probability, but –ve probability is meaningless,

Hence the wave function $\boldsymbol{\psi}$ is complex number and is of the form a+ib

Even though $\boldsymbol{\psi}$ has no physical meaning, the square of its absolute magnitude $|\boldsymbol{\psi}^2|$ gives a definite meaning and is obtained by multiplying the complex number with its complex conjugate then $|\boldsymbol{\psi}^2|$represents the probability density 'p' of locating the particle at a place at a given instant of time. And has real and positive solutions.

$$\boldsymbol{\psi}(\mathbf{x},\mathbf{y},\mathbf{z},\mathbf{t}) = \mathbf{a}+\mathbf{ib}$$

$$\boldsymbol{\psi}^*(\mathbf{x},\mathbf{y},\mathbf{z},\mathbf{t}) = \mathbf{a}-\mathbf{ib}$$

$$\mathbf{p} = \boldsymbol{\psi}\boldsymbol{\psi}^* = |\boldsymbol{\psi}^2| = a^2 + b^2$$

Where 'P' is called the probability density of the wave function.

If the particle is moving in a volume 'V', then the probability of finding the particle in a volume element dv, surrounding the point x, y, z and at instant 't' is Pdv

$$\int_{-\infty}^{\infty} |\boldsymbol{\psi}^2| dv = 1 \; if\ particle\ is\ present$$

= 0 if particle does not exist

This is called normalization condition.

9). Schrodinger time independent wave equation:

Schrodinger describes the wave nature of a particle in mathematical form and is known as Schrodinger's wave equation.

Consider a plane wave moving along +ve x- direction with velocity 'v'. The equation of the wave is written in the from $y = a sin \frac{2\pi}{\lambda}(x - vt)$…(1)

Where$\lambda =$ wavelength of the wave, a= amplitude of wave

y=displacement of wave in y- direction

x= displacement along x- axis at any instant of time't'.

Taking first order derivative w.r.to 'x' on both sides of eqn (1)

$$\frac{dy}{dx} = a\cos\frac{2\pi}{\lambda}(x - vt)\frac{2\pi}{\lambda}$$

$$\frac{d^2y}{dx^2} = -a\left(\frac{2\pi}{\lambda}\right)^2 \sin\left(\frac{2\pi}{\lambda}\right)(x - vt)\text{….(2)}$$

Substitute (1) in (2)

$$\frac{d^2y}{dx^2} + \left(\frac{2\pi}{\lambda}\right)^2 y = 0\text{…(3)}$$

This is known as differential plane wave equation.

In complex wave, the displacement 'y' is replaced by 'ψ' and wavelength' λ' is replaced by de-Broglie's wavelength λ' $= \frac{h}{mv}$ in eqn (3)

$$\frac{d^2\psi}{dx^2} + \left(\frac{2\pi}{\lambda}\right)^2 \psi = 0$$

$$\frac{d^2\psi}{dx^2} + \frac{4\pi^2 m^2 v^2}{h^2}\psi = 0\text{…. (4)}$$

For a moving particle, the\ total energy is $E = U + V i.e U = E - V$….(5)

Where E= total energy, V= potential energy, U= kinetic energy $=\frac{1}{2}mv^2$

$2mu = m^2v^2$…. (6), substitute (5) in (6)

$2m(E - V) = m^2v^2$…. (7) Substitute (7) in (4)

$$\frac{d^2\psi}{dx^2} + \frac{4\pi^2 2m(E-V)}{h^2}\psi = 0$$

$$\frac{d^2\psi}{dx^2} + \frac{8\pi^2 m(E-V)}{h^2}\psi = 0 \text{…. (8)}$$

This equation is known as Schrodinger's time independent wave equation in one dimension.

In three dimensions, it can be written as

$$\nabla^2\psi + \frac{8\pi^2 m(E-V)}{h^2}\psi = 0 \text{… (9)}$$

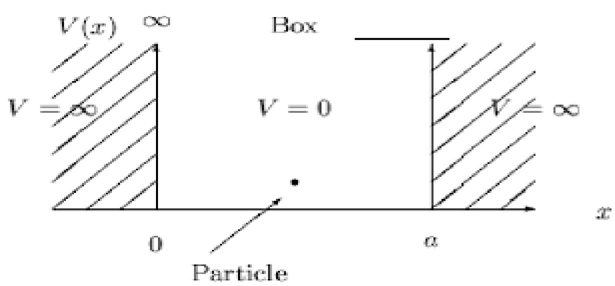
$$\nabla^2\psi + \frac{2m(E-V)}{h^2}\psi = 0$$

For a free particle, the P.E is equal to zero i.e. V=0 in equation (9)

Therefore the Schrodinger's time independent wave equation for a free particle is

$$\nabla^2\psi + \frac{8\pi^2 mE}{h^2}\psi = 0$$

10). Particle enclosed in one-dimensional potential box:



- The wave nature of a moving particle leads to some remarkable consequences when the particle is restricted to a certain region of space instead of being able to move freely .i.e when a particle bounces back and forth between the walls of a box.
- If one –dimensional motion of a particle is assumed to take place with zero potential energy over a fixed distance, and if the potential energy is assumed to become infinite at the extremities of the distance, it is described as a particle in a 1-D box, and this is the simplest example of all motions in a bound state.

- The Schrodinger wave equation will be applied to study the motion of a particle in 1-D box to show how quantum numbers, discrete values of energy and zero point energy arise.
- From a wave point of view, a particle trapped in a box is like a standing wave in a string stretched between the box's walls.
- Consider a particle of mass 'm' moving freely along x- axis and is confined between x=0 and x= a by infinitely two hard walls, so that the particle has no chance of penetrating them and bouncing back and forth between the walls of a 1-D box.
- If the particle does not lose energy when it collides with such walls, then the total energy remains constant.
- This box can be represented by a potential well of width 'a', where V is uniform inside the box throughout the length 'a' i.e. V= 0 inside the box or convenience and with potential walls of infinite height at x=0 and x=a, so that the PE 'V' of a particle is infinitely high V=∞ on both sides of the box.
- The boundary condition are

$v(x) = 0\,, \psi(x) = 1 when\ 0 < x < a$.... (1)

$v(x) = \infty\,, \psi(x) = 0 when\ 0 \geq x \geq a$... (2)

Where $\psi(x)$ is the probability of finding the particle.

- The Schrodinger wave equation for the particle in the potential well can be written as

$\frac{d^2\psi}{dx^2} + \frac{8\pi^2 m}{h^2} \mathrm{E}\,\psi = 0, \mathrm{as\ V} = 0$ for a free particle... (3)

- In the simplest form eqn (3) can be written as

$\frac{d^2\psi}{dx^2} + k^2\psi = 0$.... (4) Where k= propagation constant and is given by $k = \sqrt{\frac{8\Pi^2 mE}{h^2}}$....(5)

- The general solution of equation (4) is $\psi(\mathrm{x}) = \mathrm{Asinkx} + \mathrm{Bcoskx}$... (6)
- Where A and B are arbitrary constants, and the value of these constant can be obtained by applying the boundary conditions.
- Substitute eqn(1) in (6)

$0 = Asink(0) + Bcosk(0)$ → B=0 in eqn (6)

$\psi(\mathrm{x}) = \mathrm{Asinkx}$... (7)

Substituting eqn (2) in (7)

$0 = Asink(a)$

$\rightarrow A = 0\ or\ sinka = 0$, But 'A' ≠ 0 as already B=0 & if A= 0, there is no solution at all.

- Therefore sinka = 0(if Sinθ = 0,then general solution is θ=nπ), i.e. Ka=nπ

$k = \frac{n\pi}{a}$.......(8), Where n= 1,2,3,4,…and n≠0,because if n=0,k=0,E=0 everywhere inside the box and the moving particle cannot have zero energy.

From (8) $k^2 = \left(\frac{n\pi}{a}\right)^2$

From (5) $\frac{8\Pi^2 mE}{h^2} = \frac{n^2\pi^2}{a^2}$

$$E = \frac{n^2h^2}{8ma^2}$$

$$E_{n=}\frac{n^2h^2}{8ma^2} = \text{the discrete energy level… (9)}$$

- The lowest energy of a particle is given by putting n=1 in the eqn (9),$E_{1=}\frac{h^2}{8ma^2}$ = lowest energy, minimum energy, ground state energy or zero point energy of the system.
- The wave functions ψ_n corresponding to E_n are called Eigen functions of the particle, the integer 'n' corresponding to the energy E_n is called the quantum number of the energy level E_n.

Substituting (8) in (7),$\psi_n = Asin\frac{n\pi x}{a}$..(10)

- Normalization of wave function: The wave functions for the motion of the particle are

$$\psi_n = Asin\frac{n\pi x}{a}, for\ 0 < x < a$$

$$\psi_n = 0, for\ 0 \geq x \geq a$$

- According to normalization condition, the total probability that the particle is somewhere in the box must be unity.

$$\int_0^a p_x dx = \int_0^a |\psi_n|^2 dx = 1$$

- From eqn(10), $\int_0^a A^2 sin^2\frac{n\pi x}{a}dx = 1$

$$A^2\int_0^a \frac{1}{2}\left[1 - cos\frac{2\pi nx}{a}\right]dx = 1$$

$$\left(\frac{A}{2}\right)^2\left[x - \frac{a}{2\pi n}sin\frac{2\pi nx}{a}\right] = 1$$

- The second term of the integrand expression becomes zero at both the limits.

$$\frac{A^2}{2} = a, \text{ then } A = \sqrt{\frac{2}{a}}$$

- The normalized wave function is $\psi_n = \sqrt{\frac{2}{a} sin \frac{n\pi x}{a}}$

Questions:

Short answer questions:

1. State De-Broglie hypothesis.
2. What are matter waves?
3. Define black body radiation.
4. State photo electric effect.
5. What is Compton Effect?
6. State Heisenberg’s uncertainty principle.

Long answer questions:

1. Explain black body radiation.
2. Write a short note on Planck’s quantum theory.
3. Distinguish between a) Photo electric effect b) Compton effect.
4. Explain photoelectric effect and derive an expression for Einstein Photoelectric equation.
5. What are matter waves? Derive an expression for De-Broglie wave length associated with an electron.
6. Describe De-Broglie hypothesis in detail. Provide an experimental (Davison and Germer experiment) validity for De-Broglie hypothesis or Explain the experimental verification of matter waves by Davison and Germer experiment.
7. Describe Heisenberg’s uncertainty principle.
8. Explain the physical significance of Wave function.
9. Derive an expression for Schrödinger’s time independent wave equation.
10. Obtain a solution for particle enclosed in one-dimensional potential box or Derive an expression for the energy states of a particle trapped in one-dimensional potential box.

UNIT – II: Semiconductor Physics

1). Intrinsic Vs Extrinsic semiconductor:

BASIS OF DIFFERENCE	**INTRINSIC SEMICONDUCTOR**	**EXTRINSIC SEMICONDUCTOR**
Doping of impurity	Doping or addition of impurity does not take place in intrinsic semiconductor.	A small amount of impurity is doped in a pure semiconductor for preparing extrinsic semiconductor.
Density of electrons and holes	The number of free electrons in the conduction band is equal to the number of holes in the valence band.	The number of electrons and holes are not equal.
Electrical conductivity	Electrical conductivity is low.	Electrical conductivity is high
Dependency of electrical conductivity	Electrical conductivity is a function of temperature alone.	Electrical conductivity depends on temperature as well as on the amount of impurity doping in the pure semiconductor.
Example	Crystalline form of pure Silicon and Germanium.	Impurity like As, Sb, P, In, Bi, Al etc. are doped with Germanium and Silicon atom.

2). **Expression for carrier concentration of intrinsic semiconductor:**

- A semiconductor in which holes in the valance band and electrons in the conduction band are created by thermal excitations is called intrinsic semiconductors i.e., A pure semi-conductor is considered as intrinsic semiconductor.
- The number of electrons moving into the conduction band is equal to the number of holes created in the valence band.
- The Fermi level lies exactly in the middle of forbidden energy gap.
- Intrinsic semiconductors are not of practical use in view of their poor conductivity.

Carrier concentration in intrinsic semi-conductors:

- In the conduction band, the level density Z(E) at an energy E is given by the expression.

$Z(E)dE = \frac{4\pi}{h^3}(2m)^{3/2}E^{1/2}dE$

- The probability of an energy level filled with electrons is given by Fermi-Dirac function.

$F(E) = \frac{1}{1+\exp(\frac{E-E_F}{KT})}$

- The no of electrons 'n' filling into energy level between the energies E and E+dE is

n = Z(E) F(E) dx

- $n = \frac{4\pi}{h^3}(2m)^{3/2}E^{1/2}dE\frac{1}{1+\exp(\frac{E-E_F}{KT})}$
- In the above expression, mass of the electron 'm' is replaced with effective mass m_e^*.
- The number of electrons in the conduction band is obtained by integrating between the limits Ec to ∞. Minimum energy in the conduction band is Ec.
- For conduction band we write E-Ec for E

$$n=\frac{4\pi}{h^3}(2m_e^*)^{3/2}\int_0^\infty \frac{(E-E_C)^{\frac{1}{2}}}{1+\exp(\frac{E-E_F}{KT})}dE$$

For all possible temperatures E-E_F>>>> KT

Hence $F(E) = \exp -(\frac{(E-E_F)}{KT}) = \exp(\frac{E_F-E)}{KT})$

Equation 1 becomes

$n = \frac{4\pi}{h^3}(2m_e^*)^{3/2}\int_{E_c}^\infty((E-E_c)^{\frac{1}{2}}\exp(\frac{E_F-E)}{KT})dE$

$n = \frac{4\pi}{h^3}(2m_e^*)^{3/2}\exp(E_F/KT)\int_{E_c}^\infty((E-E_c)^{\frac{1}{2}}\exp(\frac{-E}{KT})dE$

To solve this Integral Part

E-Ec = x

E = Ec+x

dE = dx

n = $\frac{4\pi}{h^3}(2m_e^*)^{3/2}$exp(EF/KT) $\int_0^\infty x^{\frac{1}{2}} \exp -(\frac{Ec+x}{KT})dx$

n = $\frac{4\pi}{h^3}(2m_e^*)^{3/2}\exp(\frac{EF-Ec}{KT}) \int_0^\infty x^{\frac{1}{2}} \exp -(\frac{x}{KT})$

Using gamma function, it can be shown that

$\int_0^\infty x^{\frac{1}{2}} \exp -(\frac{x}{KT})\, dx = (KT)^{3/2} (\frac{\pi}{2})^{1/2}$

Hence, n = $\frac{4\pi}{h^3}(2m_e^*)^{3/2}\exp(\frac{E_F-Ec}{KT})(KT)^{3/2}(\frac{\pi}{2})^{1/2}$

No of electrons per unit volume is given by

n= $2(\frac{2\pi m_e^* KT}{h^2})\exp(\frac{E_F-Ec}{KT})$

The expression for no of holes in the valance band is given by the expression

p= $2(\frac{2\pi m_p^{*v} KT}{h^2})\exp(\frac{Ev-E_F}{KT})$

In Intrinsic semiconductor n=p then the Intrinsic carrier concentration is n=p=n_i;

$(n_i)^2 = 4(\frac{2\pi KT}{h^2})^3(m_e^* m_p^*)^{3/2} \exp(\frac{Ev-Ec}{KT})$

$(n_i)^2 = 4(\frac{2\pi KT}{h^2})^3(m_e^* m_p^*)^{3/2}\exp(\frac{-Eg}{KT})$

Here Ec-Ev = Eg (forbidden energy gap)

Hence $n_i = 2(\frac{2\pi KT}{h^2})^{3/2}(m_e^* m_p^*)^{3/4} \exp(\frac{-Eg}{2KT})$

Fermi Level: In Intrinsic semiconductor n=p and assuming the effective mass of electron and hole to be same, i.e. $m_e^*=m_p^*$

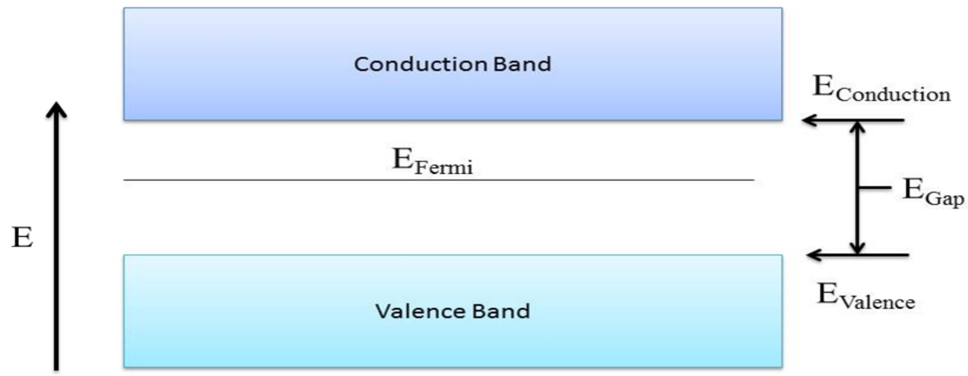
Exp$(\frac{Ef-Ec}{KT})$ = exp $(\frac{Ev-Ef}{KT})$

E_F –Ec = Ev- E_F

2 E_F = Ev+Ec

$E_F = \frac{Ev+Ec}{2}$

Thus the Fermi level is located half way between the valance band and conduction band and its position is independent of the temperature.



3). Expression for carrier concentration in n-type extrinsic semiconductor:

- When pentavalent impurities like P, As, Sb is added to the intrinsic semi-conductors, resultant semiconductor is called n-type semi-conductor.
- The concentration of free electrons is more when compared to concentration of holes.

Expression for carriers' concentration in n-type semiconductors:

- In this type of semiconductor, there will be donor levels formed at an energy E_d.
- N_d Represents number of impurity atoms per unit volume of semi conductor.
- At low temperature 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 the conduction band is given by

$$n = 2\left(\frac{2\pi m_e^{*} KT}{h^2}\right)^{3/2} \exp\left(\frac{E_f - E_c}{KT}\right) \text{ -----------1}$$

- The Fermi level (E_F) lies in between E_d & E_c
- The density of empty donor levels is given by

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

- At low temperature, there are no excitations of the electrons from donor level to the conduction band.
- Hence, density of donors and the electron density in conduction band should be same

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

- Taking log on both the sides & rearranging

$(\frac{E_f-E_c}{KT}) - (\frac{E_d-E_f}{KT})$=log N_d – log $2(\frac{2\pi m_e^*KT}{h^2})^{3/2}$

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

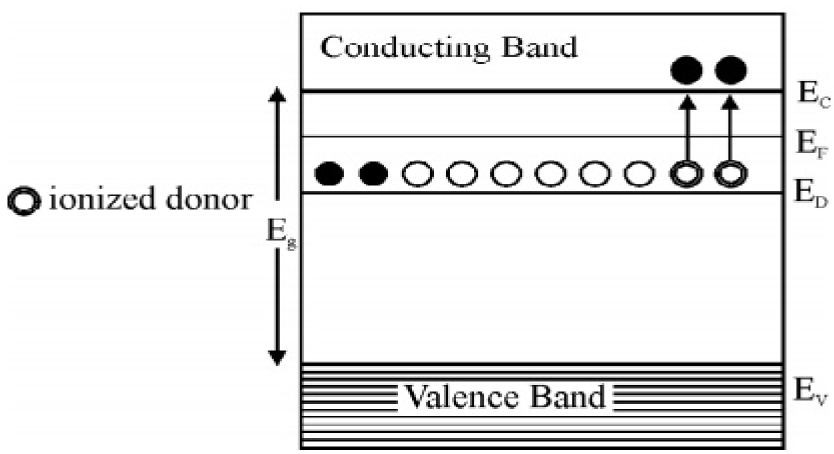
- At absolute zero $E_F = \frac{Ec+E_d}{2}$

i.e. Fermi level lies exactly at the middle of donor level E_d and the bottom of the Conduction band E_c.

Substituting equation 2 in eqn. 1 & re-arranging,

$N = (2\ N_d)^{1/2}(\frac{2\pi m_e^*KT}{h^2})^{3/4}\exp(\frac{E_d-Ec}{2KT})$

- Hence the density of the electrons in the conduction band is proportional to the square root of the donor concentration at low temperature. As higher temperature intrinsic behavior predominates and donor concentration becomes insignificant.
- As temperature increases Fermi level also increases since more donor atoms are ionized. At a particular temperature all the donor atoms are ionized. Further increase in temperature results in generation of electron – hole pairs due to breaking of covalent bonds. The material tends to behave in intrinsic manner.



4). Expression for carrier concentration in p-type extrinsic semiconductor:

- P-type semi-conductors are fabricated by addition of trivalent atoms like Al as impurity to the intrinsic semi-conductor.
- Hence, holes are majority charge carriers and free electrons are minority charge carriers.

Expression for Carrier concentration in P type semi-conductors:

- In this type of semi-conductor, there will be there will be acceptor levels formed at an energy E_a.
- N_a represents no. of impurities per unit volume of semi-conductor.
- At low temperatures, all the acceptor levels are empty.
- With increase of temperature, acceptor atoms get ionized i.e. the electrons moves from valance band and occupy the vacant sites in the acceptor energy levels, there by leaving holes in the valence band
- Density of holes in the valance band is given by

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

- Since E_f lies below the acceptor levels, the density of ionized acceptors is given by

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

- Hence, density of holes in the valance band is equal to the density of ionized acceptors.

