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COURSE FILE FOR THE ACADEMIC YEAR 2017-18

COURSE: I YEAR B.TECH

SUBJECT: ENGINEERING PHYSICS-II

4. JNTUH SYLLABUS:

ENGINEERING PHYSICS – II

UNIT - I

Principles of Quantum Mechanics:

Waves and particles, de-Broglie hypothesis, matter waves,Davisson and Germer experiment, Heisenberg uncertainty principle, Schrodinger time independent wave equation, physical significance of wave function, particle in 1-D potential box, electron in periodic potential, Kronig-Penny model (qualitative treatment), E-K curve,origin of energy band formation in solids.

UNIT - II

Semiconductor Physics:

Fermi level in intrinsic and extrinsic semiconductors, calculation of carrier concentration in intrinsic & extrinsic semiconductors, direct and indirect band gap semiconductors, formation of PN junction, open circuit PN junction, energy diagram of PN junction diode, solar cell: I-V characteristics and applications.

UNIT - III

Dielectric Properties:

Electric dipole, dipole moment, dielectric constant, polarizability,electric susceptibility, displacement vector, electronic, ionic and orientation polarizations and calculation of their polarizabilitites, internal field, Clausius-Mossotti relation, Piezoelectricity, pyroelectricity and ferroelectricity-$BaTiO_3$ structure.

UNIT - IV

Magnetic Properties & Superconductivity:

Permeability, field intensity, magnetic field induction, magnetization, magnetic susceptibility, origin of magnetic moment, Bohr magneton,classification of dia, para and ferro magnetic materials on the basis of magnetic moment,hysteresis curve based on domain theory, soft and hard magnetic materials, properties of antiferro and ferri magnetic materials.

Superconductivity:

Superconductivity phenomenon, Meissner effect, applications of superconductivity.

UNIT - V

Introduction to nanoscience:

Origin of nanoscience, nanoscale, surface to volume ratio,quantum confinement, dominance of electromagnetic forces, random molecular motion, bottomup fabrication: Sol-gel, CVD and PVD techniques, top-down fabrication: ball mill method,characterization by XRD, SEM and TEM.

(5) WEBSITES:

1) ***sites***.*google.com/site/galgotia***physics***/my-forms*
2) *ebookbrowse.com/en/***engineering-physics***-unit-2*
3) **https://sites.google.com/site/1btechfuturelink/**
4) www.motionmountain.net/

(6) SUBJECT EXPERTS DETAILS:

NATIONAL:

1) **Dr. B.APPA RAO, Professor of Physics,** University College of Science, Osmania University, Hyderabad –500 007
2) **Dr. S.P.Mallikarjun Rao, Professor of Physics,** University College of Science, Osmania University, Hyderabad –500 007
3) **Dr Katta Narasimha Reddy, Professor of Physics,** University College of Science, Osmania University, Hyderabad –500 007
4) **Dr. S. Chandralingam** is Professor of Physics at JNTUH College of Engineering, Hyderabad.
5) **Dr.Khaja Altaf Hussain,** Professor of Physics, Department of Physics,Kakatiya University, Warangal
6) **Dr. .G. Sathaiah,** Professor of Physics, Department of Physics ,Kakatiya University, Warangal

INTERNATIONAL:

1. **Serge Haroche, Professor at Collège de France (Holder of the chair in quantum physics).**
2. **David J. Wineland**, a lecturer in the University of Colorado Boulder physics department .

(7) JOURNALS

INTERNATIONAL

1. Journal of material science
2. Journal of Applied Physics
3. Journal of Nano Technology
4. American Journal Of Physics

5. Physics of Solid State
6. Journal of Super Conductivity
7. Journal of Applied Crystallography
8. Semiconductor Physics, Quantum Electronics & OPTO Electronics

NATIONAL

1. Resonance (Indian Academy of Science, Bangalore)
2. Indian Journal of Pure and Applied Physics
3. Current Science.
4. Sadhana (Indian Academy Of science, Bangalore)
5. Pramana (Indian Academy Of science, Bangalore)
6. Journal of pure and applied Physics
7. Indian journal of Physics.

(8) Lesson Plan/Subject Plan: Subject: Engineering Physics- II

Course: I B.Tech II sem

NAME OF THE TOPIC	NO OF CLASSES	TEXT BOOKS	REMARKS
UNIT-1			
Waves and particles	L1	T1,T2	
de-Broglie hypothesis	L2	T1,T2	
matter waves,Davisson and Germer experiment	L3,L4	T3	
Heisenberg uncertainty principle	L5	T1,T2	
Schrodinger time independent wave equation	L6,L7	T1,T2	
physical significance of wave function	L8	T1,T3	
particle in 1-D potential box	L9,L10	T2,T3	
electron in periodic potential	L11	T1	
Kronig-Penny model	L12	T2	
E-K curve	L13	T1,T2	
origin of energy band formation in solids.	L14	T3	
Unit-II			
Fermi level in intrinsic and extrinsic semiconductors	L15	T1,T2	
calculation of carrier concentration in intrinsic semiconductors	L16,L17	T1,T3	
calculation of carrier concentration in extrinsic semiconductors,	L18,L19	T1,T2	
direct and indirect band gap semiconductors	L20	T3	
formation of PN junction	L21	T2	
open circuit PN junction	L22	T1,T2	
energy diagram of PN junction diode	L23	T2,T3	
solar cell	L24	T2	
I-V characteristics and applications.	L25	T2,T3	
UNIT III			
Electric dipole, dipole moment	L26	T1,T2	
dielectric constant, polarizability,electric susceptibility	L27	T3	
displacement vector	L28	T1,T2	
electronic, ionic and orientation polarizations	L29,L30,L31	T2,T3	
calculation of polarizabilitites	L32	T1,T3	
internal field in solids	L33	T1,T2	
Clausius-Mossotti relation	L34	T3	
Piezoelectricity, pyroelectricity and ferroelectricity	L35,L36	T1,T2	
$BaTiO_3$ structure	L37	T1	

UNIT-IV			
Permeability, field intensity	L38	T1,T2	
magnetic field induction, magnetization	L39	T3	
magnetic susceptibility	L40	T1,T3	
origin of magnetic moment, Bohr magneton	L41,L42	T2,T3	
classification of dia, para and ferro magnetic materials	L43,L44	T1,T2	
hysteresis curve based on domain theory	L45,L46	T2	
soft and hard magnetic materials	L47	T1,T3	
properties of antiferro and ferri magnetic materials	L48,L49	T2	
Superconductivity phenomenon	L50	T1,T2	
Meissner effect	L51	T2	
applications of superconductivity	L52	T2,T3	
UNIT-V			
Origin of nanoscience, nanoscale	L53	T1,T2	
surface to volume ratio	L54	T2	
quantum confinement	L55	T1,T3	
dominance of electromagnetic forces	L56	T1,T2	
random molecular motion	L57,L58	T2,T3	
bottomup fabrication: Sol-gel	L59,L60	T2,T3	
CVD and PVD techniques	L61,L62	T3	
top-down fabrication: ball mill method	L63	T1,T2	
characterization by XRD, SEM and TEM.	L64,L65	T2	

UNIT-I

Principles of quantum mechanics

Introduction

To overcome the failures in classical mechanics quantum mechanics was introduced. Quantum mechanics deals with tiny objects which are moved at ordinary temperature. Quantum mechanics removes all the failures of classical mechanics. It successfully explained the motion of micro particles, interference, diffraction & polarization of electromagnetic waves, black body radiation, photoelectric effect, Compton effect & line spectrum.

Planck's quantum theory:

Planck proposed the quantum theory of radiation in 1901. According to this theory energy transformation & transformed from one place to other by small energy particles each packet is called quantum of energy

According to this theory energy transformations are taking place in a discrete way. This gives the origin for quantum mechanics

$E=h\nu$

$E=hc/\lambda \quad (\nu= c/\lambda)$

h→ is Planck's constant $=6.625 \times 10^{-34}$ J s

c→speed of light

λ→Wavelength

Wave: A wave is spread out over a relatively large region of space & can't be said to locate just here & there. Actually a wave is nothing but rather a spread out disturbance. A wave is specified by its frequency, wavelength, phase or wave velocity, amplitude & intensity

Particle: a particle has mass & it is located at some definite point. It can move from one place to another & it gives energy when slowed down or stopped

The particle is specified by its mass, velocity, momentum & energy.

Matter waves: the waves associated with the particles of matter (electrons, photons, etc) are known as matter waves.

[OR]

We know that light has dual nature (particle & wave)

Differences between matter waves & electromagnetic waves

Matter wave

1) it is associated with moving particle
2) wavelength depends on the mass & velocity of particle
   i.e., $\lambda = h / m v$
3) can travel with a velocity greater than the velocity of light
4) matter wave is not electromagnetic wave

Electromagnetic wave

1) oscillating charged particle gives rise to electromagnetic wave
2) wavelength depends on the energy of photon

   i.e., $\lambda = hc /E$

3) travels with velocity of light
   i.e., $C=3\times10^8$ m/s
4) electric field & magnetic field oscillate perpendicular to each other

DE-BROGLIE HYPOTHESIS:

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

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

$$E = h\nu$$

$$E = hc/\lambda \qquad (\nu = c/\lambda) \text{------}\rightarrow 1$$

C→ is velocity of light

λ is wavelength

According to Einstein mass-energy relation

$$E = mc^2 \text{--------}\rightarrow 2$$

From eqns (1) and (2)

$$hc/\lambda = mc^2$$

we get $hc/\lambda = mc^2$

$$\Longrightarrow \lambda = h/mc = h/p$$

Where: p→ is momentum of particle

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

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

$$\boxed{\lambda = h/mv = h/p}$$

Where: p=mc →momentum associated with photon

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

DE- BROGLIE WAVELENGTH ASSOCIATED WITH ELECTRONS

Let us consider the case of an electron of rest mass m_0 & charge 'e' being accelerated by a potential 'V' volts. If 'v' is the velocity attained by the electron due to acceleration

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

$$v^2 = 2eV/m$$

$$v = (2eV/m)^{1/2}$$

By substituting 'v' in de-Broglie wavelength we get

$$\lambda = h/mv$$

$$\lambda = h/m(2eV/m)^{1/2}$$

$$\boldsymbol{\lambda = h/(2meV)^{1/2}}$$

Where: h→Planck's constant=6.625 x 10^{-34} J.S

m→Mass of electron=9.1 x 10^{-31} Kg

e→Charge of electron=1.602 x 10^{-19} C

V→Velocity of electron

$$\boxed{\lambda = 12.26/(v)^{1/2} A^0}$$

If the voltage applied to accelerate the electron 'V' is 100 volts then

$$\lambda = 1.226 \text{ angstroms}$$

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

CHARATERISTICS OF MATTER WAVE:

Since de Broglie wavelength $\lambda = h/p$

- Lighter the particles greater is the wavelength associated with it. Lesser the velocity of the particle longer is the wavelength associated with it
- for v=o λ= infinity this means that only with moving particle matter wave is associated
- Whether the particle is charged or not matter wave associated with it. This reveals that these waves are not electromagnetic but a new kind of waves. It can be proved that the matter waves travel faster than light.

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

$$h\nu = mc^2$$

$$\nu = (mc^2)/h$$

The wave velocity 'w' is given by

$$w = (mc^2/h)\,\lambda$$

$$\boxed{w = c^2/v}$$

as the particle velocity v cannot exceed velocity of light 'c'

W → is velocity of light

No single phenomena exhibits both particle & wave nature simultaneously

While position of a particle is confined to a particular location at any time the matter wave associated with it has some spread as it is a wave. Thus the wave nature of matter introduces an uncertainty in the location of the position of the particle. Heisenberg's uncertainty principle is based on this concept

EXPERIMENTAL STUDY OF MATTER WAVE:

How can de Broglie hypothesis be verified?

