LECTURE NOTES

ON

APPLIED PHYSICS

ACADEMIC YEAR 2021-22

I B.Tech –II SEMESTER (R20)

J. LAVANYA, Assistant Professor

DEPARTMENT OF HUMANITIES AND BASIC SCIENCES

V S M COLLEGE OF ENGINEERING

RAMCHANDRAPURAM

E.G DISTRICT - 533255

JAWAHARLAL NEHRU TECHNOLOGICAL UNIVERSITY: KAKINADA
KAKINADA – 533 003, Andhra Pradesh, India
DEPARTMENT OF ELECTRONICS AND COMMUNICATION ENGINEERING

I Year - II Semester		L	T	P	C
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APPLIED PHYSICS

Unit-I: Wave Optics 12hrs

Interference: Principle of superposition –Interference of light - Interference in thin films (Reflection Geometry) & applications - Colors in thin films- Newton's Rings- Determination of wavelength and refractive index.

Diffraction: Introduction - Fresnel and Fraunhofer diffraction - Fraunhofer diffraction due to single slit, double slit - N-slits (Qualitative) – Diffraction Grating - Dispersive power and resolving power of Grating(Qualitative).

Polarization: Introduction-Types of polarization - Polarization by reflection, refraction and Double refraction - Nicol's Prism -Half wave and Quarter wave plates.

Unit Outcomes:

The students will be able to

- **Explain** the need of coherent sources and the conditions for sustained interference(L2)
- **Identify** engineering applications of interference(L3)
- **Analyze** the differences between interference and diffraction with applications(L4)
- **Illustrate** the concept of polarization of light and its applications(L2)
- **Classify** ordinary polarized light and extraordinary polarized light(L2)

Unit-II: Lasers andFiberoptics *8hrs*

Lasers: Introduction – Characteristics of laser – Spontaneous and Stimulated emissions of radiation – Einstein's coefficients – Population inversion – Lasing action - Pumping mechanisms – Ruby laser – He-Ne laser - Applications of lasers.

Fiber optics: Introduction –Principle of optical fiber- Acceptance Angle - Numerical Aperture - Classification of optical fibers based on refractive index profile and modes – Propagation of electromagnetic wave through optical fibers - Applications.

Unit Outcomes:

The students will be able to

- **Understand** the basic concepts of LASER light Sources(L2)
- **Apply** the concepts to learn the types of lasers(L3)
- **Identifies** the Engineering applications of lasers(L2)
- **Explain** the working principle of optical fibers(L2)
- **Classify** optical fibers based on refractive index profile and mode of propagation(L2)
- **Identify** the applications of optical fibers in various fields(L2)

Unit III: Quantum Mechanics, Free Electron Theory andBand theory *10hrs*

Quantum Mechanics: Dual nature of matter – Heisenberg's Uncertainty Principle – Significance and properties of wave function – Schrodinger's time independent and dependent wave equations– Particle in a one-dimensional infinite potential well.

Free Electron Theory: Classical free electron theory (Qualitative with discussion of merits and demerits) – Quantum free electron theory– Equation for electrical conductivity based on quantum free electron theory- Fermi-Dirac distribution- Density of states (3D) - Fermi energy.

Band theory of Solids: Bloch's Theorem (Qualitative) - Kronig - Penney model (Qualitative)- E vs K diagram - v vs K diagram - effective mass of electron – Classification of crystalline solids–concept of hole.

Unit Outcomes:

The students will be able to

- **Explain** the concept of dual nature of matter(L2)
- **Understand** the significance of wave function(L2)
- **Interpret** the concepts of classical and quantum free electron theories(L2)
- **Explain** the importance of K-Pmodel
- **Classify** the materials based on band theory(L2)
- **Apply** the concept of effective mass of electron(L3)

Unit-IV: Dielectric andMagneticMaterials *8hrs*

DielectricMaterials: Introduction - Dielectric polarization - Dielectric polarizability, Susceptibility and Dielectric constant - Types of polarizations- Electronic (Quantitative), Ionic (Quantitative) and Orientation polarizations (Qualitative) - Lorentz internal field- Clausius- Mossotti equation-Piezoelectricity.

Magnetic Materials: Introduction - Magnetic dipole moment -Magnetization- Magnetic susceptibility and permeability - Origin of permanent magnetic moment - Classificationof
magnetic materials: Dia, para, Ferro, antiferro & Ferri magnetic materials - Domain concept for Ferromagnetism & Domain walls (Qualitative) - Hysteresis - soft and hard magnetic materials- Eddy currents- Engineering applications.

Unit Outcomes:

The students will be able to

- **Explain** the concept of dielectric constant and polarization in dielectric materials(L2)
- **Summarize** various types of polarization of dielectrics(L2)
- **Interpret** Lorentz field and Claussius- Mosotti relation indielectrics(L2)
- **Classify** the magnetic materials based on susceptibility and their temperature dependence (L2)
- **Explain** the applications of dielectric and magnetic materials(L2)
- **Apply** the concept of magnetism to magnetic data storage devices(L3)

Unit – V: SemiconductorsandSuperconductors *10hrs*

Semiconductors: Introduction- Intrinsic semiconductors – Density of charge carriers – Electrical conductivity – Fermi level – extrinsic semiconductors – density of charge carriers – dependence of Fermi energy on carrier concentration and temperature - Drift and diffusion currents – Einstein's equation- Hall effect – Hall coefficient –Applications of Hall effect.
Superconductors: Introduction – Properties of superconductors – Meissner effect – Type I and Type II superconductors – BCS theory (Qualitative) – Josephson effects (AC and DC) – SQUIDs – High T_c superconductors – Applications ofsuperconductors.

Unit Outcomes:

The students will be able to

- **Classify** the energy bands of semiconductors(L2)
- **Interpret** the direct and indirect band gap semiconductors(L2)
- **Identify** the type of semiconductor using Hall effect(L2)
- **Identify** applications of semiconductors in electronic devices(L2)
- **Classify** superconductors based on Meissner's effect(L2)
- **Explain** Meissner's effect, BCS theory & Josephson effect in superconductors(L2)

Text books:

1. M. N. Avadhanulu, P.G.Kshirsagar & TVS Arun Murthy" A Text book ofEngineering Physics"- S.Chand Publications, 11th Edition2019.
2. Engineering Physics" by D.K.Bhattacharya and Poonam Tandon, Oxford press(2015).
3. Applied Physics by P.K.Palanisamy SciTechpublications.

Reference Books:

1. Fundamentals of Physics – Halliday, Resnick and Walker, John Wiley&Sons

. Engineering Physics by M.R.Srinivasan, New Age international publishers(2009).

. Shatendra Sharma, Jyotsna Sharma, " Engineering Physics", Pearson Education,2018

. Engineering Physics - Sanjay D. Jain, D. Sahasrabudhe and Girish, UniversityPress

. Semiconductor physics and devices- Basic principle – Donald A, Neamen, Mc GrawHill

. B.K. Pandey and S. Chaturvedi, Engineering Physics, CengageLearning

VSM COLLEGE OF ENGINEERING

RAMACHANDRAPURAM DEPARTMENT
OF BASIC SCIENCES AND HUMANITIES

Course Title	Year/Sem	Branch	Periods per Week
Applied physics	1/1,11	CSE ,ECE,EEE	5

Course Outcomes: CO1:Explain the need of coherent sources and the conditions for sustained interference ,identify engineering applications of interference,differences between interference and diffractions,concept if polarization light and its applications ,classify ordinary and extraordinary polarised light.

CO2:Understand the basic concept of LASER light source ,types and applicationsof lasers,working principle of optical fibers and applications.

CO3: Explain the concept of dual nature of matter,significance of wave function,free electron and band theory of solids,K-P model, concept of effective mass of electron.

CO4: Explain the concept of dielectric constant and polarization and its types,classiuus mosotti relations,applications of dielectric and magnetic matetrials.

CO5 : Explain the concept of semiconductors, Superconductors ,hall effect and

Unit No	Outcomes	Name of the Topic	No. of Periods required	Total Periods	Reference Book	Methodology to be adopted
		Unit-1				
I	CO1: Expain the concept of interference,difference between interference diffraction concept,classify ordinary and extraordinary polarized light	Interference in thin films by reflection,thin films ,Newton rings concept	3	16	T1, T2 R20	Black Board
		Introduction and Fresnel&fraunhofer diffraction	1			Black Board
		Single slit	1			Black Board
		Double slit	1			Black Board
		n- slits	1			Black Board
		Dispersive and resolving power of grating	1			Black Board
		Polarization introduction and its types	2			Black Board
		Polarization by reflection	1			
		Polarization by refraction	1			Black Board
		Double refraction	1			Black Board
		Nicols prism	1			Black Board
		Quarter and half wave plates	1			Black Board
		Based on problems	1			E-Classroom

		Unit-2				
II	CO2:Understand the basic concept of LASER light sources,applications and working principle of optical fibres.	Introduction and charecteristics of laser	1	12	T1, T2 R20	Black Board
		Spontaneous and stimulated emission of radiation	1			Black Board
		Einstein coefficient and population inversion	1			Black Board
		Pumping mechanisms of ruby laser	2			Black Board
		He Ne laser	2			
		Introduction of optical fiber	1			Black Board
		Claasification of optical fiber	2			Black Board
		Numerical aperture and acceptance angle of an optical fiber	2			E-Classroom
		Unit-3				
III	CO3: Explain the concept of matter waves,free electron and band theory of solids and concept of effective mass of electron.	Explain the concept of dual nature of matter	1	14	T1, T2 R20	Black Board
		Heisenberge uncertainity principles	1			Black Board
		significance and properties of wave function	1			Black Board
		Schrodinger time independent and dependent wave equations	2			Black Board
		Concept of classical and quantum free electron theory	2			Black Board
		and explain the concept of Fermi dirac distribution functions and its levels.	2			Black Board
		Expain the concept of band theory	1			Black Board
		bloch theorem,and concept Kronig-Penny model	2			Black Board
		E-K diagrams	1			Black Board
		effective mass of electron	1			Black Board
						E-Classroom

						o m

IV	CO4: Explain the concept of Dielectric and Magnetic materials.	**Unit-4**		14	T1, T2 R20	
		Explain the concept of dielectric materials	1			Black Board
		,types of polarization	2			Black Board
		concept of Lorentz internal fields	2			Black Board
		Introduction of magnetic materials	1			Black Board
		magnetic dipole moment	1			
		susceptibility&permeability	1			Black Board
		Classification of magnetic materials	2			Black Board
		domain walls,	1			Black Board
		Hysteresis	2			
		concept of soft and hard magnetic materials	2			Black Board

V	CO5:Expain the concept semiconductors,superconductors,caerier concentration of p and n type,ans concept of BCS theory	**Unit-5**		12	T1, T2 R20	
		Introduction of semiconductors and its types	2			Black Board
		carrier concentration of p and n type semiconductors	2			Black Board
		concept of Hall effect and its applications.	2			E-Classroom
		Introduction of superconductors and its types	2			
		BCS theory	1			Black Board
		concept of Josephson effect	1			
		applications of superconductors	2			Black Board

TEXT BOOKS:
M.N. Avadanulu ,P.G.K Shrisagar&T.V.S Arunmurthy ,P.K. Palaniswamy 3rd addition SciTech publication 2013.
Engineering physics by D.K.Battacharya and Poonam Tandon and S.Chand publication 11th edition.

REFERENCE BOOKS:

1. Fundamentals of physics-Hallyday Resnick and Walker 10th edition John Wiley&sons.
2. Engineering physics by M.R.srinivasan, New age international publisher 2019.
3. Semiconductor physics and devices-Basic principle-Donald A, Neamen 3rd edition.
4. B.K Pandey and chaturvedhi,Engineering physics 1st edition Cengage learning 2013.

Faculty Member **Head of the Department** **Principal**

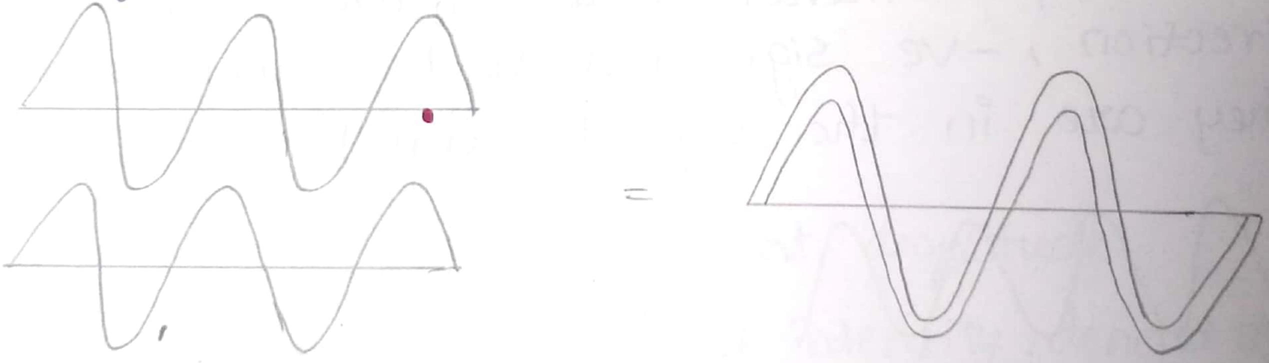
I. Wave Optics

Interference :-

When two light waves from different coherent sources meet together, then the distribution of energy due to one wave is disturbed by the other. This modification in the distribution of light energy due to super-position of two light waves.

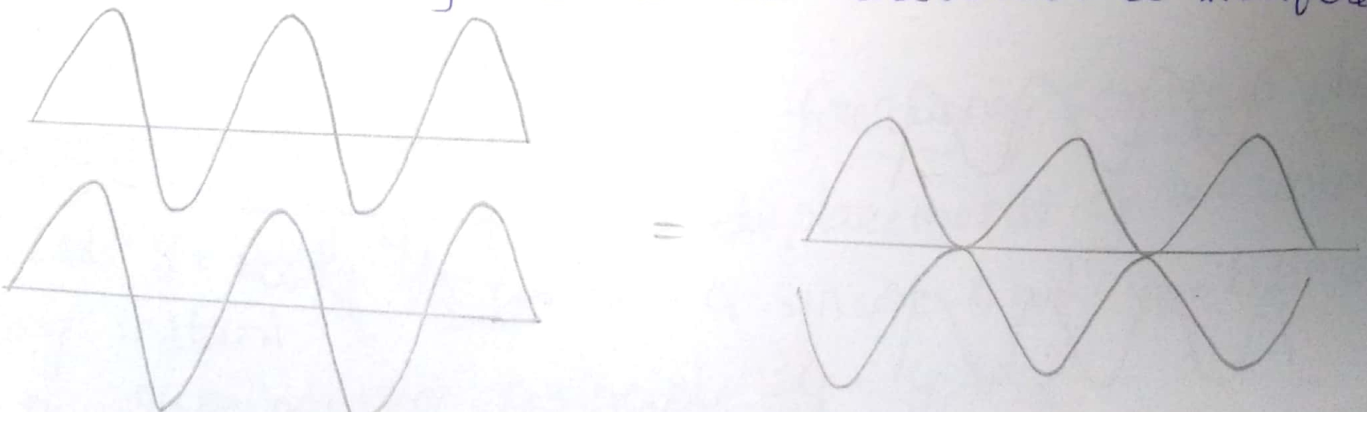
Constructive interference :

The interference taking place at point of maximum intensity is called constructive interference.



Destructive interference :-

The interference taking place at points of minimum intensity is called destructive interference



Principle of superposition of Waves :-

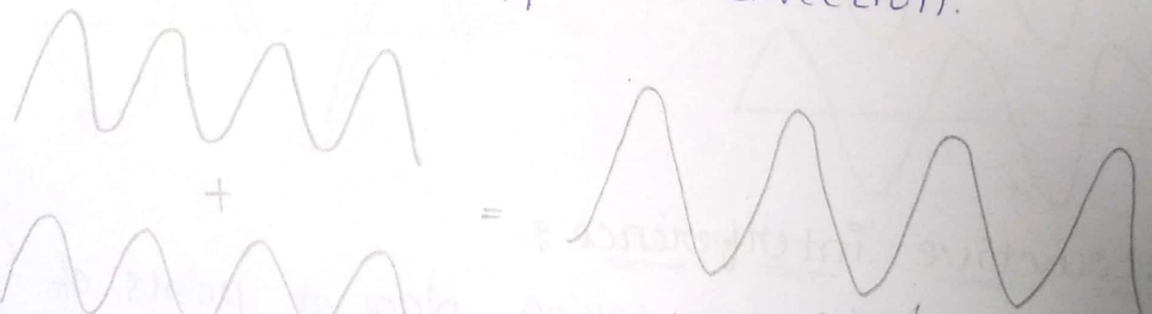
When two or more waves travel simultaneously in a medium, the resultant displacement at any point is due to the algebric sum of the displacement due to individual waves. This is the principle of superposition.

Letus consider two waves travelling simultaneously in a medium at any point. Let y_1 be the displacement due to one wave at any instant in the absence of the other and y_2 be the displacement of the other wave at the same instant in the absence of the first wave.

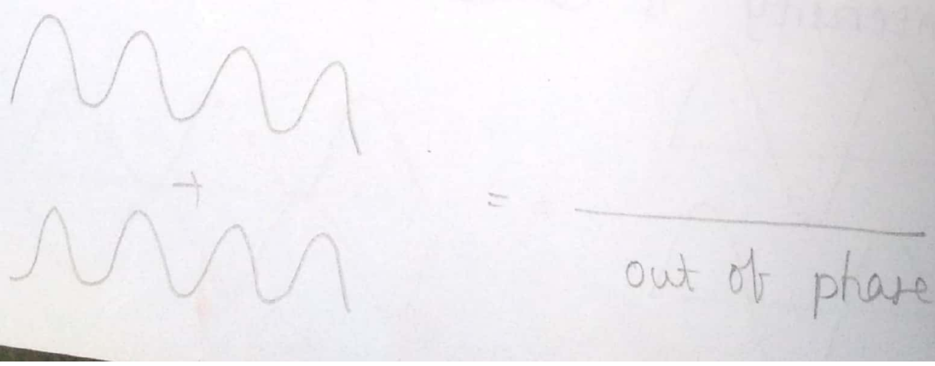
Then the resultant displacement due to the presence of both the waves is given by

$$y = y_1 \pm y_2$$

Here +ve sign has to be taken when both the displacements y_1 and y_2 are in the same direction, -ve sign has to be taken when they are in the opposite direction.



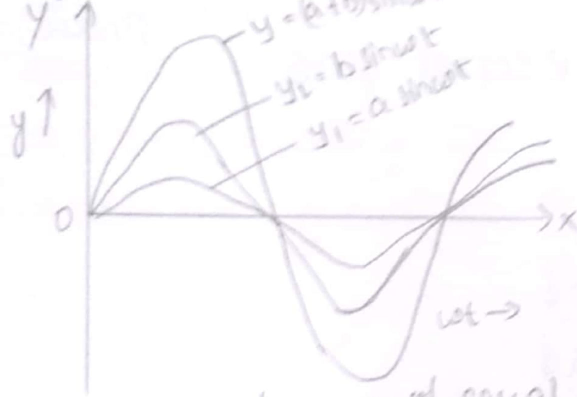
waves in phase



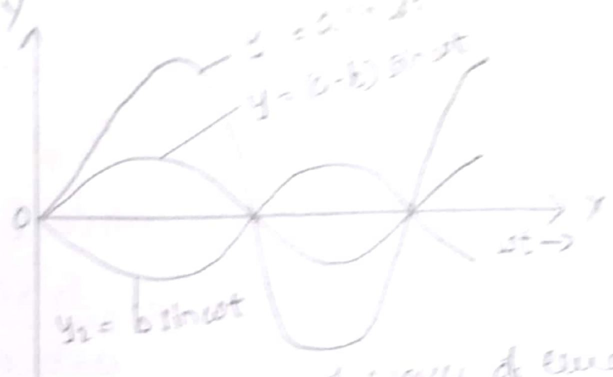
out of phase

Superposition of waves of equal phase and frequency:-

When two waves are having the same frequency and same phase travelling together in a medium then ~~on~~ the crest of one wave falls exactly on the crest of other wave. Similarly trough of one wave falls on the trough of another wave. The resultant amplitude is equal to sum of individual amplitudes



Superposition of waves of equal freq. and in same phase



Superposition of waves of equal freq. and in opposite phase

If $y_1 = a \sin \omega t$, $y_2 = b \sin \omega t$

$$y = y_1 + y_2$$

$$y = a \sin \omega t + b \sin \omega t$$

$$y = (a+b) \sin \omega t$$

$$y = A \sin \omega t$$

Where $A = (a+b)$ is the resultant amplitude.

The square of amplitude is called intensity, denoted by I.

The intensity $I = A^2 = (a+b)^2$

When both waves travel in the opposite direction

Then the resultant amplitude $A = a - b$

$$I = A^2 = (a-b)^2.$$

Superposition of waves of same frequency & constant phase

Let y_1 and y_2 be the displacements of two waves at any instant 't' then $y_1 = a \sin \omega t$ and $y_2 = b \sin(\omega t + \phi)$

A/c to superposition principle $y = y_1 + y_2$

$$y = a\sin\omega t + b\sin(\omega t+\phi)$$
$$= a\sin\omega t + b\sin\omega t\cdot\cos\phi + b\cos\omega t\cdot\sin\phi$$
$$= (a+b\cos\phi)\sin\omega t + b\cos\omega t\cdot\sin\phi$$

Letus assume $a+b\cos\phi = R\cos\theta$ and $b\sin\phi = R\sin\theta$

Squaring & adding $(R\cos\theta)^2+(R\sin\theta)^2 = (a+b\cos\phi)^2+(b\sin\phi)^2$

$$R^2 = a^2+b^2+2ab\cos\phi$$

Where, R is the resultant amplitude, θ is the resultant phase

Therefore $y = R\sin\omega t\cos\theta + R\cos\omega t\sin\theta$

$$= R\sin(\omega t+\theta)$$

where $R = \sqrt{a^2+b^2+2ab\cos\phi}$

$$\tan\theta = \frac{R\sin\theta}{R\cos\theta} = \frac{b\sin\phi}{a+b\cos\phi}$$

$$\theta = \tan^{-1}\frac{b\sin\phi}{a+b\cos\phi}$$

If $\phi=0$ then $R=a+b$

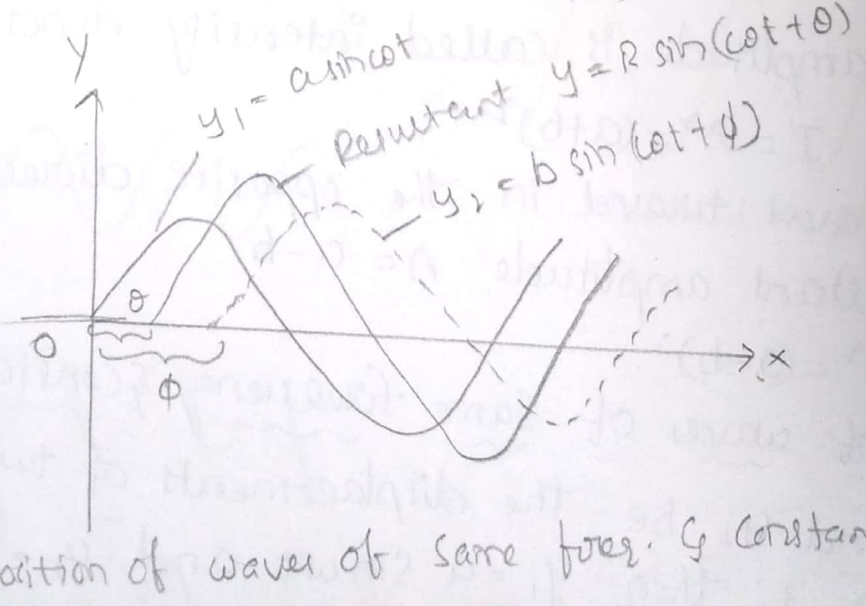
Intensity $I = R^2 = (a+b)^2$

When the amplitude of both waves are equal i.e $b=a$

$$I = (a+a)^2 = a^2+a^2+2a^2\cos\phi$$

$$I = 2a^2(1+\cos\phi)$$

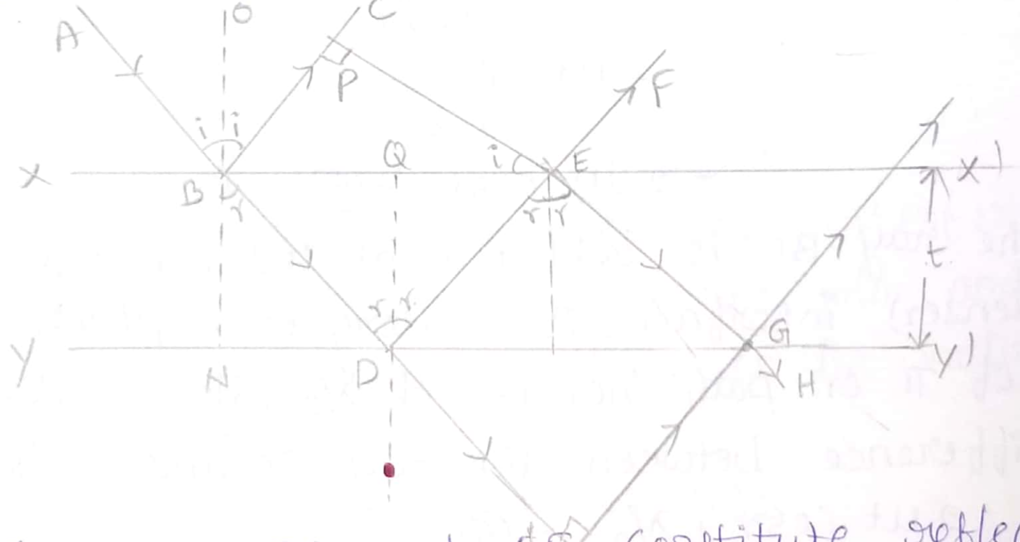
$$I = 4a^2\cos^2(\phi/2)$$



Superposition of waves of same freq. & constant phase.

Interference in thin films by Reflection:

Let us consider a thin film of thickness 't' bound by two plane surfaces xy and x'y' and let 'μ' be the refractive index of the material of the film. A ray of light AB incident on the surface xy at an angle 'i' is the partially reflected along BC and partially refracted along BD. Let the angle of refraction be r_1 on the surface x'y', the refracted ray is partly reflected along DE and partly refracted along DK. Similar reflection and refraction occur at E and G also shown in figure.



The rays BC and EF constitute reflected system. To find the path difference between these reflected rays EP is drawn perpendicular to BC.

$$\text{Path difference} = (BD+DE)\mu - BP \quad ①$$

In ΔBDQ $\quad \cos r = \frac{DQ}{BD} = \frac{t}{BD}$

$$BD = \frac{t}{\cos r} = DE \longrightarrow ②$$

Hence path difference $\quad \frac{2\mu t}{\cos r} - BP \quad ③$

In ΔBPE $\quad \sin i = \frac{BP}{BE}$

$Bp = BE \sin i$

$= (BQ+QE)\sin i$ — ④

In ΔBDQ

$$\tan r = \frac{BQ}{QD}$$

$$BQ = t\tan r = QE$$

From ④ $BP = 2t\tan r\cdot\sin i$

$$\because \mu = \frac{\sin i}{\sin r}$$

$$= 2t\frac{\sin r}{\cos r}\cdot\mu\sin r$$

Hence path difference $= \frac{2\mu t}{\cos r} - 2\mu t\cdot\frac{\sin^2 r}{\cos r}$

$$= 2\mu t\frac{(1-\sin^2 r)}{\cos r}$$

$$= 2\mu t\frac{\cos^2 r}{\cos r}$$

$$= 2\mu t\cos r \quad \text{— ⑤}$$

Since the ray BC is reflected at the air-medium (rarer-denser) interface, it undergoes a phase change of π or path increase of λ/2. Hence the path difference between the ray BC and EP is

$$2\mu t\cos r \pm \lambda/2 \quad \text{— ⑥}$$

Condition for bright band:

The film will appear bright if the path difference

$$2\mu t\cos r \pm \lambda/2 = n\lambda$$

$$2\mu t\cos r = (2n\pm1)\lambda/2$$

where $n = 0, 1, 2, 3 \ldots$

Condition for dark band:

The film will appear dark if the path difference

$$2\mu t\cos r \pm \lambda/2 = (2n\pm1)\lambda/2$$

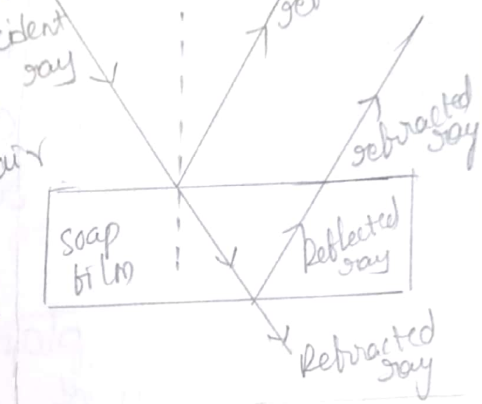
$$2\mu t\cos r = n\lambda \quad \text{where } n = 0,1,2,3\ldots$$

If the film thickness is extremly small when compared to λ, then $2\mu t\cos r$ can be neglected in eq^n ⑥ and then the net path difference is $\lambda/2$. Hence destructive interference will occur and the film will appear dark.

Colours in thin films :-

A thin film is very thin layer of transparent material with thickness ranging from nanometer to micrometer (inorder of wavelength of light)

Ex : Soap bubble



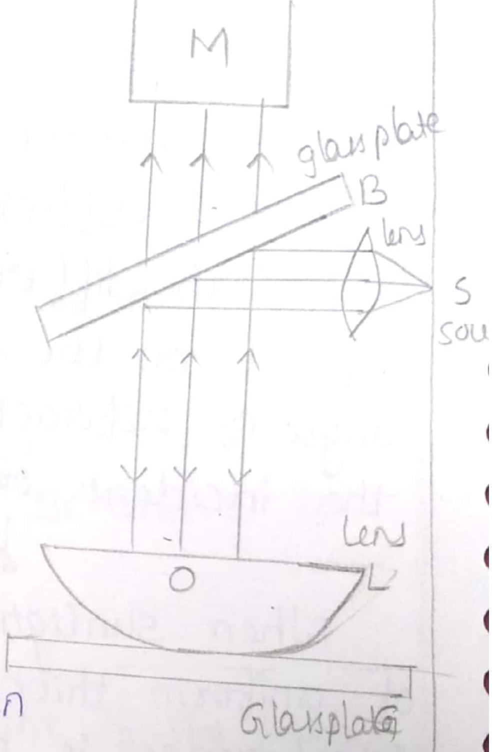
When a thinfilm is exposed to sunlight, it shows beautiful colours in the reflected system. Light is reflected from top and bottom surface of a thinfilm. and the reflected rays interfere. The path difference between the interfering rays depend on the thickness of the film and the angle of refraction and hence on the inclined of the incident ray

$$\Delta x = 2\mu t \cos r + \lambda/2$$

When sunlight is used to illuminate a thinfilm f uniform thickness, the condition for constructive nterference is satisfied for different wave (i.e diffrent olour) at different angles of refraction i.e for different ngle of incidence. Since sun is extended source of ight, the divergence of reflected at different angles will be small as shown in figure. The eye of the bserver will be able together light for a Large range of angles of incidence and hence will observe arious colours observing the same region of the film.

Newton Rings :

Newton rings are another example of fringes equal thickness. Newton's rings are formed when a plano-Convex lens L of a large radius of curvature placed on a sheet of plane glass AB. The combination forms a thin circular air film of variable thickness in all directions around the point of contact of the lens and the glass plate. Interference fringes are observed these concentric circular fringes and hence they are called Newton's rings. The experiment~~al~~ for observing Newton's rings.



'L' is a planoconvex lens of larger radius of curvature placed on a optically plane glass plate G. The lens touches the glass plate G. The lens touches the glass plate O. S is monochromatic source of light and lens L callimates the light from source S. The glass plate B reflects part of the light incident on it towards the air film enclosed between the lens L and glass plate G.

Part of light incident on the lens L is reflected back by the curved surface of the lens L and the other part transmitted is partly reflected back by the upper surface of the glass plate G. These two reflected beams have some path difference depending on the thickness of air film and hence interfere producing Newton's rings. These rings can be viewed through a microscope M.

The path difference between the reflected beam becomes $2t+\lambda/2$, when this path difference is $n\lambda$ constructive interference occurs.

Hence the condition for bright rings is

$$2t + \lambda/2 = n\lambda$$

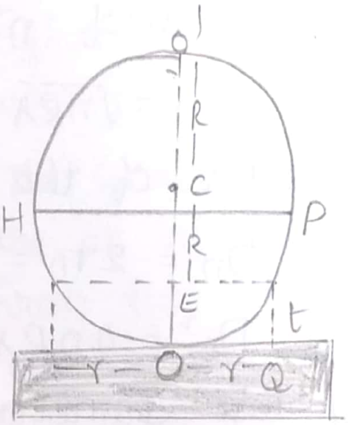
$$2t = (2n-1)\lambda/2 \quad — ① \qquad \text{Where } n = 1,2,3 \ldots$$

Similarly for dark rings the condition is

$$2t + \lambda/2 = (2n+1)\lambda/2$$

$$2t = n\lambda \quad — ②$$

Letus Consider the curved surface of the lens as an arc of a circle whose Centre is at C.



$$HE \times EP = OE \times EO'$$

$$r^2 = t(OO' - EO)$$

$$r^2 = t(2R - t)$$

$$r^2 = 2Rt - t^2$$

$$r^2 = 2Rt$$

Hence $t = \frac{r^2}{2R}$ — ③

Substituting this in the condition for bright ring from eqn ①

$$2t = (2n-1)\lambda/2$$

$$2 \cdot \frac{r^2}{2R} = (2n-1)\lambda/2$$

$$r^2 = \frac{(2n-1)\lambda R}{2} \qquad \text{where } n = 1,2,3 \ldots$$

$$r = \sqrt{\frac{(2n-1)\lambda R}{2}}$$

For dark rings from ②

$$2t = n\lambda$$

$$2 \cdot \frac{r^2}{2R} = n\lambda$$

$$r^2 = nR\lambda$$

$$r = \sqrt{nR\lambda}$$

For 1st dark ring $n=1$

$$r_1 = \sqrt{R\lambda}$$

2nd dark ring $r_2 = \sqrt{2R\lambda}$

$\vdots$

For nth dark ring $r_n = \sqrt{nR\lambda}$

We find that with increase of order the rings get closer.

Determination of Wavelength :-

Let 'R' be the radius of curvature of the curved surface in contact with the glass plate and λ is the wavelength of light used.