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

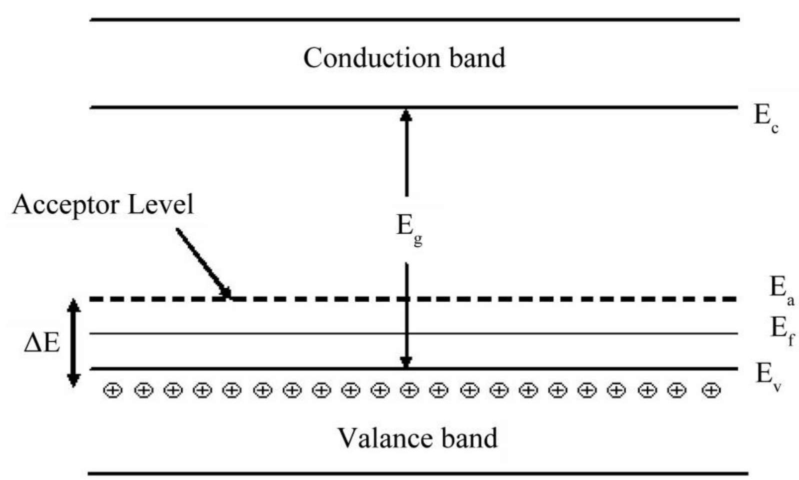
i.e. $\exp\left(\frac{E_v - E_f - E_f + E_a}{KT}\right) = \frac{Na}{2\left(\frac{2\pi m_h^* KT}{h^2}\right)^{3/2}}$

- Taking log, $\frac{E_v + E_a - 2E_f}{KT} = \log \frac{N_a}{2\left(\frac{2\pi m_h^* KT}{h^2}\right)^{3/2}}$
- $E_f = \frac{Ev + Ea}{2} - \frac{KT}{2} \log \frac{N_a}{2\left(\frac{2\pi m_h^* KT}{h^2}\right)^{3/2}}$ --------- 2
- At 0 K, $E_f = \frac{Ev + Ea}{2}$

i.e. At 0 K, Fermi level lies exactly at the middle of the acceptor level and in the top of the valance band.

- Sub. eqn. 2 in eqn. 1 & re-arranging, $p = (2N_a)^{1/2}\left(\frac{2\pi m_h^* KT}{h^2}\right)^{3/4} \exp\left(\frac{E_v - E_a}{2KT}\right)$
- Thus the density of the holes in the valance band is proportional to the square root of the acceptor concentration at low temperature. As temperature increases intrinsic behavior predominates and the contribution due to acceptor atoms becomes insignificant.
- As temperature increases Fermi level decreases since more acceptor atoms are ionized. At a particular temperature all the acceptor atoms are ionized. Further increase in temperature results

in generation of electron – hole pairs due to breaking of covalent bonds. The material tends to behave in intrinsic manner.



5). Carrier generation and recombination in semiconductors:

When sufficient energy is given to the semiconducting material, covalent bonds are broken and a pair of electron and hole is generated.

- The electrons are raised from valence band to conduction band. Holes remain in the valence band.
- The process of generation can occur only when the energy given to the semiconducting material is greater than its forbidden energy gap.
- Recombination is the process where an electron from the conduction band recombines with a hole in the valence band. This is called band to band recombination and in the process a photon is released.

6). Drift and Diffusion current in semiconductors and equation for total current due to electrons and holes:

Under the condition of thermal equilibrium, the electrons and holes are uniformly distributed in a crystal and when no external field is applied current does not flow in the crystal.

- Drift current: When an electric field E is applied to a semiconductor, the charge carriers(electrons and holes) start to move and produce drift current.

The electrons drifting in the conduction band produce a current component $\mathbf{J_e}$ given by

$\mathbf{J_e}(\text{drift}) = ne\mu_e\mathbf{E}$, where μ_e is the mobility of electrons.

The hole drifting in the valence band cause a current component $\mathbf{J_h}$given by

$\mathbf{J_h}$drift) = peμ_h**E,** where μ_h is the mobility of holes.

The total drift current density is,

J (drift) = $\mathbf{J_e}$(drift) + $\mathbf{J_h}$drift)

= e (nμ_e+ pμ_h) **E**

Although electrons and holes move in opposite directions, the direction of conventional current flow due to both the carriers is in the same direction.

- Diffusion current: In semiconductors, current can also flow without the application of external electric field. The charge carriers(electrons and holes) diffuse from regions of high concentration to regions of low concentrations until the charge carriers are evenly distributed in the material. This motion of charge carriers produce a current component known as diffusion current.

The current component due to electron diffusion is given by

$\mathbf{J_e}$(diff) = e $D_e\frac{dn}{dx}$

The current component due to hole diffusion is given by

$\mathbf{J_h}$(diff) = - e $D_h\frac{dp}{dx}$

$D_e$and D_h are diffusion coefficients for electrons and holes respectively.

- Drift and diffusion are present in a material

The total current density due to drift and diffusion of electrons is given by

$\mathbf{J_e}$ =$\mathbf{J_e}$(drift) + $\mathbf{J_e}$(diff)

= neμ_e**E** +e $D_e\frac{dn}{dx}$

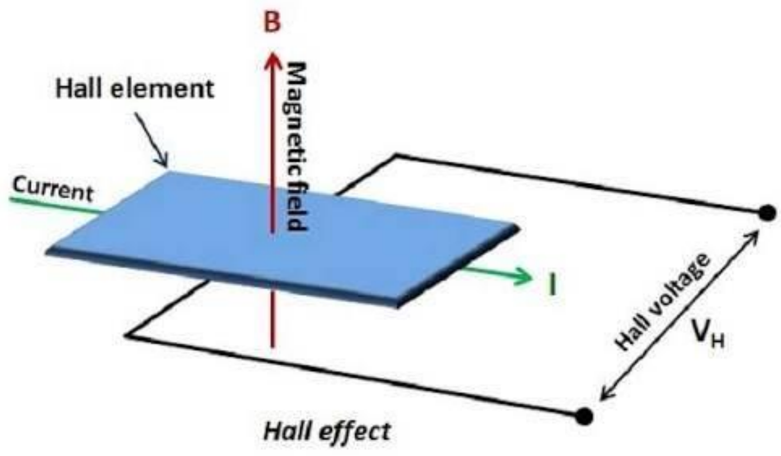
The total current density due to drift and diffusion of holes is given by

$\mathbf{J_h}$ **=** $\mathbf{J_h}$drift) + $\mathbf{J_h}$(diff)

= peμ_h**E** -e $D_h\frac{dp}{dx}$

7). Hall Effect and expression for Hall coefficient.

When a piece of conductor (metal or semiconductor) carrying current is placed in a transverse (perpendicular) magnetic field, an electric field is produced inside the conductor in a direction normal to both the current and the magnetic field. This phenomenon is known as Hall Effect and the generated voltage is known as Hall voltage.



- If the material is a p type semiconductor, when electric and magnetic field is applied at right angle to each other, holes experience a force and are accumulated on one face of the material. This causes a potential difference and a voltage is developed called Hall voltage.
- If the material is a n type semiconductor, when electric and magnetic field are applied at right angle to each other, electrons experience a force and are accumulated on one face of the material. This causes a potential difference and a voltage is developed called Hall voltage.

Consider a n type semiconductor in which electrons have a velocity v due to current flow. Let B be the applied magnetic field. The electrons experience a force of Bev due to the magnetic field. This causes the electron current tobe deflected causing a negative charge to accumulate on one face of the semiconductor. A potential difference is established across the two faces of the material causing a field E_H. This field gives rise to a force e E_H on electrons in opposite direction.

At equilibrium

$e E_H = Bev$

$E_H = Bv$

If J is the current density, then $J = nev$ where n is the number of charge carriers.

$$v = \frac{J}{ne}$$

$$E_H = Bv$$

$$= B\frac{J}{ne}$$

The Hall effect is described by means of Hall coefficient, R_H

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

$$E_H = B\frac{J}{ne}$$

$$= R_H B J$$

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

In n type material since Hall field is developed in negative direction compared to the field developed for p type material, negative sign is used.

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

For p type material, $R_H = \frac{1}{pe}$ where p is the density of holes.

Application of Hall Effect:

Determination of the type of Semi-conductors:

The Hall coefficient R_H is negative for an n-type semiconductor and positive for p-type semiconductor. Thus the sign of Hall coefficient can be used to determine whether a given Semi-conductor is n or p-type.

Calculation of carrier concentration:

$R_H = -\frac{1}{ne}$ or $n = \frac{1}{eR_H}$(number of electrons)

Determination of Mobility:

If the conduction is due to one typeof carriers, electrons

$\sigma = ne\mu$

$\mu = \frac{\sigma}{ne} = \sigma R_H$

$\mu = \sigma R_H$ where μ is the mobility of charge carriers.

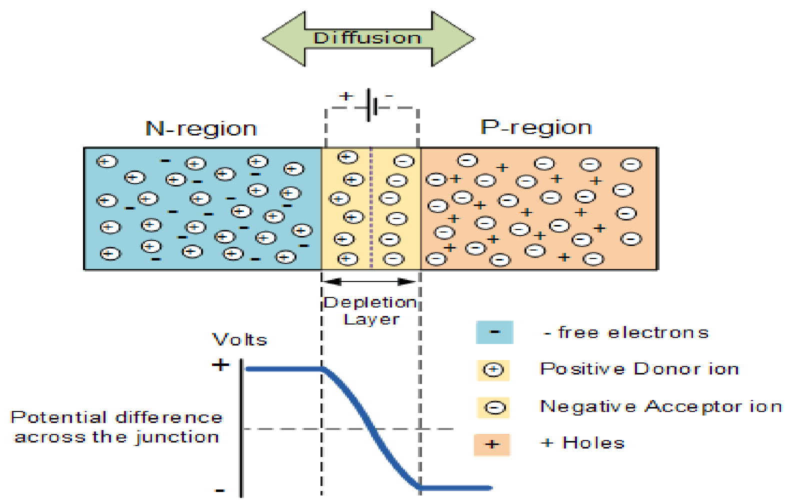
Measurement of Magnetic Flux Density:

Hall Voltage is proportional to the magnetic flux density B for a given current I. so, Hall Effect can be used as the basis for the design of a magnetic flux densityin metal.

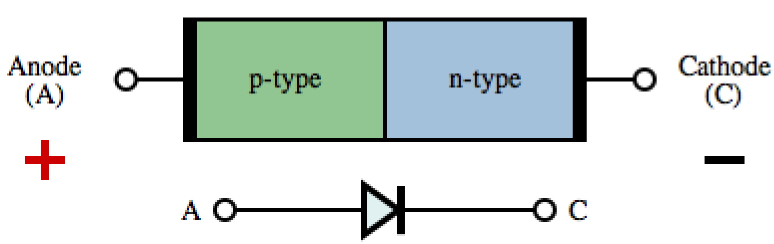
8). Formation of p-n junction.

- A p-n junction is formed when a p- type and n- type semiconductor are joined through the process of crystal growth. Within the semiconductor the region where there is a transition from p-type to n- type is called a junction.

- In p-type material holes are majority charge carriers and electrons are minority charge carriers.
- In n-type material electrons are majority charge carriers and holes are minority charge carriers.
- At the junction, holes diffuse from p region to n region and likewise electrons diffuse from n region to p region. The electrons and holes recombine and disappear at the junction region.
- Around the junction region, free electrons and holes recombine and only immobile ions are present. This region is called space charge region. This region is also called depletion region.
- The fixed ions in the depletion region produce electric field, **E**. This electric field opposes the further diffusion of electrons and holes from n-type region to p-type region. The electric field gives rise to a potential called potential barrier.
- Further diffusion of electrons and holes across the potential barrier can only take place when they overcome the potential barrier.



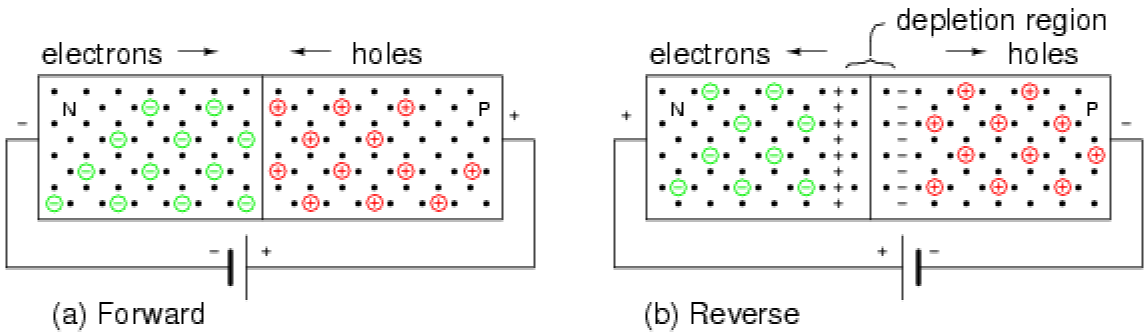
Circuit symbol of p-n junction diode:



Working of forward bias and reverse bias p-n junction diode:

p-n junction under forward bias:

- When a dc voltage, V_F is connected to the diode in such a way that the positive terminal of the source is connected to the p-region and the negative terminal to the n-region, then the junction is forward biased.
- The voltage across the junction decreases by an amount, V_O - V_F, whereV_O is the barrier voltage.
- The majority charge carriers diffuse across the junction and hence the width of the depletion region decreases.



p-n junction under reverse bias:

- When a dc voltage, $V_{R,}$ is connected to the diode in such a way that the positive terminal of the source is connected to the n-region and the negative terminal to the p-region, then the junction is reverse biased.
- The voltage across the junction increases and is equal to, $V_O + V_R$, where V_O is the barrier voltage.
- The majority charge carriers are pushed away from the junction and hence the width of the depletion region increases.
- Minority charge carriers drift across the barrier and give rise to current.

I - V characteristics of p-n junction diode:

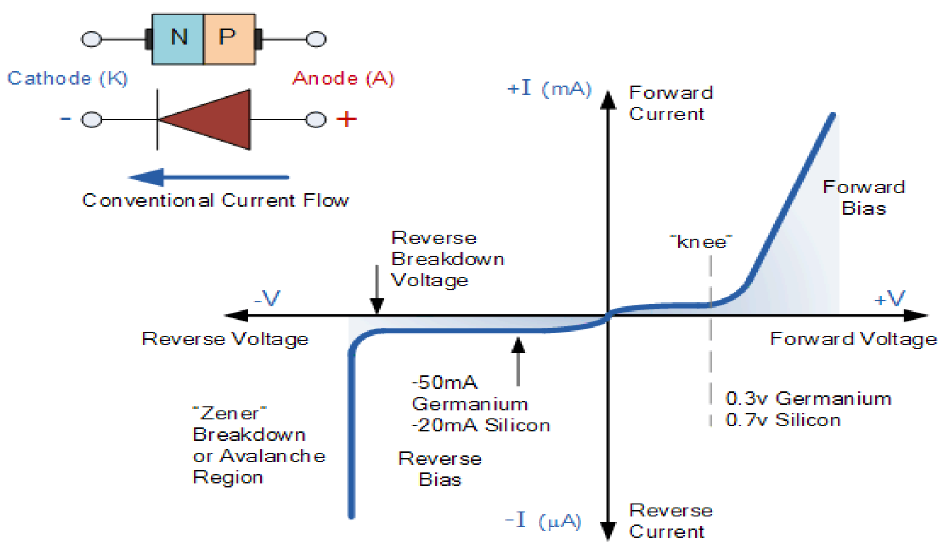
(i) Unbiased circuit:

When the junction is not connected to any voltage source, it is said to be unbiased. Due Due to the presence of barrier potential across the junction, there is no flow of charge carriers and hence there is no current flow through the junction.

(ii) Forward biased circuit:

When the positive terminal of the source (battery) is connected to p-type and negative terminal to n-type, the junction is said to be forward biased.

- As long as the forward bias voltage is less than the voltage across the potential barrier, the current through the junction is negligibly small.
- The voltage at which the current increases sharply is called cut - in voltage or knee voltage.
- As the forward voltage increases beyond the potential barrier voltage, there is an exponential increase in forward current. The current is in mA.
- The knee voltage for germanium is 0.3 V and for silicon it is 0.7 V.



(iii) Reverse biased circuit:

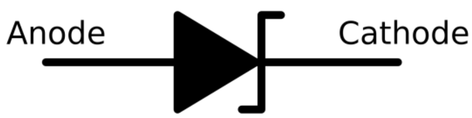
When the positive terminal of the source (battery) is connected to n-type and negative terminal to p-type, the junction is said to be reverse biased.

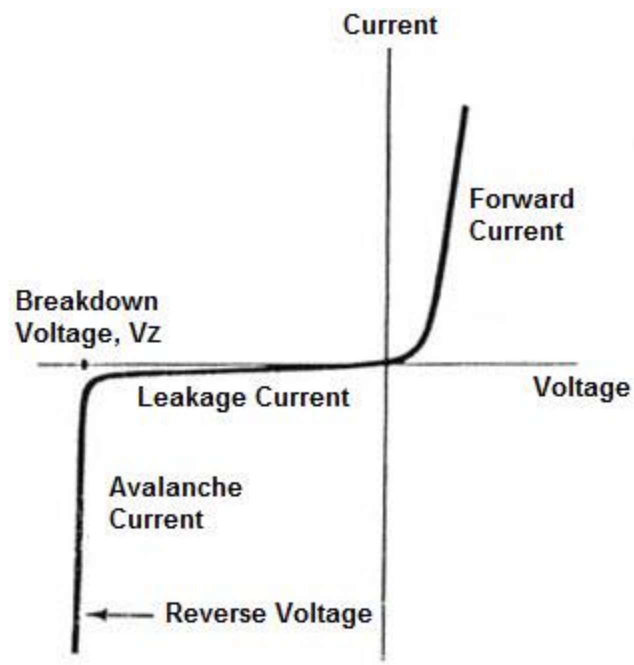
- Under reverse bias condition a small reverse current (in μ A) flows across the junction due to minority charge carriers.
- When the applied reverse voltage is high, it breaks the covalent bonds of the crystal and a large number of charge carriers are produced. Thus the current rises suddenly in the reverse direction. The reverse voltage at which the diode breaks down is called breakdown voltage or Zener voltage.
- The diode break down may be due to Avalanche break down or due to Zener break down.
- Avalanche break down occurs in diodes which are lightly doped.
- Zener break down occurs in diodes which are thin and heavily doped.

Application: A p-n junction can be used as a switch or rectifier.

9). Zener diode characteristics and explanation:

Zener diode is a semiconductor diode specially designed to operate in the breakdown region of the reverse bias. Zener diodes are always operated in the reverse bias condition. The breakdown phenomenon is reversible and harmless.



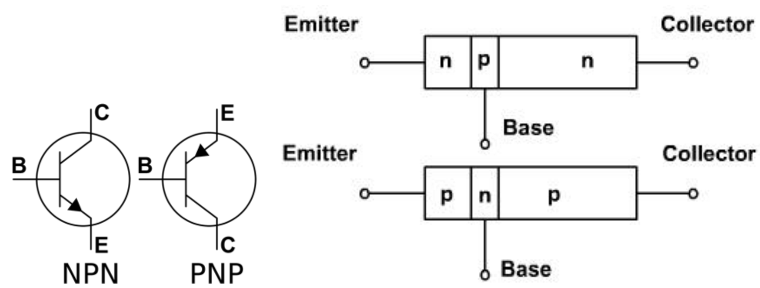


- Zener diode acts similar to a ordinary diode under forward bias condition.
- In reverse bias condition, as the reverse voltage is increased a small amount of current called leakage current flows. Leakage current is due to minority charge carriers.
- At a particular value of reverse voltage, the current increases suddenly. This voltage is called breakdown voltage or Zener voltage, V_Z.
- In ordinary diodes the breakdown voltage is high and if reverse current is allowed to flow, then the diode will be damaged.
- Zener diodes are designed so that their Zener voltage is much lower, about 2.4 volts.
- When a reverse voltage above the Zener voltage is applied to a Zener diode, there is a controlled breakdown which does not damage the diode.
- In the Zener region the voltage across the Zener diode remains constant but the current changes depending on the supply voltage.

- The location of Zener region can be controlled by varying doping levels. An increase in doping will decrease the Zener potential.
- Zener diodes are available in the range of 2 V to 200 V.

10). Construction and principle of operation of bipolar junction transistor:

- A transistor is a semiconductor device consisting of three regions i.e. the emitter, base and collector. The three regions are separated by two p-n junctions.
- Transistors are of two types i.e. npn and pnp.
- Electrons and holes are involved in current flow through an npn or pnp transistor and hence are called bipolar junction transistor.
- Representation of transistor



- The arrow in the representation is between the base and emitter. The direction of the arrow is the direction of flow of conventional current (conventional current direction is opposite to the direction of flow of electrons).
- In npn transistor, the arrow points from base to emitter. In this device electron flow from the emitter into the base and hence the direction of conventional current flow is from base to emitter.
- In pnp transistor, the arrow points from emitter to base. In this device electron flow from the base into the emitter and hence the direction of conventional current flow is from emitter to base.
- In most transistors, emitter is heavily doped. Its job is to emit or inject electrons into the base. These bases are lightly doped and very thin, it passes most of the emitter-injected electrons on to the collector. The doping level of collector is intermediate between the heavy doping of emitter and the light doping of the base.

- The collector is so named because it collects electrons from base. The collector is the largest of the three regions; it must dissipate more heat than the emitter or base. The transistor has two junctions. One between emitter and the base and other between the base and the collector. Because of this the transistor is similar to two diodes, one emitter diode and other collector base diode.