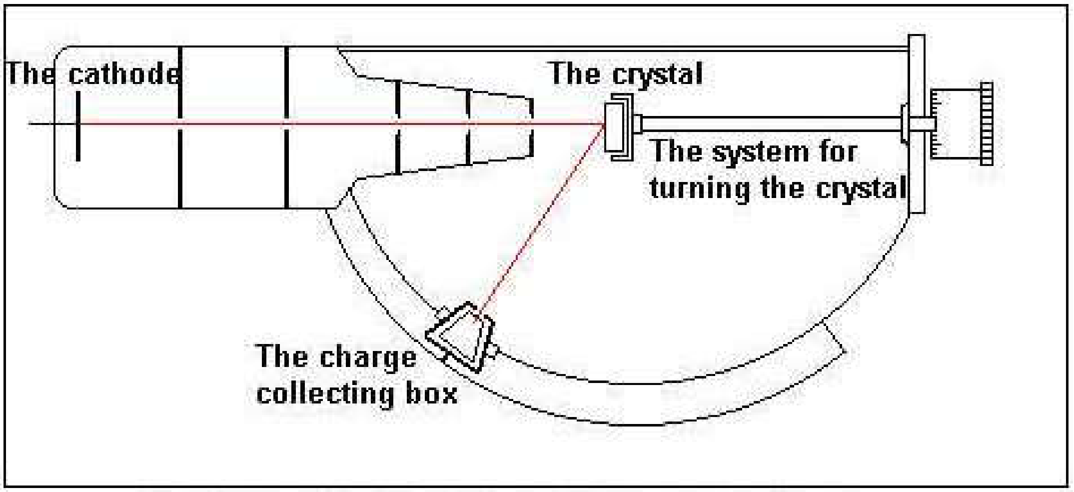
Most striking exhibition of wave behavior is the diffraction pattern which depends upon the ability of waves both to bend around obstacles & interfere constructively & destructively with one another. Several years after de Broglie's work, Davison & Germer in the US & G.P. Thomson in England independently demonstrated that streams of electrons are diffracted when they are scattered from crystals. The diffraction patterns they observed were incomplete accord with the electron wavelength predicted by

$$\lambda = h/mv$$

DAVISSON -GERMER'S EXPERIMENT:

Principle:

Based on the concept of wave nature of matter fast moving electrons behave like waves. Hence accelerated electron beam can be used for diffraction studies in crystals



The diagram for the Davisson-Germer experiment.

Aim: ***experimental verification for the existence of a matter wave***

(OR)

Experimental proof for dual nature of matter

Principle:

Based on the concept of wave nature of matter fast moving electrons behave like waves. Hence accelerated electron beam can be used for diffraction studies in crystals

Description:

experimental arrangement consists of electron gun to produce the fine beam of electrons. 'F' is the filament which is heated by using separate battery s1, s2 are two slits. 'A' is the accelerator which is maintained at high positive potential with help of high tension battery (HTB)

An accelerator is used to accelerate to electrons & due to this slow electrons are converting into fast moving electrons

The

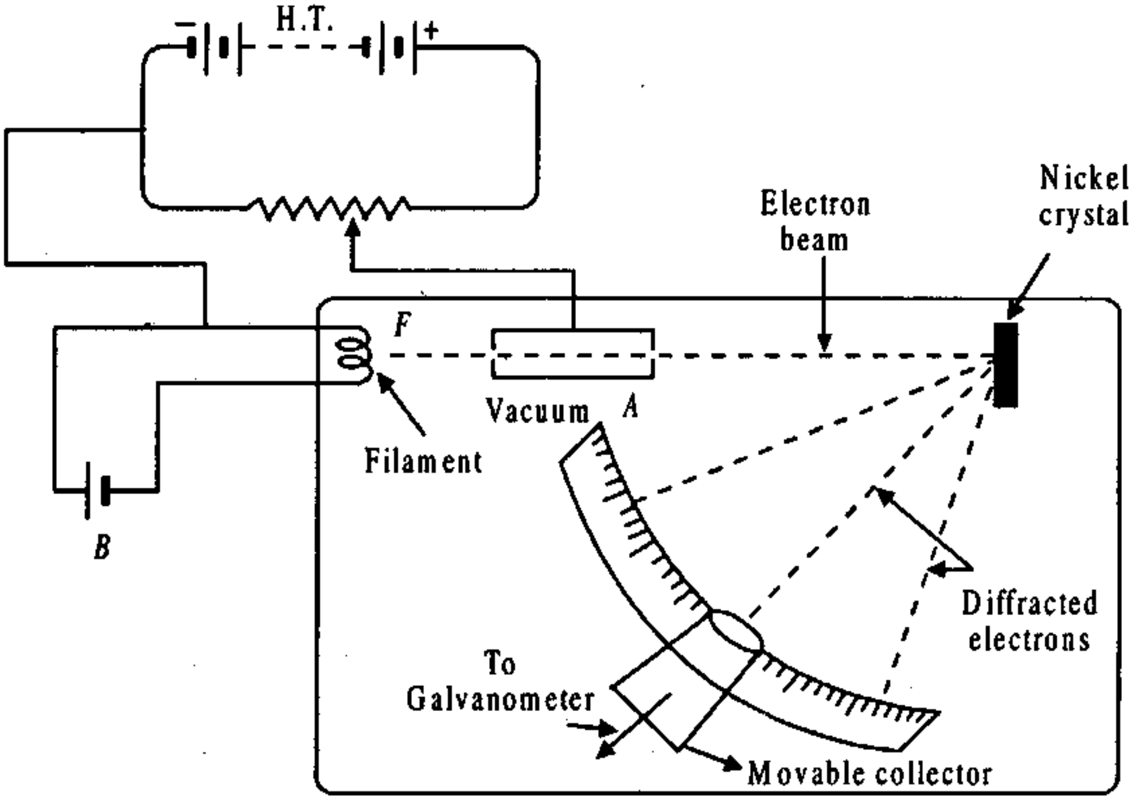


Fig. 29.2

Procedure:

The filament is heated with low tension battery (LTB). The electrons are emitted from the filament. The electrons are passing through slits s1,s2 to get narrow beam of electrons. Finally fine beam of electrons coming out from the electron gun, this electron beam is stroked the target of nickel crystal & beam is diffracted. The diffracted fast moving electrons are collected by faraday cylinder which is fitted to circular scale with the help of galvanometer. The current due to fast moving electrons is detected.

Result:

The diffraction pattern is fine at $\theta=50$ & $V=54$ volts

According to de Broglie wavelength we have

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

$= 0.166$ nm.

$= 1.668$ angstroms

Applying Bragg's law $2d\sin\theta=n\lambda$

$d=a\sin\theta= 2.15\text{X}10^{-10}\text{X}\sin 25$

$d=0.909\text{X}10^{-10}$

if $n=1$ then $\lambda = 1.648$ angstroms

Heisenberg's uncertainty principle

The wave nature of the particle is further stressed by the famous Heisenberg's principle of uncertainty

"It is impossible to measure precisely & simultaneously both momentum & position of a particle" (OR)

"It is impossible to know both the exact position and exact momentum of an object at the same time"

If 'Δx' and 'Δp' are the uncertainties in the position and momentum of a particle respectively, when they are simultaneously measured.

Then $\Delta x.\ \Delta p \geq \hbar / 2$ --------→ (1)

where h is Plank's constant = $6.625\text{X}\ 10^{-34}$ J-S

$\Delta x.\ \Delta p \geq h / 4\prod$ ---------→(2)

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

Thus the uncertainty principle is a direct consequence of the wave nature of particles. Another form of uncertainty concerns energy & time. If the energy emitted in the form of electromagnetic waves we cannot measure the frequency of the waves accurately in the limited time available. Let the minimum uncertainty in the no. of waves that we count in a wave group be a one wave.

Since, **frequency = number of waves/time interval**

$\Delta\nu \geq 1/\Delta t$ -----→ (3)

But energy of photon is $E= h\nu$

Hence, Corresponding uncertainty in energy ΔE is

$\Delta E = h\,\Delta\nu$

$\Delta E \geq h(1/\Delta t)$

$$\boxed{\Delta E.\ \Delta t \geq h}$$

A more precise calculation based on the nature of wave groups result to

$$\boxed{\Delta E.\ \Delta t \geq h/4\ \Pi}$$

The above equation gives uncertainty in the measurement of energy & time of a process.

Wave function:

The observable properties associated with the particle of the system are wave function. Any meaningful question about the result of an experiment performed upon the system can be answered if the wave function is known. In any electromagnetic wave system is the amplitude of the matter wave of any point in space then the particle density at that point may be taken as proportional to $|\psi|^2$. thus it is a measure of particle density
According to max born $\psi^* \psi = |\psi|^2$ gives the probability of finding particle in the state ψ.

Physical significance of wave function:

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

$$\int_{-\infty}^{\infty} |\psi|^2\ .d\tau = 1 \underline{\hspace{4cm}} (28)$$

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

1. It must be finite everywhere.
2. It must be single valued.
3. It must be continuous and have a continuous first derivative everywhere.

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

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

Schrodinger's Time Independent Wave Equation:

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

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

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

$$\Psi = \Psi 0 \sin(\omega t - k x) \text{ --------- } (1)$$

Where $\Psi = \Psi(x, t)$ and $\Psi 0$ is the amplitude.

Differentiating Ψ partially w.r.to x,

$$\partial \Psi / \partial x = \Psi_0 \cos(\omega t - k x)(-k)$$
$$= -k\, \Psi_0 \cos(\omega t - k x)$$

Once again differentiate w.r.to x

$$\partial^2 \psi / \partial x^2 = (-k)\, \Psi_0 (-\sin(\omega t - k x))(-k)$$
$$= -k^2 \Psi 0 \sin(\omega t - k x)$$
$$\partial^2 \psi / \partial x^2 = -k^2 \psi \text{ (from eqn (1))}$$
$$\partial^2 \psi / \partial x^2 + k^2 \psi = 0 \text{ ----------- } (2)$$
$$\partial^2 \psi / \partial x^2 + (4 \Pi^2 / \lambda^2)\, \psi = 0 \text{ --------- } (3) \quad (\text{since } k = 2 \Pi / \lambda)$$

From eqn. (2) or eqn. (3) is the differential form of the classical wave eqn. now we incorporate de-Broglie wavelength expression $\lambda = h / m v$.
Thus we obtain

$\partial^2 \psi / \partial x^2 + (4 \Pi^2 / (h / m v) 2) \psi = 0$

$\partial^2 \psi / \partial x^2 + 4 \Pi^2 m^2 v^2 \psi / h2 = 0$ -------------- (4)

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

i e $E = K + V$ -------------- (5)

And $K = mv^2 / 2$ ---------- (6)

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

From (4) and (7)

=> $\partial^2 \psi / \partial x^2 + [8\Pi 2 m (E-V) / h^2] \psi = 0$ ------------ (8)

In quantum mechanics, the value h / 2 Π occurs more frequently.

Hence we denote,

$\hbar = h / 2 \Pi$

Using this notation, we have

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

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

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

Where $\Psi = \Psi (x, y, z)$.

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

Using the Laplacian operator,

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

Eqn. (10) can be written as

$\nabla^2 \Psi + [2 m (E - V) / \hbar^2] \psi = 0$ --------------- (12)

This is the Schrödinger Time Independent Wave Equation.

Application of Schrodinger wave equation

Particle in One Dimensional Potential Box:

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

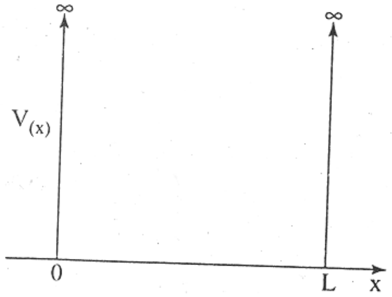


Fig. Particle in a potential well of infinite height.

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

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

The particle cannot escape from the box

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

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

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

i e $|\psi|^2 = 0$ for $0 > x > a$

$|\psi|^2 = 0$ for $x = a$ & $x = 0$

The Schrödinger one – dimensional time independent eqn. is

$\nabla^2 \Psi + [2 m (E - V) / \hbar^2] \psi = 0$ ----------(1)

For freely moving particle $V = 0$

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

Taking $2 m E / \hbar^2 = K^2$ ------------ (3)

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

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

$\Psi = A \sin kx + B \cos kx$ -----------(5) where A, B and k are unknown quantities and to calculate them it is necessary to construct boundary conditions.