W.K.T the radius of nth dark ring r is given by

$$r_n = \sqrt{nR\lambda} \quad \text{—} ①$$

The diameter of the nth dark ring is

$$D_n = 2r_n = 2\sqrt{nR\lambda}$$

$$D_n^2 = 4nR\lambda \quad \text{—} ②$$

Similarly the diameter of the (n+m)th dark ring is

$$D_{n+m} = 2r_{n+m}$$

$$= 2\sqrt{(n+m)R\lambda}$$

$$D_{n+m}^2 = 4(n+m)R\lambda \quad \text{—} ③$$

Subtracting eqn ③ & ④ we get

$$D_{n+m}^2 - D_n^2 = 4mR\lambda$$

$$\lambda = \frac{D_{n+m}^2 - D_n^2}{4mR}$$

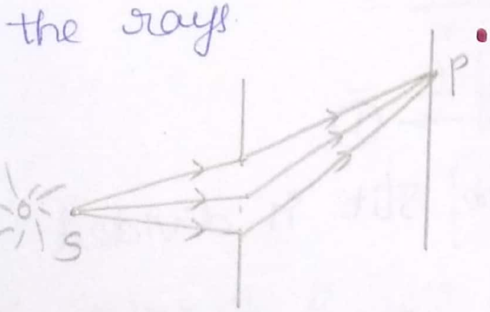
Hence by measuring the diameter of the rings of different orders and knowing the radius of curvature of the lens R. We can determine the wavelength λ of the given monochromatic source of light.

Diffraction :

The bending of light round the corners of obstacles and spreading of light waves into the geometrical shadow of an obstacle placed in the path of light is called diffraction.

Fresnel and Fraunhofer diffraction :

Fresnel	Fraunhofer
* Either a point source or an illuminated narrow slit is used.	* Extended source at infinite distance is used.
* The wave-front undergoing diffraction is either spherical or cylindrical	* The wavefront undergoing diffraction is a plane wavefront.
* The source of light and the screen are finite distances from the obstacle producing diffraction.	* The source and the screen are at infinite distance from the obstacle producing diffraction.
* No lens is used to focus the rays	* Converging lens is used to focus parallel rays



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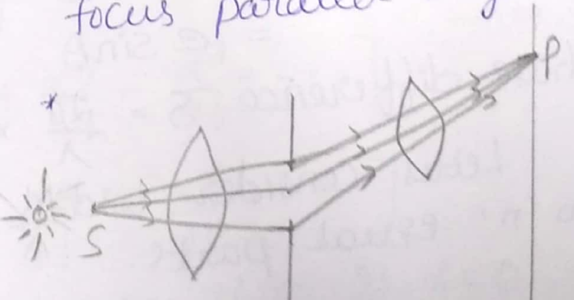
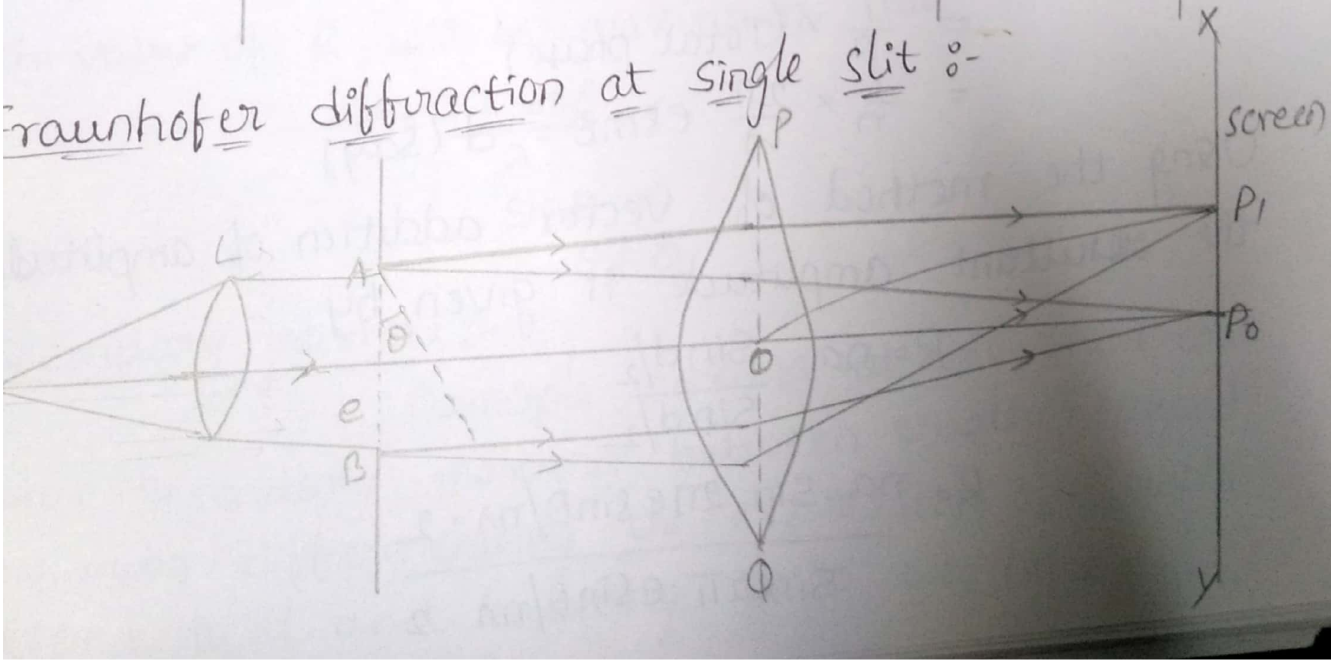


Fraunhofer diffraction at single slit :-



AB of a narrow Slits of width 'e' perpendicular to the plane of the paper. Let a plane wavefront of monochromatic light wavelength 'λ' propagating normally to the slit incident on it.

Let the diffraction be focussed by mean of a convex lens on a screen placed in the focal plane of the lens. The secondary wavelet travelling normally to the slit that is along the direction OP_0 are focussed at P_0 by the lens. P_0 is a bright central image.

The secondary wavelet travelling at an angle 'θ' with the normal are focussed at a point P_1 on the screen. The point P_1 is the minimum intensity or maximum intensity depending upon the path difference between the secondary wavelet.

To find the intensity at P_1 draw the perpendicular AC on BC, the path difference between secondary wavelets from A & B in direction.

$$\theta = BC = AB \sin\theta$$

$$= e \sin\theta$$

phase difference $\delta = \frac{2\pi}{\lambda} \times e\sin\theta$ — ①

Letus Consider width of the slit is divided into 'n' equal parts.

$$= \frac{1}{n} \times (\text{Total phase})$$

$$= \frac{1}{n} \times \frac{2\pi}{\lambda} e\sin\theta = d \text{ (say)}$$

Using the method of vector addition of amplitude the resultant amplitude is given by

$$R = na \frac{\sin d/2}{\sin d/2}$$

$$R = na \frac{\sin 2\pi e \sin\theta / n\lambda \cdot 2}{\sin 2\pi e\sin\theta / n\lambda \cdot 2}$$

$$R = \frac{a \sin \pi e \sin\theta/\lambda}{\sin \pi e \sin\theta/n\lambda}$$

Put $\frac{\pi e \sin\theta}{\lambda} = \alpha$

$$R = \frac{a \sin\alpha}{\sin(\alpha/n)}$$

α/n is very small $\qquad \sin\alpha/n \sim \alpha/n$

$$\therefore R = a\frac{\sin\alpha}{\alpha/n}$$

$$R = \frac{A \sin\alpha}{\alpha}$$

The resultant amplitude is given by $R = \frac{A\sin\alpha}{\alpha}$ — ②

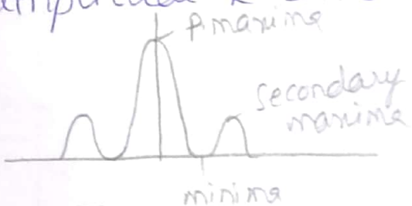
When $n \to \infty$, $a \to 0$ then the product $na = A$

Now $I = R^2 = \frac{A^2 \sin^2\alpha}{\alpha^2}$

$$I = \frac{I_0 \sin^2\alpha}{\alpha^2} \quad \text{— ③}$$

Principle maxima:

The expression for resultant amplitude R can be written as



$$R = \frac{A\sin\alpha}{\alpha}$$

$$= \frac{A}{\alpha}[\sin\alpha]$$

$$= \frac{A}{\alpha}\left[\alpha - \frac{\alpha^3}{3!} + \frac{\alpha^5}{5!} - \frac{\alpha^7}{7!} + \cdots\right]$$

$$= A\left[1 - \frac{\alpha^2}{3!} + \frac{\alpha^4}{5!} - \frac{\alpha^6}{7!} + \cdots\right]$$

The value of R will be maximum that is $\alpha = 0$

$$\alpha = \frac{\pi e \sin\theta}{\lambda} = 0$$

$$\sin\theta = 0$$

$$\theta = 0$$

Secondary maxima:-

Principle maxima at $\alpha = 0$, there are weak secondary maxima between equally spaced minimum differenciating the expression of I with respect to α and equating to '0' we have

$$\frac{d}{d\alpha}(I) = 0$$

$$\frac{d}{d\alpha}\left(\frac{I_0 \sin^2\alpha}{\alpha^2}\right) = 0$$

$$I_0\left[\frac{1}{\alpha^2} \cdot 2\sin\alpha\cos\alpha + \sin^2\alpha - \frac{2}{\alpha^3}\right] = 0$$

$$\frac{2\sin\alpha}{\alpha^2}\left[\cos\alpha - \frac{\sin\alpha}{\alpha}\right] = 0$$

$$\alpha\cos\alpha - \sin\alpha = 0$$

$$\alpha\cos\alpha = \sin\alpha$$

$$\boxed{\alpha = \tan\alpha}$$

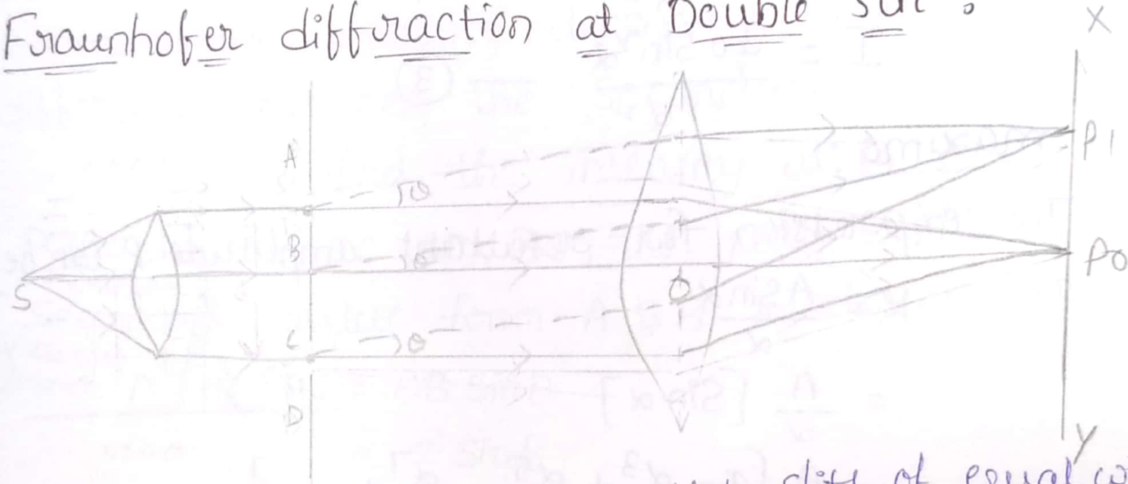
$$I_0 \frac{d}{d\alpha}\left(\frac{\sin^2\alpha}{\alpha^2}\right) = 0$$

$$\frac{\alpha^2\, 2\sin\alpha\cos\alpha - \sin^2\alpha\,(2\alpha)}{\alpha^4}$$

$$\frac{2\alpha\sin\alpha}{\alpha^4}\left[\alpha\cos\alpha - \right.$$

The value of α satisfying the above eqn in all secondary maxima.

Fraunhofer diffraction at Double slit :



Let AB & CD be two parallel slits of equal width 'e' Separated by a distance 'd'. The distance between the corresponding middle point of the two slits (e+d) Let a parallel beam of monochromatic light of wavelength λ be incident normally upon the two Slits. The light diffracted from these slits is focussed by a lens on the system xy placed in the focal plane of the lens.

When a plane wavefront is incident normally on both slits. The secondary waves travelling in the direction of incident light comes to a focus Po while the s travelling in a direction come making an an angle θ with the incident direction come to a focus at P_1.

Resultant amplitude $R = \frac{A\sin\alpha}{\alpha}$

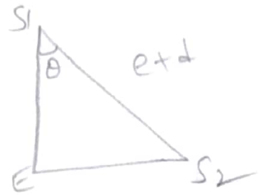
Where A is constant being equal to the amplitude due to a single slit when $\theta = 0$ and $\alpha = \frac{\pi e\sin\theta}{\lambda}$

The phase difference δ (say)

To calculate δ we draw a perpendicular S_1E on S_2E

The path difference between the wavelets from S_1 & S_2 in the direction $\theta = S_2E$ $\quad \sin\theta = \frac{S_2E}{e+d}$

$$= (e+d)\sin\theta$$



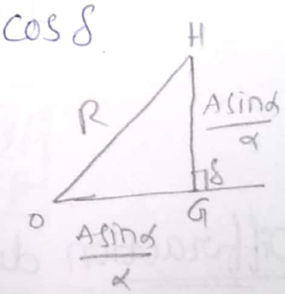
phase difference $\delta = \frac{2\pi}{\lambda} \times \text{path diff}$

$$\delta = \frac{2\pi}{\lambda} \times (e+d)\sin\theta$$

The resultant amplitude R at P_1 can be obtained with the help of Δ^{le}

From figure $(OH)^2 = (OG)^2 + (GH)^2 + 2(OG)(GH)\cos\delta$

$$R^2 = \left[\frac{A\sin\alpha}{\alpha}\right]^2 + \left[\frac{A\sin\alpha}{\alpha}\right]^2 + 2\left[\frac{A\sin\alpha}{\alpha}\right]\left[\frac{A\sin\alpha}{\alpha}\right]\cos\delta$$



$$R^2 = \frac{A^2\sin^2\alpha}{\alpha^2}(1+1+2\cos\delta)$$

$$R^2 = 2\frac{A^2\sin^2\alpha}{\alpha^2}(1+\cos\delta)$$

$$R^2 = 2\frac{A^2\sin^2\alpha}{\alpha^2}(1+2\cos^2\delta/2 - 1)$$

$$R^2 = 2\frac{A^2\sin^2\alpha}{\alpha^2}(2\cos^2\delta/2)$$

$$R^2 = 4\frac{A^2\sin^2\alpha}{\alpha^2}\cos^2\delta/2$$

Where $\delta = \frac{\pi(e+d)\sin\theta}{\lambda}$

$$R^2 = 4\frac{A^2\sin^2\alpha}{\alpha^2}\cos^2\frac{\pi(e+d)\sin\theta}{\lambda}$$

$$R^2 = 4\frac{A^2\sin^2\alpha}{\alpha^2}\cos^2\beta$$

The resultant intensity is given by

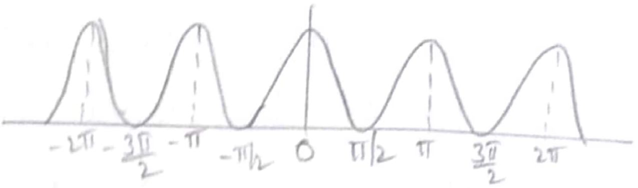
$$\boxed{I = 4\frac{A^2 \sin^2\alpha}{\alpha^2} . \cos^2\beta}$$

For maxima: $\sin^2\alpha = 0$

$\sin\alpha = 0$

$\alpha = \sin^{-1}(0)$

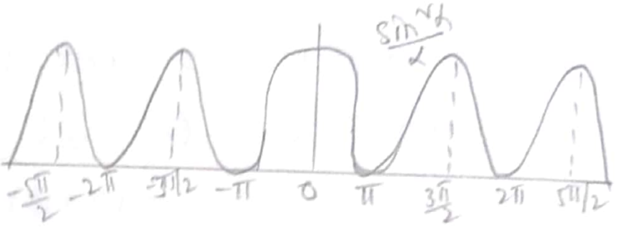
$\alpha = 0$



But $\alpha \neq 0$, then $\alpha = \pm n\pi$

$$\frac{\pi e \sin\theta}{\lambda} = \pm n\pi$$

$$\boxed{e \sin\theta = \pm n\lambda}$$

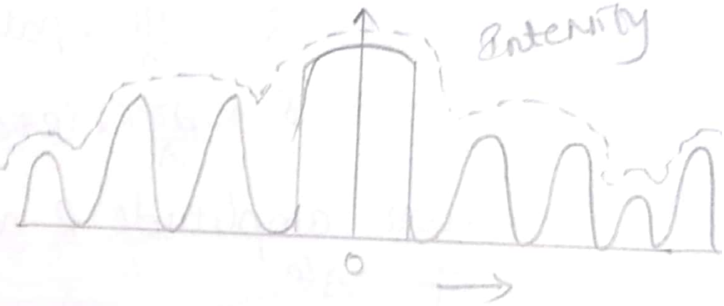


For minima:- $\cos^2\beta = 1$

$\cos\beta = 1$

$\beta = \cos^{-1}(1)$

$\beta = 0$

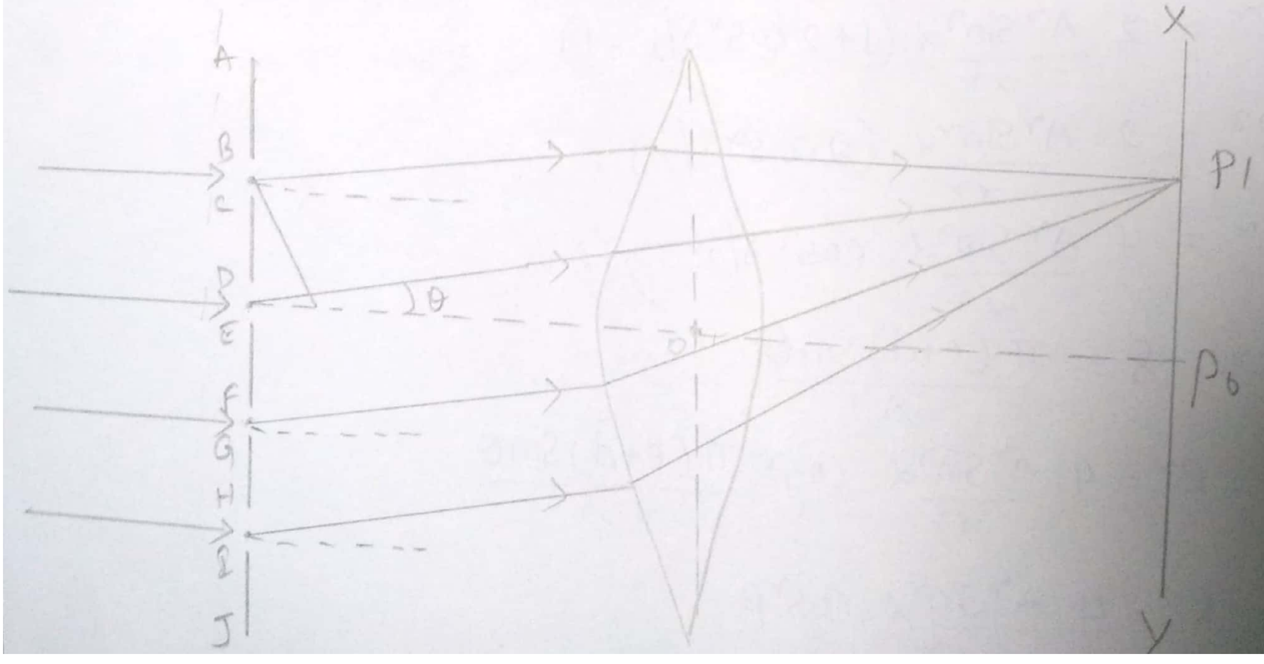


But $\beta \neq 0$ then $\beta = \pm n\pi$

$$\frac{\pi(e+d)\sin\theta}{\lambda} = \pm n\pi$$

$$\boxed{(e+d)\sin\theta = \pm n\lambda}$$

Diffraction due to N- slits :-



Letus consider the diffraction pattern produced by N-slits, each of width a. The separation between consecutive slits is $d = a+b$, where 'a' is the width of the open portion and b is width of the opaque portion. Such a device consisting of a large no. of parallel slits of equal width and separated from one another by equal opaque spaces is called a diffraction grating. The distance 'd' between the centers of the adjacent slits is known as the grating period.

path difference b/w two suscessive slits $(e+d)\sin\theta$.

$$\phi = \frac{2\pi}{\lambda}(e+d)\sin\theta = 2\beta$$

$$\therefore \beta = \frac{\pi}{\lambda}(e+d)\sin\theta$$

$$\phi = 2\beta$$

Resultant amplitude on screen due to N-slits

$$R = \frac{A\sin\alpha}{\alpha} \cdot \frac{\sin N\beta}{\sin\beta}$$

$$I = R^2 = \frac{A^2\sin^2\alpha}{\alpha^2} \cdot \frac{\sin^2 N\beta}{\sin^2\beta}$$

Now the intensity term $\boxed{I = \frac{A^2\sin^2\alpha}{\alpha^2} \cdot \frac{\sin^2 N\beta}{\sin^2\beta}}$

principle maxima:

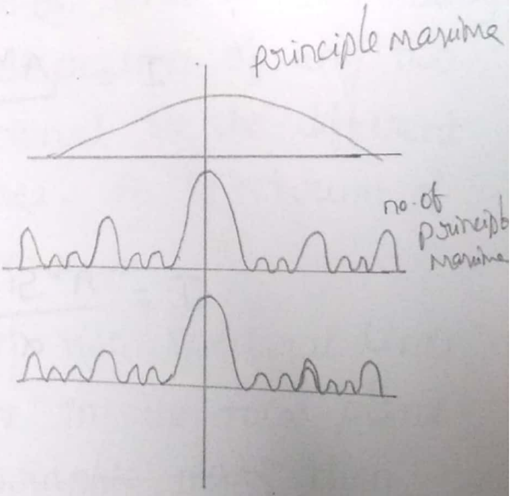
$$I = \frac{A^2\sin^2\alpha}{\alpha^2} \cdot \frac{\sin^2 N\beta}{\sin^2\beta}$$

$\sin\beta = 0,\ \beta = \pm n\pi$

$n = 0, 1, 2, 3 \ldots$

$\sin N\beta = 0$

$\frac{\sin N\beta}{\sin\beta} = 0$ (Indeterminate)



$$\lim_{\beta \to \pm n\pi} \frac{\sin N\beta}{\sin\beta} = \lim_{\beta \to \pm n\pi} \frac{d/d\beta(\sin N\beta)}{d/d\beta(\sin\beta)}$$

$$= \frac{N\cos N\beta}{\cos\beta} \Rightarrow \pm N$$

$$\boxed{I_{p.m} = \frac{A^2 \sin^2\alpha}{\alpha^2} \cdot N^2}$$

Secondary maxima :

$$I = \frac{A^2 \sin^2\alpha}{\alpha^2} \cdot \frac{\sin^2 N\beta}{\sin^2\beta}$$

$$\frac{dI}{d\beta} = 0$$

$$\frac{dI}{d\beta} = \frac{A^2 \sin^2\alpha}{\alpha^2} \cdot \frac{d}{d\beta}\left(\frac{\sin N\beta}{\sin\beta}\right)^2 = 0$$

$$\frac{A^2 \sin^2\alpha}{\alpha^2} \cdot 2\left(\frac{\sin N\beta}{\sin\beta}\right)\left[\frac{\sin\beta(N\cos N\beta) - \sin N\beta \cos\beta}{\sin^2\beta}\right] = 0$$

$$\sin\beta\,(N\cos N\beta) - \sin N\beta \cos\beta = 0$$

$$N \sin\beta \cos N\beta = \sin N\beta \cos\beta$$

$$\frac{N\sin\beta}{\cos\beta} = \frac{\sin N\beta}{\cos N\beta}$$

$$\operatorname{Tan} N\beta = N \operatorname{Tan}\beta$$

$$\sin N\beta = \frac{N\operatorname{Tan}\beta}{\sqrt{1+N^2\operatorname{Tan}^2\beta}}$$

$$I = \frac{A^2 \sin^2\alpha}{\alpha^2} \cdot \frac{\sin^2 N\beta}{\sin^2\beta}$$

$$I = \frac{A^2 \sin^2\alpha}{\alpha^2} \cdot \frac{1}{\sin^2\beta}\left(\frac{N^2\operatorname{Tan}^2\beta}{1+N^2\operatorname{Tan}^2\beta}\right)$$

$$I = \frac{A^2 \sin^2\alpha}{\alpha^2} \cdot \frac{1}{\sin^2\beta} \cdot \frac{N^2 \sin^2\beta / \cos^2\beta}{1 + N^2 \frac{\sin^2\beta}{\cos^2\beta}}$$

$$I = \frac{A^2 \sin^2\alpha}{\alpha^2} \cdot \frac{1}{\sin^2\beta} \cdot \frac{N^2 \sin^2\beta / \cos^2\beta}{\frac{\cos^2\beta + N^2 \sin^2\beta}{\cos^2\beta}}$$

$$\boxed{I = \frac{A^2 \sin^2\alpha}{\alpha} \cdot \frac{N^2}{\cos^2\beta + N^2 \sin^2\beta}}$$

Polarization:

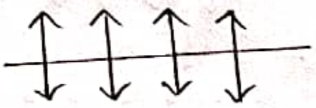
Introduction:

Interference and Diffraction are the phenomenon which onfirmed the wave Nature of light beyond any doubt. ut, It could not Establish whether light waves are longitudinal r Transverse.

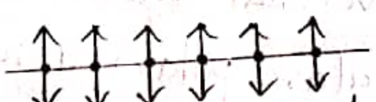
The transverse Nature of light has been Established by larization phenomenon. In transverse motion, the particles the medium Execute periodic oscillations in a direction rpendicular to the direction of propagation of the wave. the oscillations are confined to only one direction, en it is called plane Polarized light.".

presentation of Polarized and unpolarized lights:

ight waves are Transverse and so have vibrations at ight angles to the direction of Propagation. If the irection of propagation of light is considered along the lane of paper, then vibrations of unpolarized light are ndicated by dots and arrows.



Vertical Vibrations



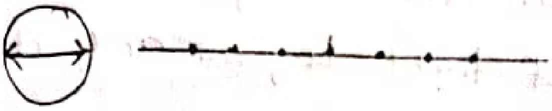
unpolarized light

Horizontal Vibrations.

ypes of polarized light:

Plane polarized light: If the vibrations are confined , a single plane, then it is called plane polarized ght.

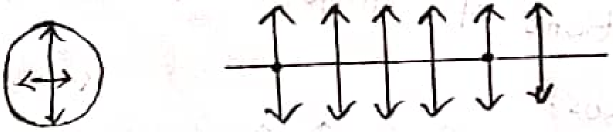
vertical vibrations



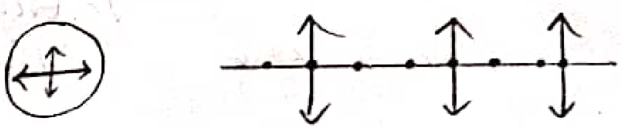
Horizontal vibrations.

Note: The vibrations along the plane of the paper ar Represented by arrows. The vibrations perpendicular to th Plane of the paper are Represented by dots.

(ii) partially plane polarized light: If the linearly Polarized light contains small additional component of un-Polarized light, it becomes partially polarized light. ~~Then it is~~ ~~Represented~~ by ~~more planes~~. If the ~~direction~~ of ~~propagation~~ of ~~light is considered~~ along ~~the plane of the paper,~~ ~~them~~ ~~unpolarized~~ vibrations are ~~Indicated~~ by ~~dots~~ and ~~arrows~~. less Then it is Represented by either more arrows and dots (or) more dots and less arrows.

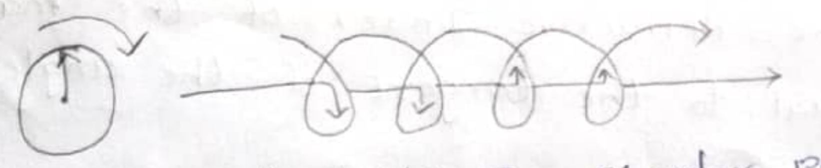


More vertical and less horizontal vibrations.

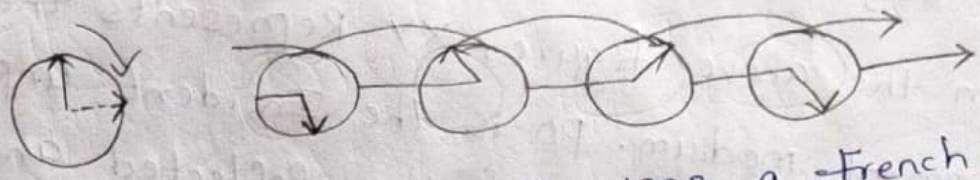


More Horizontal and less Vertical vibrations.

Circularly polarized light: In circular polarization, the vector Rotates in the clockwise direction with Respect to the direction of propagation. It Results in Right circularly Polarized light while the Rotation in the anti clock wise direction Results in left circularly polarized light.

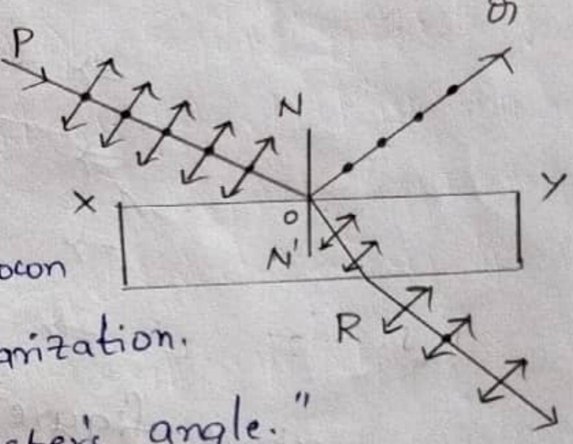


Elliptically polarized light: In Circular polarization, the Electric vector of constant Amplitude Rotates. If the Amplitude of the Electric vector is Not constant but varies periodically, then it Results in Elliptically polarized light.



Polarization by Reflection: In 1808, a French Scientist Malus found that when unpolarized light was Reflected at the Surface of some transparent medium such as glass, water Etc. The Reflected light was found to be partially plane polarized. The degree of polarization changes with the angle of Incidence. For a particular angle of Incidence, the Reflected light was found to be completely plane polarized.

The angle of Incidence for which the Reflected beam is completely plane polarized ~~lig~~ is known as polarizing angle (or) angle of polarization. This angle is also known as "Brewster's angle."



At this angle, the Reflected and transmitted lights are at Right angles to each other.

Brewster's law: The Refractive Index of the material medium μ is equal to the tangent of the angle of Polarization i_p.

i.e., $\mu = \tan i_p$.

This is called Brewster's law. Applying this law, it can be proved that the Reflected and Refracted Rays ar at Right angles.

Proof: In the above figure, XY Represents the Surface of transparent medium. PO is the Incident unpolarized light while OQ and OR are the Reflected and Refracte light Rays.

From Snell's law; $\mu = \dfrac{\sin i}{\sin r} \longrightarrow ①$

from Brewster's law; $\mu = \tan i = \dfrac{\sin i}{\cos i} \longrightarrow ②$

from Eq ① & ②; $\dfrac{\sin i}{\sin r} = \dfrac{\sin i}{\cos i}$

$$\Rightarrow \sin r = \cos i$$

$$\Rightarrow \sin r = \sin(90-i)$$

$$\Rightarrow r = 90 - i$$

$$\Rightarrow r + i = 90^\circ.$$

from the above figure;

$$\angle NOQ + \angle QOR + \angle N'OR = 180^\circ$$

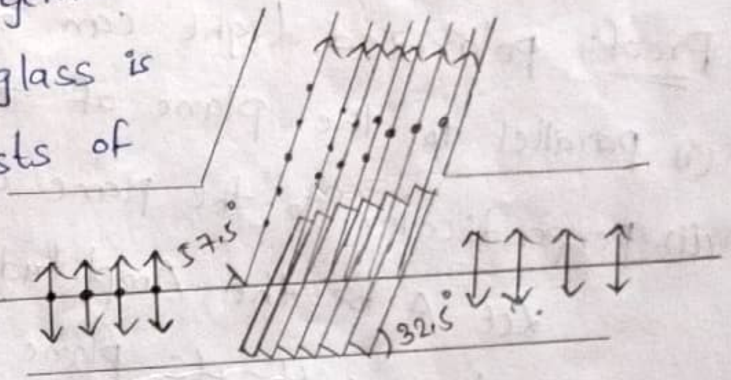
$$\text{i.e., } i + \angle QOR + r = 180^\circ$$

$$\text{Hence } \angle QOR = 180^\circ - (i+r)$$

$$= 180^\circ - 90^\circ = 90^\circ.$$

Hence it is proved that the Reflected and Refracted Rays are at Right angles.

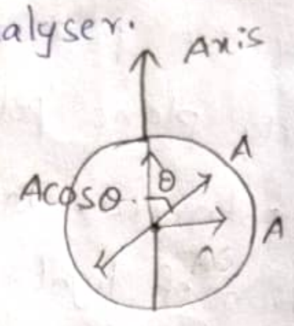
Polarization by Refraction: when unpolarized light is Incident at polarizing angle, the Reflected light is completely plane polarized and transmitted light is partially plane polarized. The transmitted light contains a greater proportion of light vibrating parallel to the plane of Incidence. If the process of Reflection at polarized angle is Repeated using Number of plates, all Inclined at polarizing angle, finally the transmitted light becomes purely plane polarized. Such an arrangement is known as pile of plates.



The polarizing angle for glass is 57.5°. The pile of plates consists of Number of glass plates fixed in a tube of Suitable size inclined at an angle of 32.5° to the axis of the tube. So that the angle of Incidence is 57.5°. A Beam of monochromatic light Entering the tube falls on the pile of plates at the polarizing angle. Each plate filters the vibrations at Right angles to the plane of Incidence by Reflection. Hence after the beam has traversed about 15 plates, the transmitted light has vibrations only in the plane of Incidence. Thus pile of plates produce polarization by Refraction.

Malus law: when unpolarized light passes through a polarizer, the transmitted light is plane polarized. when the polarized light is passed through an analyser the Intensity of transmitted light varies with the angle between the planes of polarizer and analyser.

Malus stated that "The Intensity of the polarized light transmitted through the analyser varies as the square of cosine of the angle between the plane of transmission of the analyser and the plane of polarizer.



Proof: polarized light can be Resolved into two components

(i) parallel to the plane of transmission of the analyser.

(ii) perpendicular to the plane of analyser.

Let A be the Amplitude of the Incident plane polarized light with its plane of vibration at an angle θ with the axis of the analyser. The Resolved Component of the Amplitude along optic axis is Acosθ. This component is transmitted through the analyser. The Intensity of the transmitted light is given by.

$$I_1 = (A\cos\theta)^2 = A^2\cos^2\theta.$$

when $\theta = 0$; i.e., the plane of vibration is along the optic axis of the analyser.

let this maximum value be $I_0 = A^2$.

$$\Rightarrow I_1 = I_0\cos^2\theta.$$

when θ=90°, i.e., the plane of vibration is Normal to the optic axis of the analyser

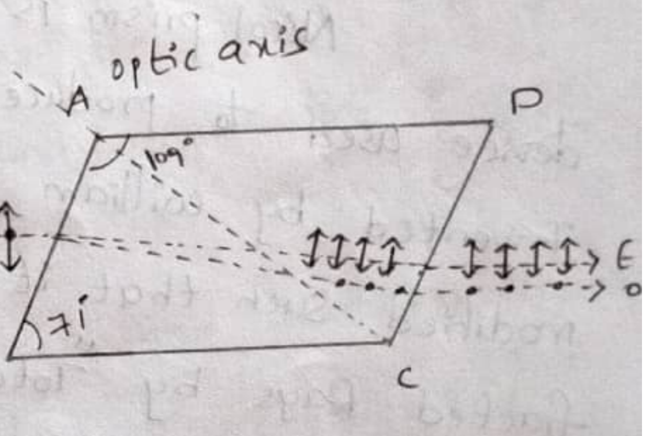
$$I_1 = I_0 \cos^2\theta = 0.$$

The Intensity at polarized light transmitted through the analyser varies as the square of cos θ, where θ is the angle between the plane of vibration of incident plane polarized light and the axis of the transmitter.