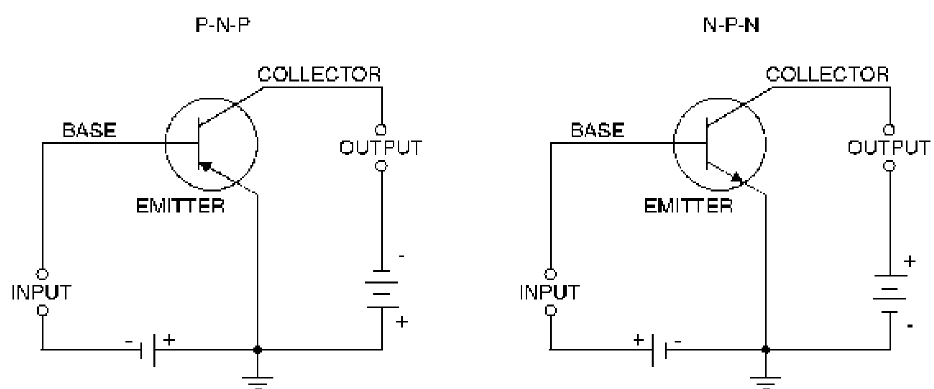
- **Biasing a transistor:**

The two junctions of the transistor can be biased in four different ways

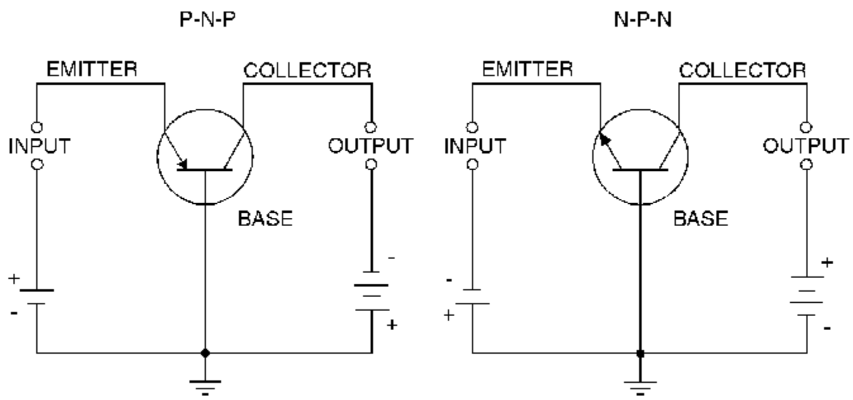
1. Both the junction are forward biased causing a large current to flow across the junctions. Then the transistor is said to be operating in the saturation region.
2. Both the junction are reverse biased causing a small current to flow across the junctions. Then the transistor is said to be operating in the cut-off region.
3. EB junction is reverse biased and CB junction is forward biased. The transistor is said to be operating in an inverted mode.
4. EB junction is forward biased and CB junction is reverse biased. The transistor is said to be operating in active region or normal mode.

- **Circuit configuration:**

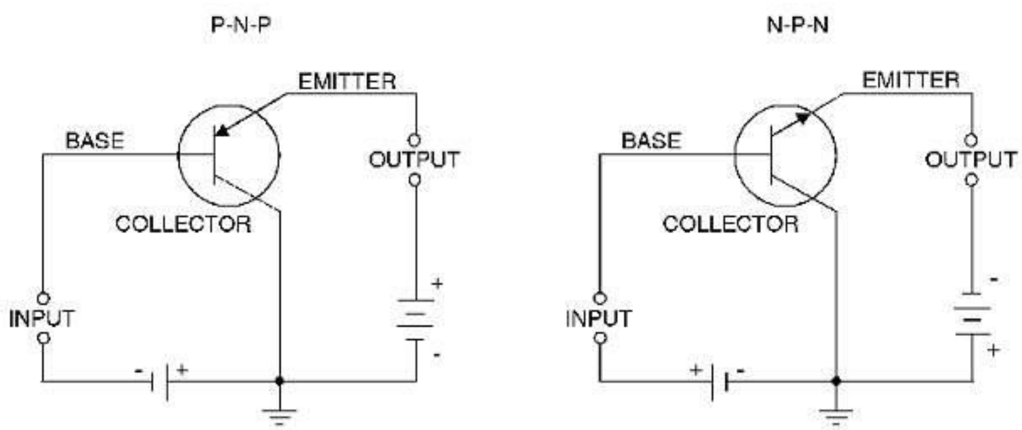
In normal mode when EB junction is forward biased and CB junction is reverse biased, the three configurations for pnp and npn transistor are shown



Common emitter configuration of pnp and npn transistor



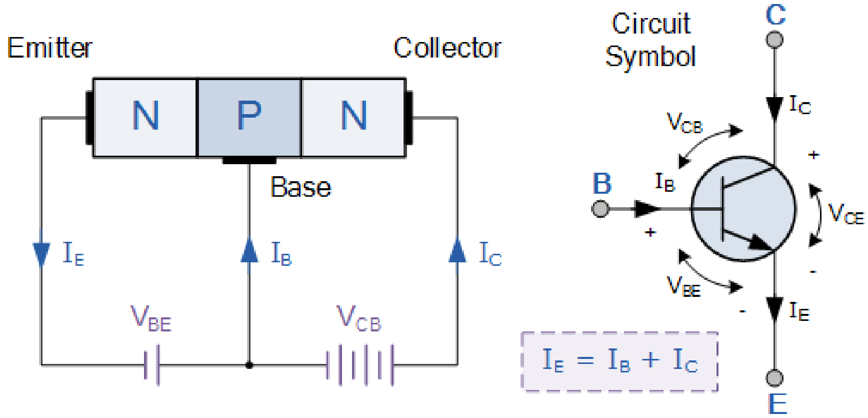
Common base configuration of pnp and npn transistor



Common collector configuration of pnp and npn transistor

Working of npn transistor:

The circuit diagram of the npn transistor is shown in the figure below. The forward biased is applied across the emitter-base junction, and the reversed biased is applied across the collector-base junction. The forward biased voltage V_{EB} is small as compared to the reverse bias voltage V_{CB}.



The emitter of the npn transistor is heavily doped. When forward bias is applied across the emitter, the majority charge carriers (electrons) move towards the base. This causes the emitter current I_E. The electrons enter into the p-type material and combine with the holes.

The base of the npn transistor is lightly doped. Due to which only a few electrons combine with holes in the base and remaining constitutes the base current I_B. This base current enters into the collector region. The reversed bias potential of the collector region causes high attractive force on the electrons reaching collector junction. Thus the electrons are attracted or collected at the collector. Large amount of heat is produced in the collector and hence to dissipate heat the collector region is made large.

A majority of electrons emitted by the emitter flow into the collector and cause a large reverse current I_C.

The ratio of number of electrons arriving at the collector to the number of electrons emitted by the emitter is called the base transportation factor, denoted by 'β'. Typically it is around 0.995.

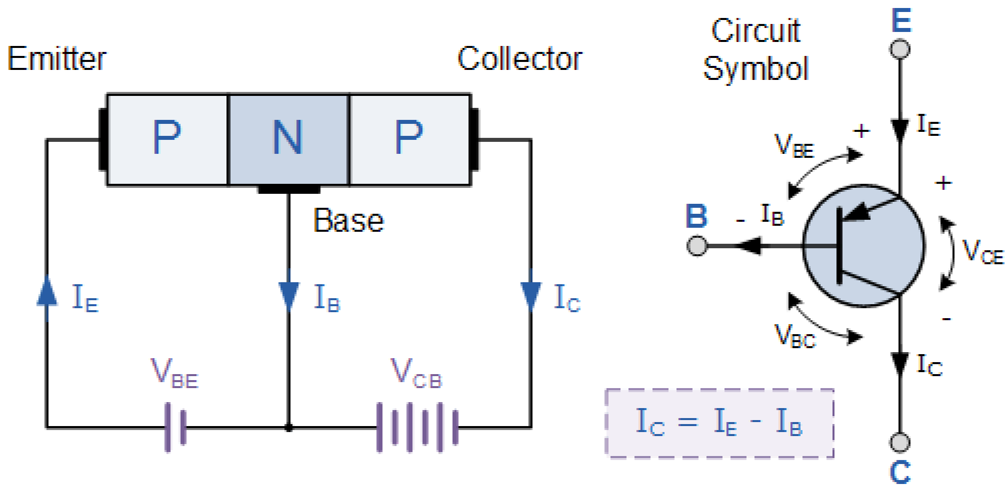
The whole of the emitter current is entered into the base. Thus, we can say that the emitter current is the sum of the collector or the base current.

$I_E = I_B + I_C$

Working of pnp transistor:

The circuit diagram of the pnp transistor is shown in the figure below. The forward biased is applied across the emitter-base junction, and the reversed biased is applied across the collector-base junction.

The forward bias causes the holes in the p-type emitter to flow towards the base. This constitutes the emitter current I_E . As these holes cross into n-type base, they tend to combine with the electrons. As the base is lightly doped and very thin, therefore, only a few holes (less than 5%) combine with the electrons. The remainder (more than 95%) cross into the collector region to constitute collector current I_C. In this way, almost the entire emitter current flows in the collector circuit. It may be noted that current conduction within pnp transistor is by holes. However, in the external connecting wires, the current is still by electrons.



Questions:

Short answer questions

1. Differentiate between intrinsic and extrinsic semiconductor.

2. Describe drift and diffusion current in semiconductors and write an equation for total current due to electrons and holes.

3. Explain the working of forward bias and reverse bias p-n junction diode.

4. Draw I - V characteristic curve of p-n junction diode and explain.

5. What is a Zener diode? Draw I - V characteristic curve of Zener diode and explain.

Long answer questions

1. Derive an expression for carrier concentration of intrinsic semiconductors?

2. Derive an expression for carrier concentration in n-type extrinsic semiconductors?

3. Derive an expression for carrier concentration in p-type extrinsic semiconductors?

4. What is Hall Effect? Write an expression for Hall coefficient.

5. Describe the formation of p-n junction and discuss I – V characteristics of p – n junction diode in forward and reverse bias conditions.

6. Describe the construction, principle, working of NPN and PNP bipolar junction transistors.

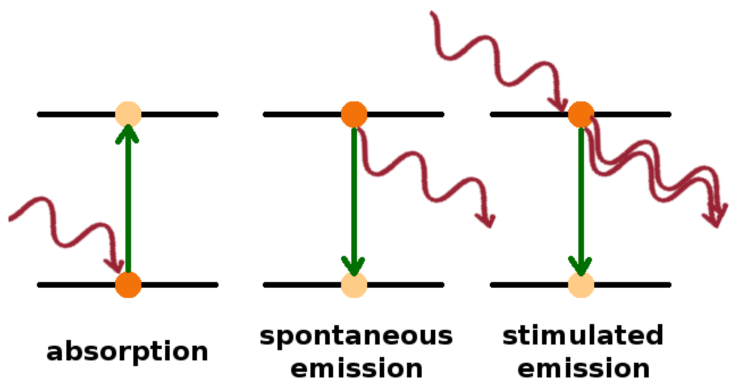
UNIT - III: Optoelectronics

1. Radiative, Non-Radiative transitions and recombination in semiconductors.

- When one electron leaving the energy level creates a hole, the process is called electron-hole pair generation. Similarly, when an electron combines with the hole, the process is called recombination.
- Generation and recombination of electron - hole pair essentially require external energies such as optical, electrical or thermal energies. Such processes are mainly between the valence band and the conduction band.

Radiative recombination:

- **Radiative recombination** occurs when an electron in conduction band recombines with a hole in the valence band and the excess energy is given out as photon.
- Optical process associated with radiative recombination is: Absorption, Spontaneous emission and Stimulated emission.



- **Absorption:** When at atom absorbs an amount of energy 'hv' in the form of photon from the external agency and excited into the higher energy levels from ground state, then this process is known as absorption. Atom + hv→ atom*
- **Spontaneous Emission:** When an atom in the excited state emits a photon of energy 'hv' coming down to ground state by itself without any external agency, such an emission is called spontaneous emission. Atom* → atom + hv
- Photons released in spontaneous emission are not coherent. Hence spontaneous emission is not useful for producing lasers.

- **Stimulated Emission:** When an atom in the excited state, emits two photons of same energy 'hν' while coming to down to ground state with the influence of an external agency, such an emission is called stimulated emission. Atom* ➝ atom + 2hν
- In the two photons one photon induces the stimulated emission and the second one is released by the transition of atom from higher energy level to lower energy level.
- Both the photons are coherent.

Non - radiative recombination:

- **Non - Radiative recombination** occurs when an electron in conduction band recombines with a hole in the valence band and the excess energy is given out as heat.
- Non-Radiative recombination process involves: Augur recombination, Surface recombination, recombination at defects.
- **Augur recombination:**

Augur recombination is of two types:

(1) One electron from conduction band recombines with hole in valence band (heavy-hole state) by giving away energy to another electron in conduction band. The energy gained electron jumps to a higher state and subsequently relaxes to valence band by giving energy as phonon. This is called conduction-conduction- heavy hole conduction **(CCHC)**.

(2) One electron from conduction band recombines with hole in the valence band (heavy hole state) and knocks one hole deep into the split-off level. This is conduction heavy hole-heavy hole-split off **(CHHS)** process.

Both the processes are non-radiative.

- **Surface recombination:** Recombination at surfaces and interfaces can have a significant impact on the behavior of semiconductor devices. This is because surfaces and interfaces typically contain a large number of recombination centers because of the abrupt termination of the semiconductor crystal, which leaves a large number of electrically active states. In addition, the surfaces and interfaces are more likely to contain impurities since they are exposed during the device fabrication process.
- **Defect Recombination:** It is known that the presence of impurities or crystal defects in semiconductors determines the lifetime of carriers, because a modified electronic

structure within the crystal will give rise to defect levels, or energy levels that do not lie near the edge of the band gap. Deep defects may lie deep within the forbidden band; these impurity levels are also called trap levels because they are traps for charge carriers. These levels can effectively facilitate a two-step recombination process called Shockley-Read-Hall (SRH) recombination where conduction electrons can relax to the defect level and then relax to the valence band, annihilating a hole in the process.

2. Carrier generation and recombination in semiconductors:

When sufficient energy is given to the semiconducting material, covalent bonds are broken and a pair of electron and hole is generated.

- The electrons are raised from valence band to conduction band. Holes remain in the valence band.
- The process of generation can occur only when the energy given to the semiconducting material is greater than its forbidden energy gap.
- Recombination is the process where an electron from the conduction band recombines with a hole in the valence band. This is called band to band recombination and in the process a photon is released.

3. Construction, working and characteristics of LED:

Principle: A Light emitting diode (LED) is essentially a p-n junction diode that gives off light when it is forward biased. When carriers are injected across a forward-biased junction, it emits incoherent light. Most of the commercial LEDs are realized using a highly doped n and p Junction.

The wavelength of the light emitted, and hence the color, depends on the band gap energy of the materials forming the p-n junction. The emitted photon energy is approximately equal to the band gap energy of the semiconductor.

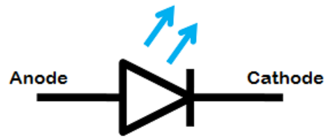
The following equation relates the wavelength and the energy band gap.

$h\nu = E_g$

$hc/\lambda = E_g$

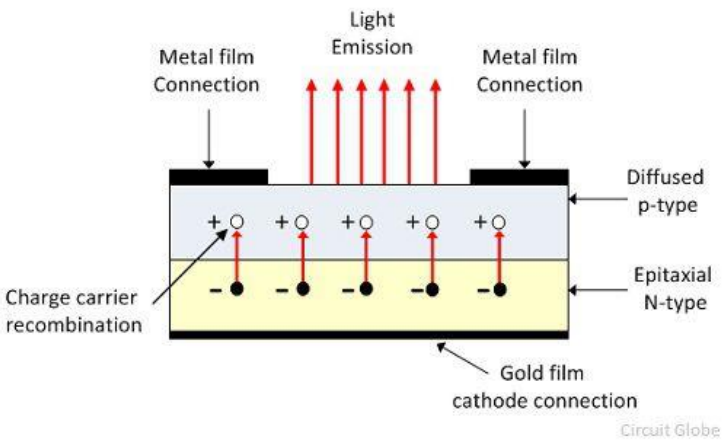
$\lambda = hc/E_g$

Where h is Plank’s constant, c is the speed of the light and Eg is the energy band gap.



LED symbol

Construction:



- In a surface emitting LED light is emitted in a direction perpendicular to the p-n junction plane.
- An n-type layer is grown on a substrate and a p-type layer is grown on it by the process of diffusion.
- The p-layer is made very thin to prevent loss of photons due to absorption in the layer. Metal contact is present on the p-layer such that some part of p-layer will allow photons to escape.
- Metal contact is present at the bottom for reflecting the photons into the material and to provide electrical contact.
- The generated light may suffer total internal reflection at the semiconductor-air interface and hence the device is enclosed in a epoxy resin of suitable refractive index so that the photons escape.

Working:

When a Voltage V is applied across the junction, the potential barrier across the p-n junction is reduced. This allows the electrons from the n side to get injected into the p-side. Since electrons are the minority carriers in the p-side, this process is called minority carrier injection. But the hole injection from the p side to n side is very less and so the current is primarily due to the flow of electrons into the p-side.

Electrons injected into the p-side recombine with the holes which results in spontaneous emission of photons (light). This effect is called injection electroluminescence. These photons should be allowed to escape from the device without being reabsorbed.

The recombination can be classified into the following two kinds

• Direct recombination

• Indirect recombination

In direct band gap materials, the minimum energy of the conduction band occurs at the same value of momentum vector as the maximum energy of the valence band.. The efficiency of transition is good. GaAs is an example of a direct band-gap material.

In in-direct band gap materials, the minimum energy of the conduction band and maximum energy of valence band occur at different values of momentum vector. Due to this difference in momentum, the probability of direct electron-hole recombination is less. GaP is an example of an indirect band-gap material.

The amount of light emitted is directly proportional to the forward current.

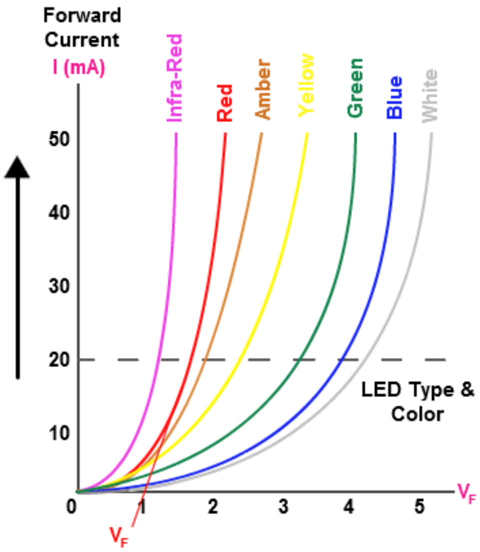
Characteristics of LED:

One of the major characteristics of an LED is its colour.

- Gallium Arsenide, GaAs emits light in infrared region.
- Gallium Arsenide-Phosphide, GaAsP emits red or yellow colour.
- Gallium Phosphide, GaP emits red or green colour.

The diagram below shows some typical approximate curves for the voltages that may be expected for different LED colours. Typically the LED voltage drop is between around 2 and 4 volts.

The actual LED voltage that appears across the two terminals is dependent mainly upon the type of LED in question - the materials used.



Applications of LED:

- As indicators and light source in fiber optics communication.
- A number of LED'S may be grouped together to form a display

4. Principle, construction and working of Semiconductor laser with relevant energy level diagram:

Semi-Conductor Laser:

- Semiconductor lasers are of two types, Except the Construction, Principle and working are same for both.

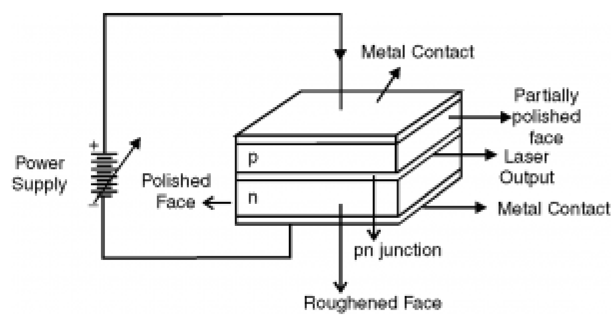
1. Homojunction semiconductor Laser
2. Hetrojunction semiconductor Laser

Principle:

- After the invention of semiconductor leaser in 1961, laser have become at common use.
- In conventional lasers, lasers are generated due to transition of electrons from higher to lower energy level.
- But in semi-conductor lasers the transition takes place from conduction band to valence band.

- The basic mechanism responsible for light emission from a semiconductor laser is the recombination of electrons and holes at pn-junction when current is passed through the diode.
- Stimulated emission can occur when the incident radiation stimulates an electron in conduction band to make a transition into valence band and in this process radiation will be emitted.
- When current is passed through pn – junction under forward bias, the injected electrons and holes will increase the density of electrons in CB and holes in VB. At some value of current the stimulated emission rate will exceed the absorption rate.
- As the current is further increased at some threshold value of current the amplification will take place and laser begin to emit coherent radiation.
- The properties of semiconductor laser depend upon the energy gap.

Fabrication/construction:



- Homojunction Semiconductor Laser

Homojunction Semiconductor Laser:

- Ga – As is heavily doped with impurities in both p & n regions. n region is doped with tellurium & p – region by Germanium.
- The concentration of doping is of the order of 10^{17} to 10^{19} impure atoms per cm.
- The size of the diode is small i.e., 1mm each side & the depletion layer's thickness varies from 1 to 100 μAm.

Hetrojunction Semiconductor Laser:

- Hetrojunction means the material on one side of the junction differs from that on the other side.i.e;Ga-AS on one side and GaAlAs on other side.
- Generation and recombination takes place very fast.

Working:

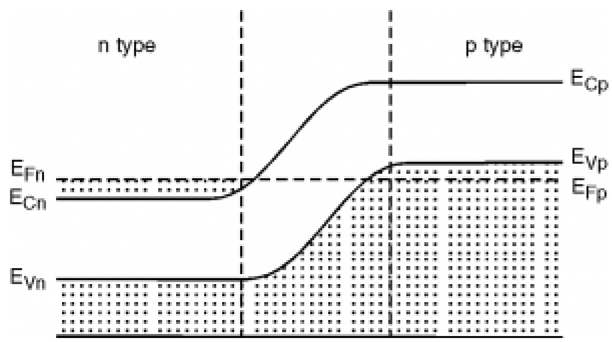


Fig a) when no biasing

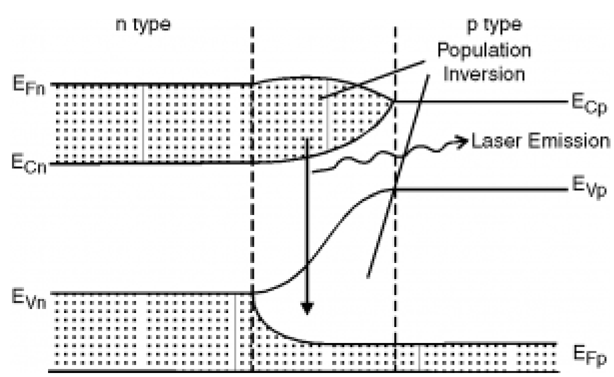


Fig b) with biasing

- When the junction is forward biased, electrons from n-region & holes from p-region move to cross the junction in opposite directions.
- In the junction region the electrons &holes recombination due to transition of electrons from CB to VB.
- For low currents population inversion does not take place, hence only spontaneous emission takes place and the photons released are not coherent.