Hence boundary conditions are

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

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

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

$A \sin ka = 0$

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

$\text{Sin } ka = 0$

$Ka = n \Pi$

$k = n \Pi / a$ -------------- (8)

Substituting the value of k in eqn. (3)

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

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

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

In general $E_n = n^2 h^2 / 8 m a^2$ ------------ (9)

The wave eqn. can be written as

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

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

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

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

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

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

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

From eqn’s. (10) & (11)

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

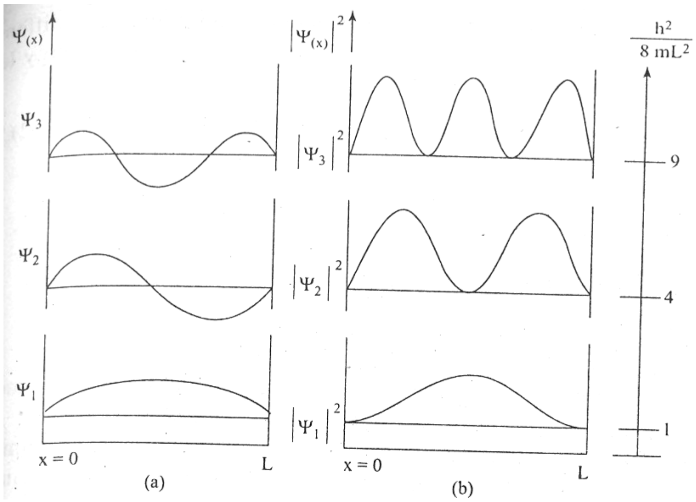
Eqn. (9) represents an energy level for each value of n. the wave function this energy level is given in eqn. (12). Therefore the particle in the box can have discrete values of energies. These values are quantized. Not that the particle cannot have zero energy .The normalized wave functions $\Psi 1$, Ψ_2, Ψ_3 given by eqn (12) is plotted. the values corresponding to each E_n value is known as Eigen value and the corresponding wave function is known as Eigen function.

The wave function $\Psi 1$, has two nodes at $x = 0$ & $x = a$

The wave function $\Psi 2$, has three nodes at $x = 0$, $x = a / 2$ & $x = a$

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

The wave function $\Psi_{n,}$ has (n + 1) nodes



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

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

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

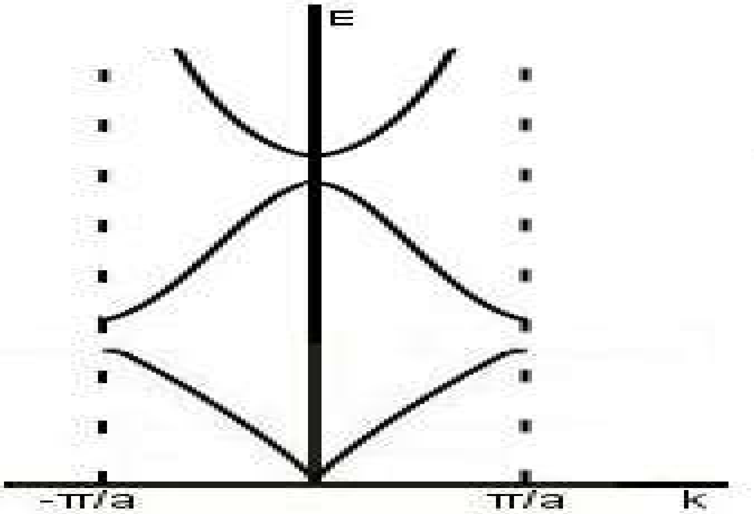
$$k = p / \hbar = p / (h / 2\,\Pi) = 2\,\Pi\,p / h$$

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

Bloch Theorem: A crystalline solid consists of a lattice which is composed of a large number of ionic cores at regular intervals, and, the conduction electrons can move freely throughout the lattice.

Let the lattice is in only one-dimension i.e., only an array of ionic cores along x-axis is considered. If we plot the potential energy V of a conduction electron as a function of its position in the lattice, the variation of potential energy.

Since the potential energy of any body bound in a field of attraction is negative, and since the conduction electron is bound to the solid, its potential energy V is negative.



Further, as it approaches the site of an ionic core V → - ∞. Since this occurs symmetrically on either side of the core, it is referred to as potential well. The width of the potential well b is not uniform, but has a tapering shape.

If V_0 is the potential at a given depth of the well, then the variation is such that

$b \to 0$, as $V_0 \to \infty$., and ,

The product $b\,V_0$ is a constant.

Now, since the lattice is a repetitive structure of the ion arrangement in a crystal, the type of variation of V also repeats itself. If a is the interionic distance, then , as we move in x-direction , the value of V will be same at all points which are separated by a distance equal to a.

ie $V(x) = V(x + a)$ where, x is distance of the electron from the core. Such a potential is said to be a periodic potential.

The Bloch's theorem states that, for a particle moving in a periodic potential, the Eigen functions for a conduction electron are of the form,

$$\chi(x) = U(x) \cos kx$$

Where $U(x) = U(x + a)$

The Eigen functions are the plane waves modulated by the function U (x). The function U (x) has the same periodicity as the potential energy of the electron, and is called the modulating function.

In order to understand the physical properties of the system, it is required to solve the Schrödinger's equation. However, it is extremely difficult to solve the Schrödinger's equation with periodic potential described above. Hence the Kronig – Penney Model is adopted for simplification.

THE KRONIG -PENNEY MODEL:

It is assumed in quantum free electron theory of metals that the free electrons in a metal express a constant potential and is free to move in the metal. This theory explains successfully most of the phenomena of solids. But it could not explain why some solids are good conductors and some other are insulators and semi conductors. It can be understood successfully using the band theory of solids.

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

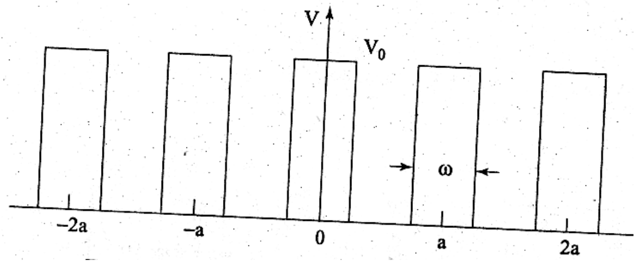


Fig. One dimensional periodic potential

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

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

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

$$d^2\Psi / dx^2 + 2mE\Psi / \hbar^2 = 0 \quad \text{for region } 0 < x < a \text{ -----------(2)}$$

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

Substituting $\alpha^2 = 2mE / \hbar^2$ ---------------(4)

$$\beta^2 = 2m(E - V) / \hbar^2 \text{ -----------(5)}$$

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

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

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

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

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

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

$$U_k(x) = U_k(x+a) \text{ ------------------(9)}$$

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

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

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

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

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

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

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

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

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

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

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

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

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

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

and is a measure of potential barrier strength.

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

From fig , the following conclusions are drawn.

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

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

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

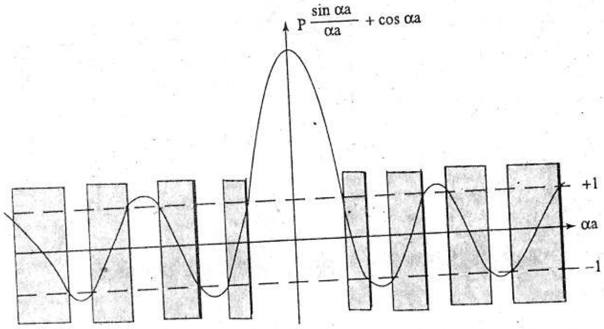


Fig Plot of $P\frac{\sin\alpha a}{\alpha a} + \cos\alpha a$ versus αa.

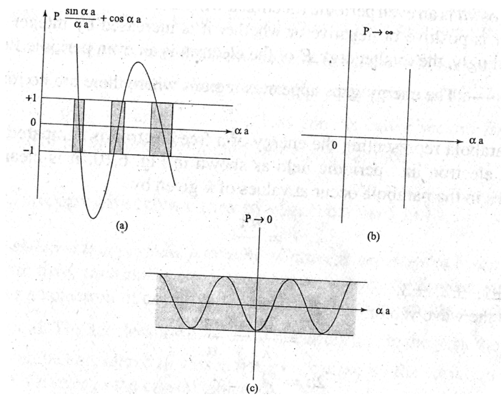


Fig. a) P=6pi b) p--> infinity c) p--> 0

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

If $P \rightarrow \infty$, then the equation (11) has solution ie

$$\sin \alpha a = 0$$
$$\alpha a = \pm n \Pi$$
$$\alpha = \pm n \Pi / a$$
$$\alpha^2 = n^2 \Pi^2 / a^2$$

But $\alpha^2 = 2 m E / \hbar^2$

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

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

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

4) When $P \rightarrow 0$ then

$$\cos \alpha a = \cos ka$$
$$\alpha = k , \quad \alpha^2 = k^2$$

but $\alpha^2 = 2 m E / \hbar^2$

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

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

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

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

Origin Of Energy Bands In Solids:

Solids are usually moderately strong, slightly elastic structures. The individual atoms are held together in solids by interatomic forces or bonds. In addition to these attractive forces, repulsive forces also act and hence solids are not easily compressed.

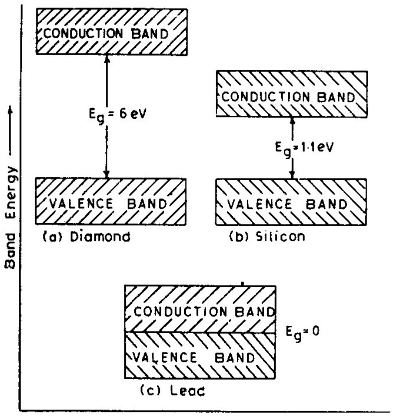
The attractive forces between the atoms are basically electrostatic in origin. The bonding is strongly dependent on the electronic structure of the atoms. The attraction between the atoms brings them closer until the individual electron clouds begin to overlap. A strong repulsive force arises to comply with Pauli’s exclusion principle. When the attractive force and the repulsive force between any two atoms occupy a stable position with a minimum potential energy. The spacing between the atoms under this condition is called equilibrium spacing.

In an isolated atom, the electrons are tightly bound and have discrete, sharp energy levels. When two identical atoms are brought closer , the outermost orbits of these atoms overlap and interact. When the wave functions of the electrons on different atoms begin to overlap considerably, the energy levels corresponding to those wave functions split. if more atoms are brought together more levels are formed and for a solid of N atoms, each of the energy levels of an atom splits into N levels of energy. The levels are so close together that they form an almost continuous band. The width of this band depends on the degree of overlap of electrons of adjacent atoms and is largest for the outermost atomic electrons. In a solid many atoms are brought together so that the split energy levels form a set of bands of very closely spaced levels with forbidden energy gaps between them.

Classification Of Materials:

The electrons first occupy the lower energy bands and are of no importance in determining many of the electrical properties of solids. Instead, the electrons in the higher energy bands of solids are important in determining many of the physical properties of solids. Hence the two allowed energy bands called valence and conduction bands are required. The gap between these two allowed bands is called forbidden energy gap or band gap since electrons can’t have any energy values in the forbidden energy gap. The valence band is occupied by valence electrons since they are responsible for electrical, thermal and optical properties of solids. above the valence band we have the conduction band which is vacant at 0K. According to the gap between the bands and band occupation by electrons, all solids can be classified broadly into two groups.

In the first group of solids called metals there is a partially filled band immediately above the uppermost filled band .this is possible when the valence band is partially filled or a completely filled valence band overlaps with the partially filled conduction band.



In the second group of solids , there is a gap called band gap between the completely filled valence band and completely empty conduction band. Depending on the magnitude of the gap we can classify insulators and semiconductors.

Insulators have relatively wide forbidden band gaps. For typical insulators the band gap $E_g > 3$ eV. On the other hand , semiconductors have relatively narrow forbidden bands. For typical semiconductors $E_g \leq 1$ eV.