Polarization by Double Refraction:

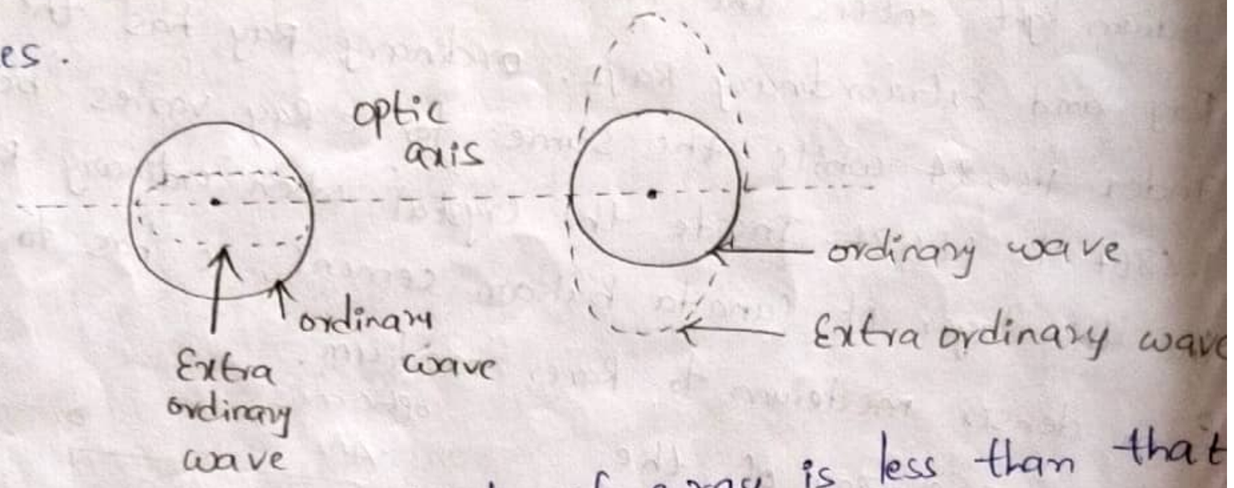
Every unpolarized light Rays has two components, one vertical and another horizontal. when unpolarized light passes through certain crystals such as calcite (or) Quartz, Velocity of propagation of these two components vary. This means that the material exhibits two different Refractive Indices. Both the components have same angle of Incidence but different Refractive Indices.

when unpolarized light passes through such crystals, we get two Refracted beams and this phenomenon is called double Refraction.



calcite is a good example of hese crystals. It is Rhombic n shape and the line AC joining he blunt corner A and C is called he crystal Axis.

Wave plates: Let us assume a point source inside the crystal at its centre to understand the variation of velocity of Extraordinary Ray with direction. The wave corresponding to ordinary Ray travels with same velocity in all directions Resulting in sphere. The wave Correspondin to Extraordinary Ray travels with different velocities in different directions and the wavefront advances in the for of Ellipses.



(i) In some crystals, velocity of e-ray is less than that of o-Ray.

Ex: Quartz crystals.

(ii) The Ellipsodial wavefront of e-Rays in these crystals. lies within the spherical wavefront of o-Ray. Such crystals are called Positive uniaxial crystals.

(iii) In other crystals, the ellipsodial wavefront of e-Ray lie away from the o-Ray such crystals are called Negative uniaxial crystals.

Ex: calcite crystals.

Quarter and Half wave plates:

Let us consider a Doubly Refracting crystal. Like calcite in which its optic axis lies along the Surface. Suppose an unpolarized light of wavelength λ incident Normally on the crystal Surface. then ordinary and extra ordinary Rays travel with Increasing path difference along the direction of propagation.

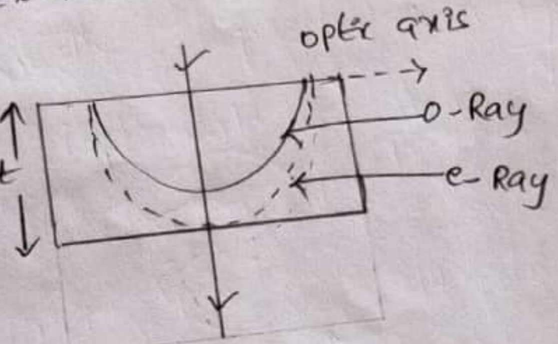
If t is the thickness of the wave plate, then

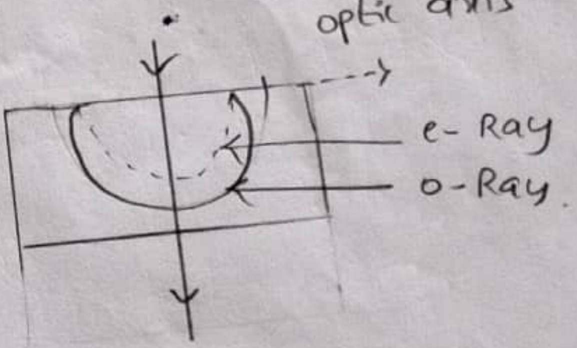
optical path of o-Ray is $\mu_o . t$

optical path of e-Ray is $\mu_e . t$.

$\therefore$ optical path difference $\Delta = (\mu_o \sim \mu_e) t$.

where μ_o and μ_e are the Refractive Indices of ordinary and Extra-ordinary Rays Respectively.





Hence optical path difference $= (\mu_o \sim \mu_e) t$.

If the thickness of the plate is Such that this Path difference is $\lambda/4$, then this plate is called Quarter wave plate.

$$(\mu_o \sim \mu_e) t = \lambda/4$$

$$\Rightarrow$$

$$\Rightarrow t = \lambda/4(\mu_o \sim \mu_e).$$

If the thickness of the plate is such that the path difference is $\lambda/2$, then the plate is called Half wave plate.

i.e., $(\mu_o \sim \mu_e)\, t = \lambda/2$

$$\Rightarrow t = \frac{\lambda}{2(\mu_o \sim \mu_e)}$$

LASERS & FIBER OPTICS

LASERS: Introduction, charecterstics of laser, Spontaneous and stimulated Emissions of Radiations, Einstein's co-efficients, population Inversion, lasing Action, pumping mechanisms, Ruby laser, He-Ne laser, Applications of laser.

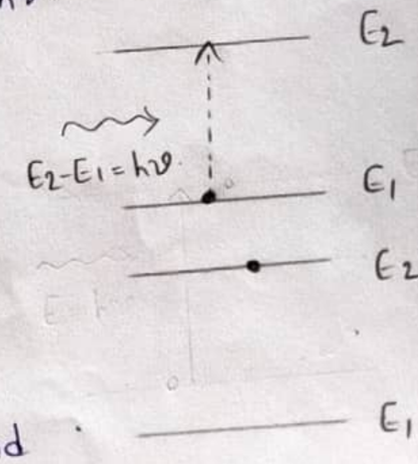
Fiber optics: Introduction, principle of optical fiber, Acceptance Angle, Numerical Aperture, classification of optical fibers based on Refractive Index profile and modes, propagation of Electromagnetic wave through optical fibers, Applications.

2. LASERS AND FIBER OPTICS

LASER: LIGHT AMPLIFICATION BY STIMULATED EMISSION OF RADIATION.

Introduction: The word LASER is an acronym for light Amplification by Stimulated Emission of Radiation. In 1960 T.H. Maiman first achieved laser action at optical frequen in Ruby. It is a device to produce a powerful monochromatic Narrow beam of light. The first two successf lasers developed during 1960 were Ruby laser and He laser. Some lasers Emit light in pulses while others Emit as a continous wave.

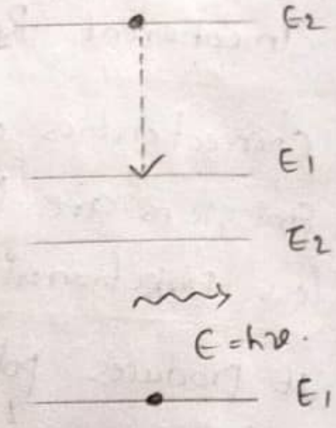
Definitions: In lasers, the Interaction between matter and light is of three different types. They are; Absorption, Spontaneous Emission and stimulated Emission. In these processes, two Energy levels of atoms are Involved let E_1 and E_2 be ground and Excited states of an atom Transition between these states Involves Absorption or Emission of photon of Energy $E_2 - E_1 = h\nu$. where h is planck's constant.



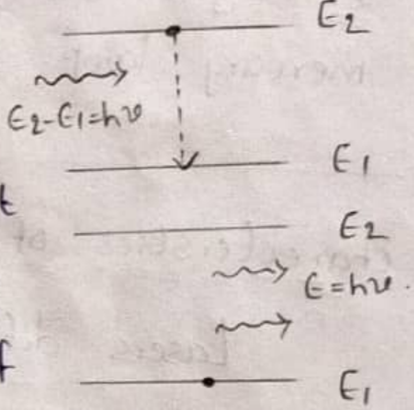
ABSORPTION: Let us consider a system in which two Energy levels are present whose Energies are E_1 and E_2. where E_1 is ground State and E_2 is Excited State.

usually atoms are in the Ground state as long as External forces are Not applied. when a photon of Energy $E_2-E_1=h\nu$ is incident on the atom lying in the ground State, then it Excites to higher state E_2. This phenomenon is known as Stimulated Absorption.

Spontaneous Emission: let us assume that the atom is in its Excited state E_2. This Electrons drops to the lower Energy state After they have stayed in the Excited state for such a short duration of time called life time. During this process, photons of Energy $E_2-E_1=h\nu$ are Emitted.



Stimulated Emission: let us assume that the atom is in the Excited state E_2. If a photon of Energy $h\nu=E_2-E_1$ is Incident on it before the lifetime, it stimulates the atom from E_2 to E_1, then a photon of Energy $h\nu$ Releases along with the Incident photon. These two photons will have Same Energy and are in phase. and are coherent.



Life time: After Excitation of an atom, it can Remain in the higher Energy level for a limited time known as life time. The life time of the Excited Hydrogen atom is of the order of 10^{-8} sec. However, there Exist such Excited states in which the life time is greater than 10^{-8} sec. These states are called as metastable.

Differences between Spontaneous and Stimulated Emissions:

Spontaneous Emission	Stimulated Emission.
Emission takes place without any stimulus energy.	Emission takes place with the help of stimulus energy
Incoherent Radiation occurs.	coherent Radiation occurs.
charecterstics of these type of Emissions are less Intense and less Directional.	Stimulated Emissions are of High Intense and more directional.
It produces polychromatic Radiation.	It produces monochromatic Radiation.
Ex: light from Sodium (or) mercury lamp.	**Ex:** light from Ruby (or) He-Ne laser.

charecterstics of the laser:

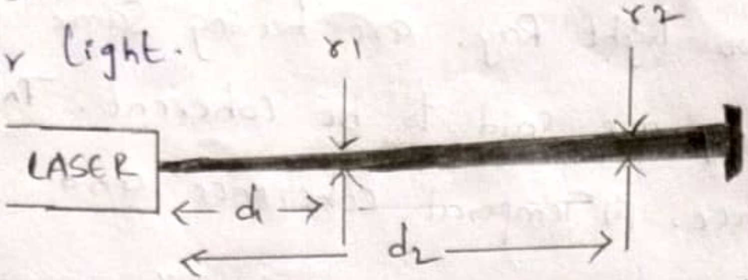
Lasers differ from conventional light sources in a Number of ways. The most striking features of a laser beam are (i) High monochromaticity

(ii) High degree of coherence

(iii) High Directionality

(iv) High Brightness.

(i) **Directionality**: The conventional light sources like lamp, Torch light, sodium lamp emits light in all directions. This is called divergence. laser on the other hand, emits light only in one direction. This is called directionality of laser light.



light from ordinary light spreads in about few kilometers. light from laser spreads to a diameter less than 1cm for many kilometers.

The directionality of laser beam is given by ~~con~~ Expressed in divergence.

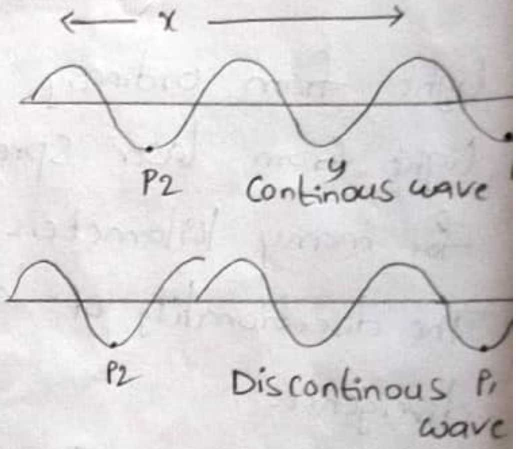
The divergence $\Delta\theta = \frac{r_2 - r_1}{d_2 - d_1}$

where r_2, r_1 are the Radius of laser beam spots. d_2, d_1 are distances Respectively from the laser source. Hence for getting a high directionality, then should be low divergence.

Monochromaticity: Transition of an atom between two energy levels will Result in Emission, or absorption of photon whose frequency lies between ν and $\nu + d\nu$. The band width of ordinary light is about 1000 Å. The Band width of laser light is about 10 Å. The Narrow band width of a laser light is called High monochromaticity.

laser light is more Monochromatic than that of conventional light source. Because of this Monochromat large Energy can be concentrated in to an Extremely Small Band width.

Coherence: when two light Rays are having Same phase difference, then they are said to be coherent. There ar two types of coherence. (i) Temporal coherence and (ii) Spatial coherence.

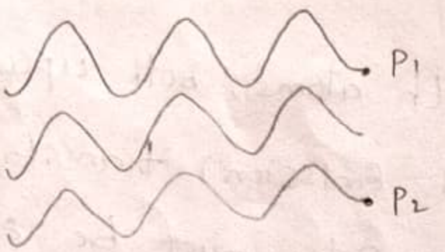


Temporal coherence: The displacement and phase at any point x on the wave train at any instant of time t is given by

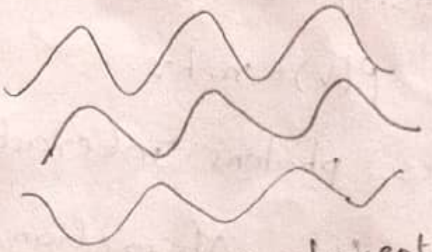
$$y = a \sin\left[\frac{2\pi}{\lambda}(ct - x)\right]$$

where c is the velocity of the wave. Since the two points P1 and P2 are on the same wave train which is continous in the first figure, they have correlation. If the phase and Amplitude at any one point is known, we can calculate the Same for any other point on the Same wave train using the amplitude wave Equation given. This predictable coherence of the called and phase between any two points on a wave train is Temporal coherence.

spatial coherence: The two light fields at different points in Space maintain a constant phase difference over any time (t), they are said to be in Spatial coherence. we have already seen that under the condition of population inversion, light Amplificat by Stimulated Emission of Radiation takes place. During Stimulated Emission, both the Stimulating and Stimulated Photons are in phase with each other. Also both travel along the direction of Stimulating photon. Those photons travelling in any direction other than optic axis are Not Reflected back. only those which are along optic axis Stimulate further and amplify, thus making all the photons to be in phase with each other. Hence when we choose two spatial points P_1 and P_2 on the cross section of the output beam, they are spatially coherent. Below figure Represent the difference between spatially coherent and incoherent waves.



spatially coherent waves



spatially incoherent waves.

Brightness: lasers are Bright and intense light sources. A one milliwatt He-Ne laser is, in fact brighter than the sun. This is because of coherence and directionality. we know that when two photons. each of amplitude a are in phase with each other, then the Resultant Amplitude is 2a and the Intensity is proportional to $(2a)^2$ i.e., $4a^2$. Since in laser, many Number of photons (say n) are in phase with each other, the Amplitude of the Resulting wave becomes na and hence intensity is $(na)^2$ i.e., n^2a^2. Thus due to coherent addition of Amplitude, the Intensity Increases. we are able to directly view a glowing 100 watts Electric bulb but we cannot see 1mw He-Ne laser which has 10^5 times lesser power. A 1mw He-Ne laser can be to be 100 times brighter than the sun.

Einstein's coefficients: In a collection of atoms, all three transition processes - Stimulated absorption, spontan Emission and stimulated Emission occur simultaneously. le N_1 be the Number of atoms per unit volume with Energy and N_2 be the Number of atoms per unit volume with Energy E_2. let n be the Number of ~~atoms~~ photons per u volume at frequency ν such that $E_2 - E_1 = h\nu$. Then, th Energy density of Interacting photons $\rho(\nu)$ is given by

$$\rho(\nu) = n . h\nu .$$

when these photons Interact with atoms, both upward a downward. (i.e., Absorption and Emission) transitions occ At Equillibrium, these transition Rates must be equal.

upward Transition: Stimulated absorption Rate depends o the Number of atoms available in the lower Energy stat for absorption of these photons as well as the Energy den of Interacting Radiation.

i.e., stimulated absorption Rate $\propto N_1$

$$\propto \rho(\nu)$$

$$= N_1 \rho(\nu) B_{12}$$

where the constant of proportionality B_{12} is the Einstein Coefficient of stimulated absorption.

Downward Transition: once the atoms are excited by Stimulated absorption, they stay in the Excited state for a short duration of time called the life time of the Excited State. After their lifetime, they move to their lower Energ level spontaneously Emitting photons. This spontaneous Emission Rate depends on the Number of atoms in the Excited state

i.e., Spontaneous Emission Rate $\propto N_2$

$$= N_2 A_{21}$$

where the constant of proportionality A_{21} is the Einstein coefficient of Spontaneous Emission.

Before Excited atoms de excite to their lower Energy states by Spontaneous Emission, they may Interact with photons Resulting in stimulated Emission of photons. Therefore stimulat Emission Rate depends on the Number of atoms available in the Excited state as well as the Energy density of the Interacting photons.

i.e., stimulated Emission Rate $\propto N_2$

$$\propto \rho(\nu)$$

$$= N_2 \rho(\nu) B_{21}$$

where the constant of proportionality B_{21} is the Einstein coefficient of Stimulated Emission.

for a system in equillibrium, the upward and downward transition Rates must be Equal. hence;

$$N_1 \rho(\nu) B_{12} = N_2 \rho(\nu) B_{21} + N_2 A_{21}$$

$$\Rightarrow \quad N_1 \rho(\nu) B_{12} - N_2 \rho(\nu) B_{21} = N_2 A_{21}$$

$$\Rightarrow \rho(\nu)\left[N_1B_{12} - N_2B_{21}\right] = N_2A_{21}$$

$$\Rightarrow \rho(\nu) = \frac{N_2A_{21}}{N_1B_{12} - N_2B_{21}}$$

$$= \frac{\cancel{N_2}A_{21}}{\cancel{N_2}B_{21}\left[\frac{N_1B_{12}}{N_2B_{21}} - 1\right]}$$

$$= \frac{\frac{A_{21}}{B_{21}}}{\left[\frac{N_1}{N_2}\frac{B_{12}}{B_{21}} - 1\right]} \longrightarrow ①$$

According to Boltzmann's Distribution law;

$$N_1 = N_0 \exp\left(\frac{-E_1}{KT}\right) \; ; \; N_2 = N_0 \exp\left(\frac{-E_2}{KT}\right).$$

$$\therefore \frac{N_1}{N_2} = \frac{\cancel{N_0}\exp\left(-\frac{E_1}{KT}\right)}{\cancel{N_0}\exp\left(-\frac{E_2}{KT}\right)} = \exp\left(\frac{-E_1}{KT}\right)\cdot\exp\left(\frac{E_2}{KT}\right)$$

$$= \exp\left[\frac{E_2 - E_1}{KT}\right].$$

$$= \exp\left(\frac{h\nu}{KT}\right) \quad \left[\because E_2 - E_1 = h\nu\right.$$

ubstituting the value of N_1/N_2 in Eq ①; we get

$$\rho(\nu) = \frac{\frac{A_{21}}{B_{21}}}{\left[\frac{B_{12}}{B_{21}}\exp\left(\frac{h\nu}{KT}\right) - 1\right]} \longrightarrow ②$$

According to Planck's theory of Black Body Radiation;

$$\rho(\nu) = \frac{8\pi h\nu^3}{c^3}\left(\frac{1}{\exp\left(\frac{h\nu}{KT}\right) - 1}\right) \longrightarrow ③$$

from the above Equations ② & ③;

$$\frac{\frac{A_{21}}{B_{21}}}{\left[\frac{B_{12}}{B_{21}}\exp\left(\frac{h\nu}{kT}\right)-1\right]} = \frac{8\pi h\nu^3}{c^3}\left[\frac{1}{\exp\left(\frac{h\nu}{kT}\right)-1}\right]$$

Hence; we get $\frac{A_{21}}{B_{21}} = \frac{8\pi h\nu^3}{c^3}$; $\frac{B_{12}}{B_{21}} = 1$

$$\Rightarrow \frac{A_{21}}{B_{21}} \propto \nu^3 \quad ; \quad B_{12} = B_{21}$$

The first Relation shows that the Ratio of Einstein's coefficients of A_{21} and B_{21} is proportional to the cube of frequency of the photon and The second Relation shows that the Rate of probability of Induced absorption and Emission are Equal when the system is in Equillibrium.

Population Inversion: The population Inversion condition Required for light Amplification is a Non Equillibrium distribution of atoms among the various Energy levels. Boltzmann distribution law Specifies what fraction of atoms are found in any particular Energy state for any given Equillibrium Temperature. If N_0 is the Number of atoms in the ground state, N_i is the Number of atoms in the Excited state of Energy E_i, then

$$N_i = N_0 \exp\left[\frac{-E_i}{kT}\right]$$

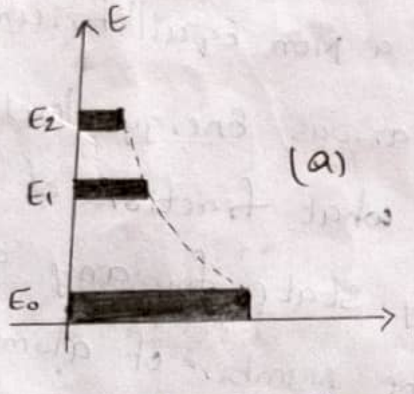
where T is the absolute Temperature in degree kelvin

k is the Boltzmann Constant

i.e., 1.38×10^{-23} Joule/k.

Since the Right hand side of the above Equation is Exponential of a Negative quantity. maximum possible value attainable is 1. That happens when $kT >> E_i$. Even then this Extreme case, N_i can be Equal to N_0 but it will Never Exceed N_0. Hence, from this it is very obvious t Higher Energy level can Never be made more populated than the lower level. i.e., By directing pumping, populatio Inversion is Not possible. if two Energy levels are Invo Hence, these Restictions Imposed on two level scheme have been overcome in three and four level schemes by pumpin atoms to the upper state of transition involving more tha two Energy levels.

Three level Scheme:



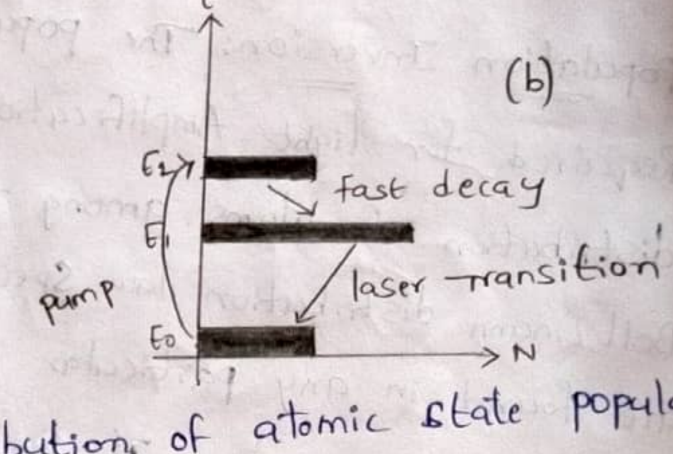
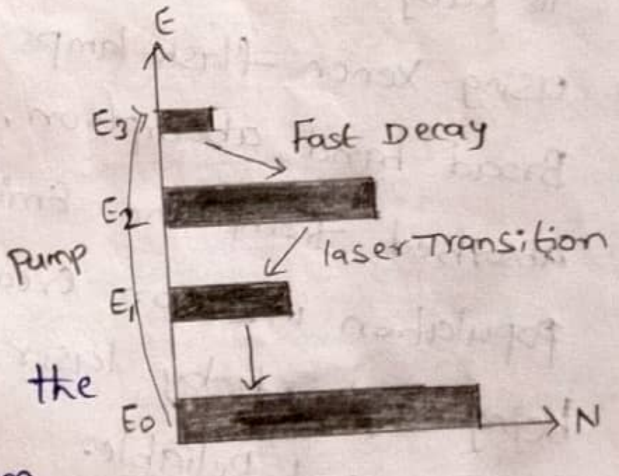


Figure (a) shows the distribution of atomic state populati obeying Boltzmann law. with a Xenon flash lamp, a large Numb of atoms are Excited through Stimulated absorption to the highest Energy level E_2. If the level E_2 has very short life time, the atoms decay fast to level E_1. If the level E_1 has Relatively longer life time (a state known as metastable) atom tend to accumulate at E_1. with Intense pumping from E_0 t

E_2, because of Rapid decay to E_1, It is possible to bring in Non Equillibrium distribution of atoms. Hence E_1 is more populated than E_0 and laser transition takes place between level E_1 (called upper laser level) and level E_0 (called lower laser level) as shown in figure (b). Since ground level E_0 happens to be the lower laser level, more than one half of the ground state atoms must be pumped to the upper state to achieve population Inversion ($N_1 > N_0$). Therefore, three level pumping schemes generally Require very high pump powers. If pumping continues when the condition ($N_1 > N_0$) Reached, Stimulated Emission Rate Exceeds Stimulated absorption Rate. This immediately depopulates the upper laser level and populates lower laser level. Hence, it is Not possible to continously maintain the upper laser level more populated than lower laser level. Such a system therefore works in pulsed mode only. The Ruby laser is the best Example for three level laser.

Four level Scheme:



In four level Scheme as shown in this figure, on pumping, the atoms are lifted from the ground state to the highest of the four levels. E_3. from this level, the atoms decay to the metastable State E_2. and the population of this state grows Rapidly. If the life time of (3→2) Transition is short and that of (2→1), a population inversion on (2→1) Transition is achieved and maintained. Since ground level is Not the laser level, th is No Need to pump more than one half of the popula to the higher level. Since in this scheme, level E_1 is th lower laser level, it is Relatively easier to maintain population inversion between levels E_2 and E_1 continous and can get continous wave output. He-Ne laser is a good Example for a four level laser working in this mode.

<u>pumping</u> mechanisms: The different mechanisms applied to pump the atoms of the active medium to higher Energy states to create population inversion are;

(i) optical pumping
(ii) Electric discharge
(iii) chemical Reaction
(iv) Injection current etc.

optical pumping is the very first mechanism applie to Ruby laser. Solid state lasers are optically pumped using Xenon flash lamps. Since these materials have very Broad band absorption, sufficient amount of Energy is absorbed from the Emission band of flash lamp and population inversion created. Recently, flash lamps are being Replaced by laser diodes thus making system mor Efficient and Reliable.

Ex: Ruby, dye etc.

Since gas lasers have very Narrow absorption ban pumping them using any flash lamp is Not possible. In most of the cases, inversion is possible by means of Electric discharge.

Ex: He-Ne laser, CO_2 laser Etc.

Chemical Reaction may also Result in Excitation and hence creation of population inversion in few systems.

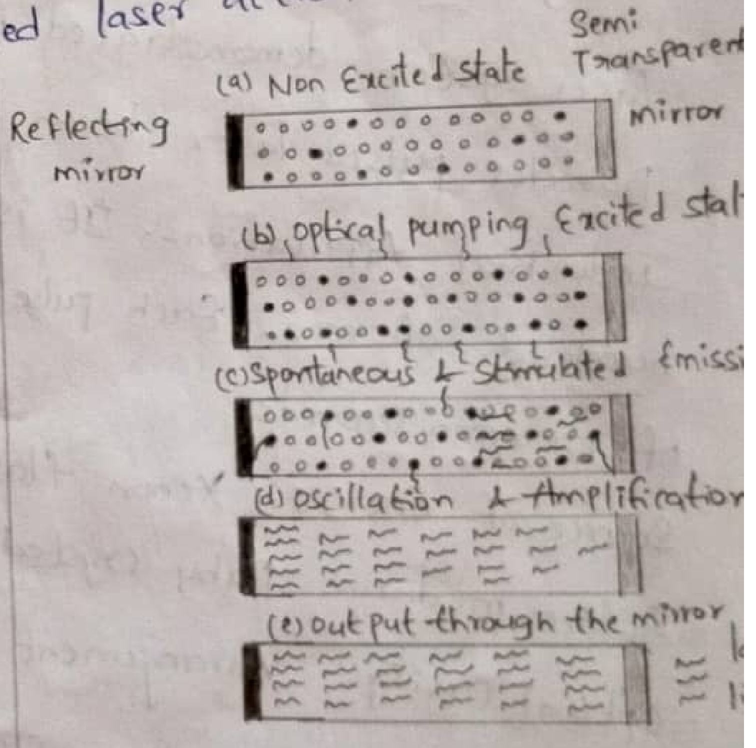
Ex: HF, Atomic iodine lasers Etc.

In Semiconductor lasers, the injection current through the junction Results in creation of population inversion among charge carriers.

Laser principle and Lasing Action:

Stimulated Emission and population inversion are the main principles involved in the working and construction of a laser.

The process of light Amplification by stimulated Emission of Radiation is called laser action.



under the conditions of population inversion, light Amplification takes place by Stimulated Emission of Radiation. but the amount of Radiation provided by most active media in a single-pass of Resonable length is much low to be useful. practically, it is ~~important~~ impossible to increase the length beyond certain value. This limitation is overcome by the use of t End mirrors to direct the amplified light to travel ba and forth through the active medium many times a shown in the figure. This multiple pass provides sufficiently larger Amplification. By keeping one of t mirrors 100% Reflecting and another slightly less than 100%, a fraction of the amplified light is drawn as output through the partially Reflecting mirror. These Amplified photons are fed back and forth due to Refl and thus undergo Round trips. As long as the Ener is pumped into the laser and the atoms Remained Excited state, then the above process will continue a the beam of laser is produced.

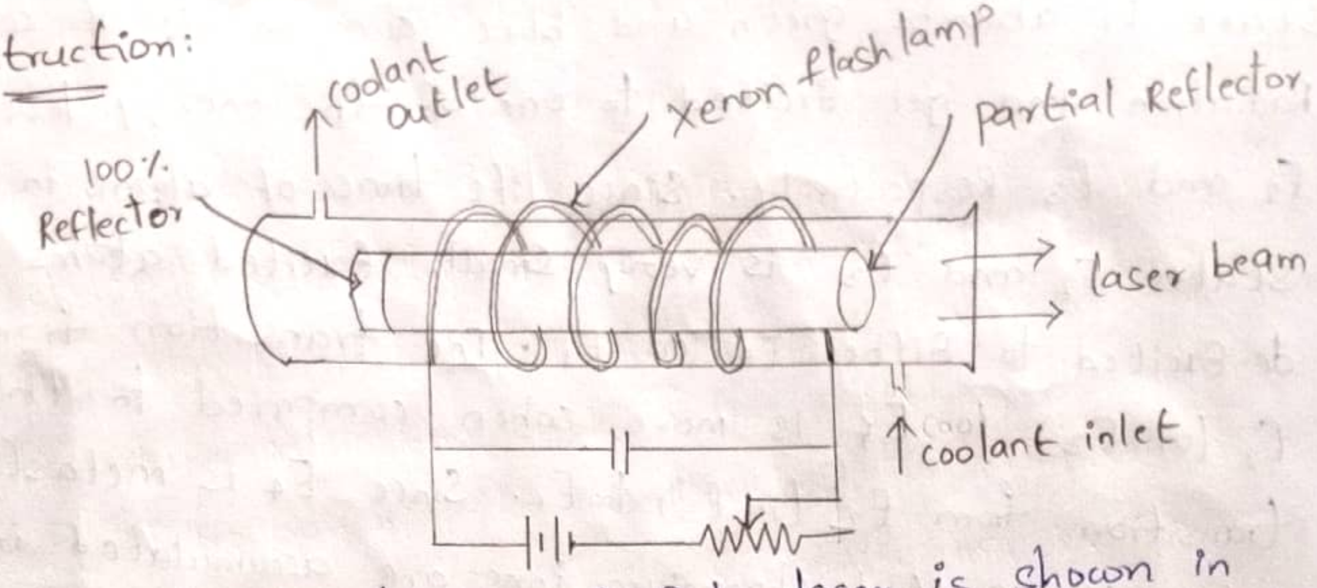
Ruby laser: Ruby laser is a solid state three level laser system demonstrated by T. Maiman in 1960. It provides pulsed laser beam which is useful for various Industrial Applications. It is a high power laser which ha hundereds of mw. Each pulse will come out in the durati of 10 nano seconds

Source of Energy: Xenon flash lamp

Active medium: Ruby crystal

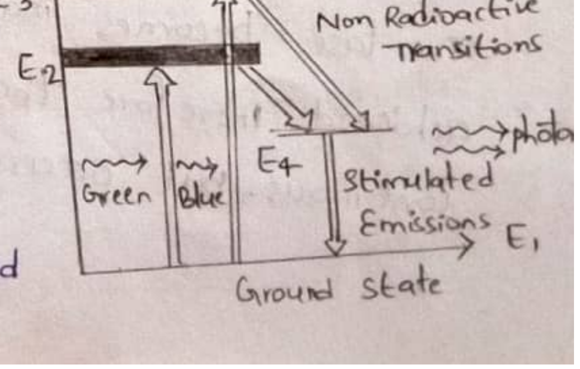
optical cavity: Arrangement of Silver polished surface on either sides of the Ruby Rod.

onstruction:



The schematic diagram of Ruby laser is shown in his figure. Ruby Rod is taken in the form of a cylindrical od of about 10cm in length and 1 cm in diameter. It is asically Al_2O_3 crystal containing of about 0.05% of chromium toms. one End face of Ruby Rod is silvered to achieve 100% Reflection while the opposite face is partially silvered to make it Semi transparent. through which laser is Emitted. This Rod is surrounded by helical xenon flash lamp. It Produces high Intense flashes of light whenever activated by Power supply. The system which gets heated due to pumping Radiation is cooled with the help of a coolant, circulated around the Ruby Rod.