- When forward current is further increased beyond the certain threshold value population inversion takes place and coherent photons are released.
- The energy gap of Gallium Arsenide (Ga-As) is 1.487eV and corresponding wavelength of radiation is 6435 A^0 which is responsible for laser emission.

LASER Characteristics:

- Directionality
- Negligible divergence
- High intensity
- High degree of coherence
- Monochromatic

5). Applications of Lasers in various fields:

1. Communication:

- Lasers are used in optical communications, due to narrow band width.
- The laser beam can be used for the communication b/w earth & moon (or) other satellites due to the narrow angular speed.
- Used to establish communication between submarines i.e; under water communication.

2.Medical:

- Identification of tumors and curification.
- Used to detect and remove stones in kidneys.
- Used to detect tumors in brain.

3. Industry:

- Used to make holes in diamond and hard steel.
- Used to detect flaws on the surface of aero planes and submarines.

4.Chemical &Biological:

- Lasers have wide chemical applications. They can initiate or fasten chemical reactions.
- Used in the separation of isotopes.
- Lasers can be used to find the size & shape biological cells such as erythrocytes

6). Internal photoelectric effect, photoconductive effect and photo detectors:

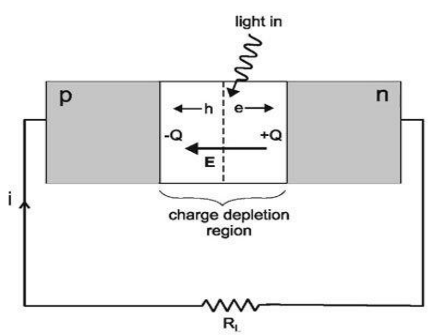
Internal photoelectric effect: When light is incident on an intrinsic semiconductor, electrons are excited from valence band to conduction band and this leads to generation of electron and hole. Thus an increase of charge carrier concentration occurs within the semiconductor and the effect is called internal photoelectric effect.

Photoconductive effect: An increase in free charge carriers leads to an increase in the conductivity of the semiconductor. The light induced increase in the electrical conductivity is called photoconductive effect or photoconductivity.

Photo detectors: These are devices that absorb optical energy and convert it to electrical energy. The operation of photoelectric detectors is based on internal photoelectric effect. There are three main types of photo detectors: Photodiodes, pin diodes and avalanche photodiodes.

7). Photo detectors: photoconductive mode and photovoltaic mode:

A photo detector is a device which absorbs light and converts the optical energy to measurable electric current. It is essentially a p-n junction diode which is reverse biased. The depletion region contains immobile ions which generate an electric field. When a photon is incident on the junction, a electron - hole pair may be generated in the depletion region. The electric field due to the immobile ions will separate the electron and holes generated as shown in the figure below.



This charge separation can be used in two ways:

1. Photoconductive mode and
2. Photovoltaic mode.

1. Photoconductive mode:

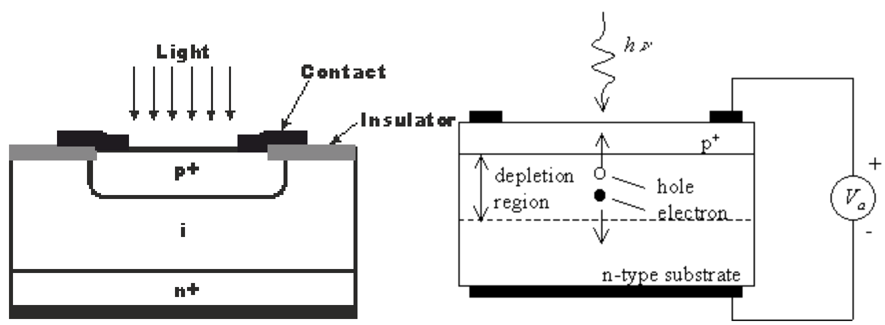
The device which is reversed biased is left on short circuit externally. The reverse voltage application will increase the depletion layer's width, which in turn decreases the response time & the junction capacitance. This mode is too fast and displays electronic noise.

2. Photovoltaic mode:

If the diode is left on open-circuit, an externally measurable voltage appears between p and n regions. This mode of operation is used in solar cells.

8). Structure and working principle of p-i-n photodiode.

It is a device that consists of p region and n region separated by a very lightly doped intrinsic region (i). The depletion region extends into the intrinsic region and hence almost the entire intrinsic region acts as depletion region. The p-i-n structure of the photodiode enables to increase the width of the depletion region to a value which is greater than a p-n junction.



The p-i-n photodiode is reverse biased and hence there are no free charge carriers in the depletion region but the depletion region contains immobile charge carriers which generate electric field. When a photon having energy greater than or equal to band gap energy is incident on the depletion region, then electron-hole pairs are generated.

The high electric field present in the depletion region cause the electron-hole pair generated by the photon to separate and be collected across the reverse biased junction. This gives rise to a current flow in the external circuit.

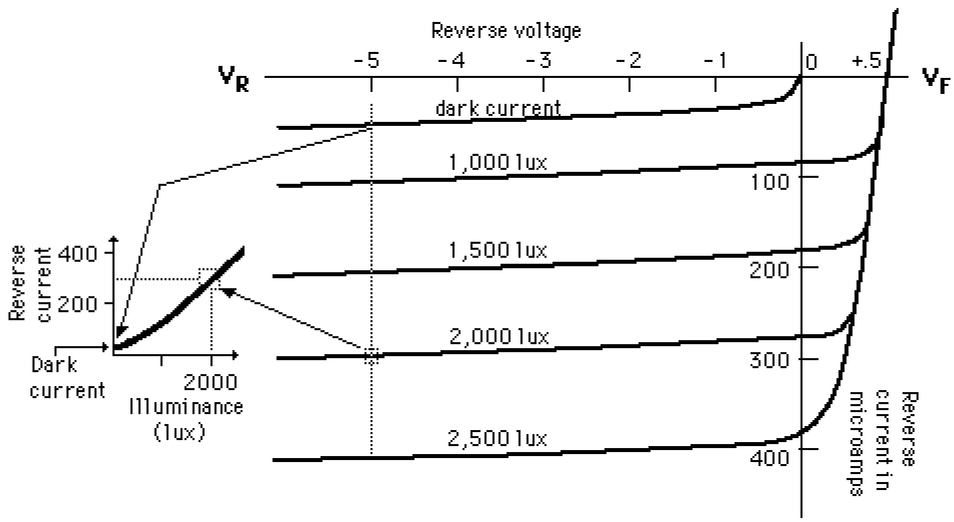
As the depletion region is wide, most of the incident photons are absorbed in this region and the efficiency of the device is high. Also the dark current is small. Dark currents are the current generated by minority charge carriers when no photons are incident on the material.

9). Characteristics of photo detectors:

Characteristics:

V – I Characteristics:

- Photodiode operates in reverse bias mode.
- The photocurrent is nearly independent of reverse bias voltage which is applied.
- For zero luminance, the photocurrent is almost zero but a small amount of dark current is present.
- As optical power rises the photo current also rises linearly.



Quantum efficiency:

The quantum efficiency, η, is the number of electron-hole pairs generated per incident photon of energy hν and is given by

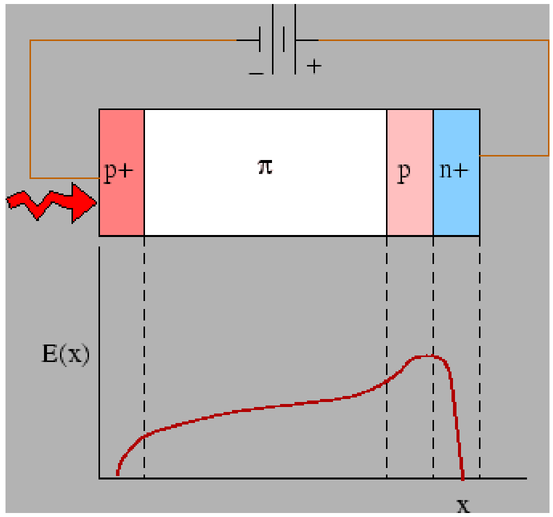
$$\eta = \frac{number of electron-hole pair generated}{number of incident photons}$$

Responsivity:

It specifies the photocurrent generated per unit optical power.

10). Structure and working principle of Avalanche photodiode:

Avalanche photodiode works on internal gain mechanism so that the photoelectric current is amplified within the detector. It is very useful when low levels of light are to be detected. The structure of Avalanche photodiode is shown in the figure below and is known as $p^+ \pi p n^+$ reach-through structure. The π region is the intrinsic region.



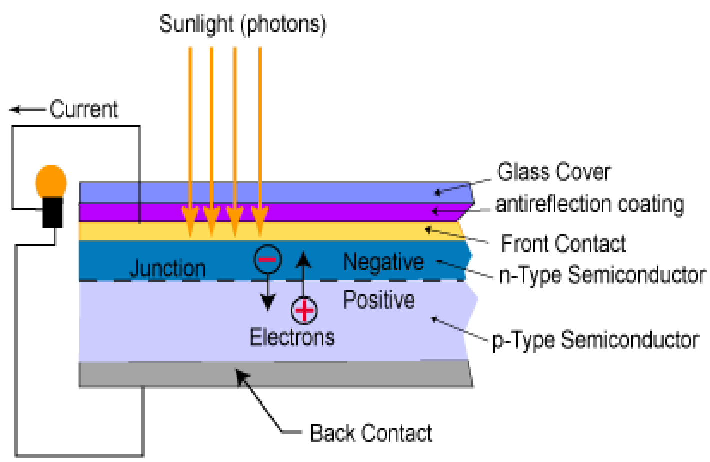
The device is a reverse biased p-n junction. The p^+ and n^+ are heavily doped semiconductors and have a very low resistance. The π region is very lightly doped and is nearly intrinsic in nature. Under reverse biased condition a depletion region is present between p and n^+ region and it covers most of the π region. Under sufficient reverse bias, the junction approaches breakdown condition. A electric field is present in the junction region due to immobile charge carriers.

A photon that enters through the p^+ region is absorbed in the intrinsic region and the resulting electron-hole pair that is generated is separated by the electric field in the π region. The hole drifts towards the p^+ region and do not take part in multiplication process. The electrons drift through the π region to the p n^+ junction. The electric field present in the p n^+ region accelerates the electrons which in turn ionize neutral atoms in its path. The effect is cumulative and builds up into an avalanche. Thus there is carrier multiplication and internal amplification. This amplification process enhances the responsivity of the detector.

11). Structure, working principle and characteristics of solar cell:

A solar cell is a p-n junction that can generate electrical power when illuminated with sunlight. They operate under photovoltaic mode i.e. if the diode is left on open-circuit; an externally measurable voltage appears between p and n regions.

The structure of a solar cell is shown in the figure below. It consists of a p – type chip on which a thin layer of n – type material is grown. The n region is heavily doped and thin so that the light can penetrate through it easily. The p region is lightly doped so that most of the depletion region lies in the p side. It also consists of a glass cover and antireflection coating. The front and back contacts are metallic contacts for the flow of electrons. Electron hole pairs are mainly created in the depletion region and due to the built-in potential and electric field, electrons move to the n region and the holes to the p region.



The movement of electrons and holes results in accumulation of charge on the two sides of the junction and produces a potential difference called photo emf. If a load (bulb in the above circuit) is connected across the cell a current flows through it.

I-V Characteristics:

The I-V characteristics depend on the intensity of the incident radiation and also the operating point (external load) of the cell.

- If the external circuit is a short circuit (external load resistance is zero) then the only current is due to the generated electron – hole pair by the incident light. This is called the photocurrent, denoted by I_{ph}. Another name for this is the short circuit current, I_{sc}.
- The photo current is related to the intensity of the incident radiation, I_{op}, by $I_{ph} = k\ I_{op}$ where k is a constant and depends on the particular device. k is equivalent to an efficiency metric that measures the conversion of light into electron-hole pairs.
- When external load, R, is connected it develops a voltage. This voltage opposes the built in potential and reduces the barrier for carrier injection across the junction.
- This is similar to a pn junction in forward bias, where the external bias causes injection of minority carriers and increased current. This forward bias current opposes the photo current generated within the device due to the solar radiation. This is because Iph is

generated due to electrons going to the n side and holes to the p side due to the electric field within the device, i.e. drift current while the forward bias current is due to diffusion current (I_d) caused by the injection of minority carriers.

- The net current can be written as $I = -I_{ph} + I_d$
- From the figure 1 below, it can be seen that Short circuit current and open circuit voltage both increase with increasing illumination.
- From figure 2 below, maximum power is indicated by the shaded area. The corresponding voltage and current are V_m and I_m

Power = $V_m \times I_m$

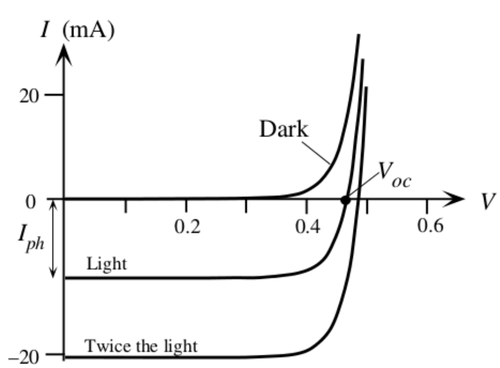


Figure 1

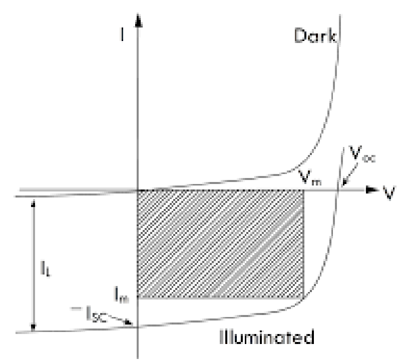


Figure 2

Questions:

Short answer questions

1. Write a note on radiative and non-radiative transitions and recombination in semiconductors.
2. Mention some important applications of Lasers in various fields?
3. Write a note on internal photoelectric effect, photoconductive effect and photo detectors.
4. What are photo detectors? Explain photoconductive mode and photovoltaic mode.
5. What is generation and recombination mechanism in Semiconductors.

Long answer questions

1. Explain the construction, working and characteristics of LED.

2. Describe the principle, construction and working of Semiconductor laser with relevant energy level diagram?

3. Explain the structure and working principle of p-i-n photodiode.

4. Explain the characteristics of photo detectors.

5. Explain the structure and working principle of Avalanche photodiode.

6. Explain the structure, working principle and characteristics of solar cell.

UNIT- IV: Lasers and Fiber Optics

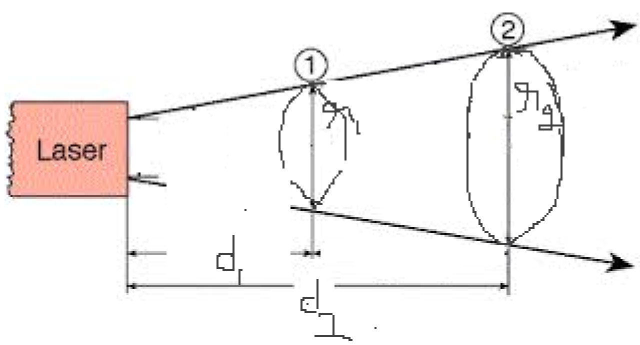
Laser: Laser means **Light Amplification by Stimulated Emission of Radiation.**

1). Characteristics/Striking features/Properties of Laser:

Characteristics of Laser Beam: Some of the special properties which distinguish lasers from ordinary light sources are characterized by:

1. Directionality
2. High Intensity
3. Mono- chromacity
4. Coherence

1. Directionality:



Laser emits radiation only in one direction due to the presence of coherent photons. The directionality of laser beam is expressed in terms of angle of divergence (Φ)

Divergence or Angular Spread is given by **$\Phi = r_2-r_1/d_2-d_1$**

Where d_1, d_2 are any two distances from the laser source emitted and r_1, r_2 are the radii of beam spots at a distance d_1 and d_2 respectively as shown in above figure. Laser light having less divergence, it means that laser light having more directionality.

2. High Intensity: Generally, light from conventional source spread uniformly in all directions. For example, take 100 watt bulb and look at a distance of 30 cm, the power enter into the eye is less than thousand of a watt. This is due to uniform distribution of light in all directions.

But in case of lasers, light is a narrow beam and its energy is concentrated within the small region. The concentration of energy accounts for greater intensity of lasers.

3. Monochromacity: The light emitted by laser is highly monochromatic than any of the other conventional monochromatic light. A comparison b/w normal light and laser beam, ordinary sodium (Na) light emits radiation at wave length of $5893A^0$ with the line width of $1A^0$. But He-Ne laser of wave length $6328A^0$ with a narrow width of only 10^{-7} A^0 i.e., Monochromacity of laser is 10 million times better than normal light.

The degree of Monochromacity of the light is estimated by line of width (spreading frequency of line).

4. Coherence: If any wave appears as pure sine wave for longtime and infinite space, then it is said to be perfectly coherent.

Practically, no wave is perfectly coherent including lasers. But compared to other light sources, lasers have high degree of coherence because all the energy is concentrated within the small region.

There are two independent concepts of coherence.

i) Temporal coherence (criteria of time)

ii) Spatial coherence (criteria of space)

Absorption:

When at atom absorbs an amount of energy ‘hv’ in the form of photon from the external agency and excited into the higher energy levels from ground state, then this process is known as absorption.

Atom + hv→ atom*

Spontaneous Emission:

When an atom in the excited state emits a photon of energy ‘hv’ coming down to ground state by itself without any external agency after life time, such an emission is called spontaneous emission.

Atom* → atom + hv

Photons released in spontaneous emission are not coherent. Hence spontaneous emission is not useful for producing lasers.

Stimulated Emission:

When an atom in the excited state emits two photons of same energy ‘hv’ while coming to down to ground state with the influence of an external agency before life time, such an emission is called stimulated emission.

Atom* → atom + 2hv

In the two photons one photon induces the stimulated emission and the second one is released by the transition of atom from higher energy level to lower energy level. Both the photons are strictly coherent. Hence stimulated emission is responsible for laser production.

2). Einstein's coefficients/ Einstein's Theory of Radiation/ Relation between the probabilities of spontaneous emission and stimulated emission in terms of Einstein's coefficient:

Einstein's Theory of Radiation:

- In 1917, Einstein predicted the existence of two different kinds of processes by which an atom emits radiation.
- Transition between the atomic energy states is statistical process. It is not possible to predict which particular atom will make a transition from one state to another state at a particular instant. For an assembly of very large number of atoms it is possible to calculate the rate of transitions between two states.
- Einstein was the first to calculate the probability of such transition, assuming the atomic system to be in equilibrium with electromagnetic radiation.
- If N_1 is the number of atoms in E_1 state, N_2 is the number of atoms in E_2 state. $U(\gamma)$ is the enrgy incident on the system, then
- The probability of transmission of atoms form E_1 to E_2 state (stimulated absorption) is

  $P_{12} \propto U(\gamma)$

  $P_{12} = B_{12}\, U(\gamma)$

  $N_1 P_{12} = N_1 B_{12}\, U(\gamma)$….. (1)

  $B_{12} = Proportioanl\ constant$
- The probability of transmission of atoms form E_2 to E_1 state (spontaneous emission) is

  $N_2 P_{21} = N_2 A_{21}$

  The number of spontaneous transitions N_{sp} taking place in time'Δt' depends on only number of atoms N_2 lying in excited state.
- The probability of transmission of atoms form E_2 to E_1 state (spontaneous emission) is

  $P_{21} \propto U(\gamma)$

  $N_2 P_{21} = N_2 B_{21}\, U(\gamma)$

  Therefore, the numbers of downward transitions are

  $N_2 P_{21} = N_2 A_{21} + N_2 B_{21}\, U(\gamma)$… (2)

- Under the thermal equilibrium, number of upward transitions = number of downward transitions per unit volume per second.
- $N_1 P_{12} = N_2 P_{21}$

  From (1) and (2)

  $N_1 B_{12}\, U(\gamma) = N_2 A_{21} + N_2 B_{21}\, U(\gamma)$

  $U(\gamma)[N_1 B_{12} - N_2 B_{21}] = N_2 A_{21}$

  $$U(\gamma) = \frac{N_2 A_{21}}{[N_1 B_{12} - N_2 B_{21}]}$$

  $$U(\gamma) = \frac{N_2 A_{21}}{N_2 B_{21}[N_1 B_{12} - 1]}$$

  $$U(\gamma) = \frac{\frac{A_{21}}{B_{21}}}{\left[\frac{N_1}{N_2}\frac{B_{12}}{B_{21}} - 1\right]} \ldots\ldots (3)$$

  According to Maxwell- Boltzmann statistics,

  $\frac{N_1}{N_2} = exp^{\frac{h\gamma}{K_B T}} \ldots\ldots (4)$ in (3)

  $$U(\gamma) = \frac{\frac{A_{21}}{B_{21}}}{\left[exp^{\frac{h\gamma}{K_B T}}\frac{B_{12}}{B_{21}} - 1\right]} \ldots (4)$$

  On comparing eq (4) with Planck's theory of black body radiation

  $$U(\gamma) = \frac{8\pi\gamma^2 d\gamma}{c^3}\,\frac{1}{exp^{\frac{h\gamma}{K_B T}} - 1} \ldots (5)$$

  $comparing\ eq(4) and\ (5)$

  $$\frac{A_{21}}{B_{21}} = \frac{8\pi\gamma^2 d\gamma}{c^3}$$

  $\frac{A_{21}}{B_{21}} \propto \gamma^2 \ldots. (6)$

  $$\frac{B_{12}}{B_{21}} = 1$$

  $B_{12} = B_{21} ..(7)$

$Eqn\ (6), (7) are\ called\ as\ Einstein's\ relations$

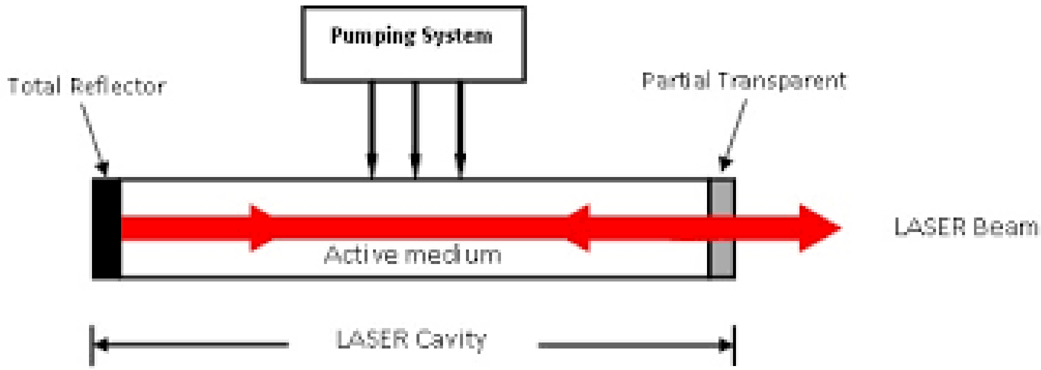
The coefficients A_{21}, B_{12}, B_{21} are known as Einstein coefficients.