Valence band, Conduction band and Forbidden energy band:

The electrons of the atoms rotate around their nuclei in certain permitted energy levels.

The electrons in the inner shells are strongly bounded to their nuclei the electrons in the outer most shells are not strongly bounded to their nuclei. The electrons in the outer most shell are called valence electrons “The band which is occupied by the Valency electrons is called Valence band”

The Valence band may be partially or completely filled up depending on the nature of the material.

“The next higher permitted band is called Conduction band”.

The energy levels occupying this band may also be defined as the lowest unfilled energy band. This band may be empty or partially filled. In conduction band the electrons can move freely.

“The conduction band and Valence bands are separately by a region or gap is known as Forbidden energy band”.

It should be remember that no electron can exist in this band. When an electron in the Valence band absorbs enough energy, it jumps the forbidden gap and enters the Conduction band. When an electron jumps to a valence band to a conduction band a positively charged hole is created. This hole is filled by the electron from the adjacent atom.

Conductors, SemiConductors and Insulators:

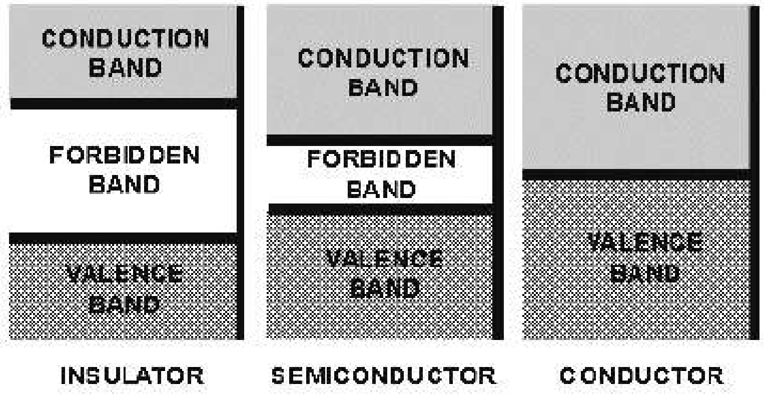


Figure 1-6.—Energy level diagram.

On the basis of magnitude of forbidden band, the solids are classified into Insulators, Semi Conductors and Conductors.

Insulators:

For insulators, the forbidden energy band is very wide due to this fact electrons cannot jump from Valence band to Conduction band.

In insulators the Valence electrons are bound very tightly to their parent atoms.

For examples glass, the valence band is completely full at Ok and the forbidden energy gap is the order of 10ev. Even in presence of high electric field, the electrons do not move from Valence band to Conduction band.

Increase in temperature enables some electrons to go to Conduction band. This explains that some insulators become conductors at high temp.

The resistivity of the insulators is of the order of 10^7 Ω-m

Semiconductors: In Semiconductors, the forbidden energy band is very small. Germanium and silicon are the best examples of Semiconductors. Forbidden energy band for Germanium is 0.72 eV and silicon is 1.12eV.

Semiconductor proposes are between insulators and good conductors. At the Valence band is completely filled and there are no electrons in conduction band. When a small energy is supplied, the electron can easily jump to conduction band.

The conductivities of semiconductors are of the order of 10^2 Ω-m

Conductors:

In case of conductors, there is no forbidden band and both valence and conduction bands overlap each other.

The conduction band, plenty of free electrons are available for the process of conduction. The electrons from Valence band freely enter into Conduction band.

The total current in conductors is simply a flow of electrons.

Velocity of the electron in periodic potential.

According to quantum theory, an electron moving with a velocity can be treated as a wave packet moving with the group velocity v_g

$$v = v_g = d\omega / dk \text{ -----------------(1)}$$

where ω is the angular frequency of deBroglie wave and $k = 2\Pi / \lambda$ is the wave vector.

The energy of an electron can be expressed as

$$E = \hbar \omega \text{ ---------------------(2)}$$

Differentiating the equation (2) with respect to k

$$dE / dk = \hbar\, d\omega / dk \text{ -------------(3)}$$

from (1) & (3)

$$v_g = 1 / \hbar \, (dE / dk) \text{ -----------------(4)}$$

According to band theory of solids, the variations of E with k as shown in fig(1). Using this graph and equation (4), the velocity of electron can be calculated. The variation of velocity with k is shown in fig(2). From this fig, it is clear that the velocity of electron is zero at the bottom of the energy band. As the value of k increases, the velocity of electron increases and reaches to maximum at K=k.Further ,the increases of k, the velocity of electron decreases and reaches to zero at K= Π / a at the top of energy band.

UNIT II

SEMI CONDUCTOR PHYSICS

Semi conductor devices play a vital role in electrical and electronics engineering. The field of electronics has been revolutionized since the transistor in 1948. The delicate vacuum tubes have been now largely replaced by solid state devices. After the invention of integrated circuit which contains a no. of diodes, transistors, resistors and capacitors in a small volume and requires small power to operate, we are mostly depending on semi conducting materials.

In semiconductors if we add impurities, they will increase the electrical conductivity of semi conductors. Further if we increase the temperature of the semi conductor its electrical conductivity also increases. These are quite contrary to the conductors or metals i.e., in metals if we increase the temperature or if we add impurity, the electrical conductivity will decrease. Germanium and Silicon are the important semiconductors which are used to manufacture diodes and transistors.

Fermi Level in intrinsic semi conductors:

A semiconductor in which holes and electrons are created slowly by thermal excitation across the energy gap is called an intrinsic semiconductor. A pure crystal of Silicon or Germanium is an intrinsic semi conductor. The electrons reaching the conduction band due to thermal excitation are equal to the no. of vacancies or holes in valance band i.e., in intrinsic semiconductor, concentration of holes and electrons must always be the same.

The Fermi energy level for an intrinsic semiconductor lies midway in the forbidden gap where the probability of finding an electron is 50% even though there are no allowed energy levels available at that position. In these semiconductors the concentration of charge carriers increases exponentially with temperature. Practically these are not useful ones because their electrical conductivity is very small and it is not a constant one.

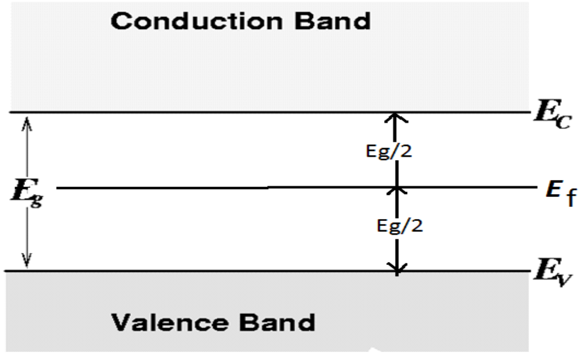
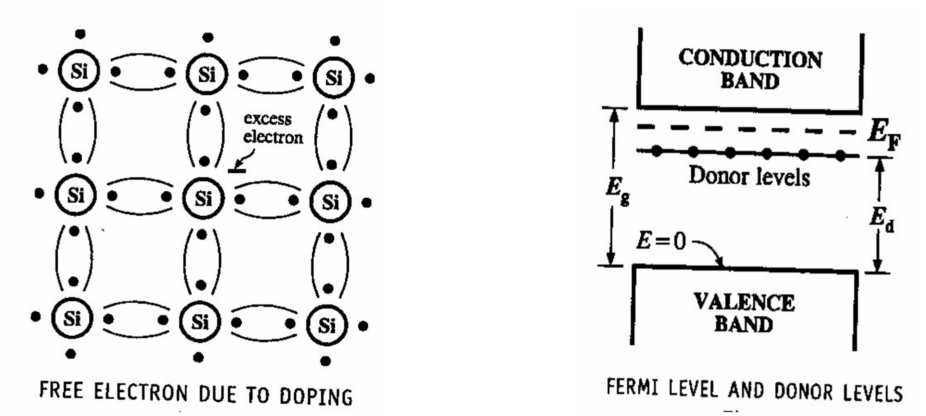


Fig: Energy levels in intrinsic semiconductors

Where Eg is the forbidden energy band.

Fermi level in extrinsic semiconductors:

A material whose charge carriers originate from impurity atoms is called an impurity semi conductor or extrinsic semiconductor. In these the conduction is mainly due to addition of impurities which increases the conductivity of a semi conductor. The phosphorous atom is said to donate electron to the semi conductor and this energy level of the fifth electron is called the donor level. Since the elements such as P, As or Sb donate negative charges (electrons). These are called N-type impurities and the semiconductor doped with them are called N-type semiconductors as shown in fig 1



FREE ELECTRON DUE TO DOPING

FERMI LEVEL AND DONOR LEVELS

Fig: N-type semiconductor

FORMATION OF HOLE DUE TO DOPING

FERMI LEVEL AND ACCEPTOR LEVELS

Fig: P-type semiconductor

Excitation of electron from the donor level into the conduction band takes place much more readily than across the energy gap from the valence band. The donor level is so close to the bottom of the conduction band and most of the donor level electrons are excited into the conduction band at room temperature and become the majority charge carriers. So in N-type semiconductors electrons are majority charge carriers.

Consider the impurities like Al, Ga or In in semiconductors. Aluminum has three electrons in outer shell and to complete its bond, it requires one more electron that is supplied by a semiconductor atom like Silicon thereby creating a vacant electron site or hole in the valence band of semiconductor.

Since aluminum accepts one extra electron, the energy level of this is called acceptor level which is just above the valence band. So Al, Ga and In are called acceptor impurities and the semi conductors doped with acceptor impurities are called P-type semiconductors as shown in fig-2. The majority charge carriers in P-type semiconductors are holes since most of the holes are free for conduction purposes at room temperature in P-type semiconductor. The minority charge carriers are electrons in the P-type semiconductors. Unlike intrinsic semiconductors the concentration of holes and electrons are unequal in extrinsic semiconductors.

Carrier concentration in intrinsic semiconductor:

We know that in intrinsic semiconductors the charge carriers are nothing but electrons in the conduction band and holes in the valence band. Since these carriers are generated due to the breaking of covalent bonds, we have equal no. of electrons and holes. At 0k, since all the bonds are intact the semiconductor acts as an insulator. With increase of thermal energy the covalent bonds are broken and electron-hole pairs are created. Now we have to calculate the carrier concentration namely no. of electrons in the conduction band per unit volume of the material (N-type) as well as no. of holes [in the valence band per unit volume of the material (P-type) low temperature.

Intrinsic semiconductors:

A pure semiconductor which is not doped is termed as intrinsic semiconductor. In Si crystal, the four valence electrons of each Si atom are shared by the four surrounding Si atoms. An electron which may break away from the bond leaves deficiency of one electron in the bond. The vacancy created in a bond due to the departure of an electron is called a hole. The vacancy may get filled by an electron from the neighboring bond, but the hole then shifts to the neighboring bond which in turn may get filled by electron from another bond to whose place the hole shifts, and so on thus in effect the hole also undergoes displacement inside a crystal. Since the hole is associated with deficiency of one electron, it is equivalent for a positive charge of unit magnitude. Hence in a semiconductor, both the electron and the hole act as charge carriers.

In an intrinsic semiconductor, for every electron freed from the bond, there will be one hole created. It means that, the no of conduction electrons is equal to the no of holes at any given temperature. Therefore there is no predominance of one over the other to be particularly designated as charge carriers.

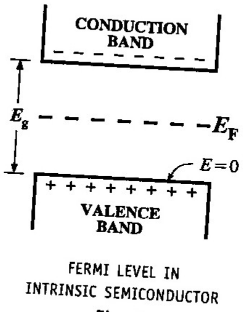
Carriers Concentration in intrinsic semiconductors:

A broken covalent bond creates an electron that is raised in energy, so as to occupy the conduction bond, leaving a hole in the valence bond. Both electrons and holes contribute to overall conduction process.

In an intrinsic semiconductor, electrons and holes are equal in numbers. Thus

$$n = p = n_i$$

Where n is the number of electrons in the conduction band in a unit volume of the material (concentration), p is the number of holes in the valance band in a unit volume of the material. And n_i, the number density of charge carriers in an intrinsic semi conductor. It is called intrinsic density.



For convenience, the top of the valence bond is taken as a zero energy reference level arbitrarily.