Working: Ruby laser is a three level laser system. The Energy levels of chromium Cr^{+3} ions in Al_2O_3 are shown in this figure. when power is switched ON, xenon flash lamp produces very high intense white Radiation for a few seconds. The atoms in the ground



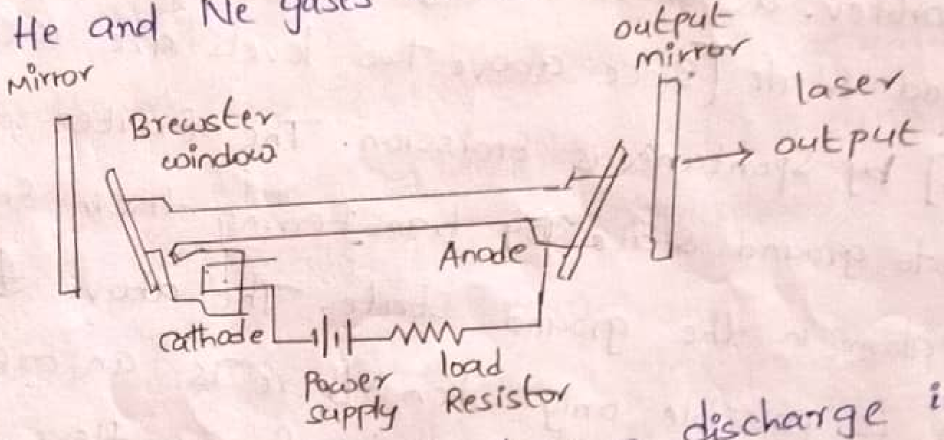
state E_1 absorbs green and blue components of whit Radiation and get Excited to one of the Energy levels E_2 and E_3 Respectively. Since life time of atoms in Exci states E_2 and E_3 is very small, Excited atoms ar de Excited to Either E_4 (or E_1. The transition from E_2 (or E_3) to E_4 is more when compared to the transition from E_2 (or E_3) to E_1. Since E_4 is metastable state, the Excited chromium ions are accumulated in that state. If pumping occurs at faster Rate, the Population at the level E_4 Exceeds that of ground level E_1 in shorter time. Therefore, the state of population inversio gets Eshtablished between E_4 and E_1.

After some time, chromium atoms are spontaneously de-Excited to ground level E_1 with the Emission of photon (Red). These spontaneously Emitted photons initiate stimulate Emission of photons from metastable state E_4. The Emitted photons which are moving along the axis of Ruby Rod, are Repeatedly Reflected by mirrors and Enhance the stimulated Emission process. When the beam develops Sufficien Intensity, it Emerges out of the partially silvered Mirror.

The Xenon flash lamp lasts for a few milli second throughout this period. However laser does not operate. The laser becomes inactive till the population inversion is achieved. Therefore the output of the laser beam is Not continous. but occurs in the form of pulses

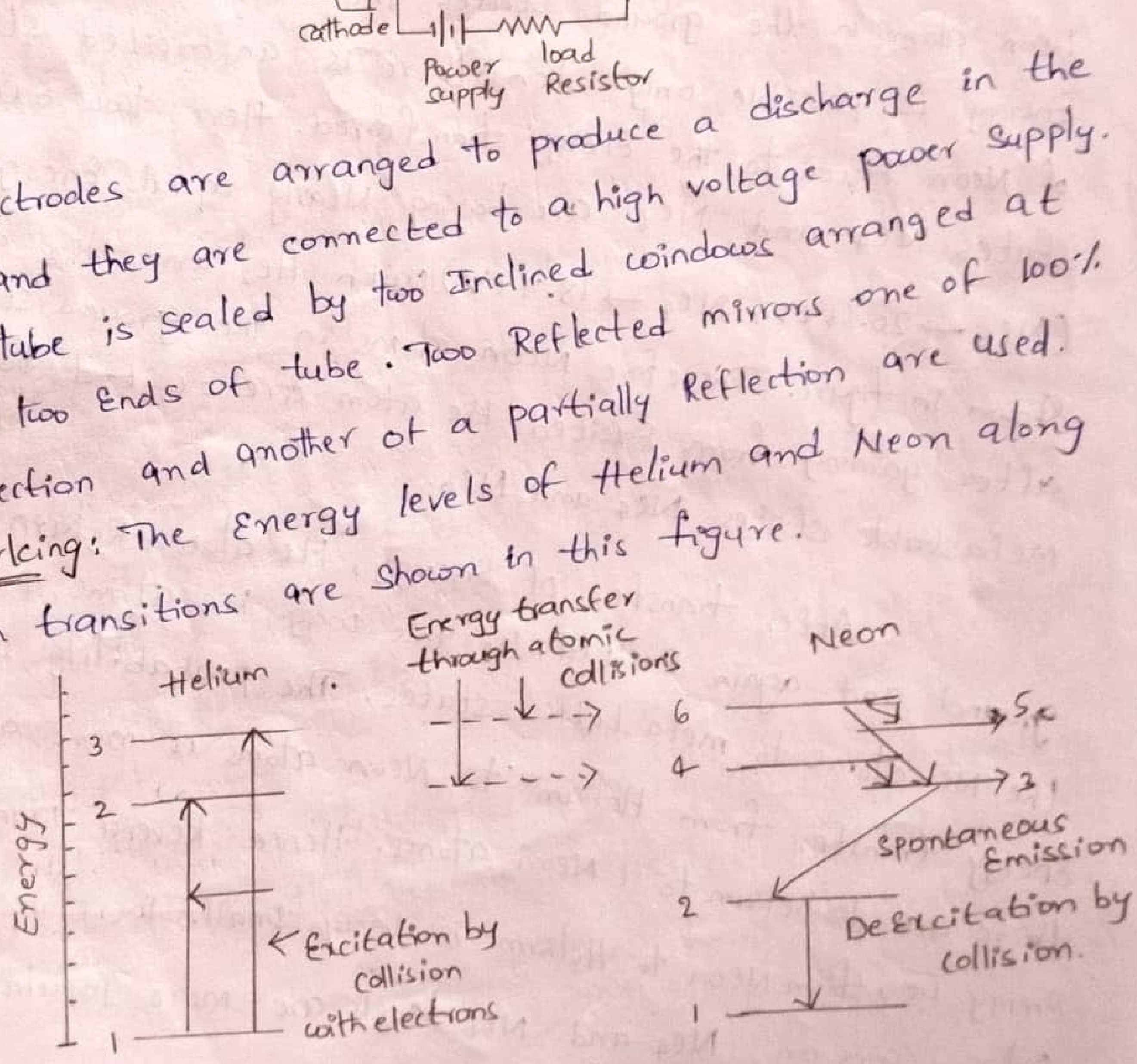
He-Ne laser: He-Ne laser was the first successful gas laser system which is used to produce a continous laser. This laser is highly directional, Monochromatic, coherent and stable.

Construction: As the Name Implies, the active medium of this laser is a mixture of Helium and Neon gas. As shown in the figure, It consists of a long discharge tube of length about 50 cm and diameter 1 cm. This tube is filled with a mixture of He and Ne gases in the Ratio 10:1.



Electrodes are arranged to produce a discharge in the gas and they are connected to a high voltage power supply. The tube is sealed by two Inclined windows arranged at the two Ends of tube. Two Reflected mirrors one of 100% Reflection and another of a partially Reflection are used.

working: The Energy levels of Helium and Neon along with transitions are shown in this figure.



In He-Ne laser, Neon provides the Energy levels for laser transition. i.e., laser light come from Transition between the Neon Energy levels. Though helium atoms are Not involved in the laser Transition, they provide an Efficient Excitation mechanism for the Neon atoms. when power is switched on, The helium atoms are Excited to two metastable states He_2 and He_3 which lie at 19.81eV and 20.61ev. as shown in figure. Helium atoms cannot Return to ground State [Since above two levels are metastable States] by Spontaneous Emission. The Excited helium atoms. Return to ground state by transferring their Energy to the Neon atom in the ground state. The above transfer of Energy is possible only when there is an Excited state of Neon Equal to the Energy transferred. Here two Excited states Ne4 and Ne6 are having Nearly Equal Energies (Ne6 → 20.66 eV, Ne4 → 18.7 eV) with He_2 and He_3 as Shown in figure. Therefore Neon atoms in the ground state after gaining from Excited He atom are Excited to metastable states Ne4 and Ne6.

After transfer of Energy, He atoms Return to ground and again Excited. In this way, He atoms, pump the Ne atoms to metastable states. The probability of Energy transfer from Helium to Neon atoms is more as there are 10 helium to 1 Neon atoms. Hence Reverse Transfer of Energy i.e., from Neon to Helium is very small. Therefore as collision goes on, Ne4 and Ne6 levels are more populated when compared to Ne_5 and Ne_3 levels. Therefore there are three possible laser transitions. i.e., from $Ne_6 \rightarrow Ne_3$; $Ne_6 \rightarrow Ne_5$; $Ne_4 \rightarrow Ne_3$. Hence three wavelengths are generated. i.e., 0.6328 μm, 1.15 μm, & 3.39 μm.

To overcome this problem (mixture of wavelengths) and in order to get only 0.6328 μm. as output laser beam, the discharge tube windows are made up of glass or quartz that absorb energy strongly 1.15 μm and 3.39 μm. moreover the End mirrors, which provide optical feed back are multilayer dielectric coated to provide Reflectivity only for 0.6328 μm beam.

He-Ne laser is a Relatively low power device. By increasing the discharge current through the gas, one cannot Increase the laser output power beyond certain value.

Applications of laser:

lasers in scientific Research:

* lasers are used to clean delicate pieces of art, to develop hidden finger prints.
* lasers are used in the field of 3D photography called holography.
* using lasers, the Internal structure of microorganisms and cells are studied very accurately.
* lasers are used to produce certain chemical Reactions.

lasers in medicines

- The heating action of a laser beam is used to Remove diseased tissue.
- lasers are used for the elimination of moles and tumours, which are developing in the Skin tissue.
- Argon and CO_2 lasers, are used in the treatment of liver and lungs.
- laser beam is used to correct the Retinal detachment.

lasers in communication:

- More amount of data can be sent due to the large band width of semiconductor lasers.
- more channels can be simultaneously transmitted.
- Signals cannot be tapped.
- Atmospheric pollutants concentration, ozone concentrati and water vapour constration can be measured.

lasers in Industry: lasers are used

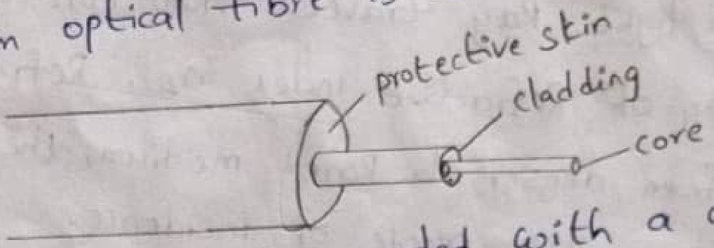
- To blast holes in Diamonds and hard steel.
- To cut, drill, welding and Removing metal from surfaces.
- To measure distances for making maps. by surveyors.
- for cutting and drilling of metals and Non metals such as ceramics, plastics, glass etc.

FIBRE OPTICS

Introduction: fibre optics, also called optical fibres, are Microscopic strands of very pure glass with about the same diameter of a human hair. Thousands of these optical fibres are arranged in bundles in optical cables and are used to transmit light signals over long distances.

Structure of an optical fibre: optical fibre is a very thin and flexible medium having a cylindrical shape consisting of three sections. (i) The core; (ii) The cladding and (iii) The outer Jacket.

The structure of an optical fibre is shown below.



The fibre has a core surrounded with a cladding with Refractive Index slightly less than that of the core to satisfy the condition for Total Internal Reflection. To give mechanical protection to the fibre, a protective skin called outer jacket is also provided.

Total Internal Reflection: The light launched inside the core through its one End propagates to the other End due to Total Internal Reflection at the core cladding Interface.

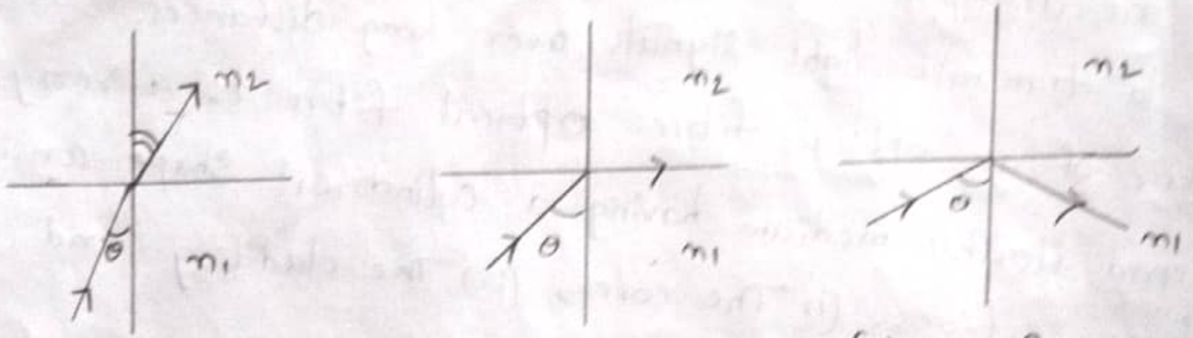
Total Internal Reflection at the fibre Interface can occur only if two conditions are met.

(i) The Refractive Index of the core material n_1 must be slightly higher than that of the cladding n_2 surrounding it.

(ii) At the core cladding interface, the angle of Incidence θ must be greater than critical angle defined as

$$\sin\theta = \frac{n_2}{n_1}$$

These conditions are illustrated as follows.



(a) $\theta < \theta_c$ (b) $\theta = \theta_c$ (c) $\theta > \theta_c$

When a light Ray travels from core of Refractive index n_1 to cladding of Refractive index n_2, Refraction occurs. Since it travels from denser to Rarer medium, the angle of Refraction is greater than the angle of incidence.

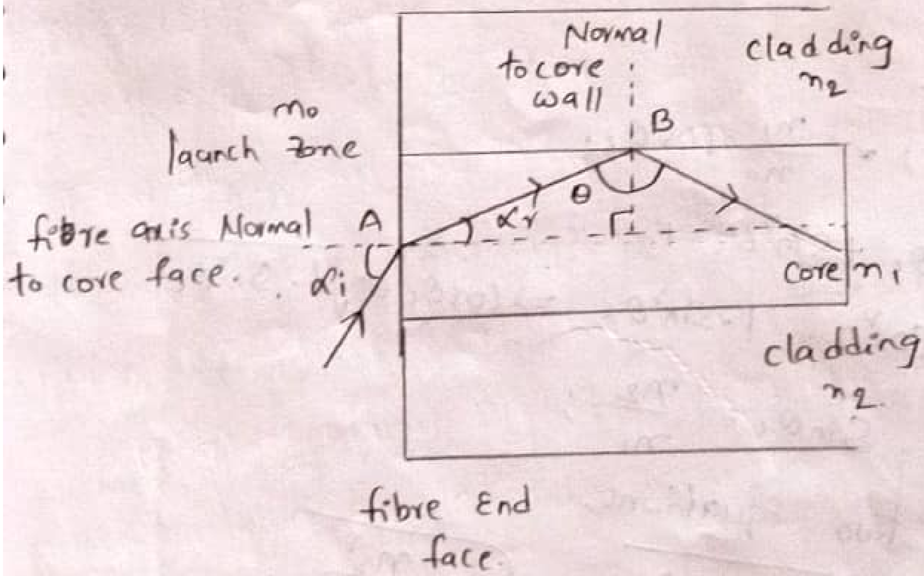
With increase in angle of incidence, the angle of Refraction also increases and at a particular angle of incidence, the Refracted Ray just grazes the interface between the core and cladding. This angle of Incidence is known as critical angle θ_c

When angle of incidence is further increased, the Ray is Reflected back into the core at the Interface obeying the laws of Reflection. This phenomenon is known as Total Internal Reflection.

Acceptance Angle: when the light beam is launched into a fibre at its one End, the Entire light may not pass through the core and propagate. only the Rays which make the angle of Incidence greater than critical angle at the core-cladding interface undergo total Internal Reflection and propagate through the core. The other Rays are Refracted through the cladding and are lost.

Hence, the angle at which the light beam is launched and propagated through the core is known as Acceptance Angle. Hence Acceptance angle is defined as the maximum angle of launch that a light Ray can have with respect to the axis of the fibre so that all the Rays within the angle propagate through the fibre by Total Internal Reflection.

Below figure shows the launch end of a fibre with a Ray Entering it. The light is launched from a medium of Refractive Index n_0 into the core of Refractive Index n_1.



The Ray Enters within the angle of incidence α_i to the fibre End face. This particular Ray Enters the Core at its axis

Point A and proceeds after Refraction at an angle α_r fr the axis. It then undergoes Total Internal Reflection at on core wall at an Internal Incidence angle θ.

from the Δle ABC;

$$\alpha_r = 90 - \theta.$$

from Snell's law; $\dfrac{\sin\alpha_i}{\sin\alpha_r} = \dfrac{n_1}{n_0}$

$$\Rightarrow \sin\alpha_i = \frac{n_1}{n_0}\cdot\sin\alpha_r.$$

$$= \frac{n_1}{n_0}\cdot\sin(90-\theta)$$

$$= \frac{n_1}{n_0}\cdot\cos\theta.$$

If θ is less than critical angle θ_c, the Ray will be lost by Refraction. Therefore, the limiting value for containing the beam inside the core, by total internal Reflection is θ_c.

let $\alpha_i(max)$ be the maximum possible angle of incidenc for which θ is Equal to θ_c. If for a Ray α_i exceeds α_i(m then θ will be less than θ_c and hence at B, the Ray will be Refracted.

Hence; $\sin\alpha_i(max) = \dfrac{n_1}{n_0}\cos\theta_c.$

we know that $\cos^2\theta_c + \sin^2\theta_c = 1$

$$\Rightarrow \cos^2\theta_c = 1 - \sin^2\theta_c \Rightarrow \cos\theta_c = \sqrt{1-\sin^2\theta_c}$$

Since we know that $\sin\theta_c = \dfrac{n_2}{n_1}$;

By comparing these two Equations;

$$\cos\theta_c = \sqrt{1-\left(\frac{n_2}{n_1}\right)^2} = \sqrt{1-\frac{n_2^2}{n_1^2}}$$

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

$$\therefore \cos\theta_c = \frac{\sqrt{n_1^2 - n_2^2}}{n_1}$$

$$\therefore \sin\alpha_i(max) = \frac{\cancel{n_1}}{n_0} \cdot \frac{\sqrt{n_1^2 - n_2^2}}{\cancel{n_1}}$$

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

$$\therefore \alpha_i(max) = \sin^{-1}\left(\frac{\sqrt{n_1^2 - n_2^2}}{n_0}\right)$$

This maximum angle $\alpha_i(max)$ is called the acceptance angle.

Numerical Aperture: Light collecting capacity of the fibre is expressed in terms of acceptance angle using the Terminology Numerical Aperture. Sine of the maximum acceptance angle is called the Numerical Aperture (NA) of the fibre.

$$NA = \sin\alpha_i(max)$$

$$= \frac{\sqrt{n_1^2 - n_2^2}}{n_0}.$$

Numerical Aperture of a fibre is effectively dependant only on the Refractive indices of the core and cladding materials and is not a function of the fibre dimensions.

If the light is launched from the air into the fibre;

Then $n_0 = 1$

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

NA in terms of Δ:

Numerical aperture can also be expressed in terms of fractional difference in Refractive indices Δ. $\left[\Delta = \frac{n_1 \sim n_2}{n_1}\right]$.

Since for most of the fibres; $n_1 \simeq n_2$.

$$\therefore n_1^2 - n_2^2 = (n_1 + n_2)(n_1 - n_2)$$

$$\Rightarrow n_1^2 - n_2^2 = (n_1+n_1)(n_1-n_2) \quad (\because n_1 \approx n_2)$$

$$= 2n_1(n_1-n_2).$$

$$= \frac{2n_1^2(n_1-n_2)}{n_1}$$

$$\Rightarrow n_1^2 - n_2^2 = 2n_1^2\Delta. \quad \left[\because \Delta = \frac{n_1-n_2}{n_1}\right].$$

(or) $\sqrt{n_1^2-n_2^2} = n_1\sqrt{2\Delta}$

∴ Numerical Apeorture NA = $\sin\alpha_i(\max)$

$$= \frac{\sqrt{n_1^2-n_2^2}}{n_0} \Rightarrow \frac{n_1\sqrt{2\Delta}}{n_0}.$$

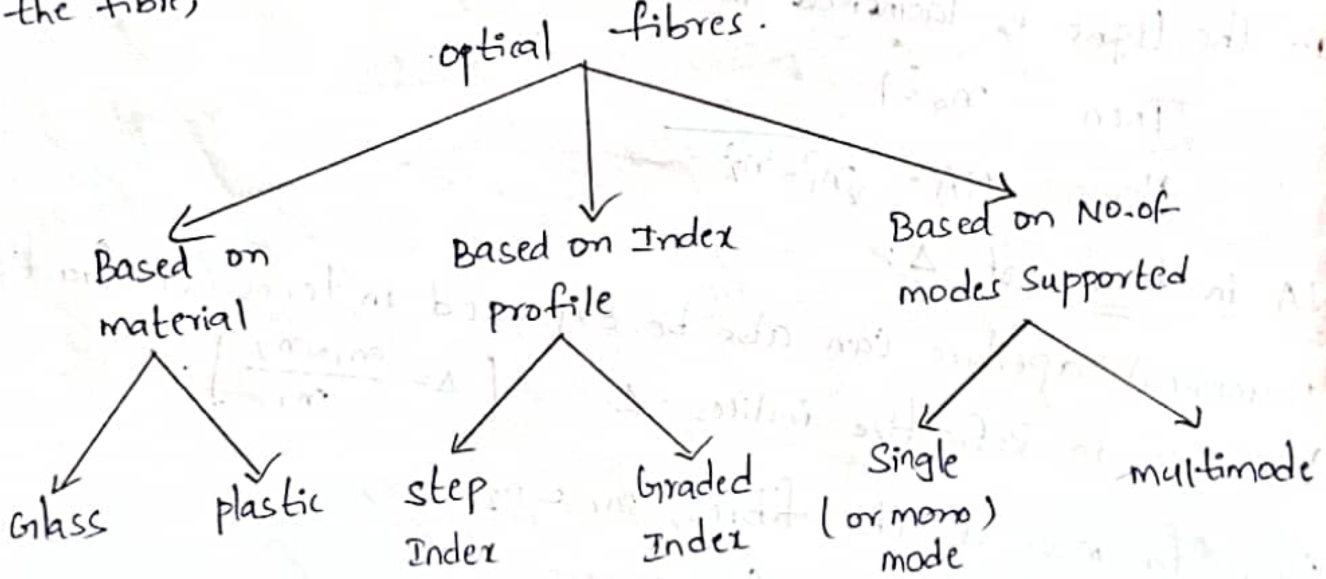
$$\therefore NA \simeq \frac{n_1\sqrt{2\Delta}}{n_0}.$$

when we launch the light into the fibre from air; $n_0 = 1$.

Then $NA = n_1\sqrt{2\Delta}$.

classification of optical fibres:

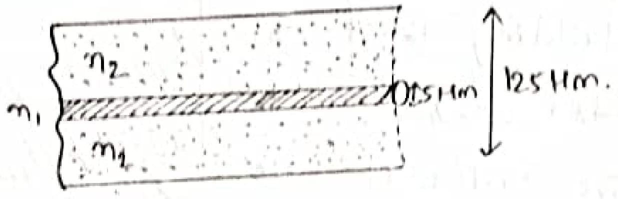
optical fibres can be classified based on either modes that they support or the Refractive Index profile of the fibre. Another classification is based on the material of the fibre, either glass or plastic.



Classification Based on Refractive Index of the core and the modes of fibre propagation:

Depending on the modes they propagate, optical fibres are classified as monomode (single mode) fibres and multimode fibres.

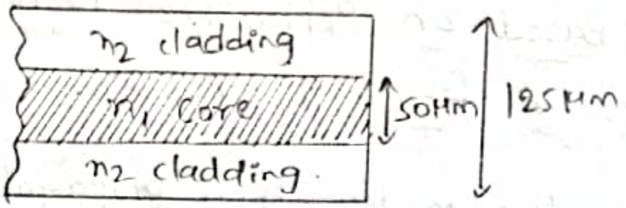
Monomode fibres: These fibres will be having a very Narrow core of diameter 5μm or less. Comparatively the cladding will be Relatively big. Because of the Narrow core, only a single mode can propagate through the central axis in this type of fibre.



Multimode fibres: These fibres will be having a core of Relatively large diameter of about 50μm. A large Number of modes (upto 100) can propagate through this type of fibre.

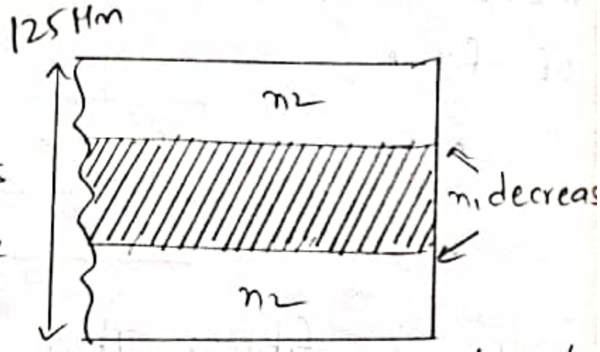
Depending on the Nature of Refractive Index of the core, these multimode fibres are again divided into two types. They are; Step Index multimode fibres and Graded index multi mode fibres.

(i) **Step Index multimode fibres:** In this type, the core will be Relatively wide and having a constant Refractive Index (n_1) through out from its centre upto the boundary with the cladding. Afterwards, the Refractive Index changes to a constant lower value (n_2) inside the cladding. This is called a step Index multimode fibre because the Refractive Index steps down from n_1 to n_2.



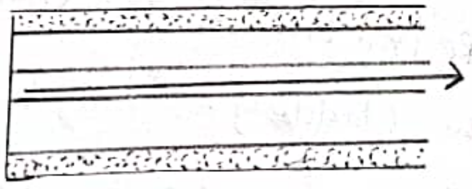
This step Index optical fibre is less Expensive. But it is Not useful for long Range communications.

Graded Index multimode fibres: In this type of optical fib the Refractive Index of the core decreases Smoothly and continously in a Nearly parabolic manner from the centre of the core to the boundary of the core-cladding. The cladding is of a fixed Refractive Index (n_2) that is less than the Refractive Index of core at the boundary. light signals can be transmitted more Efficiently in the graded-Index multimode fibre. Instead of following Sharp zig zag paths as in the step Index fibre, in a graded Index fibre, the Rays follow a smoot spiral paths Around the axis.

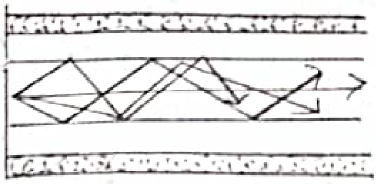


Propagation of light through optical fibres:

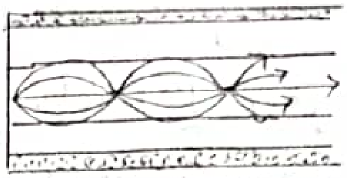
The main principle Involved in this propagation is the Concept of Total Internal Reflection. To understand this clearly observe the following diagrams.



Single mode step Index fibre.



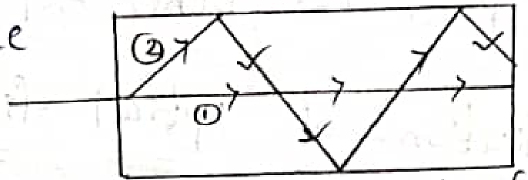
multi mode step Index



multi mode Graded Index fibres.

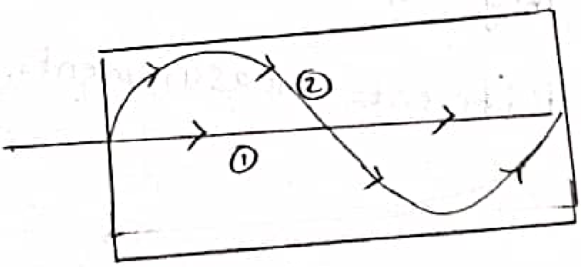
Propagation of light in step Index fibre:

Generally, the signal is sent through the fibre in digital form, i.e., in the form of pulses 0's and 1's. let us consider the propagation of one such pulse.. The same pulsed signal travels in different paths (Represented by multi modes). Hence at the Receiving End, only the Ray ① which travels along the fibre axis Reaches first while the Rays taking longer zigzag paths as ② Reach after some time. and Hence it Reduces Transmission Rate capacity. This difficulty is overcome by manufacturing graded Index fibres.



propagation of light in graded index fibre: In Graded Index multimode fibre, the Refractive Index of the core varies Radially as shown in the figure. It has maximum Refractive Index in its centre, which gradually decreases and at the core-cladding Interface, it matches with the Refractive Index of the cladding.

let us consider a signal pulse travelling through the Graded Index fibre in two different paths ① and ②.



The pulse ① travelling along the axis of the fibre, though travels along shorter Route, it travels through a medium of higher Refractive Index.

The other pulse ② travelling away from the axis undergoes Refraction and bends as shown in this figure. Though it travels longer distance, it travels along the path of Relatively lesser Refractive Index and ~~hence~~ hence both the pulses Reach the other End Simultaneously.

Applications of optical fibres:

optical fibre cables can be used in a wide variety of Industries and applications. Some uses include.

* used as light guides and lasers for surgeries in medical field.
* They can be used as hydrophones for seismic waves as wiring in aircraft, submarines Etc.
* They can be used for data transmission.
* optical fibres are used for Transmitting and Receiving i.e., for communication purposes.
* They can be used as part of fibre optic sensors use for different measurements.

Quantum Mechanics, Free Electron Theory and Band Theory

Quantum Mechanics: Dual Nature of matter, Heisenberg's uncertainty principle, Significance and properties of wave function, Schrodinger's Time Independent and Time Dependent wave Equations, particle in one Dimensional Infinite potential well.

Free Electron Theory: classical free Electron Theory, Quantum free Electron Theory. Equation for Electrical conductivity based on free Electron Theory, Fermi-Dirac Distribution, Density of States, Fermi Energy.

Band Theory of solids: Bloch's Theorem, Kronig - penney model, E vs k diagram, v vs k diagram, Effective mass of Electron, classification of crystalline solids, Concept of hole.

Quantum Mechanics:

The quantum Theory was proposed by Max planck, Albert Einstein, De-Broglie, wernier Heisenberg and Schrodinger.

wave and particle: In order to understand the concept of dual Nature, we should have the knowledge of the charecteristics of waves and particles. The particle has mass, it is located at some fixed point. and it can move from one place to another. It gives Energy when slowed down or stopped. Thus a particle is speci by its (i) mass, (ii) velocity, (iii) momentum and (iv) Ener A wave is spread out over a Relatively large Region of spac and is specified by its (i) frequency, (ii) wavelength, (iii) phase or wave velocity, (iv) Amplitude and (v) Intensity

The above concepts appear difficult to accept th Contradictory Ideas that the Radiation has dual Natur These Radiations behave as waves in Experiments based on Interference, Diffraction etc. Thus Radiation behaves like a wave. planck's quantum theory was successful in Explaining Black Body Radiation, photo Electric Effect, Compton Effect et and had clearly Eshtablished that Radiation Interacts with matter in the form of photons or quanta. Thus Radiation behave like a particle. In this way, the Radiation Sometim behave as a wave and at some other times as a particle. i.e, It has a wave particle Dualism. But the Radiation can not Exhibit Both properties Simultaneously

De-Broglie Hypothesis of matter waves: In 1924, Louis De Broglie made a great unifying hypothesis, that Just as Radiation has particle like properties, & Electrons and other material particles possesses wave like properties. According to de Broglie hypothesis, a moving particle is associated with a wave which is known as De-Broglie wave whose wavelength is

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

where m is the Mass, v is the velocity and p is the momentum of the particle.

If E is the Energy of the particle, then from quantum theory;

$$E = h\nu = \frac{hc}{\lambda} \quad \left[\because \nu = \frac{c}{\lambda}\right] \rightarrow ①$$

where c is the velocity of light, h is planck's constant and λ is wavelength.

But from Einstein's mass Energy Relation; $E = mc^2$. → ②

from Eq ① & ②; we get $mc^2 = \frac{hc}{\lambda}$

$$\Rightarrow \lambda = \frac{hc}{mc^2} \Rightarrow \lambda = \frac{h}{mc}$$

where $mc = p$ is the momentum associated with photon.

If we consider the case of material particle of mass m and moving with a velocity v, is given by

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

This Equation is known as De-Broglie wave Equation.

From this Equation, we can find that if the particles are accelerated to various velocities, can produce waves of various wavelengths.

If E is the kinetic Energy of the material particle, then $E = \frac{1}{2}mv^2$

$$= \frac{1}{2}\frac{m^2v^2}{m}$$

$$\Rightarrow 2Em = m^2v^2 \Rightarrow mv = \sqrt{2Em}$$

$\therefore$ de Broglie wavelength $\lambda = \frac{h}{\sqrt{2mE}}$

If the velocity v is given to an Electron by accelerating it through a potential difference of V volts, then the work done on the Electron is eV which is Equal to kinetic Energy of the Electrons.

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

$$\Rightarrow mv^2 = 2eV$$

$$\Rightarrow m^2v^2 = 2meV \Rightarrow mv = \sqrt{2meV}$$

$\therefore$ de Broglie wavelength $\lambda = \frac{h}{\sqrt{2meV}}$

For an Electron; mass $m = 9.1 \times 10^{-31}$ kg, planck's constant $h = 6.62 \times 10^{-34}$ Joule-sec ; charge of the Electron $e = 1.6 \times 10^{-19}$ coloumb. By substituting; we get

$$\lambda = \frac{6.62 \times 10^{-34}}{\sqrt{2 \times 9.1 \times 10^{-31} \times 1.6 \times 10^{-19} \times V}}$$

$$= \frac{1.227 \times 10^{-9}}{\sqrt{V}} m$$

$$\lambda = \frac{1.227}{\sqrt{V}} nm$$

Properties of Matter waves:

: Smaller the mass of the particle, greater is the wavelength associated with it.

: Smaller the velocity of the particle, greater is the wavelength associated with it.

* when the velocity of the particle $v=0$, then wavelength $\lambda=\infty$. So the wave becomes Indeterminate. and if $v=\infty$, then $\lambda=0$. shows that matter waves are generated.

* The matter waves are produced whether the particles are charged or uncharged. Due to this Reason, these waves are Not Electromagnetic waves.

* The velocity of matter waves depends on the velocity of material particle; that is, it is not Constant while the velocity of Electromagnetic wave is constant.

* The wave Nature of matter waves Introduces as uncertainty in the location of the position of the particle.

Heisenberg's uncertainty principle: According to classical mechanics, a moving particle at any Instant has a fixed position in space and a definite momentum which can be determined simultaneously with any desired accuracy. In wave mechanics, a moving particle is Regarded as a de Broglie wave group.

According to Born's probability, 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 an uncertainty prevails in calculating its velocity or momentum. on the other hand, if the group is considered to be wide, its momentum can be Estimated, but there is uncertainty about the Exac location of the particle.