Note: Since we are applying same amount of energy (Q) and observing in the same time (Δt), number of atoms excited into higher energy levels (absorption) = number of atoms that made transition into lower energy levels (stimulated emission)

$B_{12} = B_{21}$ i.e. absorption = stimulated emission

3). Resonating Cavity or Optical Resonator:

The optical resonator constitutes an active medium kept in-between a 100% reflecting mirror and a partially reflecting mirror as shown in figure.



This optical resonator acts as a feedback system in amplifying the light emitted from the active medium, by making it to undergo multiple reflections between the 100% mirror and the partial mirror. Here the light bounces back and forth between the two mirrors and hence the intensity of the light is increased enormously. Finally, the intense, amplified beam called LASER is allowed to come out through the partial mirror as shown in figure.

4). Active Medium, Metastable state, Population inversion and pumping:

Active Medium: The medium in which the population inversion takes place is called active medium.

Metastable state: The excited state, which has a long lifetime is known as metastable state.

Population Inversion:

- Generally, number of atoms in the ground state is greater than the number of atoms in higher energy states.
- But in order to produce a laser beam, the minimum requirement is stimulated emission.
- Stimulated emission takes place only if the number of atoms in the higher energy level is greater than the number of atoms in the lower energy level.
- Simply population inversion is nothing but number of atoms in higher energy level is greater than the number of atom in lower energy level.

- So, if there is a population inversion there by only stimulated emission will able to produce laser beam.
- Population inversion is associated with three processes.
  - Stimulated emission
  - Amplification
  - Pumping Process
- Stimulated Emission: If majority of atoms are present in higher energy state than the process becomes very easy.
- Amplification: If 'N', represents number of atoms in the ground state and 'N_2' represents number of atoms in the excited state than the amplification of light takes place only when $N_2 > N_1$.

- If $N_2 > N_1$, there will be a population inversion so induced beam and induced emission are in the same directions and strictly coherent than the resultant laser is said to be amplified.
- Boltzmann's principle gives the information about the fraction of atom found on average in any particular's energy state at equilibrium temperature as
- $\frac{N1}{N2}$ = exp (E_2-E_1/KT) = exp (ΔE/KT)

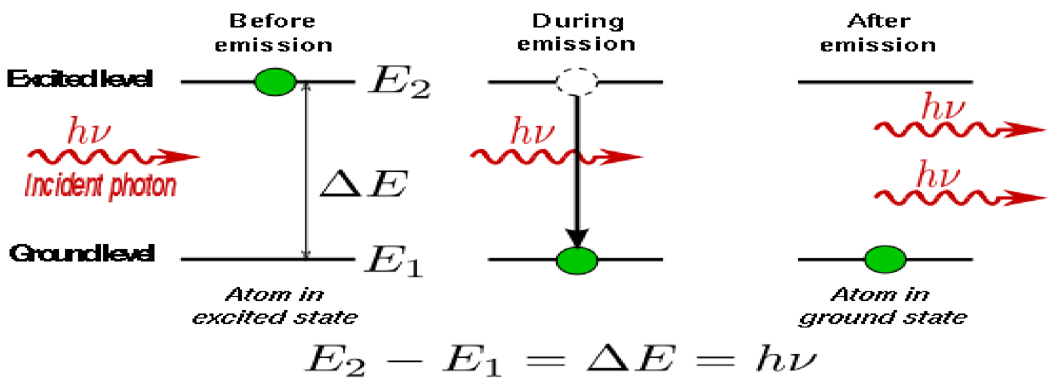
  $\frac{N1}{N2}$ = exp (hv/KT)

Pumping Process:

- This process is required to achieve population inversion.
- Pumping process is defined as: "The process which excites the atoms from ground state to excited state to achieve population inversion".
- Pumping can be done by number of ways
- i) Optical Pumping → excitation by strong source of light (flashing of a Camera)
- ii) Electrical Pumping → excitation by electron impact
- iii) Chemical Pumping → excitation by chemical reactions

5). Principle of laser/lasing action:

- **Laser Production Principle:**
- Two coherent photons produced in the stimulated emission, interacts with other two excited atoms, resulting in four coherent photons.
- Thus, coherent photons are multiplied in a lasing medium. The continuous successive emission of photons results for the production of laser beam.



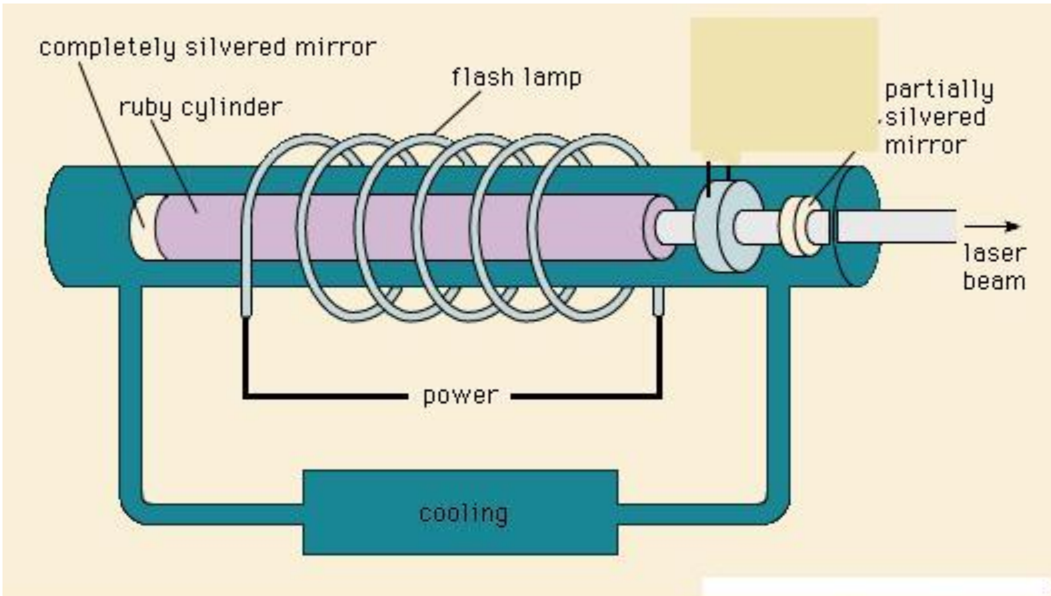
6). Principle, construction and working of ruby laser with energy level diagram:

- **Ruby Laser:** It is a 3 level solid state laser, discovered by Dr. T. Maimann in 1960.

Principle:

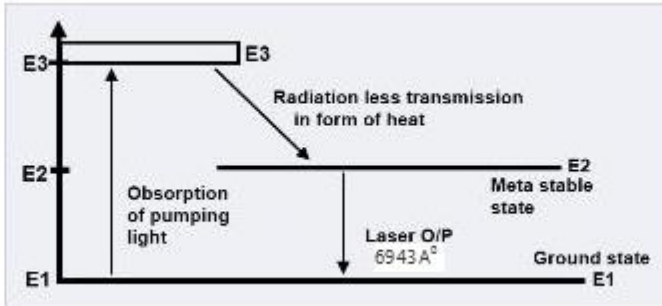
- The chromium Ions raised to excited states by optical pumping using xenon flash lamp
- Then the atoms are accumulated at metastable state by non-radiative transition.
- Due to stimulated emission the transition of atoms take place from metastable state to ground state, there by emitting laser beam.

- **Construction:**



- Ruby is a crystal of aluminum oxide (Al_2O_3) in which some of the aluminum ions (Al^{3+}) is replaced by chromium ions (Cr^{3+}). This is done by doping small amount (0.05%) of chromium oxide (Cr_2O_3) in the melt of purified Al_2O_3.
- These chromium ions give the pink color to the crystal. Laser rods are prepared from a single crystal of pink ruby. Al_2O_3 does not participate in the laser action. It only acts as the host.
- The ruby crystal is in the form of cylinder. Length of ruby crystal is usually 2 cm to 30 cm and diameter 0.5 cm to 2 cm.
- The ends of ruby crystal are polished, grounded and made flat.
- The one of the ends is completely silvered while the other one is partially silvered to get the efficient output. Thus the two polished ends act as optical resonator system.
- A helical flash lamp filled with xenon is used as a pumping source. The ruby crystal is placed inside a xenon flash lamp. Thus, optical pumping is used to achieve population inversion in ruby laser.
- As very high temperature is produced during the operation of the laser, the rod is surrounded by liquid nitrogen to cool the apparatus.

- **Working with Energy Level Diagram (ELD):**



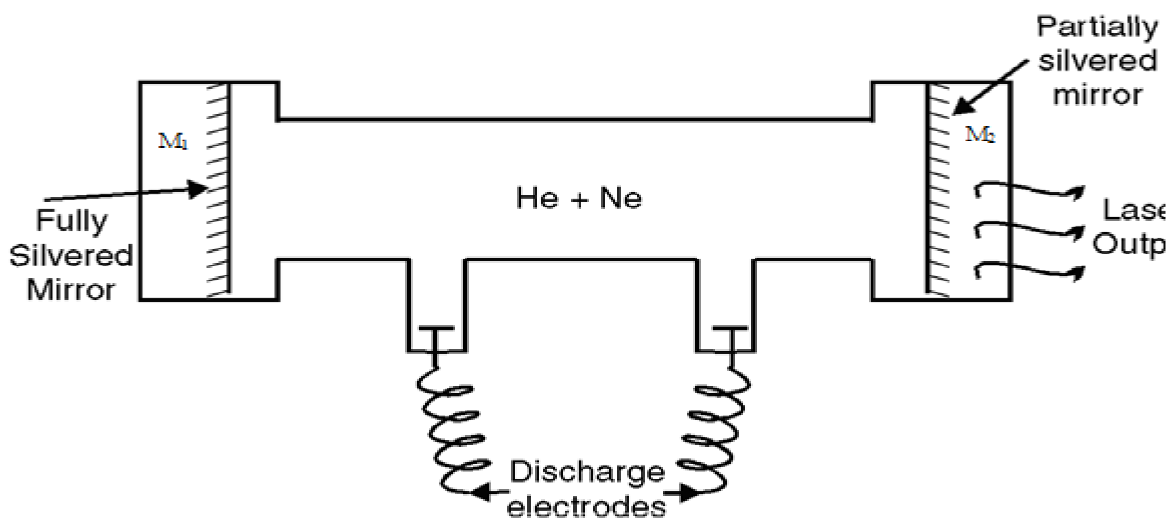
- Energy Level Diagram of Ruby Laser

- The flash lamp is switched on, a few thousand joules of energy is discharged in a few milliseconds.
- A part of this energy excites the Cr^{3+} Ions to excited state from their ground state and the rest heats up the apparatus can be cooled by the cooling arrangement by passing liquid nitrogen.
- The chromium ions respond to this flash light having wavelength 5600 A^0(Green),[4200 A^0(Red)Also]
- When the Cr^{3+} Ions are excited to energy level E_3 from E_1 the population in E_3 increases.
- Cr^{3+} Ions stay here(E_3) for a very short time of the order of 10^{-8} sec, then they drop to the level E_2 which is metastable state of lifetime 10^{-3} sec .Here the transitions from E_3 to E_2 is non radiative in nature.
- As the lifetime of the state E_2 is much longer, the number of ions in this state goes on increasing while in the ground state (E_1) goes on decreasing. By this process population inversion is achieved between E_2& E_1.
- When an excited ion passes spontaneously from the metastable state E_2 to the ground state E_1 it emits a photon of wavelength 6943A^0.
- This photon travels through the ruby rod and if it is moving parallel to the axis of the crystal, is reflected back & forth by silvered ends until it stimulates an excited ion in E_2 and causes it to emit fresh photon in phase with the earlier photon. This stimulated transition triggers the laser Transition.
- The process is repeated again and again, because the photons repeatedly move along the crystal being reflected from ends. The photons thus get multiplied.

- When the photon beam becomes sufficiently intense, such that a part of it emerges through the partially silvered end of the crystal.

7). Principle, construction and working of He-Ne laser with energy level diagram:

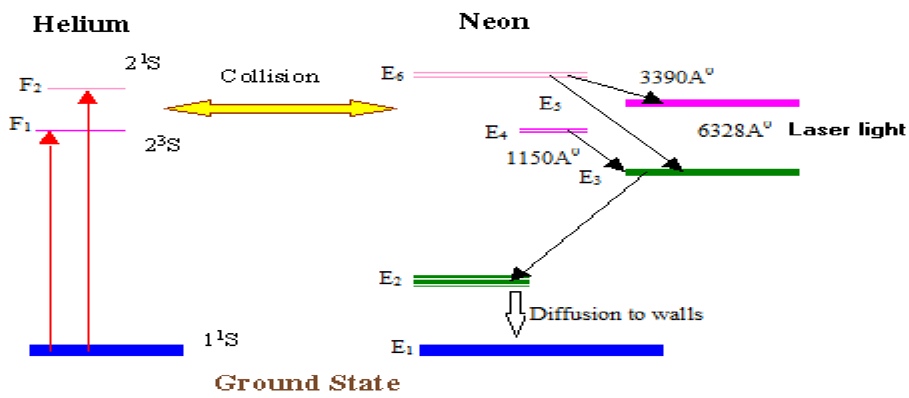
- **He-Le Laser:** The first gas laser to be operated successfully was the He-Ne laser in 1961 by the scientist A. Jawan.
- **Principle:** This laser is based on the principle of stimulated emission, produced in the active medium of gas. Here, the population inversion achieved due to the interaction between the two gases which have closer higher energy levels.
- **Construction:**



▪ He-Ne laser

- In this method, two gases helium & Neon were mixed in the ratio 10:1 in a discharge tube made of quartz crystal.
- The dimensions of the discharge tube are nearly 80 cm length and 1.5 cm diameter, with its windows slanted at Brewster's angle i.e., $\theta = \mathrm{Tan}^{-1}(n)$,Where n = refractive index of the window substance.
- The purpose of placing Brewster windows on either side of the discharge tube is to get plane polarized laser output.
- Two concave mirrors M_1& M_2 are made of dielectric material arranged on both sides of the discharge tube so that their foci lines within the interior of discharge tube.

- One of the two concave mirrors M_1 is thick so that all the incident photons are reflected back into lasing medium.
- The thin mirror M_2 allows part of the incident radiation to be transmitted to get laser output.
- **Working:**



- Energy Level Diagram

- The discharge tube is filled with Helium at a pressure of 1 mm of Hg & Neon at 0.1mm of Hg.
- When electric discharge is set-up in the tube, the electrons present in the electric field make collisions with the ground state He atoms.
- Hence ground state He atoms get excited to the higher energy levels F_1 ($2S_1$), F_2 ($2S_3$).
- Here Ne atoms are active centers.
- The excited He atoms make collision with the ground state Ne atoms and bring the Ne atoms into the excited states E_4& E_6.
- The energy levels E_4& E_6 of Ne are the metastable states and the Ne atoms are directly pumped into these energy levels.
- Since the Ne atoms are excited directly into the levels E_4& E_6, these energy levels are more populated than the lower energy levels E_3&E_5.
- Therefore, the population inversion is achieved between E_6&E_5,E_6&E_3,E_4&E_3
- The transition between these levels produces wavelengths of 3390 A^0,6328 A^0,1150 A^0 respectively.

- Now The Ne atoms undergo transition from E_3 to E_2 and E_5 to E_2 in the form of fast decay giving photons by spontaneous emission. These photons are absorbed by optical elements placed inside the laser system.
- The Ne atoms are returned to the ground state(E_1) from E_2 by non radiative diffusion and collision process, therefore there is no emission of radiation.
- Some optical elements placed inside the laser system are used to absorb the IR laser wavelengths 3390 A^0, 1150 A^0.
- Hence the output of He-Ne laser contains only a single wavelength of 6328A^0.
- The released photons are transmitted through the concave mirror M_2 there by producing laser.
- A continuous laser beam of red color at a wavelength of 6328A^0.
- By the application of large potential difference, Ne atoms are pumped into higher energy levels continuously. A Laser beam of power 5 to 50 MW comes out from He-Ne laser.

8). Applications of Lasers in various fields:

Lasers have wide applications in different branches of science and engineering because of the following.

- Very narrow band width
- High directionality
- Extreme brightness

1. Communication:

- Lasers are used in optical communications, due to narrow band width.
- The laser beam can be used for the communication b/w earth & moon (or) other satellites due to the narrow angular speed.
- Used to establish communication between submarines i.e; under water communication.

2. Medical:

- Identification of tumors and curification.
- Used to detect and remove stones in kidneys.
- Used to detect tumors in brain.

3. Industry:

- Used to make holes in diamond and hard steel.
- Used to detect flaws on the surface of aero planes and submarines.

4. Chemical &Biological:

- Lasers have wide chemical applications. They can initiate or fasten chemical reactions.
- Used in the separation of isotopes.
- Lasers can be used to find the size & shape biological cells such as erythrocytes.

9). Principle, structure and working of an optical fiber:

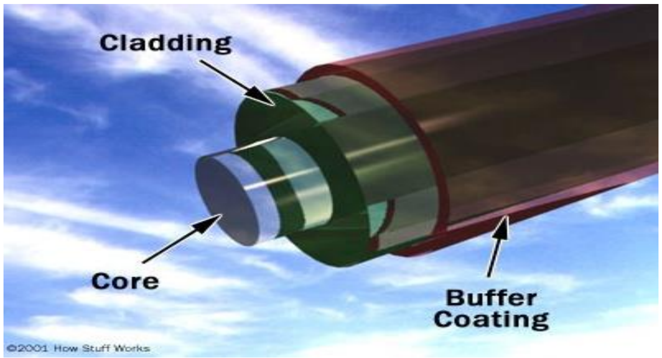
Optical Fiber: Optical fibers are the wave guides through which electromagnetic radiation of optical frequency range can be guided over a long distance in a short span of time and with minimum number of losses. These are used in the communication networks.

Principle: An optical fiber works on the principle of total internal reflection (TIR).

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 into the denser medium

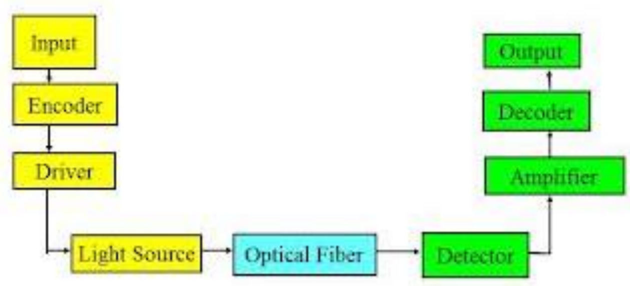
Structure & Working:

- An optical fiber consists of three (3) co-axial regions.
- The inner most region is the light-guiding region known as “Core”. It is surrounded by a middle co-axial regional known as “cladding”. The outer most regions which completely covers the core & cladding regions is called “sheath or buffer jacket”.
- Sheath protects the core & cladding regions from external contaminations, in addition to providing mechanical strength to the fiber.
- The refractive index of core (n_1) is always greater than the refractive index of cladding (n_2) i.e., $n_1 > n_2$ to observe the light propagation structure of optical fiber.
- When light enters through one end of optical fiber it undergoes successive total internal reflections and travel along the fiber in a “zig-zag” path.



10). Optical fiber communication link block diagram/ Basic components of optical fiber communication system/ Applications of Optical fibers:

Optical Fiber Communication Link:



Block Diagram of Optical fiber communication link

Optical fiber is an ideal communication medium by systems that require high data capacity, fast operation and to travel long distances with a minimum number of repeaters.

Encoder: It is an electronic system that converts the analog information signals, such as voice of telephone user, in to binary data. The binary data consists of series of electrical pulses.

Transmitter: Transmitter consists of a driver which is a powerful amplifier along with light source. The o/p of amplifier feeds to light source, which converts electrical pulses in to light pulses.

Source to Fiber Connector: It is a special connector that sends the light from sources to fiber. The connector acts as temporary joint b/w the fiber and light source, misalignment of this joint, leads to loss of signal.

Fiber to Detector Connector: It is also temporary joint, which collects the source from fiber.

Receiver: Receiver consists of a detector followed by amplifier. This combination converts light pulses in to electrical pulses.

Decoder: Electrical pulses containing information are fed to the electronic circuit called decoder. Decoder converts binary data of electrical pulses in to analog information signals.