The number of electrons in the conduction bond is

$$n = N\,P(Eg)$$

Where P(Eg) is the probability of an electron having energy Eg. It is given by Fermi Dirac function eqn., and N is the total number of electrons in both bands.

Thus,

$$n = \frac{N}{1 + \exp\left[(Eg - E_F)/KT\right]}$$

Where E_F is the Fermi Level

The probability of an electron being in the valence bond is given by putting Eg = 0 in eqn. Hence, the number of electrons in the valence bond is given by

$$n_v = \frac{N}{1 + \exp(-E_F/KT)}$$

The total number of electrons in the semiconductor. N is the sum of those in the conduction band n and those in the valence bond n_v. Thus,

$$N = \frac{N}{1 + \exp\left[(Eg - EF)/KT\right]} + \frac{N}{1 + \exp(-E_F/KT)}$$

For semiconductors at ordinary temperature, Eg >> KT as such in equation one may be neglected when compared with exp $\left(\frac{Eg - E_F}{RT}\right)$ Then

$$1 = \frac{1}{\exp\left(\frac{Eg - E_F}{RT}\right)} + \frac{1}{1 + \exp\left(\frac{-E_F}{RT}\right)}$$

Rearranging the terms, we get

$$\exp\frac{-Eg + E_F}{RT} = \frac{\exp(-E_F/RT)}{1 + \exp(-E_F/RT)}$$

$$\approx \exp\left(\frac{-E_F}{RT}\right)$$

$$\text{or} \quad \exp\left(\frac{2E_F - Eg}{RT}\right) = 1$$

This leads to

$$E_F = Eg/2$$

Thus in an intrinsic semiconductor, the Fermi level lies mid way between the conduction and the valence bonds. The number of conduction electrons at any temperature T is given by

$$n = \frac{N}{1 + \exp(Eg/2KT)} \quad (\therefore E_F = Eg/2)$$

In eqn may be approximated as

$$n \approx N \exp(-Eg / 2RT)$$

From the above discussion, the following conclusions may be drawn.

a) The number of conduction electrons and hence the number of holes in an intrinsic semiconductor, decreases exponentially with increasing gap energy Eg this accounts for lack of charge carries in insulator of large forbidden energy gap.
b) The number of available charge carries increases exponentially with increasing temperature.

The above treatment is only approximate as we have assumed that all states in a bond have the same energy. Really it is not so. A more rigorous analysis must include additions terms in eqn.

The no of conduction bond, in fact is given by

$$n = \int S(E)\, P(E)\, dE$$

Where S(E) is the density of available states in the energy range between E and E + dE, and P(E) is the probability, that an electron can occupy a state of energy E.

$$S(E)\ \frac{8\sqrt{2}\,\pi\, m^{3/2}}{n^3}\ E^{1/2}$$

Inclusion of S(E) and integration over the conduction bond leads to

$$n = N_e\ \exp[(-Eg-E_F)/RT]$$

In a similar way, we arrive at

$$p = N_V \exp[\,-E_F/RT]$$

If we multiply eq: we get

$$np = n_i^2 = N_e\, N_V \exp(-Eg/RT)$$

For the intrinsic material

$$Ni\ = 2\,\frac{(2\pi RT)^{3/2}}{h^2}\ (m_e{}^*\, m_n{}^*)^{3/4} \exp(-Eg/2RT)$$

Notice that this expression agress with the less rigorous one derived earlier since the temperature dependence is largely controlled by the rapidly varying exponential term.

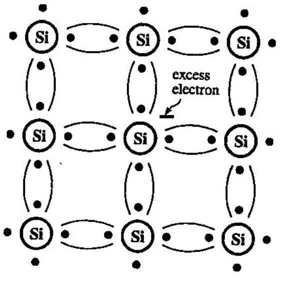
EXTRINSIC SEMICONDUCTORS:

Intrinsic Semiconductors are rarely used in semiconductor devices as their conductivity is not sufficiently high. The electrical conductivity is extremely sensitive to certain types of impurity. It is the ability to modify electrical characteristics of the material by adding chosen impurities that make extrinsic semiconductors important and interesting.

Addition of appropriate quantities of chosen impurities is called doping, usually, only minute quantities of dopants (1 part in 10^3 to 10^{10}) are required. Extrinsic or doped semiconductors are classified into main two main types according to the type of charge carries that predominate. They are the n-type and the p-type.

N-TYPE SEMICONDUCTORS:

Doping with a pentavalent impurity like phosphorous, arsenic or antimony the semiconductor becomes rich in conduction electrons. It is called n-type the bond structure of an n-type semiconductor is shown in Fig below.

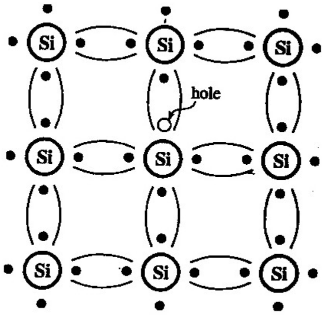


FREE ELECTRON DUE TO DOPING

Even at room temperature, nearby all impurity atoms lose an electron into the conduction bond by thermal ionization. The additional electrons contribute to the conductivity in the same way as those excited thermally from the valence bond. The essential difference beam the two mechanisms is that ionized impurities remain fixed and no holes are produced. Since penta valent impurities denote extra carries elections, they are called donors.

P-TYPE SEMICONDUCTORS:-

p-type semiconductors have holes as majority charge carries. They are produced by doping an intrinsic semiconductor with trivalent impurities.(e.g. boron, aluminium, gallium, or indium). These dopants have three valence electrons in their outer shell. Each impurity is short of one electron bar covalent bonding. The vacancy thus created is bound to the atom at OK. It is not a hole. But at some higher temperature an electron from a neighbouring atom can fill the vacancy leaving a hole in the valence bond for conduction. It behaves as a positively charge particle of effective mass m_h*. The bond structure of a p-type semiconductor is shown in Fig below.



FORMATION OF HOLE DUE TO DOPING

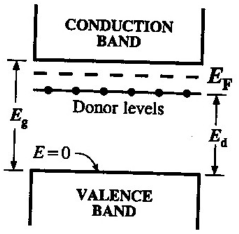
Dopants of the trivalent type are called acceptors, since they accept electrons to create holes above the tope of the valence bond. The acceptor energy level is small compared with thermal energy of an electron at room temperature. As such nearly all acceptor levels are occupied and each acceptor atom creates a hole in the valence bond. In extrinsic semiconductors, there are two types of charge carries. In n-type, electrons are more than holes. Hence electrons are majority carriers and holes are minority carries. Holes are majority carries in p-type semiconductors; electrons are minority carriers.

CARRIER CONCENTRATION IN EXTRINSIC SEMICONDUCTORS:

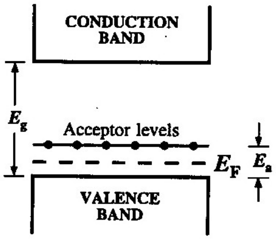
Equation gives the relation been electron and hole concentrations in a semiconductor. Existence of charge neutrality in a crystal also relates n and p. The charge neutrality may be stated as

$$N_D + p = N_A + n$$

Since donors atoms are all ionized, N_D positive charge per cubic meter are contributed by N_D donor ions. Hence the total positive charge density = N_D + p. Similarly if N_A is the concentration of the acceptor ions, they contribute N_A negative charge per cubic meter. The total negative charges density = N_A + n. Since the semiconductor is electrically neutral the magnitude of the positive charge density must be equal to the magnitude of the total negative charge density.



FERMI LEVEL AND DONOR LEVELS



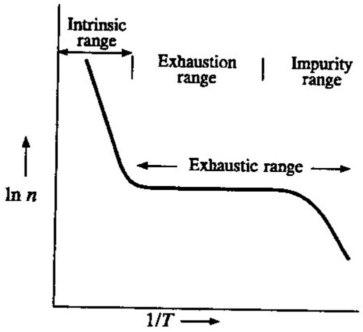
FERMI LEVEL AND ACCEPTOR LEVELS

n-type material : $N_A = 0$ Since n >> p, eqn reduces to $n \approx N_D$ i.e., in an n-type material the where subscript n indicates n-type material. The concentration p_n of holes in the n-type semiconductor is obtained from eqn i.e.,

$$n_n \, p_n = n_i^2$$

Thus $$p_n \approx \frac{n_i^2}{N_D}$$

Similarly, for a p-type semiconductor $p_p \approx N_A$ and $$n_p \approx \frac{n_i^2}{N_A}$$



DEPENDENCE OF ELECTRON CONCENTRATION ON TEMPERATUR

Expression for electrical conductivity:

There are two types of carries in a Semiconductor electrons and holes. Both these carries contribute to conduction. The general expression for conductivity can be written down as

$$\sigma = e\,(n\mu_e + \rho\,\mu_h)$$

Where μ_e and μ_h are motilities of electrons and holes respectively.

A. Intrinsic Semiconductor; For an intrinsic Semiconductor

$$n = p = n_i$$

eqn becomes

$$\sigma_i = en_i(\mu_n + \mu_p)$$

If the scattering is predominantly due to lattice vibrations.

$$\mu_e = AT^{3/2}$$

$$\mu_h = BT^{3/2}$$

We may put $\mu_e + \mu_h = (A + B)T^{3/2} = CT^{3/2}$

$$\sigma_i = n_i CT^{3/2}$$

Substituting for n_i from eq we get

$$\sigma_i = 2\left(\frac{2\mu RT}{h2}\right)^{3/2} CT^{3/2}(m_e^* m_h^*)^{3/4} \exp\left(\frac{-Eg}{2RT}\right)$$

$$\log \sigma_i = \log x - \frac{Eg}{2RT}$$

A graph of $\log \sigma_i$ Vs $1/T$ gives a straight line shown in fig below:

VARIATION OF FERMI LEVEL WITH IMPURITY CONCENTRATION*:*

In N-type semiconductor at 0K the Fermi level lies at the middle of donor level (Ed) and bottom of the conduction band (Ec) i.e.., Ef= (Ed+Ec)/2. As increasing the temperature the Fermi level shifts towards the Fermi level of intrinsic semiconductor (Ei) and the shifting takes place slowly for higher donor concentration materials. Since lightly doped semiconductor will behave in intrinsic manner only after all the donor atoms are ionized.

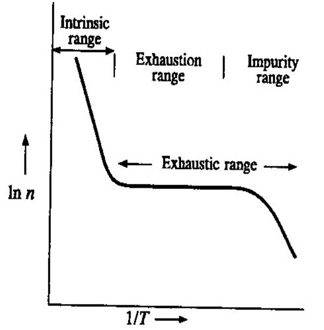
For p-type semiconductor at 0K, the Fermi level lies at the middle of acceptor level (Ea) and top of the valence band (Ev) i.e., Ef=(Ed+Ec)/2. As increasing the temperature the level shifts towards the Fermi level of intrinsic semiconductor (Ei) and this shifting takes place slowly for higher acceptor concentration materials. Since highly doped will behave in intrinsic manner only after all the acceptor atoms are ionized.

Below figures show the variation of Fermi level in N-type and P-type semiconductors with temperature and concentration of impurities

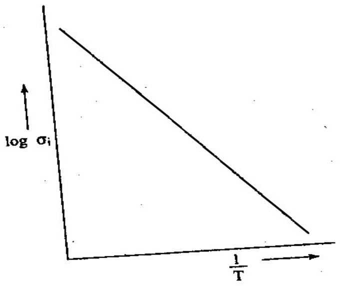
VARIATION OF CARRIER CONCENTRATION AND CONDUCTIVITY WITH TEMPERATURE:

For N-type semiconductor, the variation of N & P with temperature & conductivity are as shown in fig. At 0K both conduction & valence bands are free from any charge carriers and hence the conductivity is zero. With increase of temperature, donor atoms get ionized and hence electron concentration in conduction band increases with temperature until all the donor atoms are ionized. This range is called impurity range. The concentration of electrons in the conduction band remains constant over a certain temperature range. This region is called the exhaustion range & in this range Fermi level crosses the donor level. Though the concentration of electrons remains the same due to decrease in electron mobility with increase of temperature, the conductivity decreases slightly. As this temperature is increased further covalent bonds are broken up and electron-hole pairs are generated and more no. of electrons reaches the conduction band. The Fermi level moves down until it reaches the forbidden gap. The material practically becomes intrinsic and so this range is called intrinsic range. The holes are also generated in the intrinsic range. So the dotted line in the figure shows the increase of holes with temperature.