Thus in 1927, Heisenberg proposed a principle known as uncertainty principle, which states that "I is Impossible to determine both the Exact position a Exact momentum of a moving particle at the Sam time." In general if Δx denotes the Error in the measurement of the position of the particle and Δp Represents the Error in the measurement of momentum, then

$$(\Delta x) \cdot (\Delta p) = h.$$

where h is planck's constant. The above Relation Represents the Extent of the uncertainty involved in the measurement of both the position and momentum c the particle. when, (Δx) and (Δp) can be defined by rms deviation, then the above Equation can be writt as

$$(\Delta x.) \ (\Delta p) \geq \frac{\hbar}{2}. \qquad \left[\text{where } \hbar = \frac{h}{2\pi}\right].$$

The above Equation is one form of the uncertair principle first obtained by Heisenberg. It states that the product of uncertainty (Δx) in the position of a particle at some Instant and the uncertainty (Δp) in the momentum at the same instant, is at best Equal to planck's constant. Another form of uncertaint concerns Energy and time is

$$(\Delta E) \cdot (\Delta t) \geq \frac{\hbar}{2}.$$

Schrodinger's wave Equations:

Time Independent Schrodinger's wave Equations:

In 1925, Schrodinger gave a mathematical theory known as wave mechanics to describe the dual (wave and particle) Nature of matter. He derived a wave Equation for a single moving particle by incorporating de-Broglie wavelength. into classical wave Equation.

Consider a particle of mass 'm' moving with a velocity 'v' along the x direction and associated with a wave called deBroglie wave whose wavelength is given by $\lambda = \frac{h}{mv}$. let us consider a system of stationary waves associated with a particle. let $\psi(r,t)$ be the wave displacement for de Broglie waves at any location r and time t, then the differential Equation of the wave motion in three dimensions is given by

$$\nabla^2\psi = \frac{1}{v^2}\frac{\partial^2\psi}{\partial t^2} \longrightarrow ①$$

where v is the wave velocity. The solution of Eq ① is of the form $\varphi(r,t) = \varphi_0(r)e^{-i\omega t}. \longrightarrow ②$

where ω is the angular velocity of the particle.

Differentiating Eq ② twice; we get

$$\frac{\partial^2\varphi}{\partial t^2} = -\omega^2\varphi_0(r)e^{-i\omega t}$$

$$\Rightarrow \frac{\partial^2\varphi}{\partial t^2} = -\omega^2\varphi(r,t) \rightarrow ③$$

$$\left[\because \varphi(r,t) = \varphi_0(r)e^{-i\omega t}\right]$$

$$\left[\because \frac{\partial\varphi}{\partial t} = -i\omega\cdot\varphi_0(r)e^{-i\omega t}\right.$$

$$\frac{\partial^2\varphi}{\partial t^2} = (-i\omega)(-i\omega)\varphi_0(r)e^{-i\omega t}$$

$$= i^2\omega^2\varphi_0(r)e^{-i\omega t}$$

$$\left.= -\omega^2\varphi_0(r)e^{-i\omega t}\right]$$

By substituting Eq ③ in Eq ①; we get

$$\nabla^2\psi = \frac{1}{v^2}(-\omega^2\psi)$$

$$\nabla^2\psi = \frac{-\omega^2}{v^2}\psi. \rightarrow ④$$

we know that $\omega = 2\pi f \Rightarrow \omega = 2\pi\nu$

$$\Rightarrow \omega = 2\pi\frac{c}{\lambda}$$

$$\Rightarrow \omega = 2\pi\frac{v}{\lambda} \quad [\because c = v]$$

$$\Rightarrow \frac{\omega}{v} = \frac{2\pi}{\lambda} \Rightarrow \frac{\omega^2}{v^2} = \frac{4\pi^2}{\lambda^2}$$

$$\therefore \text{Eq } ④ \Rightarrow \nabla^2\psi = -\frac{4\pi^2}{\lambda^2}.\psi.$$

$$\Rightarrow \nabla^2\psi + \frac{4\pi^2}{\lambda^2}\psi = 0$$

$$\Rightarrow \nabla^2\psi + \frac{4\pi^2}{\left(\frac{h}{mv}\right)^2}\psi = 0 \qquad \left[\because \lambda = \frac{h}{mv}\right]$$

$$\Rightarrow \nabla^2\psi + \frac{4\pi^2 m^2 v^2}{h^2}\psi = 0$$

$$\Rightarrow \nabla^2\psi + \frac{m^2v^2}{\left(\frac{h}{2\pi}\right)^2}\psi = 0 \Rightarrow \nabla^2\psi + \frac{m^2v^2}{\hbar^2}\psi = 0 \rightarrow$$

If E and V are the total and potential Energies of the particle Respectively, then its kinetic Energy is

$$\frac{1}{2}mv^2 = E - V \qquad \left[\because E = V + \frac{1}{2}mv^2\right]$$

$$\Rightarrow mv^2 = 2(E-V) \Rightarrow m^2v^2 = 2m(E-V). \rightarrow ⑥$$

Substituting Eq ⑥ in Eq ⑤; we get

$$\nabla^2\psi + \frac{2m}{\hbar^2}(E-V)\psi = 0. \rightarrow ⑦.$$

This is the schrodinger wave Equation in three dimensions. Since time factor does not appear in this Equation, it is called time Independent schrodinger wave Equation.

For one dimension, it can be written as

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

Time Dependent schrodinger's wave Equation: The time dependent schrodinger's wave Equation may be obtained by Elimination of E from the Eq. ⑦. Differentiating the Eq ②, we get

$$\frac{\partial \psi}{\partial t} = -i\omega \psi_0(r)\, e^{-i\omega t}$$

$$= -i(2\pi\nu)\psi_0(r)\, e^{-i\omega t} \qquad \left[\because \omega = 2\pi f = 2\pi\nu\right]$$

$$= -\frac{i\, 2\pi\, E}{h}\psi_0(r)\, e^{-i\omega t} \qquad \left[\because E = h\nu,\ \nu = \frac{E}{h}\right].$$

$$= \frac{-2\pi i E}{h}\psi$$

$$= \frac{-iE}{\left(\frac{h}{2\pi}\right)}\psi \Rightarrow \frac{-iE}{\hbar}\psi.$$

$$\frac{\partial \psi}{\partial t} = \frac{-iE}{\hbar}\psi \times \frac{i}{i}$$

$$\frac{\partial \psi}{\partial t} = \frac{E\psi}{ih} \Rightarrow E\psi = ih.\frac{\partial \psi}{\partial t} \longrightarrow ⑧.$$

Substituting Eq ⑧ in Eq ⑦; we get.

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

$$\Rightarrow \nabla^2\psi + \frac{2m}{\hbar^2}\left(ih\frac{\partial \psi}{\partial t} - V\psi\right) = 0.$$

$$\nabla^2\psi = \frac{-2m}{\hbar^2}\left[i\hbar\frac{\partial\psi}{\partial t} - V\psi\right]$$

$$\Rightarrow -\nabla^2\psi\frac{\hbar^2}{2m} = i\hbar\frac{\partial\psi}{\partial t} - V\psi$$

$$\Rightarrow -\nabla^2\psi\frac{\hbar^2}{2m} + V\psi = i\hbar\frac{\partial\psi}{\partial t} \rightarrow ⑨$$

$$\Rightarrow \psi\left[\frac{-\hbar^2}{2m}\nabla^2 + V\right] = E\psi$$

This equation ⑨ contains the time and hence it i called time dependent Schrodinger's wave Equation.

The operator, $\left(\frac{-\hbar^2}{2m}\nabla^2 + V\right)$ is called Hamiltonian and is Represented by H.

$$\therefore \quad H\psi = E\psi.$$

Physical Significance of the wave function:

A first and Simple Interpretation of wave function ψ was given by schrodinger, in terms of charge density. we know that in any Electromagnetic wave system, the Energy per unit volume is a^2, where a is the amplit of the wave. The Number of photons per unit volume or Simply photon density will be

$$\frac{\text{Energy per unit Volume}}{\text{Energy of one photon}} = \frac{a^2}{h\nu}.$$

Since $h\nu$ is constant, photon density is proportional to a^2. In a Similar manner, if ψ is the amplitude of matter waves at any point in space, then the particle density at that point may be taken as proportional to ψ^2.

According to Max Born, ψ^2 does not measure the particle ensity at any point but gives the probability of finding he particle at that point at any Instant. The value of ψ^2 may be Real or Imaginary depending upon the Value of , but the probability of finding a particle at a given oint in space must be Real and is taken as $|\psi|^2$. ore Exactly, the probability of the particle being present in a volume dxdydz is $|\psi|^2 dxdydz$. for total probabilit of finding the particle somewhere is unity because the article is Certainly to be found somewhere in space.

$$\therefore \iiint_{-\infty}^{\infty} |\psi|^2 \, dx\,dy\,dz = 1$$

The wave function ψ satisfying this Condition is said to be Normalized.

If the particle is confined to X axis only, then the probability is $\int_{-\infty}^{\infty} |\psi|^2 \cdot dx = 1$. This Equation is called as Normalization wave Equation.

Properties: we have seen that $|\psi|^2$ Represents the Probabilit density, the solution that can be allowed for ψ from Schrodinger are subjected to certain limitations. They are;

- ψ must be finite for all values of x, y, z.
- ψ must be single valued. i.e., for Each set of values of x, y, z, the wave function ψ must have only one value.
- ψ must be continous in all Regions Except where otential Energy is Infinite.

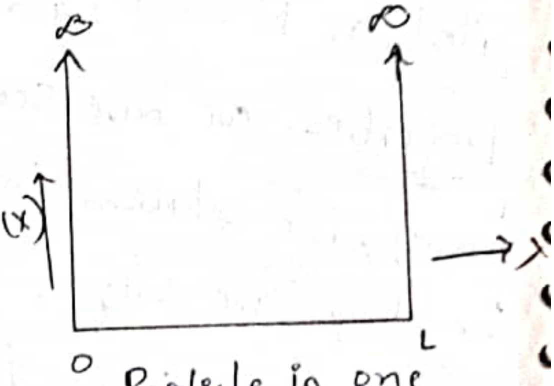
* ψ must possesse · ~~unif~~ continous first order derivati

* ψ vanishes at the Boundaries.

Particle in one Dimensional potential Box:

when the motion of the particle is confined to a limited Region such that the particle moves back and forth in the Region, the particle is said to be in Bound state. 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 at the Extremities of the distance is assumed to become Infinite, It is described as the particle is bound in one dimensional Box.

Consider a particle of mass m which is bound to move in a one dimensional potential Box of length L. The particle is prevented from leaving the potential energy Box by the presence of a large potential Energy barriers at its surfaces. The motion of electron in that box is shown in below figure.



Particle in one dimensional potential Box

The potential Energy inside the box is assumed to be Zero. Thus, we have

$V(x)=0$ for $0<x<L$

$V(x)=\infty$ for $x\leq 0$ and $x\geq L$.

The motion of Electron in one dimensional Box can be described by schrodinger wave Equation. i.e.,

$$\frac{d^2\psi}{dx^2} + \frac{2m}{\hbar^2}(E-V)\psi = 0.$$

where E Represents the kinetic Energy of the Electron and V is its potential Energy. Since V=0 inside the box; we get

$$\frac{d^2\psi}{dx^2} + \frac{2m}{\hbar^2}E\psi = 0$$

$$\Rightarrow \frac{d^2\psi}{dx^2} + k^2\psi = 0.$$

where $k^2 = \frac{2mE}{\hbar^2} \Rightarrow k = \sqrt{\frac{2mE}{\hbar^2}}$

The general solution for above Equation can be written as $\psi(x) = A\sin kx + B\cos kx$. → ①

where A, B and k are constants can be determined from the boundary Conditions. i.e.,

(i) when $x=0$, then $\psi(0)=0$;

(ii) when $x=L$; then $\psi(L)=0$.

Applying the first boundary condition;

$$0 = A\sin 0 + B\cos 0$$

$$\Rightarrow B = 0.$$

Substituting $B=0$ in the Equation ①;

$$\psi = A\sin kx.$$

Applying Second Boundary Condition;

$$\sin kL = 0 \Rightarrow kL = n\pi$$

$$\Rightarrow k = \frac{n\pi}{L}.$$

i.e., $\psi_n(x) = A\sin\left(\frac{n\pi}{L}\right)x$

Where $n = 1, 2, 3, \dots$

The allowed Energy values can be obtained as

$$E_n = \frac{\hbar^2}{2m^2}\left(\frac{n\pi}{L}\right)^2$$

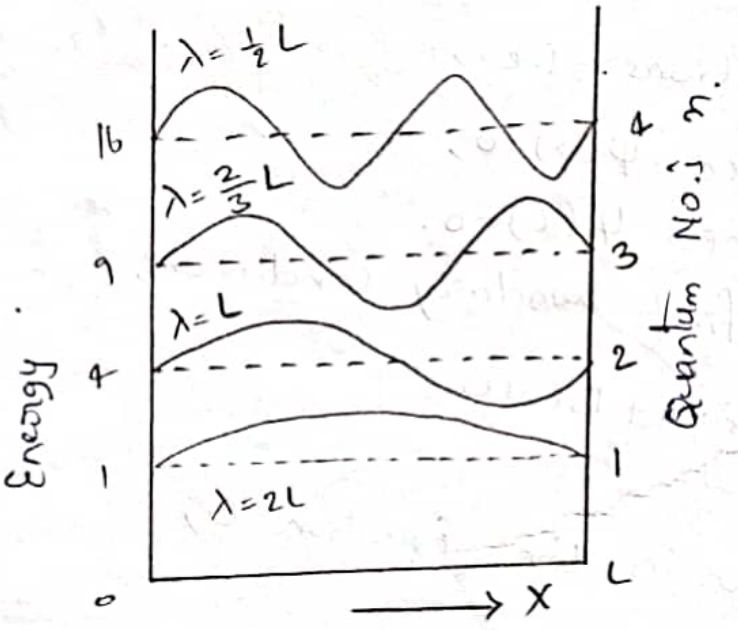
$$\Rightarrow \frac{\left(\frac{h}{2\pi}\right)^2}{2m^2}\frac{n^2\pi^2}{L^2}$$

$$\Rightarrow \frac{h^2}{8\cancel{\pi^2} m^2}\frac{n^2\cancel{\pi^2}}{L^2}$$

$$E_n \Rightarrow E_n = \frac{n^2h^2}{8m^2L^2}$$

or $E_n \propto n^2$.

The Energy levels and wave functions Corresponding T
$n = 1, 2, 3, 4, \dots$ are shown below.



First four wave functions and Corresponding Energy levels.

Free Electron Theory:

Classical free Electron Theory of metals: This Theory was developed by Drude and lorentz in 1900. According to this Theory, a metal consists of positive ions fixed and the valence electrons move freely within the Boundaries of the metal like gas molecules in a container. The assumptions of classical free Electron theory are given below.

Assumptions of classical free Electron Theory:

* In metals, there is large Number of free Electrons, moving freely in all possible directions.

* The free electrons in the metal are assumed to behave like gas molecules obeying the laws of kinetic Theory of gases.

* The mean kinetic Energy of free electron is equal to that of a gas molecule at the same Temperature

i.e., $\frac{1}{2}m\bar{c}^2 = \frac{3}{2}k_BT$

$$\Rightarrow m\bar{c}^2 = 3k_BT \Rightarrow \bar{c} = \sqrt{\frac{3k_BT}{m}}$$

where $\bar{c}$ is the Root mean square velocity of electron, m is mass of the electron, K_B is Boltzmann constant and T is absolute Temperature of Electron. At Room Temperature, $\bar{c} = 1.16 \times 10^5$ m/s

* In metals, the positive ion cores are at fixed positions, the free Electrons move Randomly and collide with either positive ions or with other free Electrons. All the collisions have No loss of Energy. Therefore, electric conduction is due to the motion of free electrons only.

* The free Electrons move in a complete uniform potential field as the ions are fixed, hence the potential Energy of the electrons is constant.

* When an electric field is applied to the metal, the free

Electrons are accelerated in the direction opposite to that of the applied Electric field.

* The electric current in the metals is due to the drift veloc acquired by the Electrons in the presence of applied Electric fiel

<u>Some Basic Definitions</u>:

<u>Mean free path</u> (λ): The Average distance Travelled by an Electron between two successive collisions during their Random motion is called mean free path.. It determines the mobility of Electrons. If τ is Mean collision time and $\bar{c}$ is Root Mea square velocity of electron, the mean free path is

$$\lambda = \bar{c}\,\tau.$$

<u>Mean collision Time</u> (τ): The average time taken by an electron between two successive collisions during their Random motion is called mean collision time. If $\bar{c}$ is Root mean square velocity of electron and λ is mean free path, then mean collision Time is

$$\tau = \frac{\lambda}{\bar{c}}$$

<u>Drift velocity</u> (vd): In the absence of applied Electric field, the free electrons in a metal move Randomly and make collision with Neighbouring Electrons and also with the positive ions. So that the direction of the electrons changes continously. When an Electric field (E) is applied to metal, the Electrons Experien a force Equal to -eE. Due to this force, the Electrons accelera in the opposite direction to the applied Electric field and velocity of electron gradually Increases. But, the velocity does not Increase continously due to the collision of conduction electrons with Ions. So the velocity of electrons becomes constant and is called drift velocity.

$$\Rightarrow \frac{K}{\sigma} = LT.$$

where $L = \frac{3}{2}\left(\frac{k_B}{e}\right)^2 = 1.12\times10^{-8}$ watt ohm deg^{-2} and is kn

as lorentz Number.

Success of classical free Electron Theory:

* It verifies ohm's law.
* It Explains the mechanism of Electrical and Thermal conduc of metals.
* It derives wiedemann - franz law.
* It Explains the optical properties of metals.

Drawbacks of classical free Electron Theory: Though the clas free Electron Theory successfully Explained Electrical Conductivi thermal conductivity and other phenomenon of metals, It could Explain Number of Experimentally observed facts. This led to th failure of classical free Electron theory of metals. The draw are;

* **Specific heat of Solids:** when heat is supplied to solids, free electrons also absorb Energy. Thus free Electrons also Contribute to the specific heat of solid. According to the free electron theory of metals, the Energy of Electrons in one kilo mole of Solid is given by

$$E = \frac{3}{2} N_A k_B T.$$

where N_A is Avagadro's Number, k_B is the Boltzmann constant and T is absolute temperature. The electronic Specific heat is given by.

$$C_V = \frac{dE}{dT} = \frac{3}{2} N_A k_B$$

$$= \frac{3}{2} \times 6.023\times10^{26} \times 1.38\times10^{-23}$$

$= 12.5$ kJ/mol. k.

But, the Experimental value of C_v is hundered times less than the above value. so the classical free Electron theory fails to Explain the specific heat of solids.

* Temperature dependance of conductivity: According to the classical free Electron Theory, the Electrical conductivity of conductor is given by $\sigma = \frac{ne^2\lambda}{\sqrt{3k_B mT}}$

i.e., $\sigma \propto \frac{1}{\sqrt{T}}$. But Experimentally, it was found that $\sigma \propto \frac{1}{T}$. So, the classical free Electron Theory fails to Explain the Temperature dependance of Electrical conductivity of metals.

* Dependence of conductivity on Electron concentration: According to the free Electron Theory of metals, the electrical conductivity of conductor is $\sigma = \frac{ne^2\lambda}{\sqrt{3k_B mT}}$

* from the above Equation, it is clear that $\sigma \propto n$. Experimentally, there is No direct Relaetionship between electron Concentration and Electrical conductivity. So, it is clear that there Exists difference between Theoretical predictions and experimental observations.

* At low Temperature, the electrical conductivity (σ) and Thermal conductivity (k) are varied in different ways. $\therefore$ $(k\sigma/T)$ is not constant.

* The phenomena such as photoElectric effect, compton effect and blackbody Radiation couldn't be Explained by free Electron Theory.

* Ferromagnetism couldn't be Explained by this theory.

Quantum free Electron theory: The Quantum free Electron Theory is proposed by Sommerfeld in 1928, overcomes many of the drawbacks of classical free electron theory. Sommerfeld Investigated this behaviour of a free electron firstly by discovering the possible Energy states for an Electron in the potential box. and secondly by considering the distribution of large Number of Electrons in Thermal Equilibrium among these States. The main assumptions are;

* The Energy of free Electron is quantized.
* The distribution of Electrons among the various permitted Energy levels is as per the pauli's Exclusion principle.
* The Electrons Travel under a constant potential inside the metal, however their moment is confined to the boundaries of the metal.
* The attraction between ions and Electrons as well as the Repulsion between Electrons are Neglected.

Success of Quantum free Electron Theory:

* The specific heat behaviour of metals: According to quantum theory, when heat Energy is supplied to the solid, only those Electrons occupying Energy levels closer to fermi level absorb Energy and get Excited to higher Energy levels. Thus, only Small percentage of electrons is capable of contributing to the specific heat. Thus, according to quantum theory of free Electrons, Energy of all the Electrons in one kilo mole of solid is given by

$$E = \frac{3}{2} N_A k_B T \left(\frac{k_B T}{E_F}\right).$$

$$\rightarrow E = \frac{3}{2} N_A \frac{(k_B T)^2}{E_F}$$

Where NA is the Avagadro Number, k_B is Boltzmann Constant and T is the absolute Temperature. Thus, the Electronic specific heat is given by

$$C_V = \frac{dE}{dT} = \frac{d}{dT}\left(\frac{3}{2} N_A \frac{(k_BT)^2}{E_F}\right)$$

$$\rightarrow C_V = \frac{3}{2}\frac{N_A}{E_F} k_B^2 (2T)$$

$$= 3\frac{N_A}{E_F} k_B^2 T.$$

At Room Temperature; $T = 300k$ and for $E_F = 5eV$;

$$C_V = (6.023\times10^{26}) \times (1.38\times10^{-23})^2 \times \frac{300}{5\times1.6\times10^{-19}}$$

$$C_V = 0.129 \ kJ/k.mole.$$

which is in agreement with the Experimental Results.

* **Temperature dependence of Electrical conductivity:** The Expression for electrical conductivity at fermi level is

$$\sigma = \frac{ne^2\tau_F}{m}$$ with mean collision time $\tau = \frac{\lambda}{V_F}$.

$$= \frac{ne^2\lambda}{mV_F}$$

Since the fermi energy level E_F is independent of Temperature, V_F is also Independent of Temperature. Then, only mean free path at fermi level λ_F depends on temperature. we know that Even at very high temperature, only Electrons closer to fermi Energy got excited. Thus, only small percentage of electrons contribute to Electrical conductivity. we know that $\lambda \propto \frac{1}{T}$.

∴ It follows that $\sigma \propto \frac{1}{T}$.

* It Explains the Electrical and Thermal conductivities of metals.
* It Explains the photo Electric Effect, Thermo electric Effec and gravitational effect of metal.
* It Explains the Paramagnetic Susceptibility.

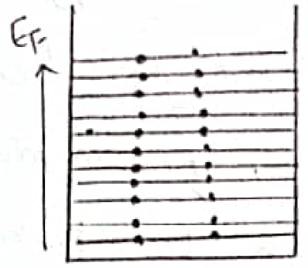
Drawbacks of Quantum free Electron Theory:

* This theory could not Explain the differences between the conductors, Semiconductors and Insulators.
* On the basis of free Electron Theory, it has been shown that the electrical conductivity is proportional to the Electron concentration. It is surprising that the divalent metals ar Even trivalent metals are consistently less conductive than monovalent metals.
* The free Electron model always predicts a Negative Hall coefficient.
* Free Electron model always predicts a spherical fermi surfa is often Non spherical.

The above mentioned difficulties are overcome by taking in consideration of Band Theory of solids.

Fermi level and Fermi Energy: The Electrons are Fermions and obey the pauli's Exclusion principle, according to which an Energy level can accomodate at most two Electrons, one with spin up and the other with spin down. Thus, in filling the energy levels, two Electrons occupy the lowest level, two more in the Next level and so forth until all the electrons in the met have been accomodated, as shown here.

The highest occupied Energy level by the ectrons at ok. is called the fermi level. = ok, below the fermi level all the nergy states are completely filled by the ectrons and above the fermi level all the nergy states are Empty. The probability occupation of electron = the fermi level is half at any temperature other than <. The maximum Energy of filled state by the electrons at k is called fermi Energy. The Fermi Energy can be Evaluated y



$$E_F = \left(\frac{3}{\pi}\right)^{2/3} \frac{h^2}{8m} (n)^{2/3}.$$

where h, m and π are constants. substituting these onstants, then the fermi Energy $E_F = 3.62 \times 10^{-19} \times n^{2/3}$ eV. ne typical value of fermi Energy in metals is about 5eV.

Fermi - Dirac distribution: The distribution of Electrons among the various Energy levels is usually described by the distribution function F(E), which is defined as the probability that the level E is occupied by an electron. Therefore their Energy distribution at any Temperature T can be Expressed by fermi dirac distribution function as

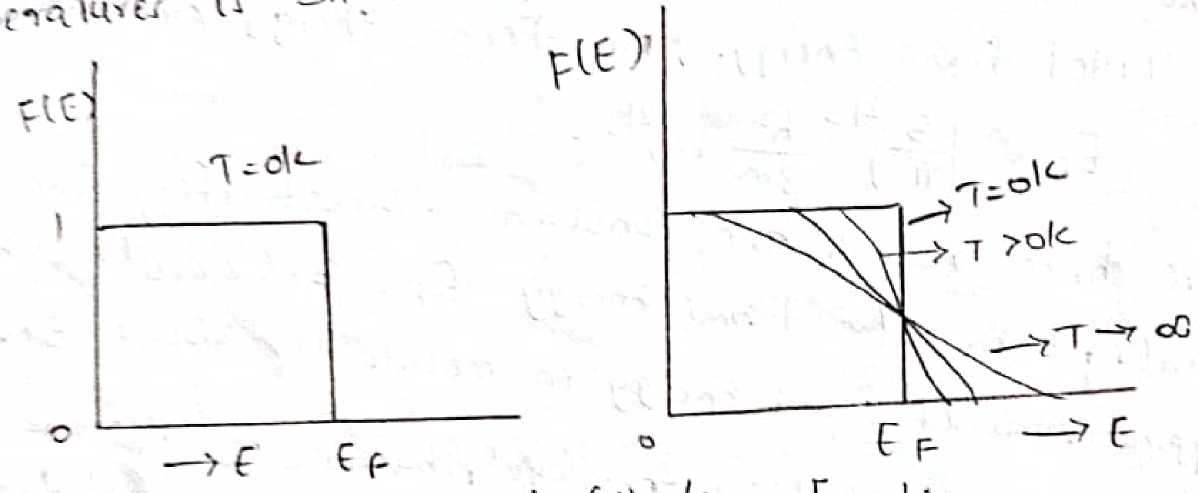
$$F(E) = \frac{1}{1+\exp\left(\frac{E-E_F}{k_B T}\right)}$$

where E is the Energy of allowed State and E_F is the Fermi Energy. At Absolute zero, the distribution function has the following properties.

$F(E)=1$ for all values of $E < E_F$

$F(E)=0$ for all values of $E > E_F$.

That is the levels below E_F are completely filled, and all those above E_F are completely Empty. Hence, E_F is the maximum Energy of filled state. However for any Temperature greater than zero, $F(E) = \frac{1}{2}$ at $E = E_F$. Therefore, the fermi level in a metal is the Energy level for which the probability occupation is half. further, at very high Temperatures as T tends to Infinity, $k_BT \gg E_F$. The electrons lose their quantum mechanical charecter and the Fermi dirac distibution function at different Temperatures is shown below.



Fermi Dirac distribution function.

Density of States: The density of states is defined as the Number of Energy levels available per unit volume per unit Energy centered at E. It is denoted by Z(E). The product of Z(E) dE gives the Number of states per unit volume between the Energy levels E and E+dE. i.e.,

$$N(E) = Z(E)dE.$$

According to quantum mechanics, the Energy of an electron confined within one dimensional potential well of width a is given by

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

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

$$\Rightarrow n = \left(\frac{8ma^2E}{h^2}\right)^{1/2}$$

where n is an integer, h is plancks Constant and a is width of the potential well. The Number of Energy states with a particular value of E depends on the Combination of quantum Numbers Result in the same value of n. The Number of Energy states having Energy values between E and E+dE is

$$Z(E)\,dE = \frac{\pi}{2} n^2 dn.$$

Differentiating the above Equation i.e., $E = \frac{n^2h^2}{8ma^2}$ with Respec to E, we get

$$2n \cdot \frac{dn}{dE} \cdot dE = \frac{h^2}{8ma^2} 2n \cdot dn$$

$$\Rightarrow dn = \frac{1}{2n} \frac{8ma^2}{h^2} dE.$$

Substituting the value of 'n in above Equation;

$$dn = \frac{1}{2\left(\frac{8ma^2E}{h^2}\right)^{1/2}} \frac{8ma^2}{h^2} dE$$

$$= \frac{1}{2}\left(\frac{h^2}{8ma^2E}\right)^{1/2}\left(\frac{8ma^2}{h^2}\right)dE$$

$$= \frac{1}{2}\left(\left(\frac{h^2}{8ma^2}\right)\left(\frac{8ma^2}{h^2}\right)^2\right)^{1/2}\frac{1}{E^{1/2}}dE$$

$$dn. = \frac{1}{2}\left(\frac{8ma^2}{h^2}\right)^{1/2}\frac{dE}{E^{1/2}}$$

Substituting the values of n^2 and dn in Z(E) dE; we get

$$Z(E)\,dE = \frac{\pi}{2}\left(\frac{8ma^2E}{h^2}\right)\frac{1}{2}\left(\frac{8ma^2}{h^2}\right)^{1/2}\frac{dE}{E^{1/2}}$$

$$= \frac{\pi}{4}\left(\frac{8ma^2}{h^2}\right)^{3/2}\frac{E}{E^{1/2}}dE$$

$$= \frac{\pi}{4}\left(\frac{8ma^2}{h^2}\right)^{3/2} E^{1/2}\,dE.$$

According to paulis Exclusion principle, Each Energy level contains two Electronic states, one with spin up and the other with

Spin down. Hence the Number of Energy states available for Electron is given by

$$Z(E)\,dE = 2 \times \frac{\pi}{4}\left(\frac{8ma^2}{h^2}\right)^{3/2} E^{1/2}\,dE$$

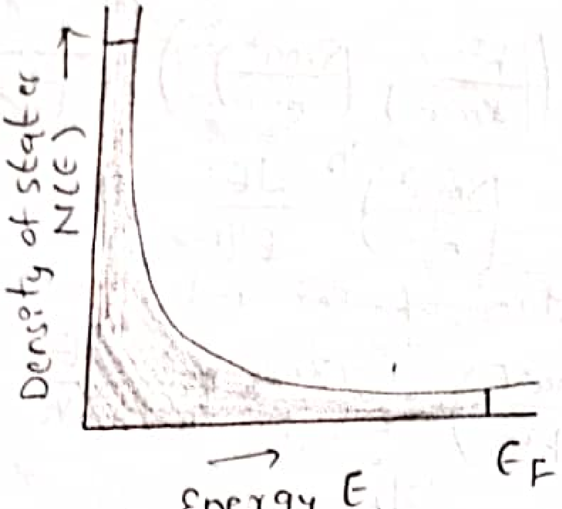
$$Z(E)\,dE = ~~4~~\,\frac{\pi}{2}\,\frac{(2m)^{3/2}\,2^3 . a^3}{h^3}\,E^{1/2}\,dE$$

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

The Number of Energy states per unit volume is called density of states. ∴ density of states is

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

The plot of density of States Z(E) dE versus E is shown below. It Indicates that all the levels present below the fermi level are filled and all those present above it are Empty. This type of situation, infact Exis at absolute zero i.e, at 0K.

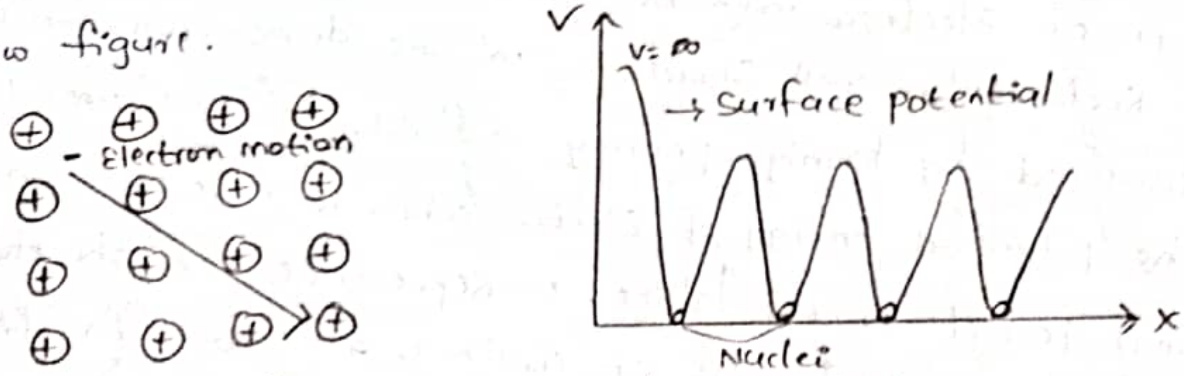


Variation of Density of states with Energy.

Band theory of solids:

Introduction: The free Electron Theory of metals assumes that a conduction electron in a metal Experiences a constant potential and so completely free to move within the metal. This Theory successfully Explained several properties like Specific heat, Electrical conductivity, magnetic susceptibility Etc. But this theory fails to Explain Some other properties like the distinction between conductors, semi conductors, Insulaters, less conductavities of divalent and trivalent metals than Monovalent metals Etc. These draw backs are overcome by taking into consideration of Electron.

Bloch Theorem: In order to understand the difference between conductors and Insulators, It is Necessary to Incorporate the variation of potential inside the crystal due to the presence of positive ion cores in the free Electron model as shown in below figure.



one dimensional periodic potential.

The potential is Minimum at the positive ion site and is aximum in between the two ions. The corresponding one dimensional chrodinger wave Equation can be written as

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

here the potential. V(x) may be defined by means of the ttice constant as $V(x)=V(x+a)$.

pplying the periodic potential, Bloch has shown that one dimensional solution of the schrodinger Equation takes th

form $\psi(x) = e^{ikx} u_k(x)$. → ①

where $u_k(x)$ has the same periodicity of the lattice give

by $u_k(x) = u_k(x+a)$.

Here k Represents the state of motion of the electron

called propagation vector and k^{th} state corresponds to an

Electron having momentum $p = \frac{hk}{2\pi}$ and $k = \frac{2\pi}{\lambda}$. λ is de-

Broglie wavelength.

In three dimensions, the solution of the schrodinger

Equation is given by $\psi_K(r) = e^{ikr} u_K(r)$ → ②

The above Equations are known as Bloch functions

in one and three dimensions Respectively.

Kronig - penney model: The Essential feature of the

behaviour of Electron may be studied by considering a

periodic Rectangular well structure in one dimension, which wa

first discussed by kronig - penney in 1931. It is assumed here

that the potential Energy of Electron when it moves in one

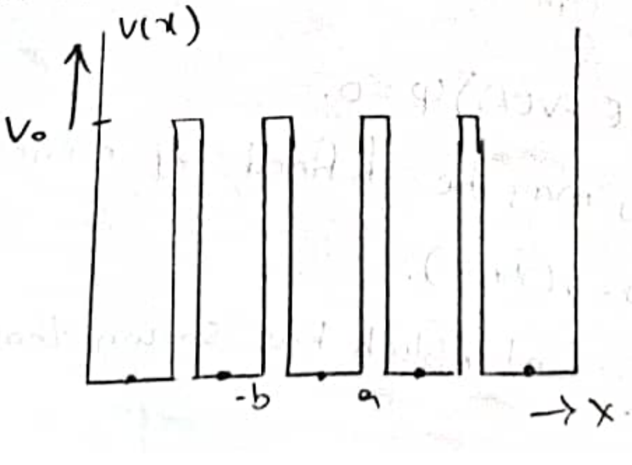
dimensional perfect crystal lattice, is Represented in the form o

Rectangular wells and barriers of width b as shown in figure.