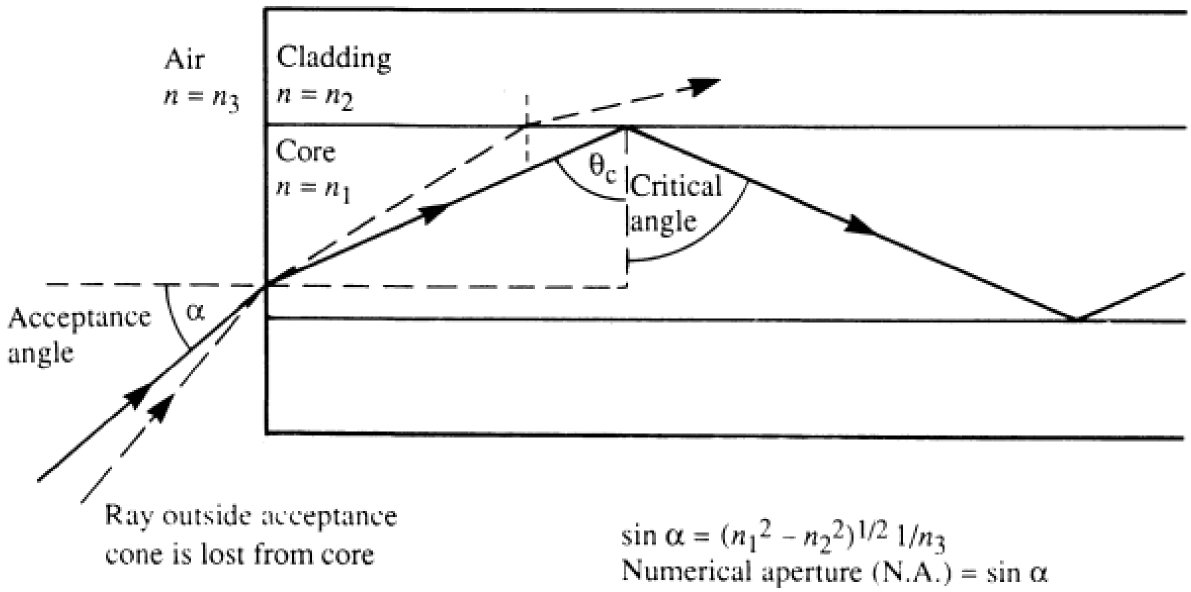
11). Comparison of optical fibers over conventional cables / Advantages of optical fibers over metallic cables:

- Optical fibers allow light signals of frequencies over a wide range and hence greater volume of information can be transmitted either in digital form or in analog form within a short time.
- In metallic cables only 48 conversations can be made at once without cross talks where as in optical fibers more than 15000 conversations can be made at once without cross talks.
- Light cannot enter through the surface of the optical fiber except at the entry interface i.e., interference b/w different communication channels is absent. Hence purity of light signal is protected.
- Optical signal do not produce sparks like electrical signals and hence it is safe to use optical fibers.
- External disturbances from TV or Radio Stations power electronic systems and lightening cannot damage the signals as in case of metallic cables.
- Materials used in the manufacture of optical fibers are SiO_2, plastic, glasses which are cheaper & available in plenty.

12). Acceptance angle and Numerical Aperture:

Acceptance Angle:

- All right rays falling on optical fiber are not transmitted through the fiber. Only those light rays making $\theta_i>\theta c$ at the core-cladding interface are transmitted through the fiber by undergoing TIR. For which angle of incidence, the refraction angle is greater than 90^0 will be propagated through TIR.
- There by Acceptance Angle is defined as: The maximum angle of incidence to the axis of optical fiber at which the light ray may enter the fiber so that it can be propagated through TIR.



- Consider the optical fiber with core refractive index n_1 and cladding refractive index n_2. Light is incident on the axis of optical fiber at an angle θ_1. It can produce an angle of refraction θ_2.
- The relationship at the interface is given by Snell's law as:

  At air-core interface (A),

  $n_0 sin\theta_1 = n_1 sin\theta_2 \dots.$ (1)

  At core-clad interface (B), for TIR,

  $n_1 sin(90^\circ - \theta_2) = n_2 sin 90^\circ$

  $n_1 cos\theta_2 = n_2$

  $cos\theta_2 = \frac{n_2}{n_1} \dots$ (2)

  Eq(1) can be written as ,

  $n_0 sin\theta_1 = n_1\sqrt{1 - cos^2\theta_2} \dots.$ (3)

  Substituting (2) in (3),

  $$n_0 sin\theta_1 = n_1\sqrt{1 - \frac{{n_2}^2}{{n_1}^2}}$$

  $$n_0 sin\theta_1 = \sqrt{{n_1}^2 - {n_2}^2}$$

  For air $n_0 = 1$,

$$sin\theta_1 = \sqrt{{n_1}^2 - {n_2}^2}$$

$$\theta_1 = \theta_A = \sin^{-1}\sqrt{{n_1}^2 - {n_2}^2}$$

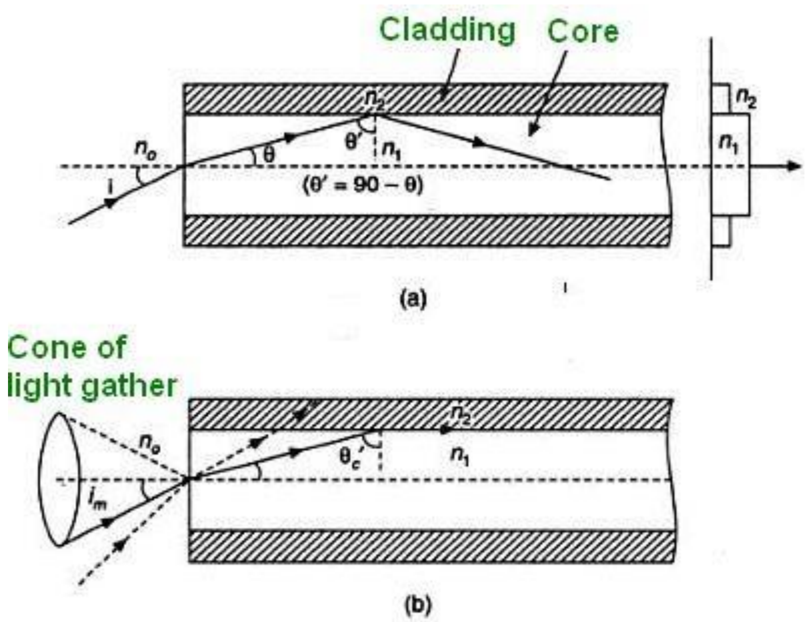
Here θ_A is called Acceptance angle. This gives max value of external incident angle for Which light will propagate in the fiber.

Numerical Aperture (NA):

Numerical aperture is defined as light gathering capacity of an optical fiber which depends on two factors i.e Core diameter & NA. The efficiency of optical fiber is expressed in terms of NA, so it is called as figure of merit of optical fiber.

NA is defined as sine of the acceptance angle i.e. $NA = \sin\theta_A$

$$NA = \sqrt{{n_1}^2 - {n_2}^2}$$



$$NA = \sqrt{{n_1}^2 - {n_2}^2} = \sqrt{(n_1 - n_2)(n_1 + n_2)} \ldots(1)$$

Fractional index change

$$\Delta = \frac{n_1 - n_2}{n_1}$$

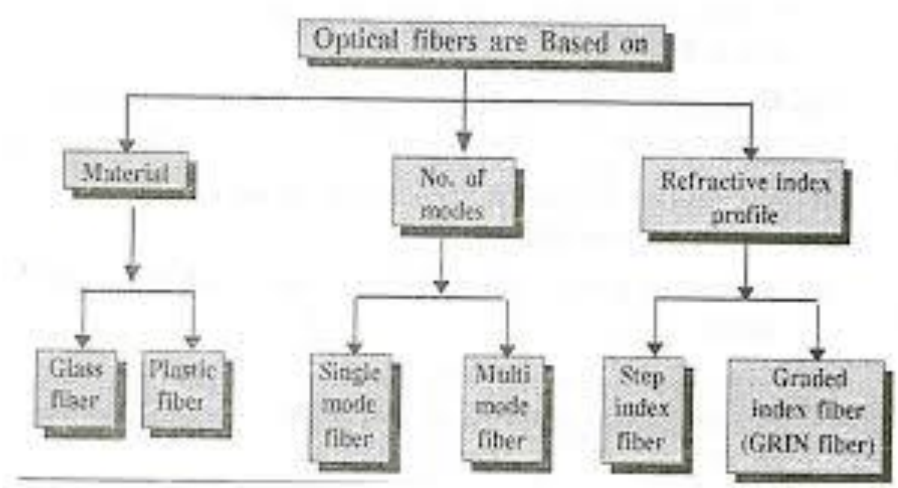
$\Delta\, n_1 = n_1 - n_2$..(2) in (1)

$$NA = \sqrt{\Delta\, n_1(n_1 + n_2)}$$

Let $n_1 = n_2, then\; n_1 + n_2 = 2n_1$

Then $NA = \sqrt{\Delta\, n_1 - 2n_1} = n_1\sqrt{2\Delta}$

13). Types(classification) of Optical Fibers:



Optical fibers are classified in to three major categories based on

i) Material

ii) Number of Modes

iii) Refractive index profile

- Based on materials in which the fibers are made it is classified into two types as follows.

  1.Glass fibers

  2.Plastic fibers

- Based on mode of propagation, fibers are further classified in to

  1. Single mode fibers
  2. Multi mode fibers

- Based on variation in the refractive index (n_1) profile of core, optical fibers are classified in to two types

  1. Step index fiber
  2. Graded index fiber

Classification based on materials:

1.Glass fibers: If the fibers are made up of mixture of metal oxides and silica glasses is called glass fibers.

Advantages:

- Glass fiber cables can be used in high-temperature applications like furnaces, ovens, and condensers in large engines, as well as in extremely low-temperature areas such as cold storage warehouses.
- Since glass cores are efficient at transmitting light and allow for significantly higher transfer speeds, glass optical fibers can be used over long sensing distances.
- Glass optical fiber enables you to use a photoelectric sensor in areas where you wouldn't normally be able to use them. With this advantage, you can choose sensors with a wide range of housings, mounting styles, and features for your specific application.
- Since glass fiber optic cables are thin and light, they are optimized for small spaces and small targets.

Disadvantages:

- The installation of glass optical fibers requires highly trained technicians, and the tools and equipment for fiber termination are usually expensive.
- The core diameter of glass fiber is very small, hence it has higher technology requirements to couple light into the core region, such as light sources.
- Glass optical fibers are fragile and more possible to break if not handled properly.

2. Plastic fibers: It is an optical fiber in which the core and cladding are both made out of plastic or polymeric materials rather than glass.

Advantages:

- The materials which POF is made up of are low-cost and the installation with associated assemblies is not expensive.
- It is flexible and solid, able to bend farther without breakage.
- The network using plastic optical fiber can be installed by untrained personnel. Even home users can handle and install these fibers.
- Plastic optical fibers use harmless green or red light that is easily visible towards the eye. They are safe when installed in a house without risk to inquisitive children.

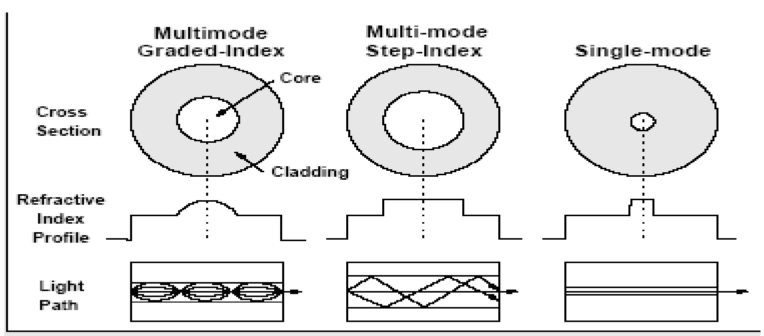
Disadvantages:

- The signal attenuation and dispersion of POF are typically very high, hence it is limited to short distances.
- POF cannot withstand the extreme temperature as glass optical fiber does.

- Based on variation in the core refractive index (n_1), optical fibers are divided in to two types
  1. Step index fiber
  2. Graded index fiber
- Based on mode of propagation, fibers are further classified in to
  1. Single mode propagation
  2. Multi mode propagation
- Step index fibers have both single & multimode propagations.
- Graded index fibers have multimode propagation only
- All together in total three (3) types of fibers
  1. Single mode step index fiber
  2. Multi mode step index fiber
  3. Multi mode graded index fiber

Transmission of Signal in Optical Fibers:

1. Step Index Fiber: The refractive index of core material is uniform throughout and undergoes a sudden change in the form of step at the core-clad interface.



Refractive index profile & propagation in single mode, step index& graded index fibers

a) Single Mode Step Index Fiber:

- The variation of the refractive index of a step index fiber as a function of distance can be mathematically represented as longitudinal cross section.

Note: Mode of propagation: It is defined as the number of paths available for the light ray to transfer through the optical fiber.

Structure:

i) Core Diameter: 8 to 12 μm, usually 8.5μm

ii) Cladding Diameter: Around 125μm

iii) Sheath Diameter: 250 to 1000 μm

iv) NA: 0.08 to 0.15 usually 0.10

Performance Characteristics:

i) Band Width: Greater than 500 MHZ Km.

ii) Attenuation: 2 to 5 dB / Km.

iii) Applications: These fibers are ideally suited for high band width applications using single mode injection coherent (LASER) sources.

B) Multi Mode Step Index Fibers:

- These fibers have reasonably large core diameters and large NA to facilitate efficient transmission to incoherent or coherent light sources.
- These fibers allow finite number of modes.
- Normalized frequency (NF) is the cut off frequency, below which a particular mode cannot exist. This is related to NA, Radius of the core, and wave length of light as

$NF = 2\pi/\lambda\ a\ (NA)$, Where a = radius of core

Structure:

i) Core Diameter: 50 to 200 μm

ii) Cladding Diameter: 125 to 400 μm

iii) Sheath Diameter: 250 to 1000 μm

iv) NA: 0.16 to 0.5

Performance Characteristics:

i) Band Width: 6 to 50 MHZ Km.

ii) Attenuation: 2.6 to 50 db/km.

iii) Applications: These fibers are ideally suited for limited band width and relatively low cost applications.

c) Multi Mode Graded Index Fibers:

- In case of graded index fibers, the refractive index of core is made to vary as a function of radial distance from the centre of the optical fiber.
- Refractive index increases from one end of core diameter to center and attains maximum value at the centre. Again refractive index decreases as moving away from center to towards the other end of the core diameter.

- The refractive index variation is represented as $n(r) = n_1(1-2\Delta)^{1/2} = n_2$

  Here Δ = fractional change in refractive index = n_1-n_2/n_1
- The number of modes is given by the expression $N = 4.9[d(NA)/ \lambda]^2$

  Where d = core diameter, λ = wavelength of radiation

Structure:

i) Core Diameter: 30 to 100 μm

ii) Cladding Diameter: 105 to 150 μm

iii) Sheath Diameter: 250 to 1000 μm

iv) NA: 0.2 to 0.3

Performance Characteristics:

i) Band Width: 300 MHZ Km to 3 GHZ Km.

ii) Attenuation: 2 to 10 dB/km.

iii) Applications: These are ideally suited for medium to high band width applications using incoherent and coherent multimode sources.

14). Distinguish Step index & Graded index fibers and Single mode & Multi mode fibers:

Step Index	**Graded Index**
1. RI of core is uniform throughout except at one stage. 2. Single & multimode propagations exist. 3. Used for short distance applications. 4. Attenuation losses are of the order 100 dB/km. 5. Mer4dinol rays propagation takes place. 6. Easy to manufacture.	1. Refractive index varies gradually with radial distance. 2. It is a multi mode fiber. 3. Used for long distance applications. 4. 4. Attenuation losses are of the order 10 dB/km. 5. Skew rays propagation takes place. 6. Difficult to manufacture.
Single Mode	**Multi Mode**
1. Core diameter is small. 2. Signal entry is difficult. 3. Exists in step index fiber. 4. Light must be coherent.	1. Core diameter is large. 2. Signal entry is easy. 3. Exists in both step & graded index fibers.

	4. Light source may be coherent or incoherent source.

15). Attenuation in optical fibers:

Usually, the power of light at the output end of optical fiber is less than the power launched at the input end, then the signal is said to be attenuated.

Attenuation: It is the ratio of input optical power (P_i) in to the fiber to the power of light coming out at the output end (P_o).

Attenuation coefficient is given as, $\alpha = 10/L \log_{10} P_i / P_o$ db/km.

Attenuation is mainly due to

1. Absorption.
2. Scattering.
3. Bending.

1. Absorption Losses:

In glass fibers, three different absorptions take place.

Ultra violet absorption: Absorption of UV radiation around 0.14μm results in the ionization of valence electrons.

Infrared absorption: Absorption of IR photons by atoms within the glass molecules causes heating. This produces absorption peak at 8μm, also minor peaks at 3.2, 3.8 and 4.4μm.

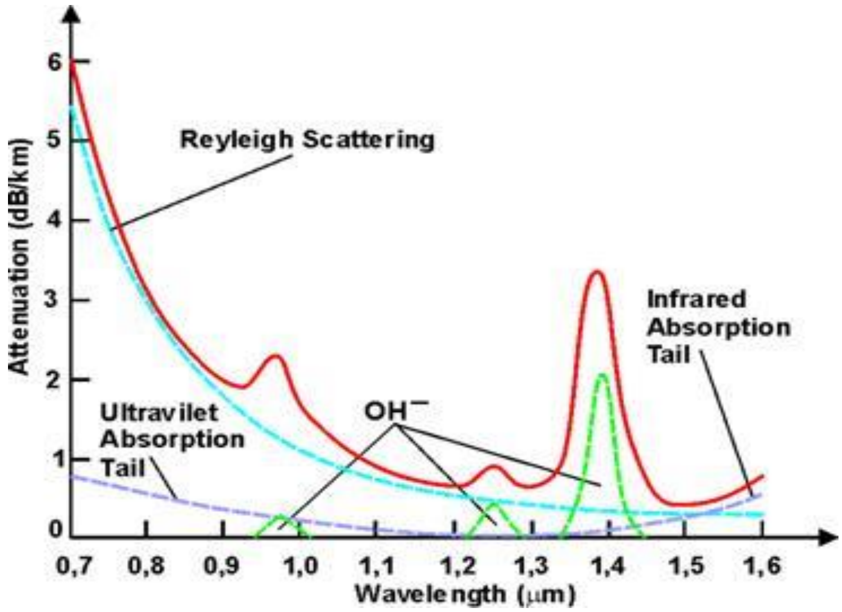
Ion resonance/OH^- absorption: The OH^- ions of water, trapped during manufacturing causes absorption at 0.95, 1.25 and 1.39μm.

2. Scattering Losses:

The molten glass, when it is converted in to thin fiber under proper tension creates sub microscopic variations in the density of glass leads to losses.

The dopents added to the glass to vary the refractive index also leads to the inhomogenities in the fiber. As a result losses occur.

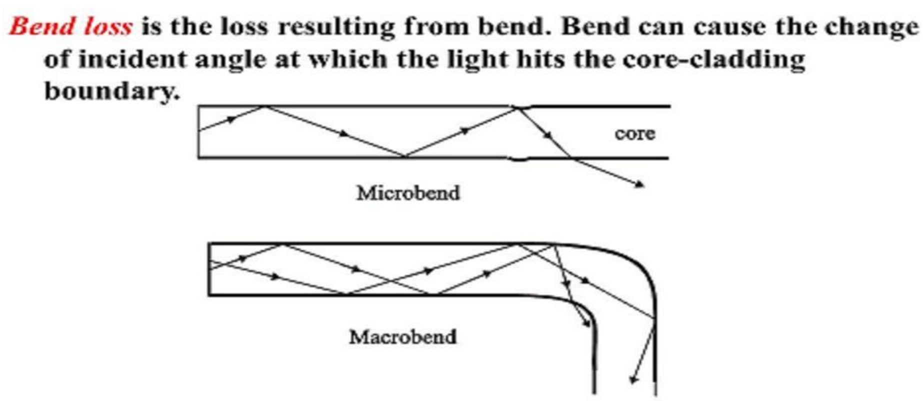
Scattering losses are inversely proportional to fourth power of λ.(λ^4)



3. Bending Losses:

In a bent fiber, there is a loss in power of the transmitted signal called as Bending Loss. According to the theory of light, the part of the wave front travelling in cladding (rarer medium) should travel with more velocity than the wave front in the core (denser medium). But according to Einstein's theory of relativity, in a single wave front one part should not travel with higher velocity than the other part.

So the part of wave front travelling in cladding medium lost in the form of radiation leads to bending losses.



16) Mention some applications of Optical Fibers in various fields?

We know that optical fiber are thin strands of glass and the core uses of optical fiber includes the transmission of information in the form of light. The use of optical fibers has genuinely proved to be beneficial compared to the traditional use of metallic wires.

The application of optical fibers in various fields are given below:

(i) Optical Fibers uses in Medical industry:

Because of the extremely thin and flexible nature, it used in various instruments to view internal body parts by inserting into hollow spaces in the body. It is used as lasers during surgeries, endoscopy, microscopy and biomedical research**.**

(ii) Optical Fibers used in Communication:

In the communication system, telecommunication has major uses of optical fiber cables for transmitting and receiving purposes. It is used in various networking fields and even increases the speed and accuracy of the transmission data. Compared to copper wires, fiber optics cables are lighter, more flexible and carry more data.

(iii) Optical Fibers used in Defense Purpose:

Fiber optics are used for data transmission in high-level data security fields of military and aerospace applications. These are used in wirings in aircraft, hydrophones for SONARs and Seismic applications.

(iv) Optical Fibers are used in Automotive Industries:

They are widely used in lighting, both in the interior and exterior of vehicles. Because of its ability to conserve space and provide superior lighting, fiber optics are used in more vehicles every day. Also, fiber optic cables can transmit signals between different parts of the vehicle at lightning speed. This makes them invaluable in the use of safety applications such as traction control and airbags.

(v) Optical Fibers used for Broadcasting:

These cables are used to transmit high definition television signals which have greater bandwidth and speed. Optical Fiber is cheaper compared to the same quantity of copper wires. Broadcasting companies use optical fibers for wiring HDTV, CATV, video-on-demand and many applications.

(vi) Uses of Optical Fiber for Lightening and Decorations:

Optical fibers give an attractive, economical and easy way to illuminate the area and that is why it is widely used in decorations and Christmas trees.

(vii) Optical Fibers used in Mechanical Inspections:

On-site inspection engineers use optical fibers to detect damages and faults which are at hard to reach places. Even plumbers use optical fibers for inspection of pipes.