The flat region (exhaustion range) is observable only if Nd is small. For higher values Nd impurity range is extended towards the intrinsic range



DEPENDENCE OF ELECTRON CONCENTRATION ON TEMPERATUR



Variation of electrical conductivity with temperature

DRIFT CURRENT:

In an electric field E, the drift velocity V_d of carriers superposes on the thermal velocity V_{th}. But the flow of charge carriers results in an electric current, known as the drift current. Let a field E be applied, in the positive creating drifts currents J_{nd} and J_{pd} of electrons and holes respectively.

Without E, the carriers move randomly with rms velocity V_{th}. Their mean velocity is zero. The current density will be zero. But the field E applied, the electrons have the velocity V_{de} and the holes V_{dh}.

Consider free electrons in a Semiconductor moving with uniform velocity Vde in the negative x direction due to an electric field E. Consider a smaller rectangular block of AB of length V_{de} inside the Semiconductor. Let the area of the side faces each be unity. The total charge Q in the elements AB is

Q = Volume of the element x density of partially change on each particle

$= (V_{de} \times 1 \times 1) \times n \times -q$

Thus $Q = -qnV_{de}$

Where n is the number density of electrons. The entire charge of the block will cross the face B, in unit time. Thus the drift current density Jnd due to free electrons at the face B will be.

$J_{nd} = - q\ nV_{de}$

Similarly for holes $J_{pd} = q\ nV_{dh}$

but $\mathbf{V_{de} = -\mu_n E}$

and $V_{dh} = \mu_p E$

hence $J_{nd} = n\ q\mu_n E$

and $J_{pd} = p\ q\mu_n E$

The total drift current due to both electrons and holes J_d is

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

Even though electrons and holes move in opposite direction the effective direction of current flow, is the same for both and hence they get added up. Ohm's Law can be written in terms of electrical conductivity, as

$$J_d = \sigma E$$

Equating the RHS of eq we have

$$\sigma = nq\mu_n + pq\mu_p = \sigma_n + \sigma_p$$

For an intrinsic Semiconductor $n = p = n_i$

$$\sigma_i = n_i\ q(\mu_n + \mu_p)$$

DIFFUSION CURRENTS:

1. Diffusion Current: Electric current is Setup by the directed movement of charge carriers. The movements of charge carriers could be due to either drift or diffusion. Non- uniform concentration of carriers gives rise to diffusion. The first law of diffusion by Fick States that the flux F, i.e., the particle current is proportional and is directed to opposite to the concentration gradient of particles. It can be written mathematically, in terms of concentration N, as

$$F = -D\ \overline{V}\ N$$

Where D stands for diffusion constant.

In one dimension it is written as

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

In terms of Je and Jp the flux densities of electrons holes and their densities n and p respectively.

We get $J_e = -D_n \frac{\partial N}{\partial x}$

and $J_n = -D_p\ \frac{\partial p}{\partial x}$

Where D_n and D_p are the electron and hole diffusion constant constants respectively. Then the diffusion current densities become

$$J_n \text{ diff} = q D_n \frac{\partial N}{\partial x}$$

$$J_p \text{ diff} = - q D_p \frac{\partial p}{\partial x}$$

THE EINSTEIN RELATIONS:

When both the drift and the diffusion currents are present total electron and hole current densities can be summed up as

$$J_n = J_{nd} + J_n \text{ diff}$$

$$J_n = nq\mu_n E + qD_n \frac{\partial n}{\partial x}$$

$$J_p = pq\mu_p E - qD_p \frac{\partial p}{\partial x}$$

Now, let us consider a non uniformly doped n-type slab of the Semiconductor fig shown below (9) under thermal equilibrium. Let the slab be intrinsic at x = 0 while the donor concentration, increases gradually upto x = 1, beyond which it becomes a constant. Assume that the Semiconductor is non-degenerate and that all the donors are ionized. Due to the concentration gradient, electrons tend to diffuse to the left to x = l. This diffusion leaves behind a positive charge of ionized donors beyond x = 1 and accumulates electron near x = 0 plane. This charge imbalance. Sets up an electric field in which the electrons experience fill towards x = 1.

Fig shows illustrates the equilibrium potential $\phi(x)$ fig shown refers to the bond diagram of the Semiconductor.

Both E1 and EF coincide till x = 0 when n0 = ni that EF continues to be the same throughout the slab. But since the bond structure is not changed due to doping, the bond edges bond with equal separation all along. How ever, the level Ei continues to lie midway between EV and E.

In thermal equilibrium, the electrons tend to diffuse down the concentration tending to setup a current from the right to left. The presence of electric field tends to set up drift current of electrons in the opposite direction. Both the currents add upto zero. Thus we obtain

$$J_n = qD_n \frac{\partial n}{\partial x} + nq\mu_n E = 0$$

$$\text{i.e.,}\quad D_n \frac{\partial n}{\partial x} + n\mu_n E = 0$$

For a non degenerate Semi conductor.

$$n(x) = n_i \exp \frac{E_F - E_i(x)}{RT}$$

Thus relation is valid at all points in the Semiconductor further. The electronic concentration is not influenced by the small in balance of charge. Energy is defined in terms of $\phi(x)$ the potential.

$$E(x) = -q\phi(x)$$

Then $E_F - E_i(x) = E_i(0) - E_i(x) = -q[\phi(0) - \phi(x)]$

Assuming $\phi(0) = 0$ we get $n(x) = n_i \exp \dfrac{q\phi(x)}{RT}$

Substituting $\dfrac{dn}{dx}$ from eqn along with $E = \dfrac{-d\phi}{dx}$ we get

$$D_n \frac{nq}{RT} \frac{d\phi}{dx} = \mu_n\, n \frac{d\phi}{dx}$$

Simplifying we obtain, $D_n = \dfrac{RT}{q} \mu_n$

Simplifying for holes $D_p = \dfrac{RT}{q} \mu_p$

These are known as Einstein relations and the factor (RT/q) as thermal voltage. The above relations hold good only for non degenerate Semiconductors. For the degenerate case the Einstein's relations are complex.

It is clear from the Einstein's relation that D_p μ_p and D_n,μ_n are related and they are functions of temperature also. The relation of diffusion constant D and the mobility μ confirms the fact, that both the diffusion an drift processes arise due to thermal motion and scattering of free electrons, even though they appear to be different.

EQUATION OF CONTINUITY:

If the equilibrium concentrations of carriers in a Semiconductor are disturbed, the concentrations of electrons and holes vary with time. How ever the carrier concentration in a Semiconductor is a function of both time and position.

The fundamental law governing the flow of charge is called the continuity equation. It is arrived at by assuming law to conservation of charge provided drift diffusion and recombination processes are taken into account.

Consider a small length Δx of a Semiconductor sample with area A in the Z plane fig shown above. The hole current density leaving the volume ($\Delta x \Delta$) under consideration is $J_p(x + \Delta x)$ and the current density entering the volume is $J_p(x)$. $J_p(x + \Delta x)$ may be smaller or larger than $J_p(x)$ depending upon the generation and recombination of carriers in the element. The resulting change in hole concentration per unit time.

∂p = hole flux entering per unit time – hole flux leaving per unit

$$\frac{\partial p}{\partial t}\Big|_{x \to x+\Delta x} = J_p(x) - \frac{J_p(x+\Delta x)}{q\,\Delta x} - \frac{\delta p}{T_p}$$

Where T_p is the recombination life time. According to eqn, the rate of hole build up is equla to the rate of increase of hole concentration remains the recombination rate. As Δx approaches zero, we may write

$$\frac{\partial p}{\partial t}(x,t) = \frac{\partial\,\delta p}{\partial t} = \frac{-1\,\partial J_p}{q\,\partial x} - \frac{\delta p}{T_p}$$

The above is called the continuity equation for holes for electrons

$$\frac{\partial \delta n}{\partial t} = \frac{1}{q}\frac{\partial J_n}{dx} - \frac{\delta n}{Tn}$$

If there is no drift we may write

$$J_n(\text{diff}) = qD_n \frac{\partial \delta}{\partial x}$$

Substituting the above eqn we get the following diffusion eqn for electrons.

$$\frac{\partial \delta n}{\partial t} = D_n \frac{\partial^2 \delta n}{\partial x^2} - \frac{\delta n}{T_n}$$

For holes we may write

$$\frac{\partial \delta p}{\partial t} = D_p \frac{\partial^2 \delta p}{\partial x^2} - \frac{\delta p}{T_p}$$

FORMATION OF P-N JUNCTION:

In a piece of semiconductor material of one half is doped by P-type impurity and the other half is doped by n-type impurity. A p-n junction diode is formed. The plane dividing the two halves or zones is called p-n junction. At the junction, the free electrons diffuse over to the p-side and holes diffuse over to the n-side. This process is called diffusion. Hence acceptor ions at p-type become negatively charged and donor ions at n-side become positively charged. These charged ions repel the free electrons and holes to diffuse further to p-side and n-side respectively. This region is called depletion layer or space region or transition region. This region is of the order of few micrometers thickness. As a consequence of the induced electric field across the depletion layer an electrostatic potential difference is established between p and n-regions, which is the potential barrier, junction barrier, diffusional potential or contact potential VB. The magnitude of the contact VB varies with doping levels and temperature. VB is 0.3V for Ge and 0.72V for Si.

The shape of the charge density at the junction depends upon how the diode is doped.

There are different processes to produce p-n junction diodes. These junctions thus produced accordingly are known as (1)GROWN JUNCTION (2) ALLOY JUNCTION (3) DIFFUSED JUNCTION.

GROWN JUNCTION:

When donor impurities are introduced into oneside and acceptor impurities into the other side of a single crystal at the time of crystal growing from a molten of silicon or germanium, the grown junction are fo med. Grown junction have relatively gradual transition from p-type or n-type and are usually called as gr ded junction.

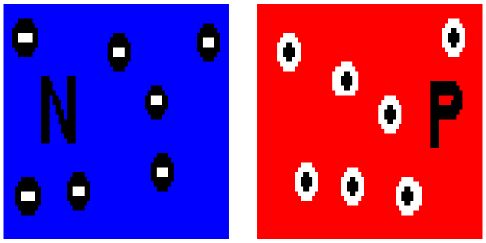
AL OY JUNCTION:

In this process a tiny dot or pellet of p-type impurity is placed on the surface of an n-type silicon wa er and the two are heated well above the melting temperature of impurity. Consequently impurity me ts and dissolves some of the silicon. Then temperature is lowered and silicon freezes to form a single cr stal having a p-n junction.

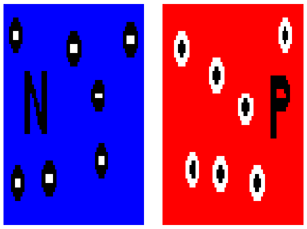
DI FUSED JUNCTION:

Solid Diffusion: In this process, a p-type impurity is painted on an n-type substrate and then su strate is heated until the impurity diffuse into the substrate at a short distance to form p-type layer.

Gaseous Diffusion: In this process, an n-type material is heated in a chamber containing a high co centration of an acceptor impurity in vapour form some of the acceptor atoms are diffused into n-type su strate to form the p-type layer thus creating a p-n type junction.

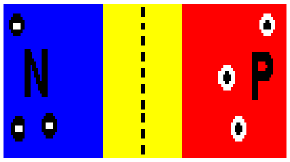


We've seen that it is possible to turn a crystal of pure silicon into a moderately good electrical conductor by adding an impurity such as arsenic or phosphorus (for an N-type semiconductor) or aluminum or gallium (for a P-type semiconductor). By itself, however, a single type of semiconductor material isn't very useful. Useful applications start to happen only when a single semiconductor crystal contains both P-type and N-type regions. Here we will examine the properties of a single silicon crystal which is half N-type and half P-type.