The periodicity of the potential Energy is $(a+b)$.

Kronig and penney model proposed a simpler potential

the form of an array of square wells as shown in figure.



Schrodinger Equation for one dimensional periodic potential field denoted by $V(x)$ can be written as

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

The solutions of this Equation (According to Bloch Theorem) are

$$\psi(x) = U_k(x)\exp(ikx)$$

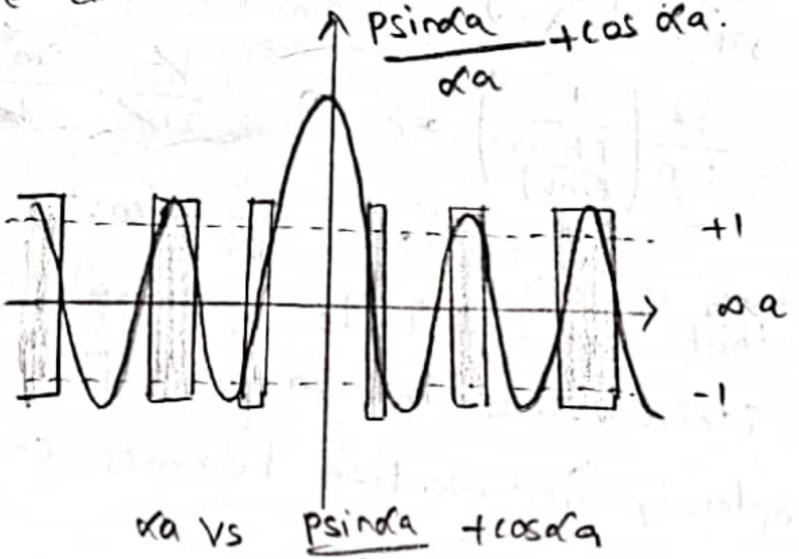
where $U_k(x)$ is periodic. i.e., $U_k(x) = U_k(x+a)$.

The form of $U_k(x)$ depends on the Exact Nature of the potential field. Further ψ and $\frac{d\psi}{dx}$ should be continous throughout the crystal. Also, in order to Simplify the computations, an assumption is made Regarding the potential barrier. As V_0 Increases, the width of the barrier ω decreases. So that the product $V_0\omega$ remains constant. i.e.,

$$\cos ka = \frac{P\sin\alpha a}{\alpha a} + \cos\alpha a.$$

where $P = \frac{4\pi^2 ma}{h^2}V_0\omega$; $a = \frac{2\pi}{h}\sqrt{2mE}$

The left side of this Equation Imposes a limitation on the values that the Right side function can have, Namely a maximum value of +1 and a minimum value of -1. Hence only certain Range of values of α are allowed. This means that Energy E is Restricted to lie within certain Ranges which form the allowed Energy bands or zones. This Concept is best understood by considering the abelow plot.



αa vs $\frac{P\sin\alpha a}{\alpha a} + \cos\alpha a$

The permitted values of Energy are shown as shaded portions. This gives Rise to the concept of Ranges of permitte values of α for a given ion lattice spacing a.

Allowed Ranges of αa which permit a wave mechanical Solution to Exist are shown by shadow portions. The motion of Electrons in a periodic lattice is charecterised by the bands of ~~allowed~~ Energy separated by forbidden Regions.

As the value of α increases the width of the allowed Ener band also increases and the width of the forbidden bands also increases and the function decreases.

If the potential barrier strength P is large, the function described by the Right band side of the equation crosses +1 and -1 Region. Thus the allowed band becomes Narrower and forbidden band becomes wider.

In the limit $P \to \infty$, the allowed band Reduces to one sing Energy level Corresponding to Energy level.

In the other extreme case when $P \to 0$,

$$\cos ka = \cos \alpha a$$

$$\Rightarrow k = \alpha \quad \Rightarrow k^2 = \alpha^2.$$

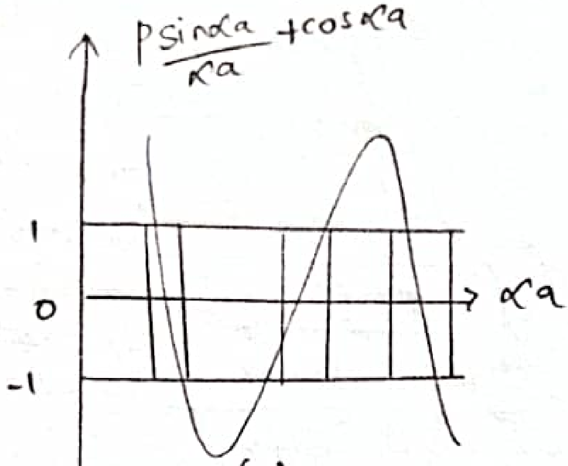
$$\Rightarrow k^2 = \frac{8\pi^2 m E}{h^2} \quad \Rightarrow E = \frac{k^2 h^2}{8\pi^2 m}$$

$$\Rightarrow E = \frac{h^2}{8\pi^2 m}\left(\frac{2\pi}{\lambda}\right)^2 = \frac{h^2}{2m}\left(\frac{1}{\lambda^2}\right)$$

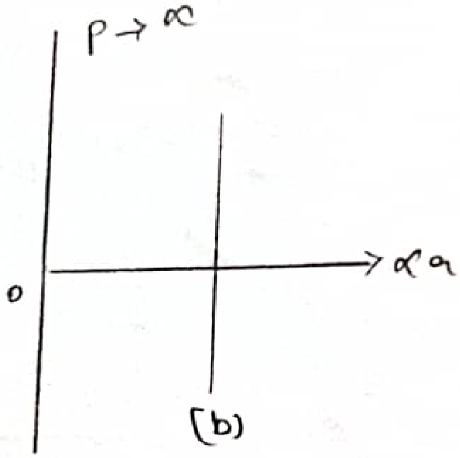
$$\therefore E = \frac{h^2}{2m}\left(\frac{1}{\left(\frac{h}{mv}\right)^2}\right) \Rightarrow E = \frac{\cancel{h^2}}{2\cancel{m}} \cdot \frac{m^{\cancel{2}} v^2}{\cancel{h^2}}$$

$$\Rightarrow E = \frac{1}{2} m v^2.$$

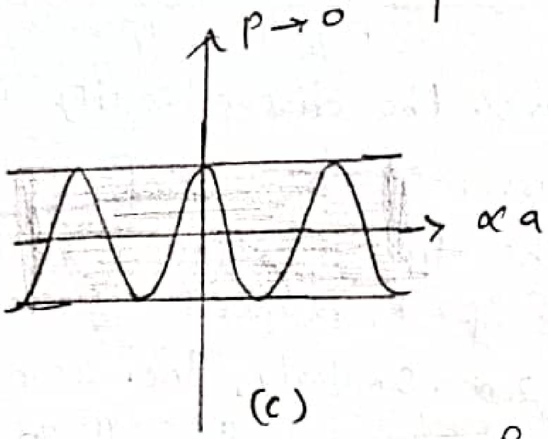
This Indicates that the particle is completely free and No Energy levels Exist. Thus by Varying P from 0 to ∞, we find that completely free electron becomes completely bound. These stages are Represented below.



(a)



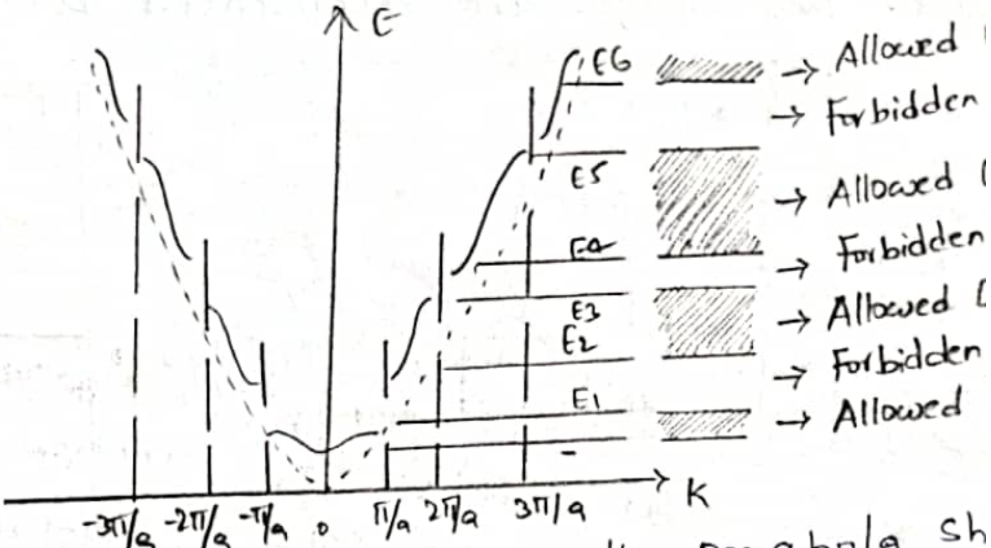
(b)



(c)

E vs k Diagram: This Diagram is a Representation of permissive values of k of the elections in one, two or three dimensions. Thus the Energy spectrum of an electron moving in the presence of periodic potential field is divided into allowed zones and forbidden zones. This can also called as Brillouin zone diagram.

using the Equation $\frac{P\sin\alpha a}{\alpha a}+\cos\alpha a=\cos ka$, It is possible to plot a curve showing the Energy E as a function of k. This Result is shown in below figure. The discontinuities in E versus k curve occurs for $k=\frac{n\pi}{a}$, where $n=\pm1,\pm2,\pm3,\ldots$ This shows the energy of the electron Increases continously from zero and the value of k Reaches $\frac{\pi}{a}$.

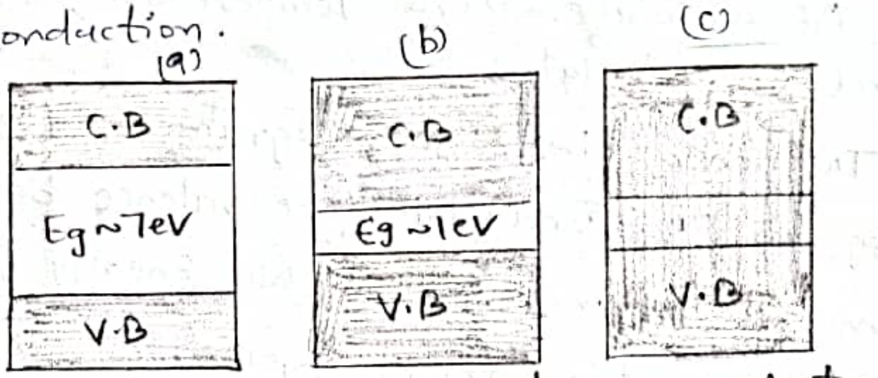


In this figure, the discontinuity in the parabola sh the Energy curves of Kronig - penney model. The dotte curve shows the free Electron parabola. The Range of allowed values of k between $-\frac{\pi}{a}$ and $\frac{\pi}{a}$ constitutes th first Brillouin zone. Similarly, the second one consists of tw parts. one part Extending from $\frac{\pi}{a}$ to $\frac{2\pi}{a}$ and another p between $-\frac{\pi}{a}$ and $-\frac{2\pi}{a}$. These zero boundaries Represent maximum energies that the electron can have without developing and discontinuity. The Energy gap at the zone boundary is called the forbidden zone.

Distinction between conductors, Semiconductors and Insul

The Electrical properties of a solid depends upon its Energy band structure and the way in which the Energy b are occupied by the electrons. Depending on the Nature of b occupation by Electrons and on the width of the forbidden b the solids can be classified as Insulators, conductors and sem conductors. The metals are good conductors of electricity wh the Insulators are bad conductors of electricity. The Electric Conductivity of Semiconductor lies between that of a metal an Insulator. The Energy band theory of solids can Explain the

Conductivity of a solid. The Electrons in the Innermost Shells, which are completely filled, do not take any part in the conduction process. The completely filled bands and the completely Empty bands do not contribute to the Electrical conduction.



Insulators semiconductors conductors

Insulators: The Energy Band structure of an Insulator is shown above. In Insulator, the conduction band is completely Empty, the valence band is completely filled and there is a large Energy gap. Eg > 2eV between conduction band and valence band. When an Electric field is applied, there is NO New Energy level available to the Electron and there is NO conduction of Electricity. Because of the large Energy band gap, the transition of Electron from valence band to conduction band is also Not possible. At Room Temperature, the thermal Energy is much less than the band gap Energy.

Semi conductors: The Energy band diagram of semiconductors is shown in figure (b). In semiconductors, the conduction and valence bands are partially filled at Room Temperature. The Energy gap between the valence band and conduction band is small compared to Insulator. Due to the small Energy gap, some of the valence band Electrons make transitions to the conduction band by acquiring Thermal Energy. These lectrons leave an Equal Number of vacant states or holes in the valence Band. These holes behave like positive charge and also contribute to the conduction of electricity. The Conductivity is in between that of Insulators and conductors. The examples of semiconductors are silicon and germanium having band gap Energies 1.1 eV and 0.7 eV Respectively. At absolute zero Temperature, all the semiconductors acts as Insulators.

Conductors: The Energy band gap diagram of a conductor is shown in fig (c). In conductors, the valence band and the conduction band overlap and there is No Energy gap between them. At Room Temperature, the free electrons Exist in the conduction band hence conductivity is high. The Resistivity Increases with Increase of Temperature as mobility of Existing Electrons will be Reduced due to Collisions. Metals are the best Examples for conductors.

Concept of Effective mass of an Electron: The Electrons n a Crystal are Not completely free but Interact with the crystal lattice. When an Electric field is applied to an Electron, then the mass of the Electron in a crystal appears different from that of free Electron mass and is called Effective mass (m^*). The Effective mass depends on the Nature of crystal lattice and varies with the direction of motion of the free Electron. Considering the free Electron as wave packet, the group velocity V_g can be written as

$$V_g = \frac{d\omega}{dk}$$

$$= \frac{d}{dk}(2\pi\nu) \qquad \left[\because \omega = 2\pi f = 2\pi\nu\right]$$

$$= \frac{d}{dk}\left(2\pi \frac{E}{h}\right) \qquad \left[\because E = h\nu,\ \nu = \frac{E}{h}\right]$$

$$= \frac{d}{dk}\left(\frac{1}{\frac{h}{2\pi}} E\right) \Rightarrow \frac{1}{\hbar}\frac{dE}{dk} \quad \left[\because \hbar = \frac{h}{2\pi}\right]$$

$$\therefore \text{Acceleration } a = \frac{dV_g}{dt} = \frac{1}{\hbar}\frac{d}{dt}\left(\frac{dE}{dk}\right)$$

$$= \frac{1}{\hbar}\frac{d^2E}{dk\,dt}$$

$$= \frac{1}{\hbar}\frac{d^2E}{dk\,dt}\left(\frac{dk}{dk}\right)$$

$$\Rightarrow a = \frac{1}{\hbar}\frac{d^2E}{dk^2}\frac{dk}{dt}.$$

let us consider an Electron of charge e and mass m moving inside a crystal lattice and subjected to the Influence of an electric field. E. It Experiences a forc of eE on the Electron. The acceleration in the Electro is $a = \frac{eE}{m}$ and is Not constant in the periodic lattice of the crystal.

∴ The distance travelled by the electron in time dt is $ds = V_g\,dt$. The work done on the electro

$$\therefore dw = F.ds. = eE\,V_g dt.$$

The work done is same as Energy dE.

$$\therefore dE = eE\,V_g\,dt$$

By substituting V_g; we get. $dE = eE\frac{1}{\hbar}\left(\frac{dE}{dk}\right)dt$

$$\Rightarrow \frac{dE}{dk} = \frac{eE}{\hbar}\frac{dE}{dk} \cdot \frac{dt}{dk}.$$

$$\Rightarrow \frac{dk}{dt} = \frac{eE}{\hbar}.$$

By substituting the above Equation in acceleration; we

$$a = \frac{1}{\hbar}\frac{d^2E}{dk^2}\left(\frac{eE}{\hbar}\right)$$

$$\Rightarrow a = \frac{1}{\hbar^2}\frac{d^2E}{dk^2}\, eE$$

$$\rightarrow a = \frac{eE}{\hbar^2\left(\frac{d^2E}{dk^2}\right)^{-1}} = \frac{F}{m^*}$$

Since $F = ma \Rightarrow a = \frac{F}{m}$.

By comparing the above Equations, we get

$$m^* = \hbar^2\left(\frac{d^2E}{dk^2}\right)^{-1}$$

(or) $$m^* = \frac{\hbar^2}{\left(\frac{d^2E}{dk^2}\right)}.$$

This is the Expression for Effective mass of the crystal.

Concept of a Hole: The concept of the hole is an Important one in band Theory. particularly in semi Conductors, in which it is Essential to the operation of many valuable devices. when we consider the dynamics of the hole in an External field, we find it far more convenient to focus on the motion of the vacant site than the motion of Electrons. In an Intrinsic semi conductor, at temperatures other than absolute zero, a certain Number of Electrons may be Excited thermally from the upper filled band into the conduction band. Thus some of the states in the Normally filled band are unoccupied. These unoccupied states lie Near the top of the filled band. let us consider a single hole in the filled band of one dimensional lattice. If $-e$ be the charge of the electron and Vi be velocities of the electrons then the current associated with all the electrons in a completely filled band in the absence of an external field may be written as

$$i = -e \sum_i v_i$$

$$= -e \left(v_j + \sum_{i \neq j} v_i\right) = 0.$$

Thus if the Electron j was missing, we should have

$$i' = -e \sum_i v_i = -e \sum_{i \neq j} v_i$$

Applying an External field E, the Rate of change of Current I due to the field is

$$\frac{di'}{dt} = e \frac{dv_j}{dt} = -\frac{e^2 E}{m_j^*}$$

In other words, a band in which an electron missing behaves as a positive hole with an effective mass (m^*).

Dielectric materials:

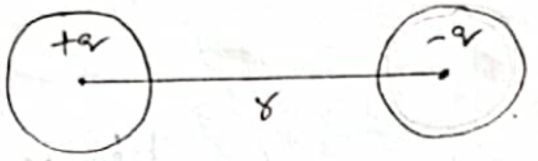
Introduction: Dielectrics are Insulating or Non conducting Ceramic materials and are used in many Applications such as capacitors, memories, sensors etc. Dielectrics are Insulating materials that Exhibit the property of Electrical polarization. A Dielectric material is any material that supports charge without conducting it. Although these materials do not conduct electrical current when an Electric field is applied, they are Not inert to the electric field. The field may cause a slight shift in the balance of charge within the material to form an Electric dipole.

The difference between dielectric material and Insulator depends on its Application. Insulating materials are used to Resist flow of current through it. on the other hand, dielectric materials are used to store Electrical Energy.

Electric Dipoles: upon the Application of a dc or Static Electric field, there is a long Range migration of charges. However, there is a limited movement of charges leading to the formation of charge dipoles and the Material in this state is considered as polarized. These dipoles are aligned in the direction of the Applied field. The Net effect is called polarization of the material

A dielectric supports charge by acquiring a polarisation in n Electric field, where by one surface develops a Net positive charge hile the opposite surface develops a Net Negative charge. This made possible by the presence of Electric dipoles - Two posite charges separated by a certain distance.

The dipole moment μ arises as



$\mu = qr$.

ome fundamental Definitions:

i) Dielectric constant ε_r: The Dielectric charecterstics of a aterial are determined by the dielectric constant or Relative ermittivity ε_r of that material. Dielectric constant is the Ratio between the permittivity of the medium and the permittivit of the free space

i.e., $\varepsilon_r = \frac{\varepsilon}{\varepsilon_0}$.

Since it is the Ratio of same quantity, ε_r has NO units.

it is the measure of polarization in the Dielectric material.

i) Electric polarization: Let us consider an atom placed inside an electric field. The centre of positive charge is displaced along the applied field direction when the centre of Negative charge is displaced in the opposite direction. Thus a dipole is produced. When a dielectric material is placed inside an electric field, Suc dipoles are created in all the atoms inside. This process of producing electric dipoles which are oriented along the field direction is called polarization in Dielectrics.

(iii) **polarizability (α):** when the strength of the Electric field E is increased, the strength of the induced dipole μ also Increases. Thus, the induced dipole moment is proportional to the intensity of the Electric field.

i.e., $\mu \propto E$

$$\Rightarrow \mu = \alpha E.$$

where α, the constant of proportionality is called as polarizability. It can be defined as Induced dipole moment per unit Electric field.

(iv) **polarization vector ($\vec{P}$):** The Dipole moment per unit volume of the dielectric material is called polarization vector $\vec{P}$. If $\vec{\mu}$ is the Average dipole moment per molecu and N is the Number of molecules per unit volume, th the polarization vector $\vec{P} = N.\vec{\mu}$

The Dipole moment per unit volume of the solid is th Sum of all the Individual dipole moments within that volu is called polarization $\vec{P}$ of the Solid.

(v) **Electric flux density (or Electric Displacement (D):**

The Electric flux density or Electric Displacement D at a point in a material is given by

$$D = \varepsilon_0 \varepsilon_r E.$$

where E is the electric field strength

ε_0 is the dielectric constant (or permittivity of the free space and

ε_r is the Relative dielectric constant (or Relative

Permittivity of the ~~fe~~ material.

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

$$D = \varepsilon_0 E + P.$$

Since; $D = \varepsilon_r \varepsilon_0 E$;

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

$$\Rightarrow P = \varepsilon_0 \varepsilon_r E - \varepsilon_0 E$$

$$P = \varepsilon_0 E (\varepsilon_r - 1)$$

(VI) Electric Susceptibility (χ_e): The polarization vector $\vec{P}$ is proportional to the total electric flux density E and is in the same direction of E. Therefore, the polarization vector can be written as; $P \propto \varepsilon_0 E$

$$\Rightarrow. \quad P = \varepsilon_0 \chi_e E.$$

where the proportionality constant χ_e is the electric susceptibility.

$$\therefore \chi_e = \frac{P}{\varepsilon_0 E}$$

$$= \frac{\cancel{\varepsilon_0}(\varepsilon_r - 1)\cancel{E}}{\cancel{\varepsilon_0}\cancel{E}}$$

$$\therefore \quad \chi_e = (\varepsilon_r - 1).$$

Measurement of Relative Dielectric constant: The polarization or the Relative dielectric constant can be measured, using a Parallel-plate capacitor. when a voltage V is supplied to the capacitor, with the plates separated by vaccum, charge develops

on the plates. The Capacitence c of the capacitor is
Measure of this Charge and is defined by

$$C = \frac{\varepsilon_0 A}{d}.$$

where A is the Area of the parallel plates and d is
distance of separation between them. If a dielectric materia
is inserted between the plates, the charge on the plates. Increas
due to the polarization in the material.

The capacitence is Now given by

$$C' = \frac{\varepsilon_0 \varepsilon_r A}{d}$$

Therefore, the Relative dielectric constant can be found by ta
the Ratio c' to c.

i.e., $$c'/c = \frac{\varepsilon_0 \varepsilon_r A}{d} \Big/ \frac{\varepsilon_0 A}{d}$$

$$\Rightarrow \varepsilon_r = \frac{c'}{c}.$$

Various polarization processes: polarization occurs due to severa
Atomic mechanisms. when the material is placed inside th
d.c., electric field, polarization is produced due to four typ
of processes.
a) Electronic polarization
b) Ionic polarization
c) orientation polarization
d) Space charge polarization.

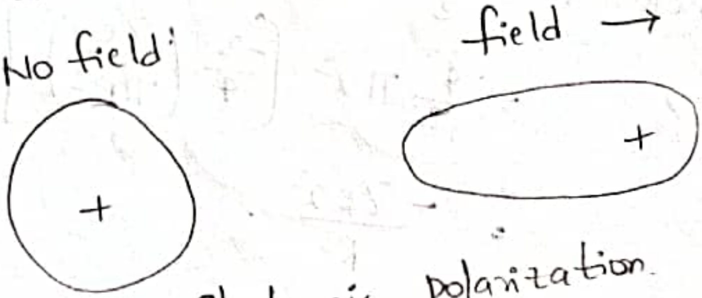
Electronic polarization: The displacement of the positively charged Nucleus and the Negatively charged Electrons of a atom in opposite directions, on Application of an Electric field, Result in electronic polarization.

on Applying the field, the Electron cloud around the Nucleus Readily shifts towards the positive End of the field. As the Nucleus and the centre of the Electron cloud are separated by a Certain distance, dipole moment is created within Each atom. The Extend of this shift is proportional to field strength. Since the dipole moment is the product of the charge and the shift distance, dipole moment is also proportional to the field strength.

Induced dipole moment $\mu \propto E$

(or) $\mu = \alpha_e E$.

where α_e is the electronic polarizability.



Electronic polarization

let us consider the Nucleus with charge $+Ze$ is Surrounded by an Electron cloud of charge $-Ze$ distributed in a sphere of Radius R. The charge density ρ is given by;

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

$$= \frac{-3}{4}\left[\frac{Ze}{\pi R^3}\right].$$

when an External field of Intensity E is applied, the Nucleus and the Electrons experience lorentz forces of magnitude ZeE in opposite directions. Hence the Nucleus and Electron cloud are pulled apart. when they are Seperated, a coloumb force develops between them which tends to oppose the displacement. when these forces Namely lorentz force and Coloumb force are equal and opposite, Equillibrium Is Reached and let x be the displacement under that condi

Since Nucleus is much heavier than the electron cloud, it is assumed that only the electron cloud is displaced. when External field is Applied.

lorentz force $= -ZeE$

Coloumb force $= Ze \times \left[\frac{\text{charge Enclosed in the sphere of Radius}}{4\pi\varepsilon_0 x^2}\right.$

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

$$= \frac{4}{3}\pi x^3 \left[\frac{-3}{4}\left(\frac{Ze}{\pi R^3}\right)\right]$$

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

Hence coloumb force is;

$$\frac{Ze}{4\pi\varepsilon_0 x^2}\left[\frac{-Zex^3}{R^3}\right] = \frac{-Z^2e^2x}{4\pi\varepsilon_0 R^3}$$

In the Equillibrium position;

$$-ZeE = \frac{-Z^2e^2x}{4\pi\varepsilon_0 R^3}$$

$$\Rightarrow \quad E = \frac{Zex}{4\pi\varepsilon_0 R^3}. \quad (\text{or}) \quad x = \frac{4\pi\varepsilon_0 R^3 E}{Ze}.$$

Thus, The displacement of the electron cloud is proportional to the Electric field applied. Thus, the two electric charges $+Ze$ and $-Ze$ are separated by a distance x under the action of applied field, thus constituting Induced Electric dipoles.

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Induced Electric dipole moment

$$\mu_e = Zex.$$

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

$$= 4\pi \varepsilon_0 R^2 E$$

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

where $\alpha_e E = 4\pi \varepsilon_0 R^3$ is called Electronic polarizability.

The dipole moment per unit Volume is called Electronic polarization. $P = N\mu_e$

$$= N\alpha_e E$$

where N is the No. of atoms/m³.

Since, we know that $P_e = \varepsilon_0 E(\varepsilon_r - 1)$;

$$\therefore \; N\alpha_e E = \varepsilon_0 E(\varepsilon_r - 1)$$

$$\Rightarrow \; \alpha_e = \frac{\varepsilon_0(\varepsilon_r - 1)}{N}.$$

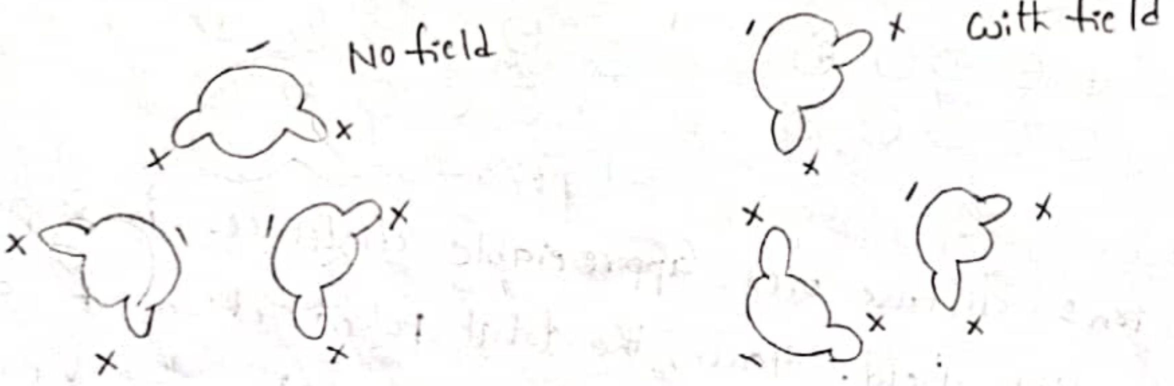
Ionic polarization: The Ionic polarization is due to the displacement of cations and anions in opposite direction and occurs in an Ionic solid.

Suppose, an electric field is applied in the positive x direction. The positive Ions move to the Right by x_1 and the Negative ions move to the left by x_2. Assuming that each unit cell has one cation and one anion, the Resultant dipole moment per unit cell due to Ionic displacement is given by

$$\mu = e(x_1 + x_2).$$

Orientational polarization: The phenomenon in which presence of electric field produces alignment of polar substances in the parallel direction of Applied field an Resulting in the Rotation of dipoles is Referred to as orientational or dipolar polarization. It is denoted by P_o.

When an electric field is applied on such molecules which posses permanent dipole moment, they tend to align th selves in the direction of Electric field Applied as shown he



orientational polarization

orientational polarization can be shown as;

$$P_o = N\cdot\vec{\mu}$$

$$= \frac{N\mu^2 E}{3kT} = N\alpha_o E.$$

i.e., $P_o \propto \frac{\text{Permanent Dipole moment} \times \text{Average Dipo Energy}}{\text{Average Thermal Energy.}}$

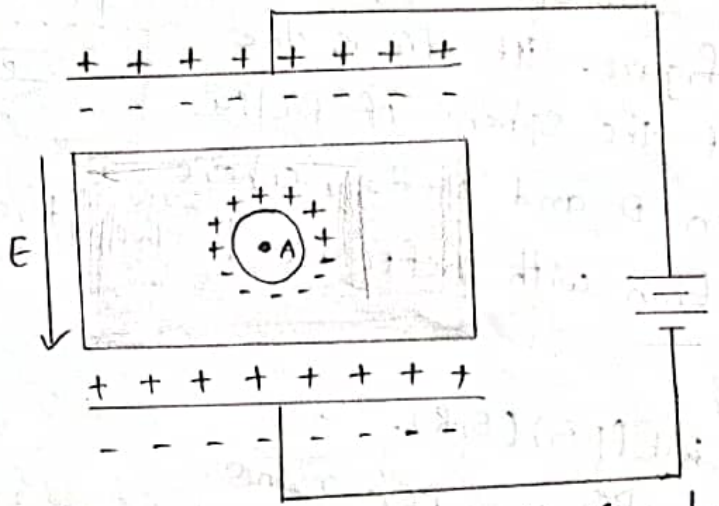
$\Rightarrow P_o \propto \frac{\mu_p \times \mu_p E}{3kT.}$ [∵ Average Thermal Energy = 3kT]

∴ $P_o = \mu \alpha_o E.$

∴ orientational polarizability $\alpha_o = \frac{P_o}{NE} = \frac{\mu^2}{3kT.}$

Lorentz Internal field:

Let a Dielectric be placed between the plates of a Parallel plate capacitor and let there be an Imaginary spherical cavity around the Atom A inside the dielectric. It is also assumed that the Radius of the cavity is large compared to the Radius of the atom. observe the diagram.



The Internal field of the Atom site A can be considered , be made up of the following four components Namely E₁, E₂, E₃ and E4.

Field E₁: E₁ is the field Intensity at A due to the charge ensity on the plates. from the field Theory;

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

$$E_1 = \frac{P + \varepsilon_0 E}{\varepsilon_0} \qquad [\because D = P + \varepsilon_0 E]$$

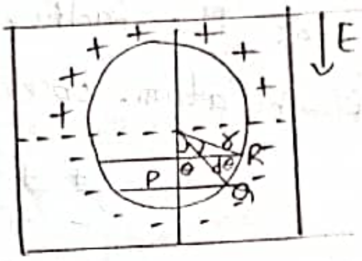
$$= E + \frac{P}{\varepsilon_0}.$$

Field E₂: E₂ is the field Intensity at A due to the charge ensity Induced on the two sides of the dielectric.

$$\therefore E_2 = \frac{-P}{\varepsilon_0}$$

ield E₃: E₃ is the field Intensity at A due to other atoms contained in the cavity. we are assuming a cubic structure so $E_3=0$ because of symmetry.

Field E_4: E_4 is the field Intensity due to polarization charges on the surface of the cavity and was calculated by lorentz as given below.



The Enlarged view of cavity is shown in this figure. If dA is the surface area of the sphere of Radius γ lying between θ and θ+dθ, where θ is the direction with Reference to the direction of the Applied force:

then $dA = 2\pi (PQ)(QR)$.

But $\sin\theta = \frac{PQ}{r} \Rightarrow PQ = r\sin\theta$.

and $d\theta = \frac{QR}{r} \Rightarrow QR = ~~r\sin\theta~~ . r d\theta$.

Hence $dA = 2\pi (r\sin\theta)(r d\theta)$.

$= 2\pi r^2 \sin\theta \, d\theta$.

The charge dq on the surface dA is equal to the Normal component of the polarization multiplied by the surface Area.