Questions:

Short answer questions:

1. Define the terms a) Absorption b) Spontaneous emission c) Stimulated emission.
2. Explain the principle of Laser or lasing action.
3. Mention the characteristics of Laser beam.
4. What is population inversion, Metastable state and optical pumping in lasers?
5. What is resonating cavity.
6. Write down any four applications of Lasers.
7. Explain the basic principle of optical fiber.
8. Define acceptance angle and Numerical aperture.
9. Write down the advantages of optical fibers in communication system.
10. Write a short note on attenuation in optical fibers.
11. Distinguish between step index and graded index fibers.
12. Mention some important applications of optical fibers.

Long answer questions:

1. Explain the characteristics of Laser beam in detail.
2. What are Einstein's coefficients and explain the relation among them? Or Derive the relation between the probabilities of spontaneous emission and stimulated emission in terms of Einstein's coefficients. Or Describe Einstein's theory of radiation in detail.
3. Explain the principle, construction and working of Ruby Laser with energy level diagram.
4. Explain the principle, construction and working of He-Ne Laser with energy level diagram.
5. Mention some important applications of Laser in various fields.
6. Explain the structure, principle and working of an optical fiber as wave guide with help of a suitable diagram.
7. Define and derive the expressions for acceptance angle and Numerical Aperture.
8. How optical fibers are classified on the basis of refractive index profile? Or Describe the step index and graded index optical fibers in detail and explain the transmission of signal through them.
9. Distinguish i) Step index and Graded index fibers ii) Single mode and Multimode fibers.
10. Mention the advantages of optical fibers over the metallic cables.
11. Explain the optical fiber communication link with help of block diagram. Or How optical fibers are used in communication filed.(Applications of optical fibers)
12. Write a short note on attenuation in optical fibers.

UNIT-V: Dielectric, Magnetic and Superconducting Materials

Electric dipole: Two equal and opposite charges small in magnitude and separated by a small distance constitute a electric dipole.

Dipole moment: The product of magnitude of both charge and the distance between the two charges. i.e. $\mu = q\,r$.

It is a vector quantity.

The direction of μ is from negative to positive.

Dielectric constant:$(\boldsymbol{\varepsilon_r})$**:** Dielectric constant is the ratio between the permittivity of the medium to the permittivity of the free space. $\boldsymbol{\varepsilon_r} = \frac{\boldsymbol{\varepsilon}}{\boldsymbol{\varepsilon_o}}$

Since it is the ratio of same quantity, $\boldsymbol{\varepsilon_r}$ has no unit.

Polarization: The process of producing electric dipoles which are oriented along the field direction is called polarization in dielectrics.

Polarization vector (P): The dipole moment per unit volume of the dielectric material is called polarization vector P.

$$P = \frac{\mu}{V}$$

If μ is the average dipole moment per molecule and N is the number of molecules per unit volume, then polarization vector, $P = N\mu = N\alpha E$

Electric displacement vector: It is a quantity which is a very convenient function for analyzing the electrostatic field in the dielectrics and is given by $D=\varepsilon_o E+P$

1). Polarization and types of polarization in dielectrics:

Polarization: The process of producing electric dipoles which are oriented along the field direction is called polarization in dielectrics.

Types of Polarizations:

Polarization occurs due to several atomic mechanisms. When the specimen is placed inside electric field, mainly three types of polarizations are possible. Those are

- Electronic polarization
- Ionic polarization
- Orientational or Dipolar polarization

Electronic polarization:

- Electronic polarization occurs due to the displacement of negatively charged electron in opposite direction.
- When an external field is applied and there by creates a dipole moment in the dielectric.
- Therefore induced dipole moment μ=α_eE.
- Where α_e is the electronic polarizability.
- Electronic polarizability is proportional to the volume of atoms.
- This Polarization is independent of temperature.

Ionic polarization:

- This is due to the displacement of cations and anions in opposite directions and occurs in an ionic solid. This type of polarization occurs in ionic dielectrics like Nacl.
- When such a dielectric material is subjected to an external electric field, adjacent ions of opposite sign undergoes displacement and this displacement results either increase or decrease in the distance of separation between ions.
- If x_1 and x_2 are the displacements of positive and negative ions in an ionic crystal due to the application of electric field E, then dipole moment$\mu = q \times (x_1 + x_2)$.

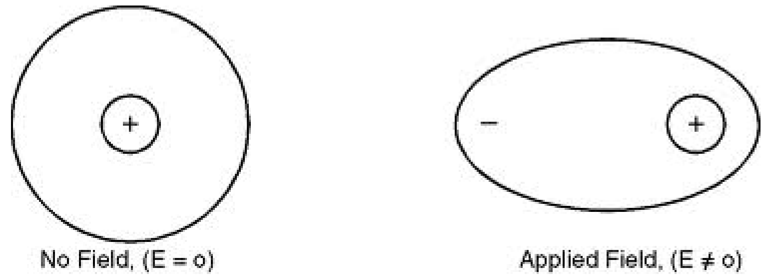
Orientational or Dipolar polarization:

- This type of polarization occurs in materials with polar molecules.
- Without the external field the molecules are oriented at random. So the net dipole moment is zero.
- When external field is applied the polar molecules orient favorably into the field direction. The process of orientation becomes easy at high temperature.
- Hence the Orientational polarizability is strongly dependent on temperature. α_o=$\frac{P_o}{NE} = \frac{\mu^2}{3KT}$

2). Expression for electronic and ionic polarizations:

Electronic polarization and calculation of Electronic polarizability:

- Electronic polarization occurs due to the displacement negative electron cloud of each atom with respect to its nucleus in the presence of electric field. When an external field is applied and there by creates a dipole moment in the dielectric.



Therefore induced dipole moment $\mu=\alpha_e E$.

- Where α_e is the electronic polarizability.
- Electronic polarizability is proportional to the volume of atoms.
- Polarizability is independent of temperature.

Calculation of electronic polarizability:

(I)Without Electric field:

- Let us consider a classical model of an atom. Assume the charge of the nucleus is +Ze and the nucleus is surrounded by an electron cloud of charge –Ze which is distributed in sphere of radius R.
- The charge density of the charged sphere = $\frac{-Ze}{\frac{4}{3}\pi R^3}$
- Charge density $\rho = \frac{-3}{4}\frac{Ze}{\pi R^3}$-------------------1

(II) With Electric field:

When the dielectric is placed in an electric field E, two phenomena occurs

- Lorentz force due to the electric field tends to separate the nucleus and the electron cloud from their equilibrium position.
- After the separation, an attractive coulomb force arises between the nucleus and electron cloud which tries to maintain the original equilibrium position.
- Let x be the displacement made by the electron cloud from the positive core .Since the nucleus is heavy it will not move when compared to the movement of electron cloud here x<<R, where R is the radius of the atom.

- Since the Lorentz and coulombs forces are equal and opposite in nature, equilibrium is reached.
- At equilibrium Lorentz force = Coulomb force

Lorentz force = charge × field = -ZeE--------------2

Coulomb force = charge × field = +Ze×$\frac{Q}{4\pi\varepsilon_O x^2}$

- Then Coulomb force = charge X $\frac{\text{total negative charges(Q)enclosed in the sphere of redius x}}{4\pi\varepsilon_O\ x^2}$---3
- Here the total number of negative charges (Q) encloses in the sphere of radius R is

X = charge density of the electron × volume of the sphere ---------------4

- Substitute ρ from 1 in 4 we get

Q= $\frac{-3}{4}\frac{Ze}{\pi R^3}$× $\frac{4}{3}\pi x^3$, i.e Q= $\frac{Zex^3}{R^3}$ ------------------------------5

- Substitute Q from 5 in 3 we get

Coulomb force = $\frac{Ze}{4\pi\varepsilon_O x^2}$($\frac{Zex^3}{R^3}$)----------6

- At equilibrium Lorentz force = Coulomb force

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

X = $\frac{4\pi\varepsilon_o R^3 E}{Ze}$---------------------------------7

- Therefore, the displacement of electron cloud x is proportional to the applied electric field E.

Dipole moment:

- Now the two electric charges +Ze and –Ze are displaced by a distance under the influence of the field and form a dipole.
- Induced dipole moment = magnitude of charge × displacement = Ze X -----------8
- Substitute the value of X from 7 in 8 we have

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

μ_e= $4\pi\varepsilon_o R^3 E$

μ_e= α_eE--------------------------------9

$\boldsymbol{\alpha_e = 4\pi\varepsilon_o R^3}$ is called electronic polarizability

Calculation of ionic polarization:

- Ionic polarization is due to the displacement of cations and anions in opposite directions and occurs in an ionic solid.
- Suppose an electric field is applied in the +ve x direction, the +ve ions move to the right by x_1 and the –ve ions move to the left by x_2.
- Assuming the each unit cell has one cation and one anion, the resultant dipole moment per unit cell due to ionic displacement is given by $\mu = \boldsymbol{e}(x_1 + x_2)$ ------------1
- If β_1 and β_2 are restoring force constants of cation and anion and F Newton's is the force due to the applied field, $F = \beta_1 x_1 = \beta_2 x_2$------------------------2
- Hence $x_1 = \frac{F}{\beta_1}$
- Restoring force constants depend upon the mass of the ion and angular frequency of the molecule in which ions are present.

$x_1 = \frac{eE}{m\omega_0^2}$----------------------3, where 'm' is the mass of +ve ion.

$x_2 = \frac{eE}{M\omega_0^2}$ --------------------------4, Where 'M'is the mass of -ve ion.

$x_1 + x_2 = \frac{eE}{\omega_0^2}\left(\frac{1}{M} + \frac{1}{m}\right)$ --------------------------5

And $\boldsymbol{\mu} = \boldsymbol{e}(x_1 + x_2) = \frac{e^2E}{\omega_0^2}\left(\frac{1}{M} + \frac{1}{m}\right)$ --------------------------6

$$\propto_i = \frac{\mu}{E} = \frac{e^2}{\omega_0^2}\left(\frac{1}{M} + \frac{1}{m}\right)$$

- Thus the ionic polarizability $\propto_i$ is inversely proportional to square of the natural frequency of the ionic molecule and is reduced mass is equal to $\left(\frac{1}{M} + \frac{1}{m}\right)^{-1}$.

Basic Definitions in Magnetism:

Magnetic flux ($\boldsymbol{\varphi}$): The number of lines passing normally through an area. Its unit is Weber.

Magnetic induction (or) Magnetic flux density (B): The magnetic induction in any material is the number of lines of magnetic force passing through unit area perpendicularly. Its unit is Weber/m^2or tesla.

Magnetic field intensity (or) strength (H): Magnetic field intensity at any point in the magnetic field is the force experienced by a unit North Pole placed at that point. Its unit is amperem^{-1}

Magnetization (or) Intensity of magnetization (I): The term of magnetization is the process of converting a non magnetic material into a magnetic material.

It is also defined as the magnetic moment per unit volume.$\mathrm{I} = \frac{\mathrm{M}}{\mathrm{V}}$. Its units is amperem^{-1}

Magnetic susceptibility (χ): The ratio of intensity of magnetization (I) produced to the magnetic field strength (H) in which the material is placed.

$x = \frac{\mathrm{I}}{\mathrm{H}}$

Magnetic permeability of medium (μ): It is defined as the ratio of magnetic induction B in a substance to the applied magnetic field intensity. $\mu = \frac{\mathrm{B}}{\mathrm{H}}$

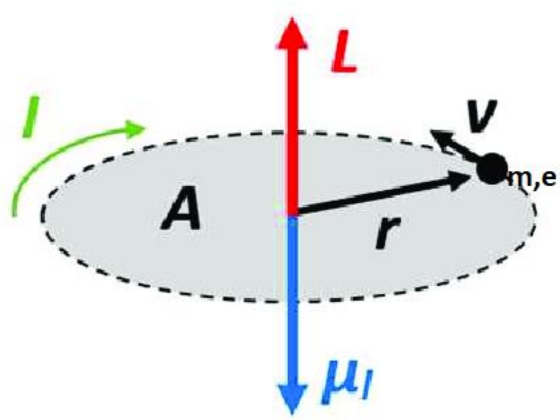
3). Origin of Magnetic Moment / Concept of Bohr Magneton:

In atoms, the permanent magnetic moments can arise due to the following:

1. the orbital magnetic moment of the electrons
2. the spin magnetic moment of the electrons, and
3. the spin magnetic moment of the nucleus.

Orbital magnetic moment of the electrons:

We know that in an atom electron revolve round the nucleus in different circular orbits. Let m be the mass of the electron and r the radius of the orbit in which it moves with angular velocity ω. We can calculate the electric current due to the moving electron.



Current I = - Charge flow / Unit time

$= - \frac{e}{T}$

Where T is the time taken for one revolution

$\mathrm{I} = - \frac{e\omega}{2\pi}$ ------------(1)

We know that the current flowing through a circular coil produces a magnetic field in a direction perpendicular to the area of the coil and it is identical to a magnetic dipole. The magnitude of the magnetic moment produced by such a dipole is

$$\mu_m = I.A$$

$$= -\frac{e\omega}{2\pi}(\pi r^2)$$

$$= \frac{-e\omega r^2}{2} = \frac{-e}{2m}(m\omega r^2) = -\left(\frac{e}{2m}\right)L \text{ ------------(2)}$$

Where L = $m\omega r^2$ is the orbital angular momentum of electron. The minus sign indicates that the magnetic moment μ_m is antiparallel to the angular momentum L.

The possible orientation of the angular momentum vector when placed in an external magnetic field is given by

$$L_{l,B} = m_l \frac{h}{2\pi} \text{ ----------------(3)}$$

Substituting 3 in 2,

$$\mu_m = -\left(\frac{e}{2m}\right) m_l \frac{h}{2\pi}$$

$$= -\left(\frac{eh}{4\pi m}\right) m_l$$

$$= -\mu_B m_l \text{-----------------(4)}$$

Where $\mu_B = \frac{h}{4\pi m} = 9 \cdot 27 \times 10^{-24} A - m^2$ and is called Bohr magneton.

Bohr magneton is the accepted one unit for measuring the magnetic moments of atomic systems.

4). Classification of magnetic materials:

- By the application of magnetic field some materials will not show any effect that are called non magnetic materials and those which show some effects are called magnetic materials.
- All magnetic materials magnetized in the presence of external magnetic field.
- Depending on the direction and magnitude of magnetization and also the effect of temperature on magnetic properties, all magnetic materials are classified into Dia, Para and Ferro magnetic materials.
- Two more classes of materials have structure very close to Ferro magnetic materials, but shows quiet different magnetic properties. They are Anti-Ferro magnetic and Ferri magnetic materials.

Diamagnetism:

- The number of orientations of electronic orbits in an atom be such that vector sum of magnetic moment is zero
- The external field will cause a rotation action on the individual electronic orbits this produces an induced magnetic moment which is in the direction opposite to the field and hence tends to decrease the magnetic induction present in the substance.
- Thus the diamagnetism is the phenomena by which the induced magnetic moment is always in the opposite direction of the applied field.

Properties of diamagnetic materials:

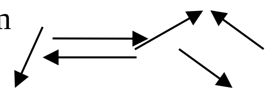
- Diamagnetic material gets magnetized in a direction opposite to the magnetic field.
- Weak repulsion is the characteristic property of diamagnetism.
- Permanent dipoles are absent.
- Relative permeability is less than one but positive.
- The magnetic susceptibility is negative and small. It is not affected by temperature.
- Diamagnetism is universal i.e. all materials when exposed to external magnetic fields, tend to develop magnetic moments opposite in the direction to the applied field.
- When placed inside a magnetic field, magnetic lines of force are repelled.

Para magnetism:

- The number of orientations of orbital and spin magnetic moments be such that the vector sum of magnetic moment is not zero and there is a resultant magnetic moment in each atom even in the absence of applied field.
- The net magnetic moments of the atoms are arranged in random directions because of thermal fluctuations, in the absence of external magnetic field. Hence there is no magnetization.
- If we apply the external magnetic field there is an enormous magnetic moment along the field direction and the magnetic induction will be increase. Thus induced magnetism is the source of par magnetism.

Properties of paramagnetic materials:

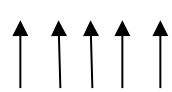
- Paramagnetic materials get magnetized in the direction of the magnetic field.
- Weak attraction is characteristic property of Para magnetism.
- Paramagnetic material has magnetic dipoles.

- Relative permeability is greater than one but small i.e. this indicate that when paramagnetic substance is placed in a uniform magnetic field, the field inside the material will be more than the applied field.
- The magnetic susceptibility is small and positive. The magnetic susceptibility of paramagnetic is inversely proportional to absolute temperature i.e. χ=C/T. This is called curie law, c is called Curie constant.
- Paramagnetic susceptibility is independent of the applied field strength.
- Spin alignment is random 
- When placed inside a magnetic field it attracts the magnetic lines of force.
- Examples: Aluminum, Manganese, oxygen.

Ferromagnetism:

- Ferromagnetism arises when the magnetic moments of adjacent atoms are arranged in a regular order i.e. all pointing in the same direction.
- The ferromagnetic substances posses a magnetic moment even in the absence of the applied magnetic field, this magnetization is known as the spontaneous magnetization.
- There is a special form of interaction called “exchange “coupling occurring between adjacent atoms, coupling their magnetic moment together in rigid parallelism.

Properties of ferromagnetic materials:

- In ferromagnetic materials, large magnetization occurs in the direction of the field.
- Strong attraction is the characteristic property of ferromagnetism.
- They exhibit spontaneous magnetization.
- The relative permeability is very high for Ferro magnetic.
- The magnetic susceptibility is positive and very high.
- Magnetic susceptibility is fairly high and constant up to a certain temperature according the equation $\chi=\frac{C}{T-T_C}$ C= curie constant T_c = Curie temperature.
- Ferromagnetism is due to the existence of magnetic domains which can be spontaneously magnetized.
- Exhibit hysteresis phenomenon.
- Spin alignment is parallel in the same direction 

- ➢ When placed inside a magnetic field they attract the magnetic lines of forces very strongly.
- ➢ Examples: Iron, Nickel, Cobalt.

5). Hysteresis curve based on domain theory of ferromagnetism:

Domain theory of ferromagnetism:

- ➢ According to Weiss, the specimen of ferromagnetic material having number regions or domains 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 for the alignment of domains.

(i)**By motion of domain walls:** The volume of domains that are favorably oriented with respect to the magnetizing field increases at the cost of those that are unfavorably oriented.

[Fig (b)]

(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. [Fig(c)]

H HH

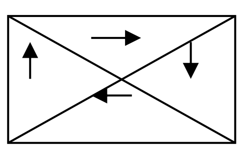


Fig (a)

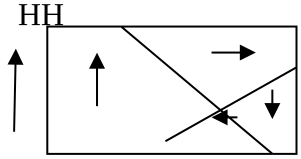
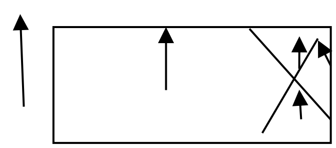
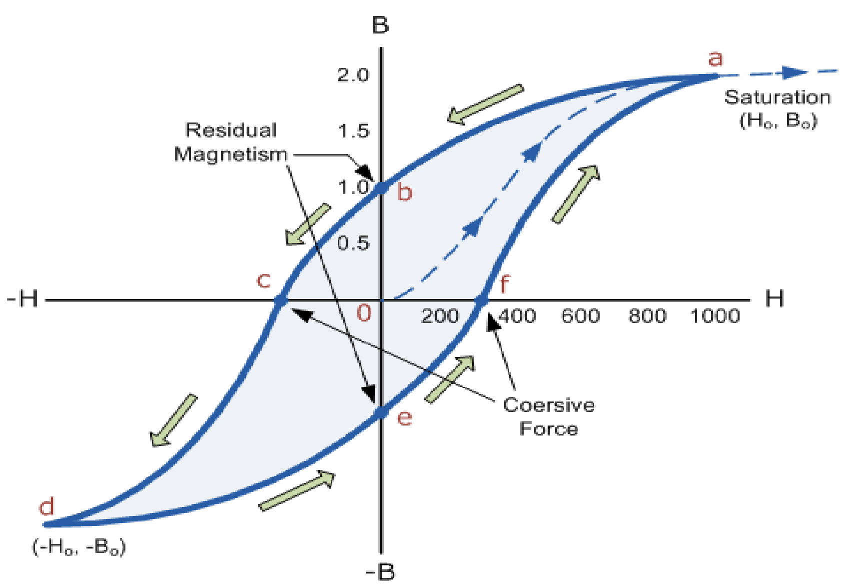


fig (b)



fig(c)

Hysteresis curve:

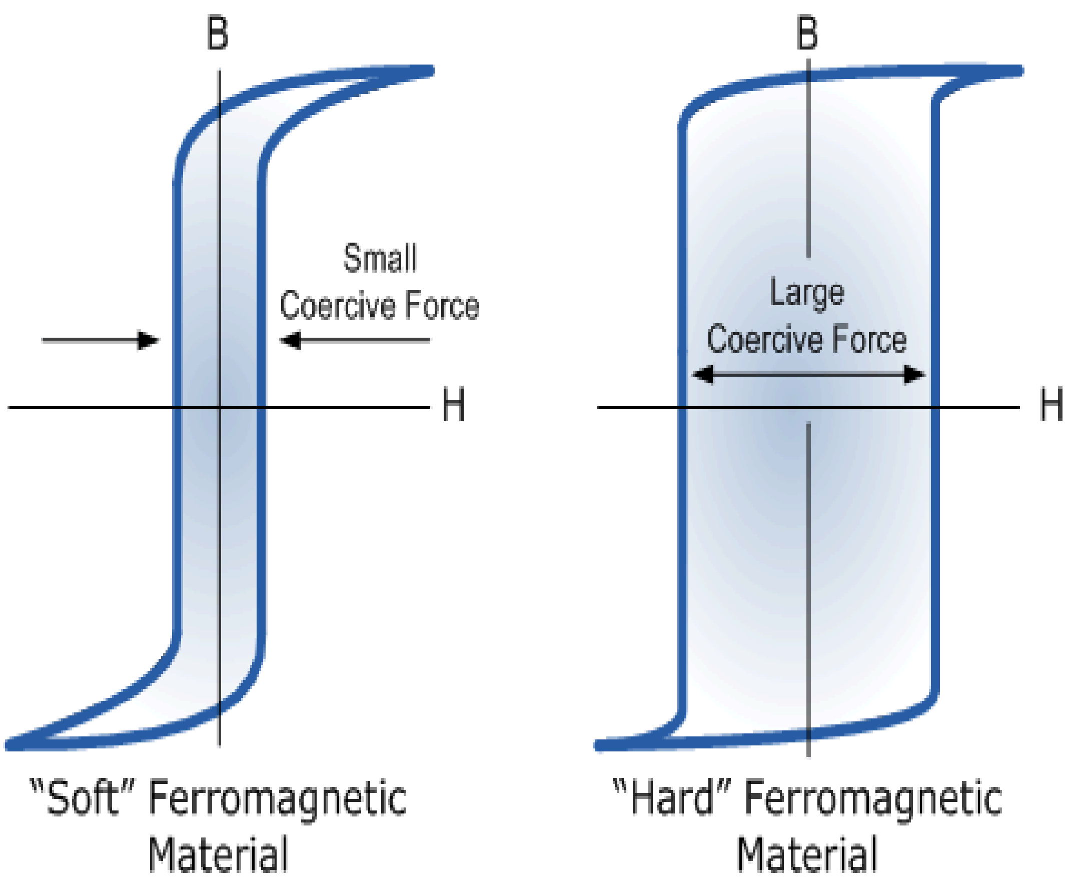


Hysteresis: Lagging of magnetization behind the magnetizing field (H).