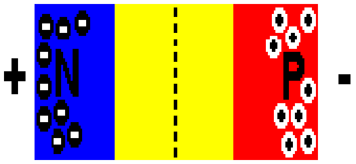
Consider the silicon crystal represented to the right. Half is N-type while the other half is P-type. We've shown the two types separated slightly, as if they were two separate crystals. The free electrons in the N-type crystal are represented by small black circles with a "-" sign inside to indicate their polarity. The holes in the P-type crystal are shown as small white circles with a "+" inside.

In the real world, it isn't possible to join two such crystals together usefully. Therefore, a practical PN junction can only be created by inserting different impurities into different parts of a single crystal. So let's see what happens when we join the N- and P-type crystals together, so that the result is one crystal with a sharp boundary between the two types.

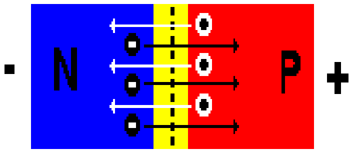


You might think that, left to itself, it would just sit there. However, this is not the case. Instead, an interesting interaction occurs at the junction. The extra electrons in the N region will seek to lose energy by filling the holes in the P region. This leaves an empty zone, or *depletion region* as it is called, around the junction as shown to the right. This action also leaves a small electrical imbalance inside the crystal. The N region is missing some electrons so it has a positive charge. Those electrons have migrated to fill holes in the P region, which therefore has a negative charge. This electrical imbalance amounts to about 0.3 volt in a germanium crystal, and about 0.65 to 0.7 volt in a silicon crystal. This will vary somewhat depending on the concentration of the impurities on either side of the junction.

Unfortunately, it is not possible to exploit this electrical imbalance as a power source; it doesn't work that way. However, we can apply an external voltage to the crystal and see what happens in response. Let's take a look at the possibilities.



Suppose we apply a voltage to the outside ends of our PN crystal. We have two choices. In this case, the positive voltage is applied to the N-type material. In response, we see that the positive voltage applied to the N-type material attracts any free electrons towards the end of the crystal and away from the junction, while the negative voltage applied to the P-type end attracts holes away from the junction on this end. The result is that all available current carriers are attracted away from the junction, and the depletion region grows correspondingly larger. There is no current flow through the crystal because all available current carriers are attracted away from the junction, and cannot cross. (We are here considering an ideal crystal -- in real life, the crystal can't be perfect, and some leakage current does flow.) This is known as *reverse bias* applied to the semiconductor crystal.



Here the applied voltage polarities have been reversed. Now, the negative volatge applied to the N-type end pushes electrons towards the junction, while the positive voltage at the P-type end pushes holes towards the junction. This has the effect of shrinking the depletion region. As the applied voltage exceeds the internal electrical imbalance, current carriers of both types can cross the junction into the opposite ends of the crystal. Now, electrons in the P-type end are attracted to the positive applied voltage, while holes in the N-type end are attracted to the negative applied voltage. This is the condition of *forward bias*.

Because of this behavior, an electrical current can flow through the junction in the forward direction, but not in the reverse direction. This is the basic nature of an ordinary semiconductor diode.

It is important to realize that holes exist only within the crystal. A hole reaching the negative terminal of the crystal is filled by an electron from the power source and simply disappears. At the positive terminal, the power supply attracts an electron out of the crystal, leaving a hole behind to move through the crystal toward the junction again.

In some literature, you might see the N-type connection designated the *cathode* of the diode, while the P-type connection is called the *anode*. These designations come from the days of vacuum tubes, but are still in use. Electrons always move from cathode to anode inside the diode.

One point that needs to be recognized is that there is a limit to the magnitude of the reverse voltage that can be applied to any PN junction. As the applied reverse voltage increases, the depletion region continues to expand. If either end of the depletion region approaches its electrical contact too closely, the applied voltage has become high enough to generate an electrical arc straight through the crystal. This will destroy the diode.

It is also possible to allow too much current to flow through the diode in the forward direction. The crystal is not a perfect conductor, remember; it does exhibit some resistance. Heavy current flow will generate some heat within that resistance. If the resulting temperature gets too high, the semiconductor crystal will actually melt, again destroying its usefulness.

Current–voltage characteristic

A semiconductor diode’s behavior in a circuit is given by its current–voltage characteristic, or I–V graph (see graph at right). The shape of the curve is determined by the transport of charge carriers through the so-called *depletion layer* or *depletion region* that exists at the p-n junction between differing semiconductors. When a p-n junction is first created, conduction band (mobile) electrons from the N-doped region diffuse into the P-doped region where there is a large population of holes (places for electrons in which no electron is present) with which the electrons “recombine”. When a mobile electron recombines with a hole, both hole and electron vanish, leaving behind an immobile positively charged donor (the dopant) on the N-side and negatively charged acceptor (the dopant) on the P-side. The region around the p-n junction becomes depleted of charge carriers and thus behaves as an insulator. However, the width of the depletion region (called the depletion width) cannot grow without limit. For each electron-hole pair that recombines, a positively-charged dopant ion is left behind in the N-doped region, and a negatively charged dopant ion is left behind in the P-doped region. As recombination proceeds and more ions are created, an increasing electric field develops through the depletion zone which acts to slow and then finally stop recombination. At this point, there is a “built-in” potential across the depletion zone.If an external voltage is placed across the diode with the same polarity as the built-in potential, the depletion zone continues to act as an insulator, preventing any significant electric current flow (unless electron/hole pairs are actively being created in the junction by, for instance, light. see photodiode). This is the *reverse bias* phenomenon. However, if the polarity of the external voltage opposes the built-in potential, recombination can once again proceed, resulting in substantial electric current through the p-n junction (i.e. substantial numbers of electrons and holes recombine at the junction).. For silicon diodes, the built-in potential is approximately 0.6 V. Thus, if an external current is passed through the diode, about 0.6 V will be developed across the diode such that the P-doped region is positive with respect to the N-doped region and the diode is said to be “turned on” as it has a *forward bias*.

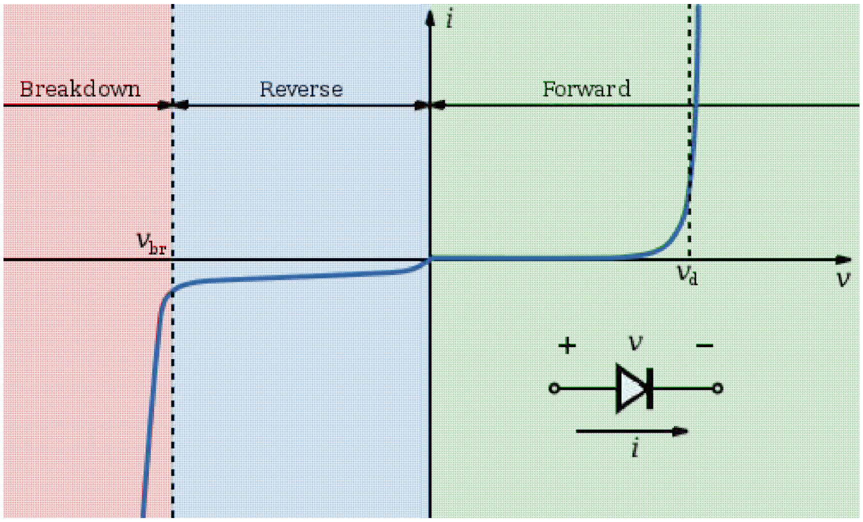


Figure 5: I–V characteristics of a P-N junction diode

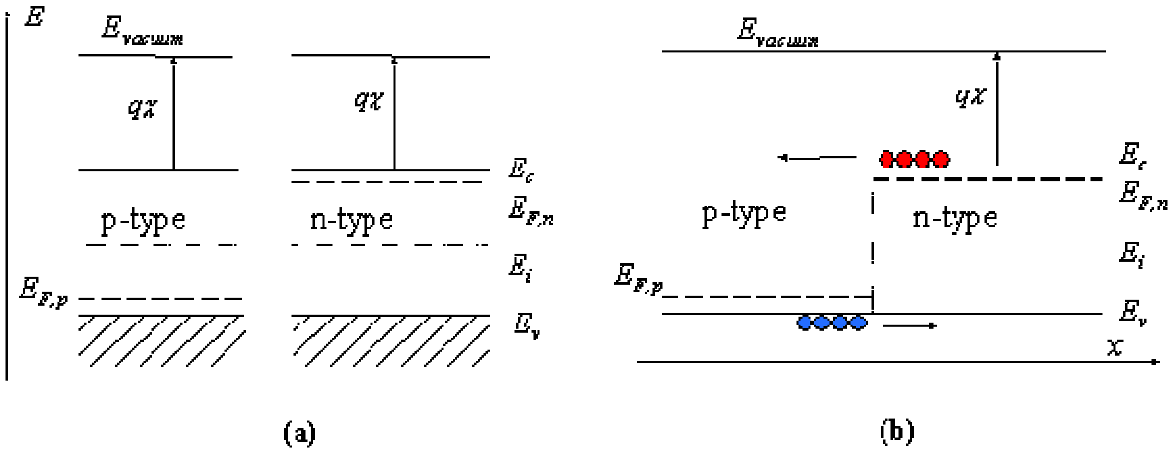
A diode's I–V characteristic can be approximated by four regions of operation (see the figure at right).

At very large reverse bias, beyond the peak inverse voltage or PIV, a process called reverse breakdown occurs which causes a large increase in current (i.e. a large number of electrons and holes are created at, and move away from the pn junction) that usually damages the device permanently. The avalanche diode is deliberately designed for use in the avalanche region. In the zener diode, the concept of PIV is not applicable. A zener diode contains a heavily doped p-n junction allowing electrons to tunnel from the valence band of the p-type material to the conduction band of the n-type material, such that the reverse voltage is "clamped" to a known value (called the *zener voltage*), and avalanche does not occur. Both devices, however, do have a limit to the maximum current and power in the clamped reverse voltage region. Also, following the end of forward conduction in any diode, there is reverse current for a short time. The device does not attain its full blocking capability until the reverse current ceases.The second region, at reverse biases more positive than the PIV, has only a very small reverse saturation current. In the reverse bias region for a normal P-N rectifier diode, the current through the device is very low (in the µA range). However, this is temperature dependent, and at suffiently high temperatures, a substantial amount of reverse current can be observed (mA or more).

The third region is forward but small bias, where only a small forward current is conducted.

As the potential difference is increased above an arbitrarily defined "cut-in voltage" or "on-voltage" or "diode forward voltage drop (V_d)", the diode current becomes appreciable (the level of current considered "appreciable" and the value of cut-in voltage depends on the application), and the diode presents a very low resistance. The current–voltage curve is exponential. In a normal silicon diode at rated currents, the arbitrary "cut-in" voltage is defined as 0.6 to 0.7 volts.

The junction is biased with a voltage V_a as shown in Figure. We will call the junction forward-biased if a positive voltage is applied to the *p*-doped region and reversed-biased if a negative voltage is applied to the *p*-doped region. The contact to the *p*-type region is also called the anode, while the contact to the *n*-type region is called the cathode, in reference to the *anions* or positive carriers and *cations* or negative carriers in each of these regions.

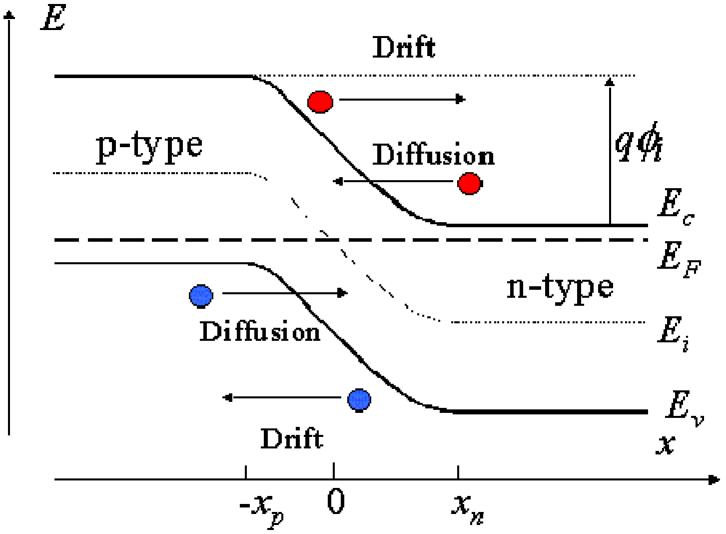


Energy band diagram of a p-n junction (a) before and (b) after merging the n-type and p-type regions

Note that this does not automatically align the Fermi energies, $E_{F,n}$ and $E_{F,p}$. Also, note that this flatband diagram is not an equilibrium diagram since both electrons and holes can lower their energy by crossing the junction. A motion of electrons and holes is therefore expected before thermal equilibrium is obtained. The diagram shown in Figure (b) is called a flatband diagram. This name refers to the horizontal band edges. It also implies that there is no field and no net charge in the semiconductor.