$\therefore dq = p\cos\theta . dA$

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

The field due to this charge at A, denoted by dE_4 in the direction $\theta=0$ is

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

$$= \frac{p\cos\theta \, 2\pi r^2 \sin\theta \cos\theta \, d\theta}{4\pi \varepsilon_0 r^2}$$

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

Thus, the total field E_4 due to the charges on the Surface of he Entire Cavity is obtained by Integrating

$$\int dE_4 = \frac{P}{2\varepsilon_0}\int_0^{\pi} \cos^2\theta \sin\theta \, d\theta$$

$$= \frac{P}{2\varepsilon_0}\int_0^{\pi} \cos^2\theta \, d(-\cos\theta).$$

$$= \frac{-P}{2\varepsilon_0}\left[\frac{\cos^3\theta}{3}\right]_0^{\pi}$$

$$= - \frac{-P}{6\varepsilon_0}\left[-1-1\right] = \frac{P}{3\varepsilon_0}$$

$$\text{i.e.,}\quad E_i = E + \frac{P}{3\varepsilon_0}$$

where E_i is the Internal field or Lorentz field.

lausius - Mosotti - Relation:

Let us consider the Dielectric Element has cubical tructure. Since there are No ions and permanent dipoles in nese materials, the Ionic polarizability α_i and orientational olarizability α_o are zero

clausius $\varepsilon_r = \frac{\varepsilon}{\varepsilon_0}$

clausiu

$$\text{i.e.,}\quad \alpha_i = \alpha_o = 0.$$

$P = N\mu \quad \mu \; \alpha_e E_i$

Hence polarization $P = N\alpha_e E_i$

$$= N\alpha_e\left(E + \frac{P}{3\varepsilon_0}\right)$$

$P = N\alpha_e\left[E + \frac{P}{3\varepsilon_0}\right]$

$$\text{i.e.,}\quad P = N\alpha_e E + \frac{N\alpha_e P}{3\varepsilon_0}$$

$$\Rightarrow P - \frac{N\alpha_e P}{3\varepsilon_0} = N\alpha_e E$$

$$\Rightarrow P\left[1 - \frac{N\alpha_e}{3\varepsilon_0}\right] = N\alpha_e E.$$

(or) $$P = \frac{N\alpha_e E}{\left[1 - \frac{N\alpha_e}{3\varepsilon_0}\right]} \longrightarrow ①$$

we know that $\underline{D = P + \varepsilon_0 E}$

$$\text{(or) } P = D - \varepsilon_0 E.$$

$$\Rightarrow \frac{P}{E} = \frac{D}{E} - \varepsilon_0$$

$$= \frac{\varepsilon_0 \varepsilon_r E}{E} - \varepsilon_0 \quad \left[\because D = \varepsilon_0 \varepsilon_r E\right]$$

$$= \varepsilon_0 \varepsilon_r - \varepsilon_0$$

$$= \varepsilon_0(\varepsilon_r - 1).$$

$$\therefore P = E\varepsilon_0(\varepsilon_r - 1). \longrightarrow ②$$

From the above Equations ① & ②;

$$P = \varepsilon_0 E(\varepsilon_r - 1) = \frac{N\alpha_e E}{\left(1 - \frac{N\alpha_e}{3\varepsilon_0}\right)}$$

$$\Rightarrow 1 - \frac{N\alpha_e}{3\varepsilon_0} = \frac{N\alpha_e \cancel{E}}{\varepsilon_0 \cancel{E}(\varepsilon_r - 1)}$$

$$\Rightarrow 1 - \frac{N\alpha_e}{3\varepsilon_0} = \frac{N\alpha_e}{\varepsilon_0(\varepsilon_r - 1)}$$

$$\Rightarrow 1 = \frac{N\alpha_e}{3\varepsilon_0} + \frac{N\alpha_e}{\varepsilon_0(\varepsilon_r - 1)}$$

$$= \frac{N\alpha_e}{3\varepsilon_0}\left[1 + \frac{3}{(\varepsilon_r - 1)}\right]$$

$$\text{i.e., } \frac{N\alpha_e}{3\varepsilon_0} = \frac{1}{\left[1 + \frac{3}{(\varepsilon_r - 1)}\right]} = \frac{1}{\frac{\varepsilon_r - 1 + 3}{\varepsilon_r - 1}} = \frac{\varepsilon_r - 1}{\varepsilon_r + 2}$$

Magnetic field Intensity (H): The force experienced by a
unit North pole placed at a point in a magnetic field is
called magnetic field Intensity. It is a measure of
magnetizing field. If F is the force experienced by a uni
North pole placed at a point in a magnetic field and m is
the pole strength of the magnet; then $H = \frac{F}{m}$

The Number of magnetic lines of force passing per unit
area Normally in free space is called magnetic field Inters
$\cdot H = \frac{B}{\mu}$. It is a Vector quantity. units are ampere/me

Magnetic flux (ϕ): The total Number of magnetic lines of
force passing Normally through a surface is called magnet
flux. units are: weber or Tesla $\cdot$ metre^2.

Magnetic flux density (B): The Number of magnetic lines
of force passing Normally through a surface of unit area is
called the magnetic field Induction (or) magnetic flux density
If ϕ is the magnetic flux and A is the area of the Surf
then magnetic flux density $B = \phi/A$.
It is a vector quantity. Its direction is along the direc
of magnetic field Intensity H. units are : weber/meter^2.

Intensity of magnetization (I): The magnetic moment per un
Volume of the material is called the Intensity of magnetiza
i.e., $I = \frac{M}{V}$.

Units are: ampere/metre.

Magnetic susceptibility: The Intensity of magnetization, produced in a material is Directly proportional to the Magnetizing field H. i.e.,

$$M(I) \propto H \text{ or } M = \chi H \Rightarrow \chi = \frac{M}{H}$$

where χ is constant called the magnetic susceptibility of the material. It is defined as the Ratio of magnetization to the magnetic field Intensity.

Magnetic permeability: when a magnetic material is placed in a magnetic field, it acquires magnetism due to Induction. The lines of force of the magnetizing field concentrate inside the material and this Results in the Magnetizing of the material.

The magnetic flux density (B) is directly proportion o the magnetic field Intensity (H). i.e.,

$$B \propto H. \Rightarrow B = \mu H \Rightarrow \mu = \frac{B}{H}$$

where μ is the constant of proportionality and is nown as permeability of the medium. Hence, permeabilit defined as the Ratio of the magnetic Induction (B) in e medium to the magnetizing field (H). The magnetic flu nsity in air or vaccum is $B = \mu_0 H$.

here μ_0 is the permeability of air or vaccum.

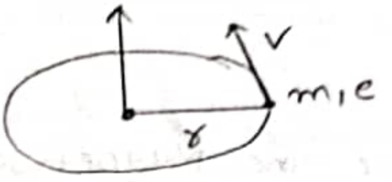
$\mu_0 = 4\pi \times 10^{-7}$ Henry/metre.

The Ratio of permeability of medium to the permeability of air or vaccum is called Relative Permeability and is

Origin of Magnetic Moment: The magnetic properties of solids originate from the motion of Electrons. So, the magnetic moment of an atom is due to;

(i) orbital magnetic Moment of the Electrons
(ii) Spin Magnetic Moment of the Electrons
(iii) Spin Magnetic moment of the Nucleus.

Orbital Magnetic Moment of Electrons: consider an electron of charge e and mass m Revolving around the Nucleus in an orbit of Radius r with an angular velocity ω as shown in the figure.



we can calculate the Electric current due to the moving electron.

current I = -(Number of Electrons flowing per sec × charge of an Electron).

Since ω is the Angular velocity, Number of Revolutions made by electron per sec = $\frac{\omega}{2\pi}$

$$\text{Hence } I = \frac{-e\omega}{2\pi}.$$

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

$$\mu_m = I \cdot A$$

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

denoted by μ_r. It has No units.

i.e., $\mu_r = \frac{\mu}{\mu_0}$.

Magnetization: Magnetization Refers to the process of converting a Non magnetic sample into a magnetic sample.

we know that $B = \mu H$

$= \mu_0 \mu_r \cdot H$ $\quad \left[\because \mu_r = \frac{\mu}{\mu_0}\right]$

i.e., $B = \mu_0 \mu_r H + \mu_0 H - \mu_0 H$

$= \mu_0 H + \mu_0 H(\mu_r - 1)$

$=$ ~~$\mu_0 H + \mu_0 M$~~ $\mu_0 H + \mu_0 M$

where the Magnetisation M is equal to $H(\mu_r - 1)$

i.e., $B = \mu_0 (H+M)$.

Thus $\mu_0 = \frac{B}{H+M}$

The Relative permeability $\mu_r = \frac{\mu}{\mu_0}$

$$= \frac{B/H}{B/H+M}$$

$$= \frac{H+M}{H}.$$

$$= 1 + \frac{H}{M}$$

$$= 1 + \frac{M}{H}$$

$$\mu_r = 1 + \chi$$

classification of Magnetic Materials: Based on the Existence of Permanent Dipoles and their orientation, the Magnetic Materials are Generally classified into five categories. They are Diamagnetic, Para magnetic, Ferro Magnetic, Anti Ferro Magnetic and Ferri Magnetic Materials.

Diamagnetic Materials: when a Magnetic field is applied to an atom, the motion of the orbital Electrons gets modified in such a way that a weak magnetic moment opposing the field is Induced. Diamagnetism is the Result of this Interaction. It is a very weak Effect and Exists only in the presence of an External magnetic field. The Applied External magnetic field acts on atoms of a materials slightly unbalancing their orbiting Electrons and creates small magnetic dipoles within atoms which oppose the applied field. This produces a Negative Magnetic Effect known as Diamagnetism.

Properties of Diamagnetic materials:

* The materials which are weakly magnetized in a direction pposite to that of applied magnetic field are called Diamagneti aterials.

* These materials are Repelled by the magnets and move from egion of high Intensity to low Intensity Region in a magnetic ield.

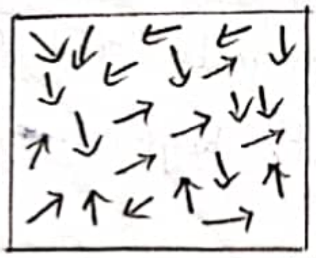
* There is No permanent dipole moment. So the magnetic fects are very small.

* The lines of force show less preference to pass through these ubstances than through Vaccum or air.

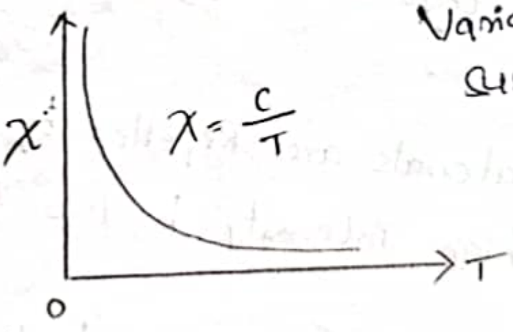
* The magnetic Susceptibility is Negative. It is Independ of Temperature and magnetic field strength.

Ex: Metals (Cu, Au, Sb, Hg), Semiconductors (Si, Ge), Rare gas Elements (He, Ne, Ar), Air, NaCl, water, Etc.

Paramagnetic materials: Materials which Exhibit a small positive magnetic susceptibility in the presence of a magne field are called paramagnetic and the effect is Termed as paramagnetism. These materials possess intrinsic permanent magnetic dipole moments. In the absence of an External fiel the moments of the atoms in a solid are Randomly orient with Respect to one another and the Solid has No Net magnetic moment as shown in this figure. If an Externa field is applied, the magnetic moments tend to align themselves parallel to the applied field. Similarly there is a spontaneous tendency for the permanent moments of the atoms of the Solid to align themselves in the direction of the field, Thereby Intensifying the lines of force in the fiel direction. This phenomenon is called paramagnetism.



Randomly oriented magnetic Dipoles.



Variation of susceptibility with Temperatur

Properties:

These materials are feebly magnetized in the direction of the magnetizing field.

* They are attracted by the magnets and move from Regions of low Intensity to High Intensity in a field.

* The magnetic susceptibility is small and positive, i.e., in the order of 10^{-3}.

* The Relative permeability μ_r is slightly more than unity. The field lines are pulled towards the material.

* In the absence of the External field, the orientation of atomic magnetic moments are Random leading No Net magnetization. However, the dipoles do not Interact with each other. So large magnetic fields are Required to align all the dipoles.

* The paramagnetic susceptibility varies Inversly with Temperature by following Relation

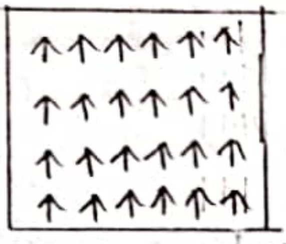
$$\chi_p = \frac{C}{T}$$

where C is curie constant. This Relation is called Curie's law.

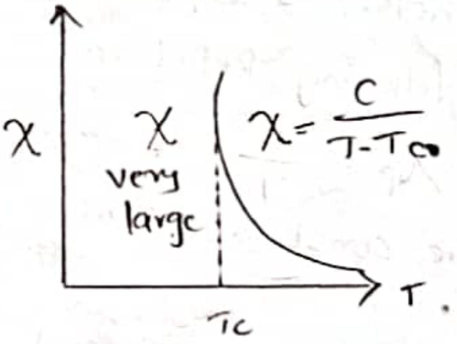
Ex: Metals (Al, Ca, Ti, Mn, Cr), salts, Rare Earths, Compounds ($FeCl_2$, $CuCl_2$, $MnCl_2$, MnO, NiO) Etc.

Ferro magnetic Materials: The materials which are strongly magnetized by Relatively weak magnetic field in the direction of applied magnetic field are called Ferromagnetic and the phenomenon is known as Ferromagnetism. These materials having permanent Magnetic dipoles are orderly oriented as shown in the figure. Ferromagnetics are solids, generally crystalline in Nature. The Magnetization may have a finite value even when the applied magnetic field is zero. This is due to

Spontaneous magnetization. There is a special form of Interaction Called Exchange Coupling which occurs betwee the adjacent atoms, coupling their magnetic moments togeth In ferromagnetic materials, saturation magnetization occu at ordinary Temperatures and at ordinary fields & even at small values of applied field. Ferromagnetic materials h charecterstic Temperature below which they Exhibit the Ferromagnetic behaviour of Spontaneous magnetization. Thi Temperature is called curie Temperature Tc. when the Temperature is Raised above curie Temperature, the Exchar coupling suddenly disappears and the material becomes Paramagnetic.



Orderly oriented magnetic Dipoles



Variation of susceptibility with Temperature

Properties:

* These materials possess Permanent magnetic moments Even when applied field is zero. i.e., They possess Spontane Magnetization.

* The aquire a Relatively high magnetization in weak fie

* These are very strong. The dipoles are line up permanently upon the application of External field.

* The magnetic susceptibility and Relative permeabilities are positive and of the order of about 10^6 and 10^3 Respectively.

* The ferromagnetic materials conduct magnetic flux much as metals conduct electric current.

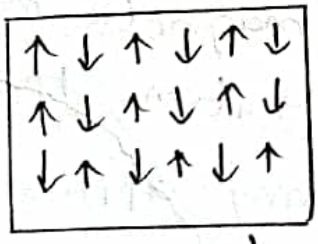
Above a certain Temperature, ferromagnetic materials behave as paramagnetic and the susceptibility varies with Temperature by Relation

$$\chi_F = \frac{C}{T-T_c}.$$

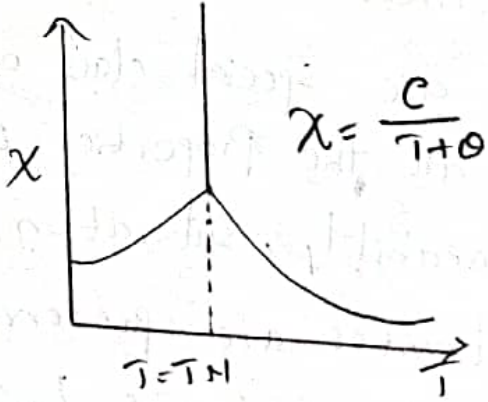
where C is The Curie Constant and T_c is Curie Temperature and is depends on the material.

Ex: Fe, Ni, Co, Fe_2O_3, $ZnFe_2O_3$, $MnFe_2O_3$ Etc.

Anti ferro magnetic materials: The Anti Ferro magnetic charecter is Explained to be a consequence of antiparallel alignment of Neighbouring magnetic moments in the Crystal as shown in the figure. As a Result, the magnetic moments cancel each other. So that the Net magnetization in the absence of the field vanishes. If the magnetic dipoles in a magnetic material are equal in magnitude and orient in the opposite directions, the materials are called Anti ferro magnetic materials. The susceptibility Increases with Increase of Temperature and Reaches a maximum value at a certain Temperature called Neel Temperature T_N. Further with Increase of Temperature, the material changes into paramagnetic state. For most of the materials, the Neel Temperature T_N lies far below Room Temperature.



Antiparallel alignment of magnetic dipoles



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

Variation of Susceptibility with Temperature

Properties:

* In these materials, the atomic dipoles are arranged Antiparallel to one another so that the Net magnetic moment is zero.

* These are Crystalline materials which Exhibit small positive Susceptibilities of the order of 10^{-3} to 10^{-5}.

* The variation of susceptibility with Temperature is given by the Relation $\chi_{aF} = \frac{C}{T+T_N}$.

where C is curie constant and T_N is curie Temperatu

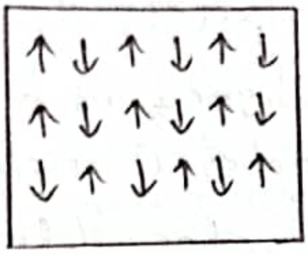
* They attain maximum susceptibility at Neel Temperat Above T_N, these materials become paramagnetic.

Ex: MnO, NiO, MnS, CoO, $FeCl_2$ etc.

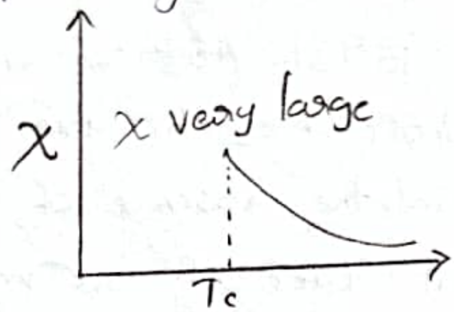
Ferri magnetic materials: It is similar to Anti ferro magnetism in that the spins of different atoms or ion line up antiparallel. However, the antiparallel spins are unequal in magnitude, so that the spins do not cancel eac other and Net spin magnetic moment Exists as shown figure. If the Neighbouring dipoles of a material are unequal in magnitude and orient anti parallel to each other, the materials are called ferri magnetic. These are also called ferrites.

Ferrites are special class of Ferromagnetic materia They Exhibit all the Properties of Ferromagnetic materia like high permeability, Saturation magnetization, Hysteres etc. But, ferrites are preferred in many applications as they have advantage of having veery high electrical

Resistivity unlike Ferromagnetic materials.



Antiparallel Alignment of magnetic dipoles.



Variation of Susceptibility with Temperature.

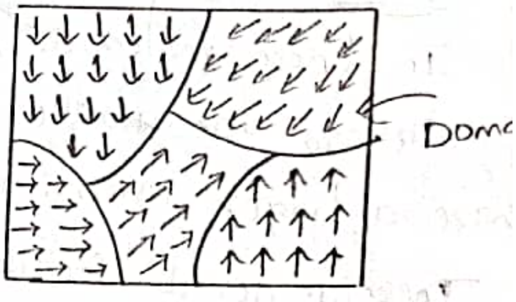
Properties:

In these materials, the atomic dipoles are arranged anti-
arallel to one another but the moments in one direction
ave a larger magnitude. so that the Net magnetization Exists.
These materials Exhibit a large magnetic susceptibility but
epends upon the magnetic field similar to ferromagnets.
They also show Curie-weiss behaviour as shown in figure.
ne susceptibility varies with Temperature is given by a
elation $\chi_{Ferri} = \frac{C}{T \pm T_N}$
here C is Curie Temperature, T_N is Neel Temperature.
The Ferri magnetic materials behave like Ferromagnetic
aterials below the Neel Temperature and are paramagnetic
ove the Neel Temperature.
x: Fe_3O_4, Fe_2O_4, $BaFe_{12}O_{19}$, etc.

omain Theory of Ferromagnetism: In order to Explain the
omain Theory of Ferromagnetism, weiss Introduced the New concep
heory of Ferromagnetism, weiss Introduced the New concept
magnetic domains. The atoms of Ferromagnetic materials
ve a permanent magnetic moment like paramagnetic
aterials. But in Ferromagnetic materials the atoms due to
rtain mutual Interaction, form Innumerable small Effective

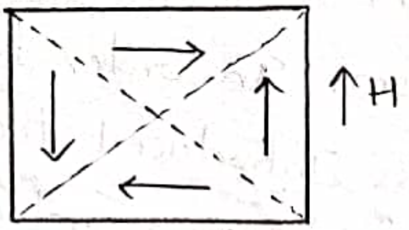
Regions called domains as shown below. Each domain ha a size varying from 10^{-9} to 10^{-5} m^3 and contains about 10^{17} to 10^{21} atoms whose magnetic axes are aligned in the Same direction Even in the absence of any External field However, in the Normal State of the material, the differe domains are Randomly distributed. Hence their Resultant magnetic moment in any direction is zero.

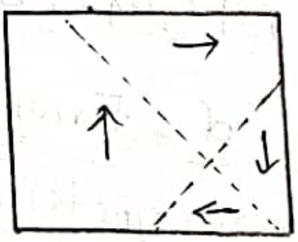
When an External magnetic field is applied to a ferromagnetic material, then the magnetization in the material is increased by two ways.



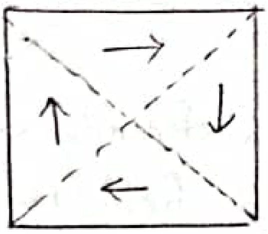
Due to the Displacement of the boundaries of the Doma

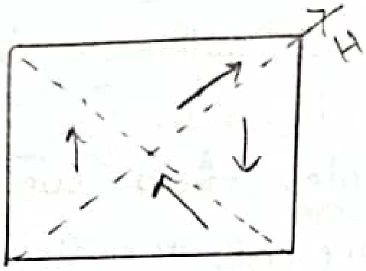
Let us consider an unmagnetized ferromagnetic specim Each domain in the specimen is in the magnetized stat and the direction of magnetization is shown in the figu when the Specimen is placed in the magnetic field, th domains which are oriented favourable with Respect to t External field Increases in size ~~with~~ while those oriented opposite to the External field are Reduced.





Due to Rotation of domains. The Domains Rotate an their magnetic moments are aligned more or less in the direction of External magnetic field as shown in the fig





when the External field is weak, the specimen is magnetized mostly by the boundary displacement. In strong magnetic field, the magnetization takes place mostly by the Rotation of domains. on the Removal of External field, the boundaries do not move completely back to their original position and hence the specimen is not completely demagnetized, i.e.; there still Remains Some Residual magnetism. At high Temperature, the domains are broken up and the ferromagnetic material becomes paramagnetic.

Weiss field theory of Ferromagnetism: weiss proposed the domain theory to Explain Ferromagnetism Exhibited by the materials as well as Relation between para and Ferromagnetic materials and is based on two hypotheses. The assumptions of weiss field theory are;

* The atomic dipoles of the Ferromagnetic materials are grouped together into domains. In Each domain, the dipoles are aligned in the same direction and have magnetic moment. In the absence of External magnetic field, the domains re spontaneously magnetized. The direction of magnetization different domains is different in an unmagnetised material. nce, on an average the Resultant magnetization is zero.

* The cause of Spontaneous magnetization within each domain the Existence of the molecular field which tries to Produce a rallel alignment of the dipoles. This Internal field Hi varies.

as the Magnetization I within a domain. Thus

$$H_i \propto I \Rightarrow H_i = \gamma I.$$

where γ is the molecular field Constant which depends o Temperature. let H Represent the External magnetic field. Hen the Effective magnetic field acting on an atom is

$$H_{eff} = H + \gamma I$$

let us consider a magnetic material having N number atoms per unit volume at Temperature T and μ is the ma moment of Each atom. Hence

$$I = \frac{N\mu^2}{3k_BT}(H_{eff})$$

$$I = \frac{N\mu^2(H+\gamma I)}{3kT} = \frac{N\mu^2}{3kT}\left[H\left(1+\gamma\frac{I}{H}\right)\right]$$

$$\Rightarrow \frac{I}{H} = \frac{N\mu^2}{3kT}\left[1+\gamma\frac{I}{H}\right]$$

$$\Rightarrow \chi = \frac{N\mu^2}{3kT}(1+\gamma\chi) \qquad \left[\because I \propto H \quad I = \chi H \quad \Rightarrow \frac{I}{H} = \chi\right]$$

$$\Rightarrow \chi = \frac{N\mu^2}{3kT} + \frac{N\mu^2}{3kT}\gamma\chi$$

$$\Rightarrow \chi - \frac{N\mu^2}{3kT}\gamma\chi = \frac{N\mu^2}{3kT}$$

$$\Rightarrow \chi\left[1 - \frac{N\mu^2}{3kT}\gamma\right] = \frac{N\mu^2}{3kT}.$$

let $\gamma\frac{N\mu^2}{3k} = T_c$ and $\frac{N\mu^2}{3k} = C$

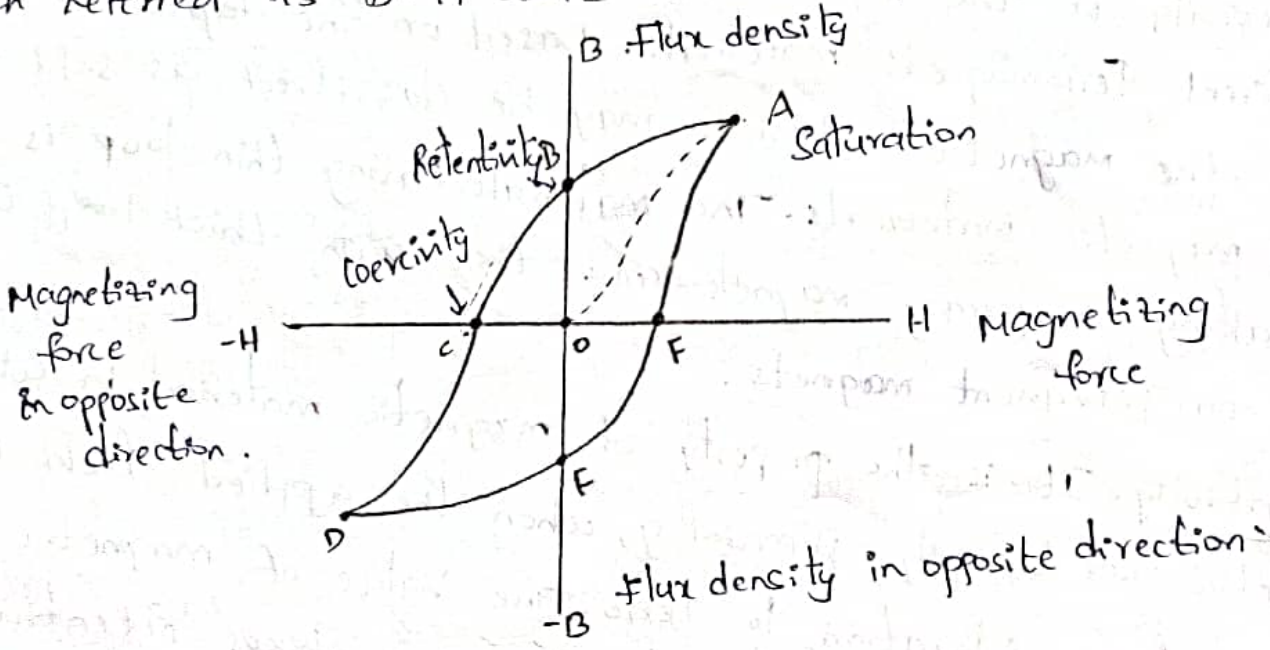
$$\therefore \chi\left[1 - \frac{T_c}{T}\right] = \frac{C}{T}$$

$$\Rightarrow \chi = \frac{\frac{C}{\cancel{T}}}{\frac{T-T_c}{\cancel{T}}}$$

$$\Rightarrow \chi = \frac{C}{T-T_c}$$

where C is curie constant and Tc is the curie Temperature of ferromagnetic material. This Relation is Called curie-weiss law.

Hysteresis loop: A typical property of ferromagnetic material is hysteresis. Hysteresis may be defined as the lag in the changes of magnetization behind the variations of the magnetic field. It gives the Relationship between the Induced magnetic flux density (B) and magnetizing field (H) often Referred as B-H curve or B-H loop.



Hysteresis loop.

Consider an unmagnetized ferromagnetic material is placed in a magnetizing field. when the material is slowly magnetized and the magnetic flux density (B) increases with Increase of magnetizing field (H) initially through OA and Reach Saturation at A. when H is decreased, B decreases but it do ot comes to zero at H=0. The Residual flux density (B) set n the material Represented by OB is called Retentivity. To ring B to zero, opposite magnetizing field is applied. This magnetizing field is Reversed, the curve closes to the point A, completing a cycle. The loop OABCDEFA is calle hysteresis loop.

The process of magnetization and demagnetization by changing H is an Irreversible process as Illustrated by the Hysteresis loop. The area of the loop gives the loss of Energy due to the cycle of magnetitation and demagnetizatio and is dissipated in the form of heat. The Retentivity and Coercivity of the hysteresis loop are the charecteristics of different ferromagnetic materials. Based on the degree of thes value, the magnetic materials may be classified as soft an Hard magnetic materials. The materials having thin loop is u for making Temporary magnets and that with thick loop is used for permanent magnets.

Retentivity: It is the property of magnetic material in which magnetic flux density Remaining, when the applied field is Reduced from saturation to zero. The value of magnetic fl density at point B on the hysteresis curve shows Retentivity.

Residual flux density: The magnetic flux density Remaining when the applied field is Reduced from saturation to zero is called Residual flux density.

Coercivity: It is the property of magnetic material in which the Residual magnetic flux density becomes zero at ertain value of Reverse magnetic field applied.

Coercive field: The amount of Reverse magnetic field applied to the magnetic material in which the Residual

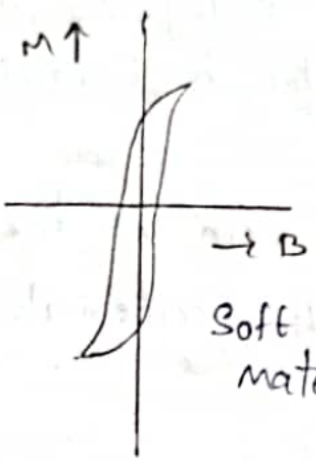
magnetic flux density becomes zero is called coercive
field. The values of H at point c on the hysteresis
curve is the coercive field.

Soft and Hard Magnetic materials: on the basis
of magnetization process, the magnetic materials can
be divided into two classes. They are:

Soft magnetic materials: Magnetic materials which are
Easily magnetized and demagnetized are known as soft
magnetic materials and also called as permeable materials.
They exhibit small Hysteresis losses. The Hysteresis curve of
soft magnetic materials shown below. They are charecteriz
by ascending magnetization curve and high permeabilities,
since the coercivity is low and the area of the loop is
small. This is an Important consideration when the
material is used for ac current Applications. They ar
used for Transformer cores, magnetic amplifiers, generato
Electric motors.
Ex: Iron - silicon alloy, Aluminium - Silicon - Iron Alloy Etc

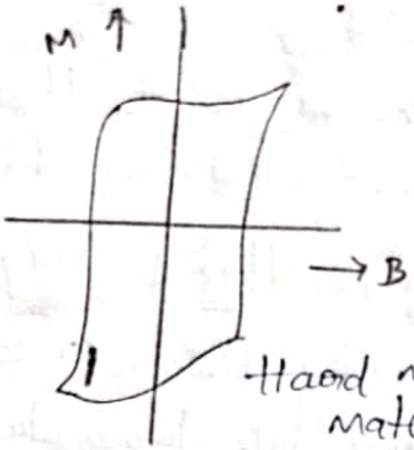
Properties:

- They are Easily magnetized and demagnetized.
- They have small hysteresis loss
- They have large values of permeability and susceptibilit
- Coercivity and Retentivity are small.
- Eddy current loss is more due to small Resistivity.
- These are free from Irregularities.



Soft magnetic material

Hysteresis loops



Hard magne materials.

Hard magnetic materials: The magnetic materials which ca not easily magnetized and demagnetized are called hard ma materials. They have large hysteriesis loss due to large ar of the hysteresis loop. The hysteresis curve of hard magne materials is shown above. In these materials, the Resist to the movement of domain walls is large. So the Coerci force is large. These domain walls are Immobilized from free movement or Imperfections. leading to high hysteresi losses. These materials has the advantages of Increasin mechanical hardness and Electrical Resestivity. They are c for the construction of permanent magnets. These perma magnets are used in dynamos, motors, Generators, galva meters, Ammeters, voltmeters, Transformers etc.

Ex: Aluminium-Nickel-cobalt-copper-Iron alloy (Alnic

opper-Nickel-Iron alloy (Cunife Etc)

Properties:

* They can not be easily magnetized and demagnetize

* These materials have small values of permeability and Susceptibility.

They have large hysteresis losses.

Semi conductors:

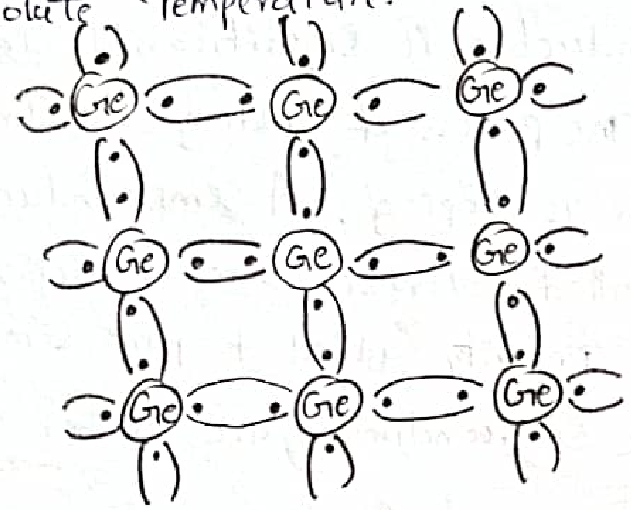
Introduction: Semiconductors are materials, whose Electro Properties are Intermediate between those of good conductor and Insulators. These Intermediate properties are determined by the Crystal Stucture, Bonding charecteristics, Electronic Energy bands Etc. The Resistivity of Semiconductors varies from 10^{-5} to 10^{+4} ohm-m, 10^{-3} to 10^{-6} ohm-m for conductors a from 10^{7} to 10^{8} ohm-m for Insulators. There are germainium and silicon Semiconductors which belong, to the group IV of the periodic table and have Resistivity of about $0.6 \times 1.5 \times 10^{3}$ ohm-m Respectively. The Band gap of Semiconductors Varies from 0.2 to 2.5eV, which is quite small as compared to that of Insulators. The Semiconductors are classified as.

(i) Intrinsic (or) pure Semiconductors

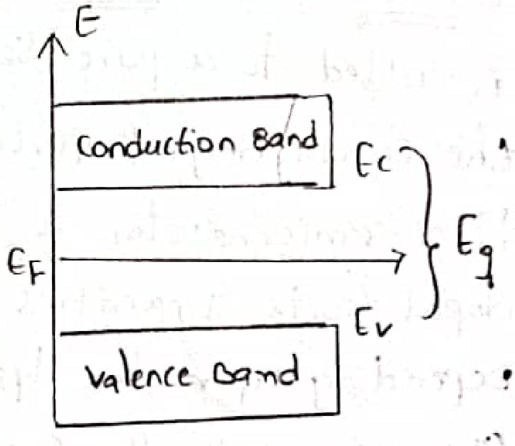
(ii) Extrinsic (or) Impure semiconductors.

Intrinsic Semiconductors: The pure form of a semiconductor is called an Intrinsic semiconductor. A pure crystal of Silicon or germanium is an Intrinsic Semiconductor. The Electrical conductiv of this type of Semiconductor is solely determined by thermall generated carriers. In order to understand the Electrical conducti let us consider the case of germanium. The Atomic Number of germanium is 32. So it has 32 Electrons 2 in the first orbit 8 in the Second orbit, 18 in the third orbit and Remaining four in the outermost orbit. Thus the germanium atom has four valence Electrons. i.e., It is a Tetravalent Element. Each of four Electrons in a germanium atom is Shared by the valen Electrons of four adjacent germanium atoms and makes four

Electron pairs as shown in below figure. These types of Electron pairs are known as Covalent bonds which provide the bonding force. In this way, the atom behaves as if their outermost orbits were complete with 8 Electrons. Thus, free Electrons are available to conduct a current through a germanium crystal. A pure germanium crystal is an Insulator at Absolute Temperature.



Bond structure



Energy Band diagram.