- When a Ferro magnetic material is subjected to external field, there is an increase in the value of the resultant magnetic moment due to two processes.
- The movement of domain walls
- Rotation of domain walls
- When a weak magnetic field is applied, the domains are aligned parallel to the field and magnetization grows at the expense of the less favorably oriented domains.
- This results in the Bloch wall (or) domain wall movement and the weak field is removed the domains reverse back to their original state. This reversible wall displacement is indicated by OA the magnetization curve.
- When the field becomes stronger than the domain wall movement, it is mostly reversible movement. This is indicated by path AB of the graph. The phenomenon of hysteresis is due to the irreversibility.
- At the point B all domains have got magnetized, application of higher field rotates the domains into the field direction indicated by BC. Once the domains rotation is complete the specimen is saturated denoted by C.
- Thus the specimen is said to be attain the maximum magnetization. At this position if the external field is removed (H=0), the magnetic induction B will not fall rapidly to zero ,but falls to D rather than O. This shows that even when the applied field is zero the material still have some magnetic induction (OD) which is called residual magnetism or retentivity.
- Actually after the removal of the external field the specimen will try to attain the original configuration by the movement of domain walls. But this movement is stopped due to the presence of impurities, lattice imperfections.
- Therefore to overcome this, large amount of reverse magnetic field (H_c) is applied to the specimen .The amount of energy spent to reduce the magnetization (B) to zero is called “coercivity” represented by OE in the fig.
- **HSTERESIS:** lagging of magnetization (B) behind the magnetizing field (H) is called hysteresis.
- **Hysteresis loss:** It 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.

6). Soft and Hard magnetic materials:

- The process of magnetization of a Ferro or Ferri magnetic material consist of moving domains walls so that favorably oriented domains grow and shrink. If the domain walls are easy to move and coercive field is low and the material is easy to magnetize. Such a material is called soft magnetic material.
- If it is difficult to move the domain walls, the coercive field is large then the material is magnetically hard. These are called hard magnetic material.



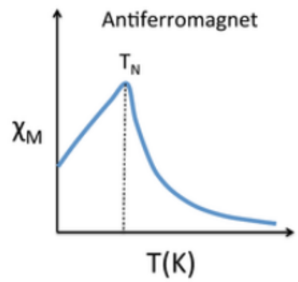
Soft magnetic materials	Hard magnetic materials
Soft magnetic materials have low hysteresis loss due to small hysteresis loop area	Hard magnetic materials have large hysteresis loss due to large hysteresis is loop area.
In these materials the domain wall movement is relatively easier, even for small changes in the magnetizing field the magnetization changes by large amount	In these materials the domain wall movement is difficult because of presence of impurities and crystal imperfection and it is irreversible in nature.
The coercivity and retentivity are small .Hence these materials can be easily magnetized and demagnetized.	The coercivity and retentivity are large. Hence these materials cannot be easily magnetized and demagnetized
These materials are free from irregularities; the magneto static energy is small.	In these materials, because of the presence of impurities and crystal imperfection the mechanical strain is more. Hence magneto static energy is large.
These materials have large values of susceptibility and permeability.	These materials have small values of susceptibility and permeability
These are used to make electronic magnets.	These are used to make permanent magnets
Applications: Mainly used in electromagnetic machinery and transformer cores. They are used in switching circuits, microwave insulators and matrix storage of computers.	Applications: For production of permanent magnets used in magnetic detectors, microphones flux meters, voltage regulators, damping devices, magnetic separators, and loud speakers.

7). Anti Ferro magnetic materials and their properties:

In ferromagnetism. the tendency for parallel alignment of the electron spins was due to the quantum mechanical exchange forces. In certain materials, for example, when the distance between the interacting atoms is small , the exchange forces produce a tendency for antiparallel alignment of electron spins of neighbouring atoms. This kind of interaction is encountered in antiferromagnetic and ferrimagnetic materials.

Neel and Bitter predicted some properties of antiferromagnetic materials even before antiferromagnetism was discovered experimentally.

From experimental point of view, the most important feature of an antiferromagnetic material is the occurrence of a sharp maximum in the (susceptibilty vs temperature) curve as shown in fig. for M_nF_2.

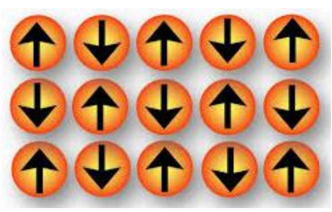


The temperature for which his maximum occurs is called the Neel Temperature, T_n. The Neel temperature plays a similar role in antiferromagnetic materials as the Curie temperature in ferromagnetic materials. Thus, above the Neel temperature the susceptibility as observed from the experimental results follows the equation given below

$$\chi_m = \frac{C}{T+\theta}$$

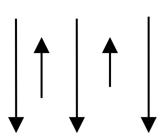
Where C is Curie constant and θ is paramagnetic Curie temperature.

Below the Neel temperature the spin system tends to be ordered in a way similar to the spin system in a ferromagnetic material, except that at T = 0, half the spins are oriented in one direction and the other half in opposite direction.



8). Ferri magnetic materials and their applications:

➢ Ferri magnetic substances are the materials in which the atomic or ionic dipoles in one direction are having unequal magnitudes. This alignment of dipole gives a net magnetization and those magnetic substances which have two or more different kind of atoms. These are also called Ferrites.



➢ In Ferri magnetic materials there, they may have large net magnetization as compared to anti Ferro magnetic materials.

- Ferrimagnetic materials generally known as ferrites consist of two or more different kind of atoms their formula is $M_e^{++}Fe_2^{++}O_4^{--}$.
- Where M_e^{++} stands for a suitable divalent metal ion such as Fe^{++},CO^{++},Ni^{++},Mg^{++}, etc, Fe_2^{++} is a trivalent ferric ion.

Applications of ferrites:

- They are used to produce ultrasonics by magnetization principle.
- Ferrites are used in audio and video transformers.
- Ferrites rods are used in radio receivers to increase the sensitivity.
- They are also used for power limiting and harmonic generation.
- Ferrites are used in computers and data processing circuits.
- Ferrites are used in switching circuits and in storage devices of computers.
- Ferrites are not metals but their resistivity lies in the range of insulators or semiconductors.

Introduction to superconductors

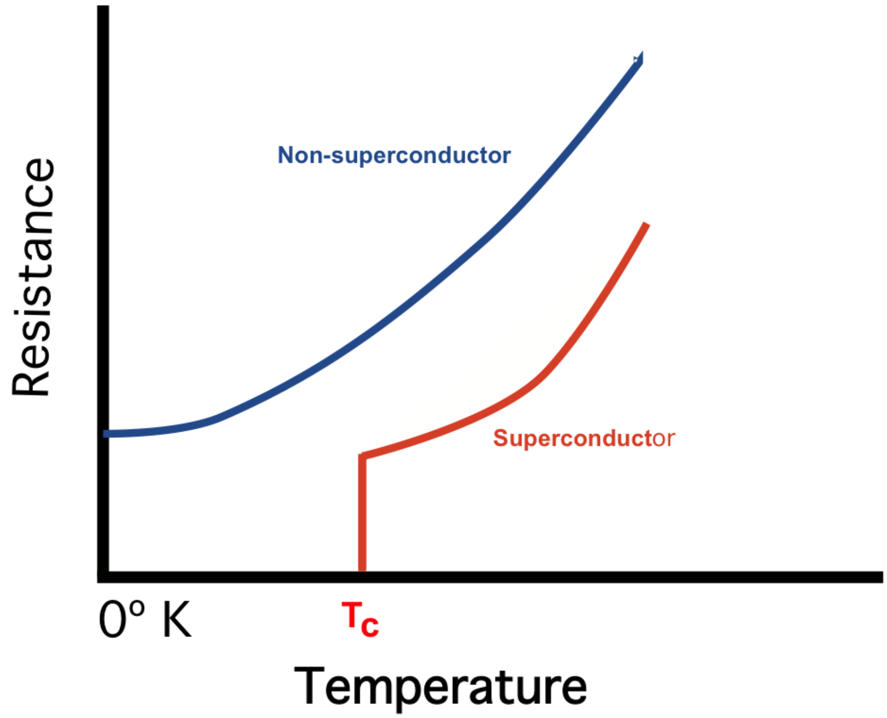
The electrical resistance R of a piece of metal is defined as the ratio of potential difference V volts applied across the piece of the material to the current I amp. flowing through it. Thus R = $\frac{\mathbf{v}}{\mathbf{i}}$ ohms. If l be the length of a piece of homogeneous material with uniform cross-sectional area A, then its specific resistance or resistivity ρ is defined as ρ = R $\frac{\mathbf{A}}{\mathbf{l}}$ or R = ρ $\frac{\mathbf{l}}{\mathbf{A}} = \frac{\mathbf{1}}{\boldsymbol{\sigma}} \times \frac{\mathbf{l}}{\mathbf{A}}$

where $\boldsymbol{\sigma} = \frac{\mathbf{1}}{\boldsymbol{\rho}}$ = conductivity

Around room temperature, the resistivity for good conductors is of the order of 10^{-8} ohm-m and for insulators, it is between the range of 10^{8} or 10^{16} ohm-m. semiconductors have ρ of the order of 10^{-1} to 10^{1} ohm-m. Metals have a positive temperature coefficient i.e. their electrical resistance decreases with the decrease in temperature. Of course, the decrease in resistance is almost proportional to the decrease in temperature. Before the production of low temperatures, it was thought the electrical resistance of a conductor becomes zero only at absolute zero. But it is found that the electrical resistivity of many metals and alloys drop to zero when they are cooled to a sufficiently low temperature. For example, Kamerlingh Onnes in 1911 observed that the electrical resistance of pure mercury suddenly drops to zero as it is cooled below 4.2 K.

9). Superconductivity

Certain metals and alloys exhibit almost zero resistivity (i.e. infinite conductivity), when they are cooled to sufficiently low temperatures. This effect is called superconductivity. This phenomenon was first of all discovered by H. K. Onnes in 1911 when measuring the electrical conductivity of metals at low temperatures.



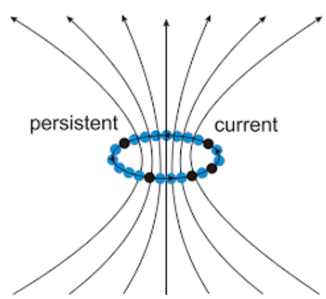
Critical temperature or Transition Temperature (Tc):

The temperature at which the transition from normal state to superconducting state takes place on cooling in the absence of magnetic field is called critical temperature or transition temperature.

10). General Properties of superconductors:

1.Electrical Resistance: A superconductor is characterized by zero electrical resistivity. Once the current is started to flow, it will continue for years without any detectable decay even if the applied voltage is removed.

2.Persistant current: When d.c current of large magnitude is once induced in a superconducting ring then the current persists in the ring even after the removal of the field as shown in figure. This is known as persistant current. This is due to the diamagnetic property. i.e. the magnetic flux inside the ring will be trapped in it and hence the current persists.

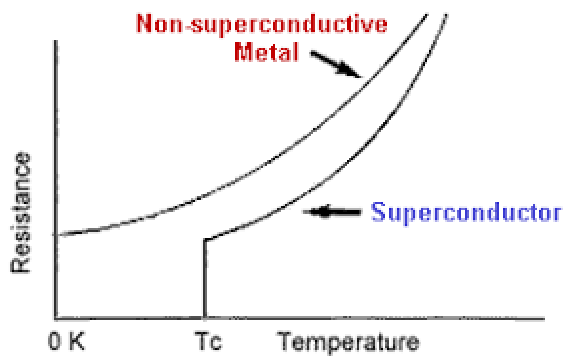


3. **Critical Temperature (T_c):** Substances in superconducting state have virtually zero electrical resistivity. The superconducting transition temperature T_c of a material is defined as a critical temperature at which electrical resistivity suddenly drops to zero. Below T_c the material is a superconductor and above T_c it behaves as a normal material with finite non zero resistivity.

   The superconducting transition temperatures of pure metals range from 0.3 kelvin to 1.25 kelvin. Common alloys have higher transition temperatures. The Niobium compounds such as Nb_3Sn (T_c = 18.1 kelvin) and Nb_3Ge (T_c = 22.65) have higher transition temperatures. These compounds are technically important superconductors.

   At the transition temperature T_c the following physical changes are observed in superconducting materials.

   a. Electrical resistivity drops to zero.
   b. The magnetic flux lines are excluded from the superconducting material and it becomes a perfect diamagnet.
   c. There is a discontinuity in the specific heat.
   d. There are small changes in thermal conductivity and volumes of the superconducting material.



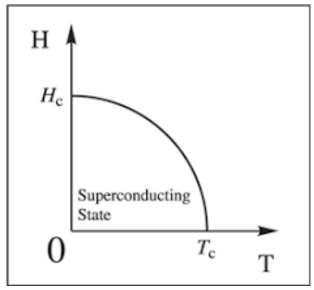
4. **Critical magnetic field (H_c):** When superconducting materials are subjected to very large vale of magnetic field, the superconducting property is destroyed. The field required to destroy the superconducting property is called as critical magnetic field (H_c) .

   The value of H_c is given by

$$\boldsymbol{H_C = H_0\left[1 - \frac{T^2}{T_C^2}\right]}$$

   Where H_0 is critical field at 0K.

   T_c is transition temperature.



From the fig we can find that when the temperature of the material increases, the value of the critical magnetic field decreases. Hence the value of the critical field will be different for different materials.

5. Critical current (I_c): Suppose a material carries electric current in superconducting state, this produces a magnetic field. If this magnetic field exceeds critical magnetic field H_c at that temperature T ($<T_c$), then normal resistance will be included in the material and it will be in the normal state. Hence, it is not possible to pass large currents through a superconductor. The maximum current that can be passed through a superconductor in superconducting state is called critical current, represented by I_c.

According to Silsbee's rule, for a superconducting wire $I_c = 2\pi r H_c$

Where I_c is the critical current and r is the radius of the wire.

6. Perfect Diamagnetism – Meissner Effect: The superconductor is a perfect diamagnet. As the material which is placed in an uniform magnetic field (whose value is smaller than the critical magnetic field H_c) , is cooled below T_c the magnetic flux inside the material is excluded from the material. This is called MEISSNER EFFECT.

Thus, a material can behave as a superconductor only when

i) The resistivity of the material should be zero

ii) The magnetic induction in the material should be zero when it is placed in an uniform magnetic field.

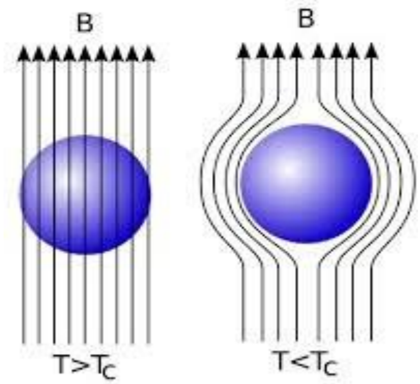
7.Thermal Properties:

a) The entropy and specific heat decreases at transition temperature.

b) The thermal conductivity of type I super conductor is low.

c) The thermo-electric effect disappears in the superconducting state.

11). Meissner effect: When a weak magnetic field is applied to a superconducting specimen at a temperature below transition temperature T_c, the magnetic flux lines are expelled as shown in fig.



This effect is reversible, i.e. when the temperature is raised from below T_c, at T= T_c the flux lines suddenly start penetrating and the specimen returns back to the normal state. Under this condition, the magnetic induction inside the specimen is given by

$$B = \mu_0(H + M) \text{ ----------- } (1)$$

Where H is the external applied magnetic field and M is the magnetization produced inside the specimen.

When the specimen is superconducting, according to Meissner effect, inside the bulk superconductor B = 0. Hence $\mu_0(H + M) = 0$

Or $$M = -H \text{ -------------------}(2)$$

Thus the material is perfectly diamagnetic. Magnetic susceptibility can be expressed as

$$\chi = \frac{M}{H} = -1 \text{ --------------}(3)$$

Let us consider a superconducting material under normal state. Let J be the current passing through passing through the material of resistivity ρ. From Ohm's law we know that the electric field E = Jρ. On cooling the material to its transition temperature ρ tends to 0, If J is held finite E must be zero. From Maxwell's equation, we know

$$\nabla \times E = -\frac{dB}{dt} \text{ -------------}(4)$$

Under superconducting condition since E is zero $\frac{dB}{dt} = 0$; or B = constant. This means that the magnetic flux passing through the specimen should not change on cooling to the transition temperature. The Meissner effect contradicts this result. According to Meissner effect perfect diamagnetism is an essential property of defining the superconducting state. Thus

From zero resistivity E = 0

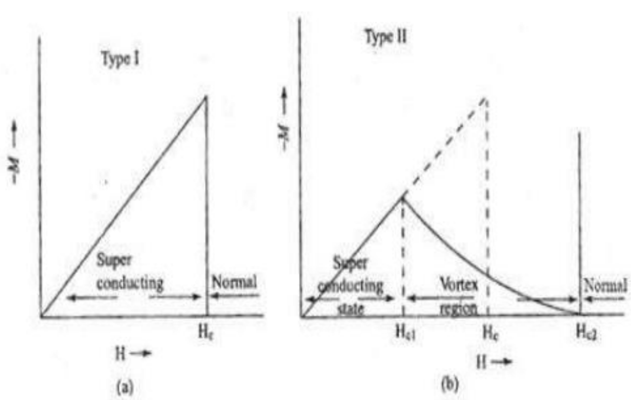
From Meissner effect B = 0

12). Type I and Type II superconductors:

Based on diamagnetic response superconductors can be classified as type I and type II. Superconductors exhibiting a complete Meissner effect (perfect diamagnetism) are called type I superconductors. (also known as soft super conductors). When the magnetic field strength is gradually increased from its initial value $H < H_c$, at H_c the diamagnetism abruptly disappears and the transition from superconducting state to normal state is sharp as shown in Fig. Pure specimens of Al, Zn, Hg and Sn are some examples of type I superconductors.

In type II superconductors as shown in fig, up to the field H_{c1} the specimen is in a pure superconducting state. The magnetic flux lines are rejected. When the field is increased beyond H_{c1}(the lower critical field), the magnetic flux lines start penetrating. The specimen is in a mixed state between H_{c1} and H_{c2} (the upper critical field). Above $H_{c2,}$ the specimen is in a normal state. This means that the Meissner Effect is incomplete in the region between H_{c1} and $H_{c2.}$ This region is known as Vortex region. Type II superconductors are known as hard superconductors. Zr and Nb are some examples of this type. Type II superconductors are of great practical interest because of the high current densities that they can carry.

Type 1 & Type 2 Superconductors



13). Applications of Superconducting Materials:

Engineering Applications:

Based on their properties, they have the following applications.

(i) Since there is no loss in power (zero resistivity) super conductors can be used for the transmission of power over very large distances.

(ii) Since the super conducting property can be easily destroyed it can be used in switching devices.

(iii) Since the variation in small voltages cause large constant current it can be used in very sensitive electrical instruments. Ex: galvanometer.

(iv) Since the current in a superconducting ring can flow without any change in its value (persistent current), it can be used as a memory or storage element in computers.

(v) Since the size of the specimen can be reduced to about 10^{-4} cm, it can be used to manufacture electrical generators and transformers in small sizes with high efficiency.

Apart from this, they are used to design cryotron, Josephson devices, SQUID, magnetic levitated trains (MAGLEV), modulators, rectifier's, commutators, etc.

Medical applications:

(i) Superconducting materials are used in NMR imaging equipment's which is used for scanning purposes.

(ii) They are applied in the detection of brain wave activity such as brain tumor, defective cells etc

(iii) Using super conducting magnets one can separate the damaged cells from the healthy cells.

(iv) Super conducting solenoids are used in magneto – hydrodynamic power generation to maintain plasma in the body.

Questions:

Short answer questions:

1. Define the terms a) Electric dipole b) Dipole moment c) Dielectric constant d) Polarization.
2. Define the terms a) Magnetic flux b) Magnetic induction c) Magnetic field strength d) Intensity of magnetization e) Magnetic susceptibility f) Magnetic permeability.
3. What is the origin for magnetic moment?
4. What are ferrites? Mention any two applications.
5. What are soft and hard magnetic materials.
6. What are applications of superconductors.
7. Define Superconductivity, Critical temperature.

Long answer questions:

1. Define polarization. Explain different types of polarizations in dielectrics.
2. Derive the expressions for electronic and ionic polarizations.
3. Explain the classification of magnetic materials on the basis of magnetic moment and mention the properties of various magnetic materials.
4. Explain the hysteresis phenomenon based on domain theory of ferromagnetism.
5. Write a short note on soft and hard magnetic materials. Or Distinguish soft and hard magnetic materials.
6. Explain the origin of magnetic moment.
7. Explain Type I and Type II super conductors.
8. Explain general properties superconductors.
9. Write a short note on Meisner effect.