However, with Increase of Temperature, a few covalent bonds are broken. when a covalent bond is broken, one electron becomes free and leaves the atom and becomes a positive ion known as hole. The hole acts as a positively charged particle having a charge equal to that of an electron but of opposite sign. Since a hole is a strong centre of attraction for the Electron, the hole attracts an Electron from the Neighbouring atom to fill it. Thus the hole is Now shifted to another place from where the Electron has migrated. on applying the Electric field, the holes move in a direction opposite to that of the valence Electrons. It constitutes a hole current. It must be Noted that in an intrinsic Semiconductor, the Number of Electrons and holes are equal and they are less. The Energy band diagram of an

Intrinsic Semiconductor is shown above. The Fermi level E_F is at the middle of valence and conduction bands. If E_v and E_c are the Energy levels, of then the Energy gap

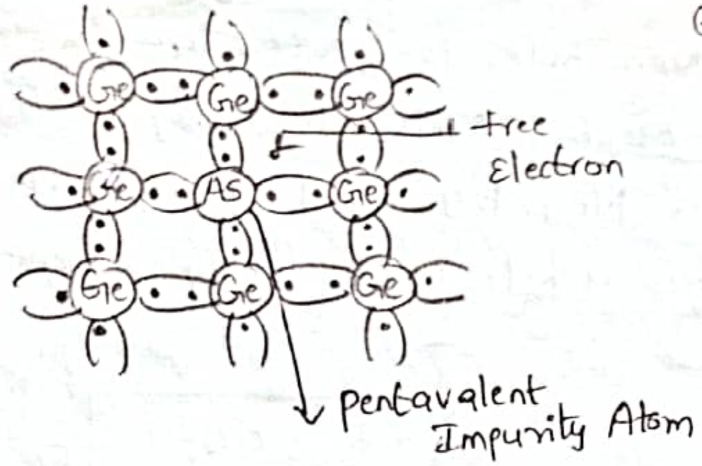
$$\therefore E_g = E_c - E_v.$$

$$E_F = \frac{E_c + E_v}{2}.$$

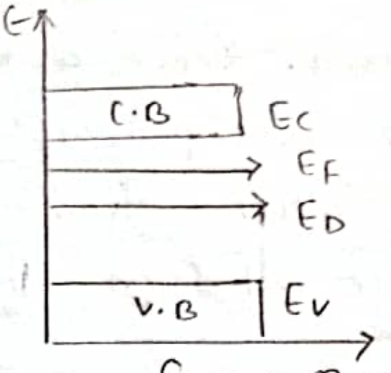
Extrinsic Semiconductors: If a small amount of Impurity is added to a pure Semiconductor, it significantly Increase the conducting properties. The process of adding the Impuritie to a semiconductor is known as Doping. A semi conductor doped with Impurities is called Extrinsic Semiconductor. Depending upon the type of Impurity added to pure semiconduct (like Ge, Si), the Extrinsic Semiconductors are further divided into (i) n-type Semiconductors

(ii) P-type semiconductors.

n-type Semiconductor: A Semiconductor doped with a pentavale Impurity is called n-type Semiconductors. Examples of pentavale Impurities are Arsenic (As, Z=33), Antimony (Sb, Z=51). when these Impurities are added to pure germanium crystal four valence Electrons of Impurity atom form covalent bond with the four valence electrons of Ge atoms. The fifth valen Electron of Impurity atom has no place to form the covalent bond and Remains free to move Randomly in the crystal latt as shown in figure. Thus each Impurity atom donates a free e Electron to the Semiconductor. Hence, the Impurity is called do mpurity. The semiconductor containing donor type Impurity is lled n-type semiconductor because it has Negative Charge Carrie



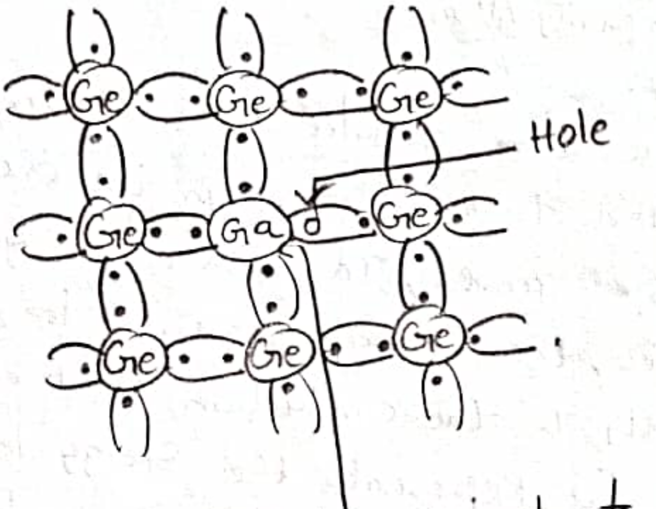
Bond structure.



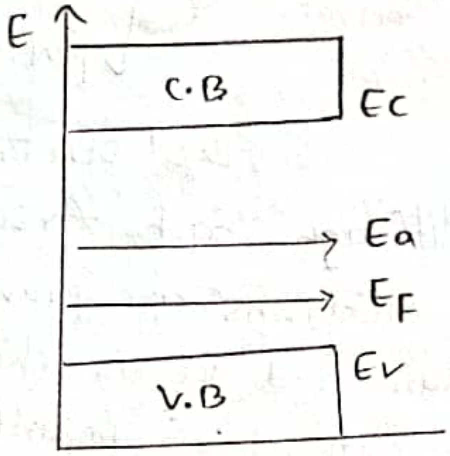
Energy Band diagram.

Although Each Arsenic atom donates one Electron, Enough free Electrons are provided to move through the crystal structure and act as charge carrier. In the case of germanium doped with donor Impurities, the Energy Required to move an Electron from donor Impurity to the conduction band is in the order of 0.0127 eV. Here, Ed Represents the Energy level corresponding to donor Impurities and it lies just below the conduction band. In n-type semiconductors, the Electrons are majority charge carriers and minority charge carriers are holes

P-type Semiconductors; A Semi Conductor doped with a trivalent Impurity is called ptype semiconductor. Examples of trivalent Impurities are gallium (Ga, Z=31) and Indium (In, Z=49). when a small amount of gallium is added to germanium crystal, three valence Electrons of Impurity atoms form Covalent bonds with three valence Electrons from germanium atoms. there is a defficiency of one Electron to complete the fourth Bond. this Electron deficiency is called the hole and it behav like a positively charged particle as shown in figure. Since there is a Strong tendency of semiconductor crystal to form Covalent bonds, a hole attracts one Electron from a Nearby covalent bond. Hence, a New hole is created at the originally occupied place of Electron. This hole is again filled by another Electron from a Nearby bond giving Rise to another hole and so on. Thus a hole moves freely throughout the crystal.



Bond Structure.

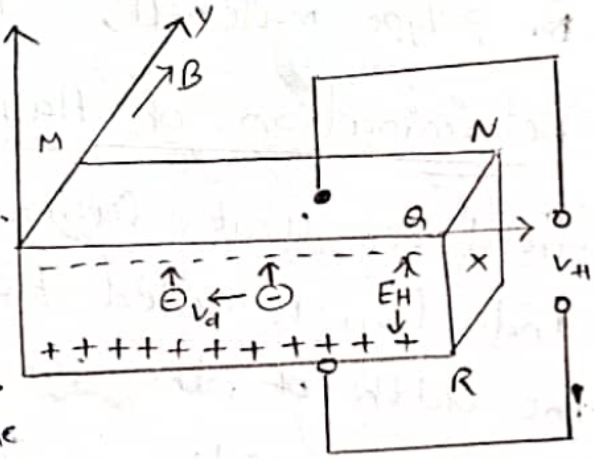


Energy band diagram.

An Impurity that Produces holes inside a semiconductor crystal is called Acceptor Impurity because it accepts Electrons from the Nearby germanium atoms. The semiconductor containing acceptor type of Impurity is called p-type semiconductor, because the charge carriers are positive holes. The Energy band diagram for p-type Semiconductor is shown above. Here, Ea Represents the Energy level corresponding to the acceptor Impurities. The Acceptor energy level is just above the valence band. In p-type semiconductors, holes are majority charge Carriers and Electrons are minority charge Carriers.

Hall Effect: when a slab of metal or semiconductor Carrying Current is placed in a magnetic field, a Potential difference is produced in the direction Normal to both current and magnetic field. This phenomeon is called Hall Effect and the generated voltage is nown as Hall voltage. It was discovered by E.H Hall.

Consider a slab of Conductor in which a current I flowing in the positive x direction. Let a magnetic field is applied along the y direction, then the Electrons Experie lorentz force given by $F_L = -BeV_d$. where e is the charge of Electron, V_d is the drift velocity. Applying the Fleming's left hand Rule, the force exerted on the lectrons is in the Negative z direction. refore, the Electrons are deflected the downward direction. As a Results density of Electrons increases in the wer End, and becomes Negatively charged. the other hand, the loss of Electrons from the upper hand. d causes positively charged. Hence, potential V_H called Hall ltage appears between the upper and lower surfaces of e semiconductor which eshtablishes an electric field E_H ca all Electric field. i.e., $F_H = -eE_H$.



Hall Effect

Now, as the deflection of electrons continues in the ownward direction due to the lorentz force, it also contribute the growth of Hall Electric field. At Equilibrium position the forces are Equal. $F_L = F_H$.

$$\Rightarrow \cancel{-}B\cancel{e}V_d = \cancel{-}\cancel{e}E_H \Rightarrow E_H = BV_d.$$

for n-type material, the current density J is

$$J = -ne v_d.$$

$$\therefore v_d = \frac{-J}{ne} \Rightarrow E_H = \frac{-JB}{ne.}$$

The Hall Effect is described in terms of Hall coeffic nt R_H and is given by $R_H = \frac{-1}{ne}$.

Hence $E_H = R_H J B \Rightarrow R_H = \frac{E_H}{JB} \left(\frac{-1}{ne}\right)$.

The Hall coefficient can be evaluated by substituting the quantities E_H, J and B. By knowing the Hall coefficient the carrier density n can be determined.

for p type material; $R_H = \frac{E_H}{JB} = \frac{1}{pe}$.

Determination of Hall Coefficient: The Hall Electric field per unit current density per unit magnetic Induction is called Hall Coefficient (R_H). If ω is the width of the sample across which Hall voltage V_H is measured;

$$E_H = \frac{V_H}{\omega}$$

$$\therefore R_H = \frac{E_H}{JB} = \frac{V_H}{JB\omega}.$$

$$\Rightarrow V_H = R_H J B \omega$$

If t is the thickness of the sample, then its cross section is ωt and current density

$$J = \frac{I}{\omega t}$$

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

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

$$\Rightarrow R_H = \frac{V_H t}{IB}.$$

The Hall voltage V_H will be opposite for n-type and P-type Semiconductors.

Applications of Hall Effect: The Hall Effect measurements are used to acquire the following Information about the Solid.

* The Sign of charge carriers can be determined.

* The Carrier density can be Estimated.

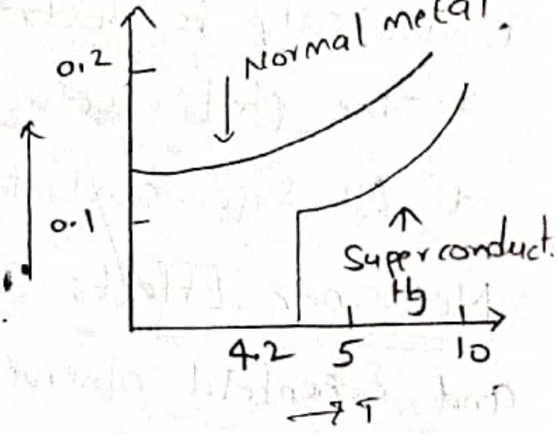
* The mobility of charge Carriers can be measured directly.

* It can be used to determine whether the given material is a metal, an Insulator or a semi conductor.

* The magnetic field can be measured by knowing the Values of Hall voltage and Hall coefficient.

Super conductivity: The

Introduction: The Electrical Resistivity of many metals and alloys drops suddenly to zero when the specimen is cooled to a sufficiently low Temperature. This zero Resistivity or infinite Conductivity is called super conductivity and the materials are called superconductors. It was first observed in 1911 by Dutch Scientist Kammerlingh onnes. For Example, a pure mercury is cooled, its Resistivity vaneshes at 4.2K as shown in figure. Above this temperature, the Resistivity is small. while the Resistivity below this point is Essentially zero. Certain Temperature Tc called critical Temperature (or Transition Temperature Exists above which, the substance is in the Normal state but below Tc, it inters Entirely into different state called Super conducting State.



Resistivity Vs Temperature curve for Mercury by H.konnes.

General properties of Super conductors:

The properties of superconducting materials can be changed by Varying Temperature, magnetic field, Impurity, Atomic structure, size, frequency of Excitation of Electrons Etc. The general properties are,

- Superconductors have zero Resistance. i.e., they Exhibit Infinite Conductivity.

* The materials of Small Atomic volume, Small atomic mass favours super Conductivity.

* The current in the superconductors persists for a very long time.

* Superconductivity has been observed only for those metallic substances which have the Number of valence Elect between 2 and 8.

* When current passing through the Superconductor is Increased beyond a critical value Ic, the Superconducto becomes a Normal Conductor.

* The materials which are good Conductors of Electricity Not good superconductors and vice versa.

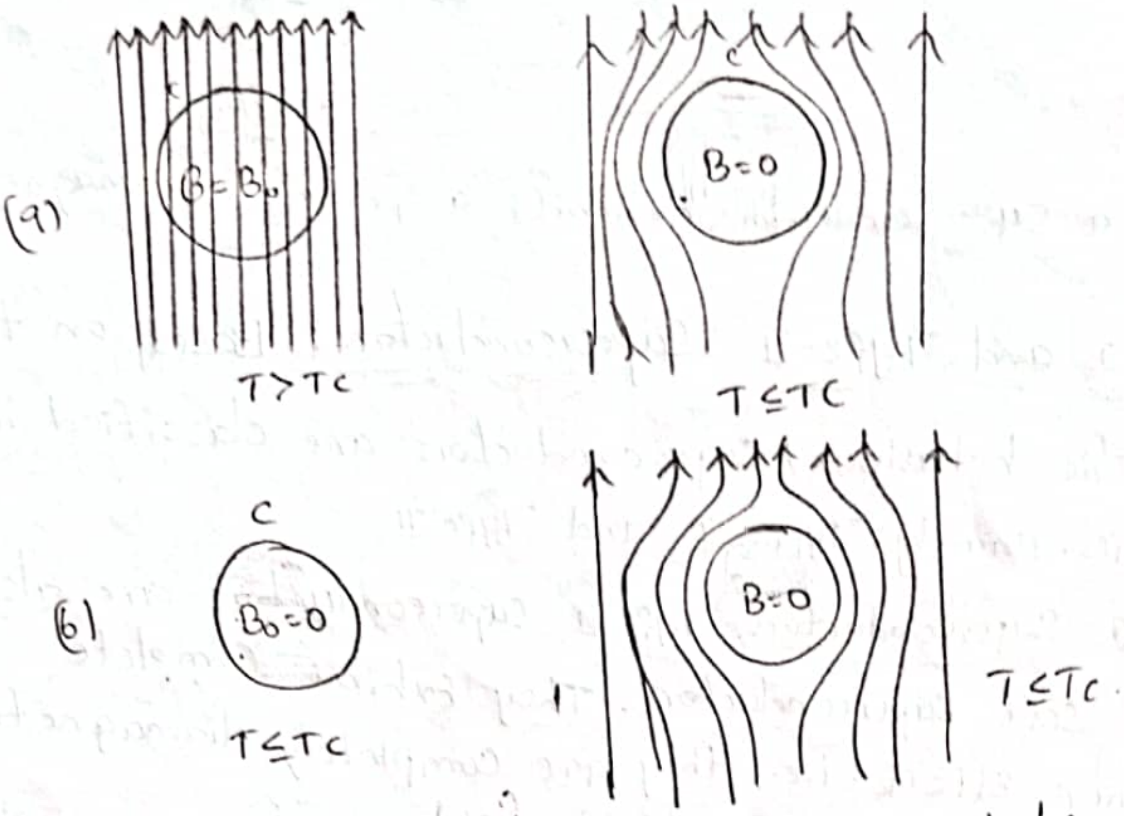
* Thermal Conductivity changes discontinously when super conductivity is destroyed in a magnetic field.

* The photo electric properties are unchanged

* All super conductors are diamagnetic.

Meissner Effect: In 1993, two Scientists Named Meissne and ochenfeld observed that a superconductor Expels Magnetic flux ~~contin~~ completely below the Transition Temperature Tc. This phenomenon is known as Meissner effect. According to Meissner, when a long cylindrical supe conductor is cooled in a longitudinal, magnetic field to below its transition Temperature Tc, the lines of Inducti will be pushed out of the material due to Infinite conductivity as shown in below figure (9).

e other hand, if the material is cooled Initially the transition Temperature and then placed in a etic field, a flux will not penetrate the material hown in figure (b).



(a) Material is cooled after applying the Electric field.

(b) field is applied after the material is cooled.

Thus, in both the cases the magnetic field is Expelled from the body of the superconductor. i.e., the magnetic field inside the superconductor is always zero (i.e., $B=0$). This Implies that the superconductor is a perfect Diamagnet as shown below.

We know that the magnetic Induction B inside a material medium is given by $B = \mu_0(H+M)$.

where H is External Magnetic field Intensity. M is the Magnetization in the medium and μ_0 is the Permeability of free space. Inside the superconductor B=0. Henc

$$\mu_0(H+M)=0$$

$$\Rightarrow H+M=0 \Rightarrow H=-M.$$

The magnetic susceptibility Ratio $\chi = \frac{M}{H}$

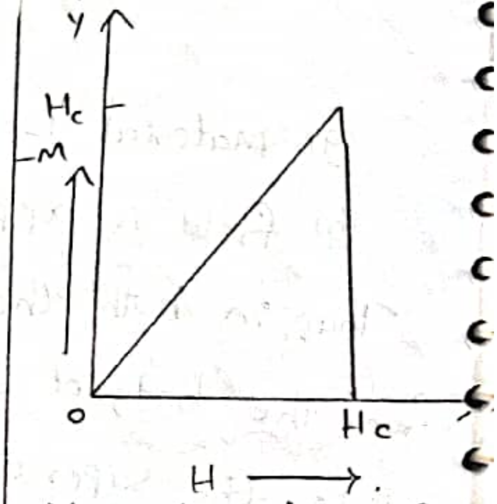
$$= \frac{-M}{M}$$

$$= -1.$$

i.e., a superconductor exhibits a perfect diamagnetism.

Type-I and Type-II Superconductors: Based on the magnetic behaviour, superconductors are classified into two types. Namely Type-I and Type II.

Type-I Superconductors: Type-I superconductors are also called soft superconductors. They exhibit complete Meissner Effect. i.e., they are completely diamagnetic. They have only one critical field Value, H_c. When the field is above the critical field H_c, the specimen is a Normal conductor and below the critical field, the specimen expels all the magnetic lines of force or it becomes a superconductor. The magnetization curve of Type I materials is shown in this figure.

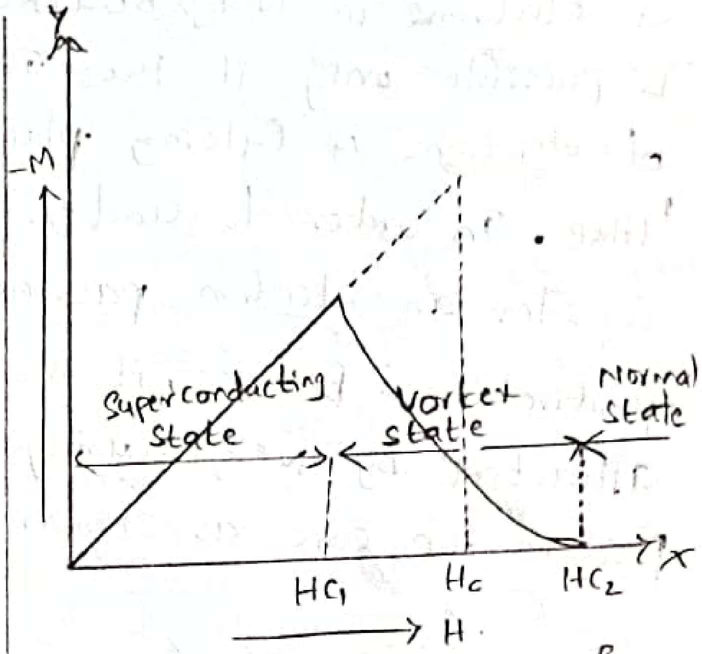


Magnetization Cu of Type I Super Conductor.

The value of the critical field for Type-I superconductors is low, of the order of 0.1 Tesla.

Ex: Al, Zn, Ga, Hg, Sn etc.

Type-II Superconductors: Type-II Superconductors are also called hard superconductors. The magnetization curve of Type-II Superconductors is shown in below figure. They have two critical field values H_{c1} and H_{c2}. If applied field is below H_{c1}, the material is diamagnetic and hence the field is completely expelled. H_{c1} is termed as lower critical field. when the field is increased beyond H_{c1}. the field starts to Enter the Specimen. until H_{c2} is Reached at which the magnetization vanishes. H_{c2} is called upper critical field. Above H_{c2} the Specimen is in Normal state. The state between H_{c1} and H_{c2} is called Vortex state. There is a gradual decrease of magnetization in the case of Type II superconductors. The value of H_c for Type II materials may be 100 times higher than that of Type I materials.

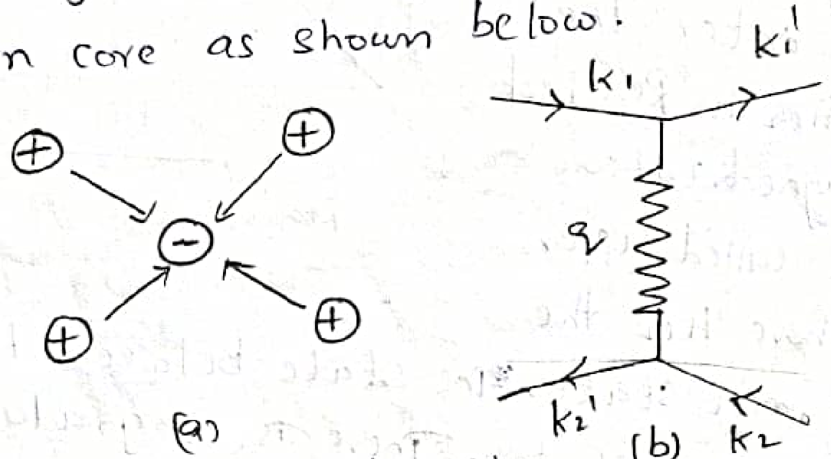


Magnetization curve for Type-II Superconductors.

Ex: Zr, Nb etc.

BCS Theory: The most successful microscopic theory developed by Bardeen, Cooper and Schrieffer in 1957 is known as BCS Theory. This theory successfully Explained all observable effects such as zero Resistivity, meissner Effect, isotope effect etc.

Electron - phonon - Electron Interaction: Frohlich in 1950, Realized that the theory of super conductivity Requires a Net attractive Interaction between a pair of Electrons in Neighbourhood of Fermi surface. This is possible only if the Interaction between the pair of electrons is taking place via positive ions of the lattice. In order to understand this concept, let us Consider an electron passing through the packing of positive ions. Because, it is Negatively charged, it is attracted by Neighbouring positive ions, which form a positive ion core as shown below.



(a) positive ions attracted towards forming positive ion

(b) Exchange of Virtual Phonons between two Electrons.

Now, suppose another electron passes by the side of the assembly of the said Electron and the ion core. The second Electron does not see simply the bare electron but deformed lattice and gets attracted towards. Thus, it can be said that the second electron interacts with the first. In the language of field theory, the above Interaction is said to be due to the Exchange of a Virtual phonon, q between the two Electrons. In terms of wave vectors, k of the two Electrons, it can be written as

$k_1 - q = k_1'$ and

$k_2 + q = k_2'$.

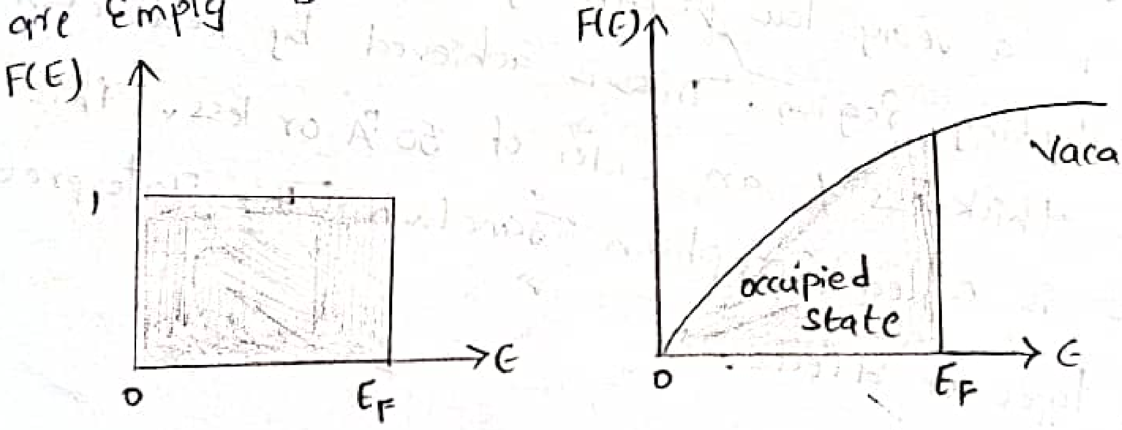
This gives $k_1 + k_2 = k_1' + k_2'$. The first Electron of wave vector k_1 creates a virtual phonon q and while the second electron of wave vector k_1 acquires this during its collision with the virtual phonon.

Cooper pair: A cooper pair is formed when the phonon mediated attractive Interaction between two electrons, The Energy of such a pair of Electrons in the 'bound state is' less than the Energy of two unbound Electrons. Its typical value is of the order of 10^{-3} eV.

In order to understand the mechanism of cooper pair formation, let us Consider the distribution of electrons in metals at absolute zero given by Fermi Dirac distribution function

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

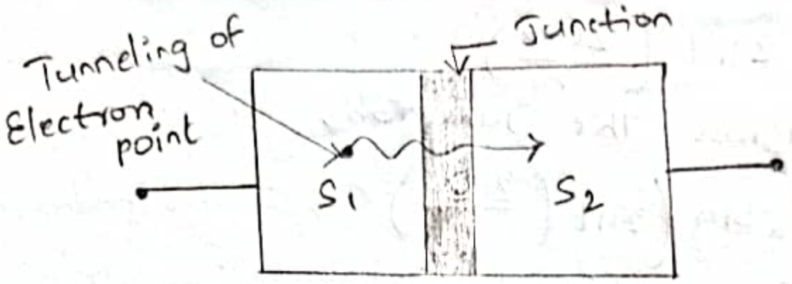
at T=0 K, all the quantum states below the Fermi level E_F are completely filled and all the quantum states above E_F are Empty as shown below.



Fermi Dirac distribution function and density of States. For T=0K when two Electrons are added to a metal at absolu zero. Since all the quantum states with Energies $E \leq E_F$ ar filled, according to pauli's Exclusion principle, they are force to occupy states having Energies $E > E_F$. In this situati Cooper showed that if there is an attraction between the two electrons, they are able to form a bound state, so th their total Energy is less than $2E_F$. These Electrons are paired to form a single system. These two electrons toget form a pair known as Cooper Electron pair. These pair of electrons are in fact super Electrons which are Responsi for superconductivity.

Josephson Effect: In 1962, Josephson theoretically showed that an Electron pair can also tunnel from one superconductor through a fine Insulating layer into anol superconductor as shown in the figure. This is known as Josephson Tunneling and this phenomenon is known as Josephson effect. The coupling between the two superconductors must be very weak provided by their Insulating material that there is a very low probability of finding a Cooper pa in the Insulating Region. This is achieved by Restricting the barrier thickness to an order of 50 Å or less. This arrangement is called Josephson Junction. This Interpretat Reveals two types of effects:

- D.C Josephson Effect
- A.C Josephson Effect.



Josephson Junction between two superconductors.

) DC Josephson Effect: when two superconductors forming the
osephson Junction are connected to Each other, a direct
urrent flows through the Junction without any External field.
is is due to tunneling of cooper pairs across the thin insulating
yer. This Effect is called D.c Josephson Effect. The tunneling
urrent across the Junction is given by

$$I = I_0 \sin\theta .$$

where θ is the phase difference between the wave functio
escribing cooper pairs on both Sides of the barrier and I_0 is
e maximum Current across the Junction. The value of I_0
epends on the thickness of the Junction and the temperature.

c Josephson Effect: If we apply a d.c voltage to the
osephson Junction of two superconductors separated by a thin
Insulating layer, an Alternating current is produced across
he Junction. This Effect is known as ac Josephson Effect.
This Results in an additional phase difference Introduced
y cooper pair during tunneling. when the Current I
through Exceeds the maximum Current I_0, the Insulating
ayer Returns to the Normal state, then a potential differen
V_0 appears across the Junction. It causes a frequency differen

$$\nu = \frac{2eV_0}{h}$$

and a phase difference between the waves $\theta = 2\pi\nu t$.

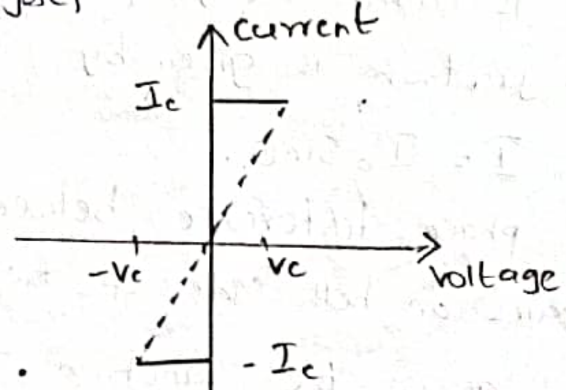
i.e., $\theta = 2\pi t\left(\frac{2eV_0}{h}\right)$.

∴ the current across the Junction,

$$I = I_0 \sin\left(2\pi t\left(\frac{2eV_0}{h}\right)\right)$$

$$I = I_0 \sin\left(\frac{4\pi eV_0}{h}\right)t$$

This Equation gives an alternating current. Thus, when a dc voltage across a Junction exists, an ac Current is produced. This is known as ac Josephson Effect. The current - voltage charecterstics of a Josephson effect are shown in below figur



Charecterstics of a Josephson Effect.

Superconducting Quantum Interference Devices (SQUIDs)

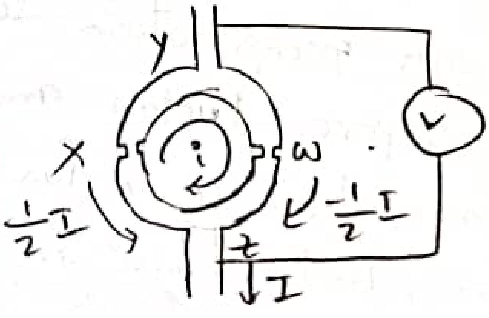
Superconducting Quantum Interference Device (SQUID).

A Superconducting Quantum Interference Device (SQUID) uses the properties of Electron-pair wave coherence and Josephson Junctions to detect Very small magnetic fields. It is basically a Superconducting loop with a weak link and is to measure magnetic flux changes within the loop and is formed from two Josephson Junctions mounted on a super conducting Ring as shown in figure.

A weak link X or ω is a Region that has a muc ower critical current than the critical current of the main Ring. his produces Very low current density making the momentum of the Electron-pairs small. The wavelength of the Electron-pai is thus very long leading to little phase difference in phase when current in the link Exceeds the Critical Current, the link becomes Normal. It allows the fluxons to penetrate the link then the current falls to critical value and the link Reverts to Superconducting state. The weak link thus acts as a gate. It can be made such that It allows only a single fluxon. The Periodic variations in the SQUID current can be sensed by a Nearby coil. ~~the~~ ~~em~~ when the magnetic field applied Normal to the plane of the Ring, the induced Current produced at the two Junctions.

SQUIDs are Extremely Sensitive magnetometers and are used in various Electrical and magnetic measurement Applications. The SQUID sensors have ultra Sensitivity at very low temperatures so these are used at liquid helium or liquid Nitroge. temperatures.

There is also great Importance in the field of medicine. SQUID magnetometers can detect the paramagnetic Response in the liver and give the amount of iron held in the lever of the body. The magnetocardiography (MCG), Magneto encephalography (MEG), Magnetoplethismography (MPG) are developed based on these sensors. It can be used in magnetic Resonance Imaging (MRI) to get high Resolution through the high flux density. It gives the details of brain tumors and blood clots in the brain very precisely. The heart and brain generate, Extremely small Electric currents which setup weak magnetic fields of the order of 10^{-15} tesla, Squids can measure these fields.



I B. Tech I Semester Regular Examinations, July/August- 2021

APPLIED PHYSICS

(Common to CSE, CSE-CS&T, IT , CSE-CS, CSE-IOT&CS incl BCT, CSE-CS & BS, CSE-IOT)

Time: 3 hours Max. Marks: 70

Answer any five Questions one Question from Each Unit
All Questions Carry Equal Marks

1. a) Describe and explain the formation of Newton's rings in reflected light. Deduce expressions for getting bright and dark rings in terms of the diameters. (10M)

   b) When Newton's rings are observed in the reflected light of wavelength $5.9\text{x}10^{-5}$cm, the diameter of the 10^{th} dark ring is found to be 0.50cm. Find the radius of curvature of the lens and thickness of the air film? (4M)

Or

2. a) With the help of neat diagrams, explain how Nicol's prism is used to produce and analyze plane polarized light. (10M)

   b) Define a quarter-wave plate and write the expression for its thickness. (4M)

3. a) Discuss various pumping mechanisms. Explain the construction and working of a Ruby Laser with a neat energy level diagram. (10M)

   b) What are the differences between the terms spontaneous and stimulated emission? (4M)

Or

4. a) Discuss the propagation of an electromagnetic wave through optical fibres. (10M)

   b) Explain the differences between single and multimode optical fibres. (4M)

5. a) Obtain Schrodinger time-independent and time-dependent wave equations. (10M)

   b) An electron has a velocity of 600 m/s with an accuracy of 0.005%. Calculate the uncertainty with which we can locate the position of the electron. (4M)

Or

6. a) Discuss quantum free electron theory. Obtain an expression for electrical conductivity by considering the quantum effects. (10M)

   b) Write the conclusions given by the Kronig-Penny model. (4M)

7. a) Explain the diamagnetism, paramagnetism, and ferromagnetism on the basis of magnetic dipoles of the atom. (10M)

   b) What are Eddy Currents? Explain how they are produced and how they can be minimized. (4M)

Or

8. a) Explain the different types of polarization mechanism involved in a dielectric material. Obtain the expression for ionic polarizability. (10M)

   b) If an ionic crystal is subjected to an electric field of 1000 Vm^{-1} and the resulting polarization 4.3×10^{-8} cm^2. Calculate the relative permittivity of NaCl. (4M)

9. a) Explain how Fermi energy dependent on temperature and carrier concentration in the case of intrinsic as well as extrinsic semiconductors. (10M)

   b) For an intrinsic Semiconductor with a band gap of 0.7 eV, determine the position of E_F at T = 300 K if the effective mass of the hole is equal to six times of effective mass of the electron. (4M)

Or

10. a) Discuss the formation of Cooper pair and energy gap in superconductors on the basis of the BCS theory. (10M)

    b) Write down the applications of superconductors. (4M)