Thermal equilibrium

To reach thermal equilibrium, electrons/holes close to the metallurgical junction diffuse across the junction into the *p*-type/*n*-type region where hardly any electrons/holes are present. This process leaves the ionized donors (acceptors) behind, creating a region around the junction, which is depleted of mobile carriers. We call this region the depletion region, extending from $x = -x_p$ to $x = x_n$. The charge due to the ionized donors and acceptors causes an electric field, which in turn causes a drift of carriers in the opposite direction. The diffusion of carriers continues until the drift current balances the diffusion current, thereby reaching thermal equilibrium as indicated by a constant Fermi energy. This situation is shown in Figure



Energy band diagram of a p-n junction in thermal equilibrium

While in thermal equilibrium no external voltage is applied between the *n*-type and *p*-type material, there is an internal potential, ϕ_i, which is caused by the workfunction difference between the *n*-type and *p*-type semiconductors. This potential equals the *built-in* potential, which will be further discussed in the next section.

The built-in potential

The built-in potential in a semiconductor equals the potential across the depletion region in thermal equilibrium. Since thermal equilibrium implies that the Fermi energy is constant throughout the p-n diode, the built-in potential equals the difference between the Fermi energies, E_{Fn} and E_{Fp}, divided by the electronic charge. It also equals the sum of the bulk potentials of each region, ϕ_n and ϕ_p, since the bulk potential quantifies the distance between the Fermi energy and the intrinsic energy. This yields the following expression for the built-in potential.

$$\phi_i = V_t \ln \frac{N_d N_a}{n_i^2}$$

Example	An abrupt silicon p-n junction consists of a *p*-type region containing 2×10^{16} cm^{-3} acceptors and an *n*-type region containing also 10^{16} cm^{-3} acceptors in addition to 10^{17} cm^{-3} donors. a. Calculate the thermal equilibrium density of electrons and holes in the *p*-type region as well as both densities in the *n*-type region. b. Calculate the built-in potential of the p-n junction

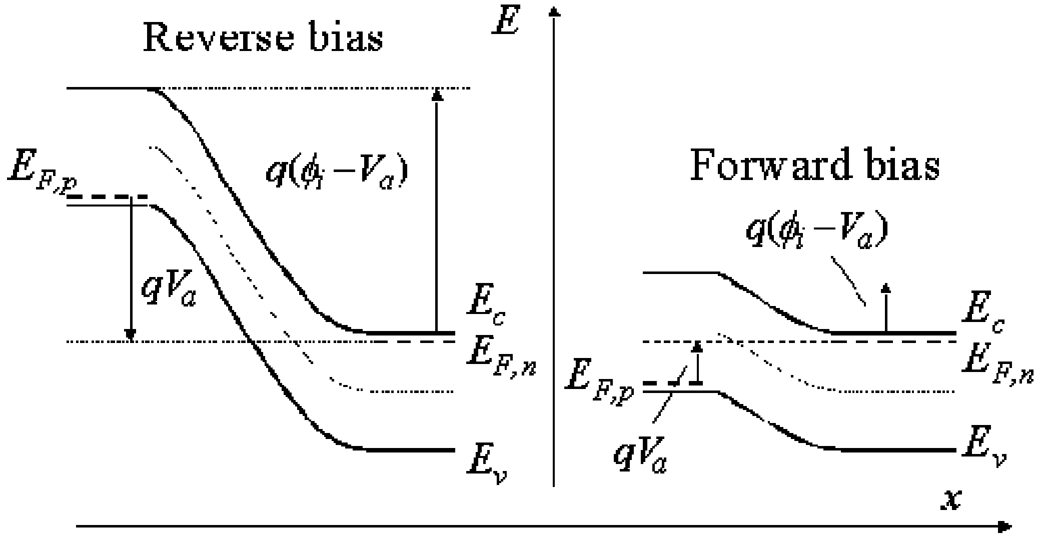
	c. Calculate the built-in potential of the p-n junction at 400 K.
Solution	a. The thermal equilibrium densities are: In the *p*-type region: $p = N_a = 2 \times 10^{16}$ cm^{-3} $n = n_i^2/p = 10^{20}/2 \times 10^{16} = 5 \times 10^3$ cm^{-3} In the *n*-type region $n = N_d - N_a = 9 \times 10^{16}$ cm^{-3} $p = n_i2/n = 10^{20}/(1 \times 10^{16}) = 1.11 \times 10^3$ cm^{-3} b. The built-in potential is obtained from: $$\phi_i = V_t \ln \frac{p_n n_p}{n_i^2} = 0.0259 \ln \frac{2\times10^{16}\times9\times10^{16}}{10^{20}} = 0.79\text{ V}$$ c. Similarly, the built-in potential at 400 K equals: $$\phi_i = V_t \ln \frac{p_n n_p}{n_i^2} = 0.0345 \ln \frac{2\times10^{16}\times9\times10^{16}}{(4.52\times10^{12})^2} = 0.63\text{ V}$$ where the instrinsic carrier density at 400 K was obtained from example 2.4.b

. Forward and reverse bias

We now consider a p-n diode with an applied bias voltage, V_a. A forward bias corresponds to applying a positive voltage to the anode (the *p*-type region) relative to the cathode (the *n*-type region). A reverse bias corresponds to a negative voltage applied to the cathode. Both bias modes are illustrated with Figure 4.2.4. The applied voltage is proportional to the difference between the Fermi energy in the *n*-type and *p*-type quasi-neutral regions.

As a negative voltage is applied, the potential across the semiconductor increases and so does the depletion layer width. As a positive voltage is applied, the potential across the semiconductor decreases and with it the depletion layer width. The total potential across the semiconductor equals the built-in potential minus the applied voltage, or:

$$\phi = \phi_i - V_a$$



Energy band diagram of a p-n junction under reverse and forward bias

P-N DIODE AS A RECTIFIER:

When ac power supply is connected across a PN junction during positive half of the a.c. cycle diode is forward biased. During negative half of the a.c. cycle diode is reverse biased and hence almost no current flows for negative half cycle. Thus the diode allows the current to flow in only one direction during forward bias. This unidirectional character of PN junction is used as a rectifier.

A rectifier is a device which converts alternating current (a.c.) to direct current (d.c.) or unidirectional current (d.c.)

There are two types of rectifiers:
(i) half wave rectifier
(ii) full wave rectifier

HALF WAVE RECTIFIER:

The eKt of half wave rectifier using the PN junction is as shown in figure. A.C. is connected to the primary winding (p) of the transformer. The diode is connected to the secondary winding of AB, the transformer through load resistance. During the positive half cycle, A is positive hence the diode is forward biased and forward current flow through the junction and load resistance R_L. When the input voltage increases, output voltage also increases when the input voltage drops to zero, output voltage also drops to zero. During negative half cycle of the input voltage the diode is reverse biased and hence there is no current flows through the junction and load resistance (R_L).

Hence across R_L the current is unidirectional but pulsating. Thus output consists of both a.c. and d.c. components. The a.c. components can be filtered by using filter ckts.

The efficiency of half wave rectifier = 40.6%

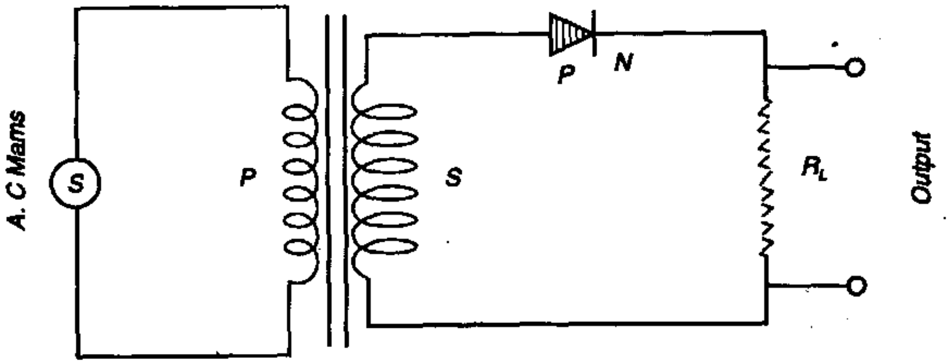


Fig. 12.3

32. *Full wave rectifier* circuit is shown in Fig. 12.4.

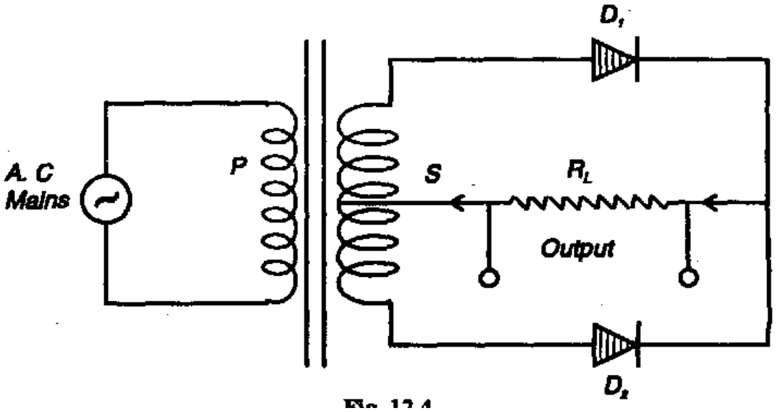
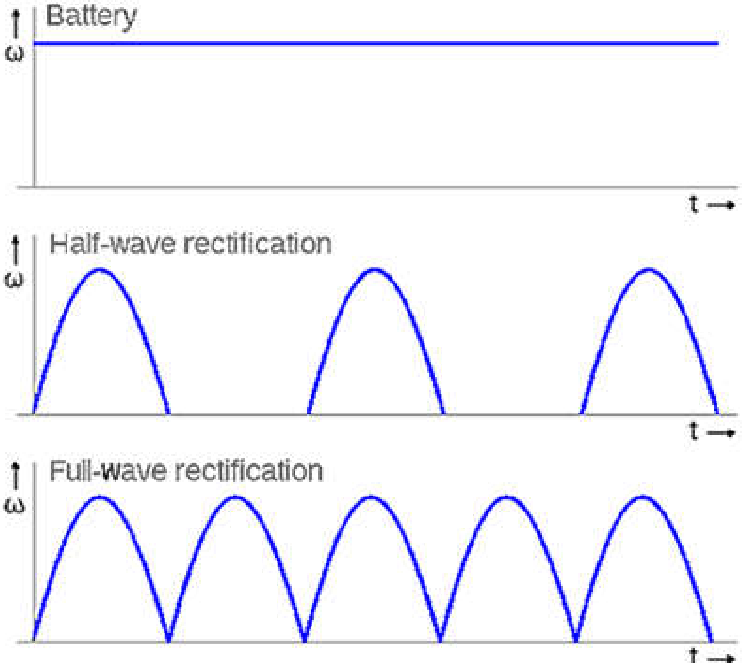


Fig. 12.4



FULL WAVE RECTIFIER:

In a full wave rectifier two PN junction diodes are used. Two half wave rectifiers are combined such that the output current flows during the entire cycle of the input voltage. The eKt diagram of a central tapped full wave rectifier is as shown in figure. The two diodes D_1 and D_2 are connected to the secondary winding (AB) of the transformer. The transformer, the load resistor in connected between the centre tap of the transformer and the line joining the n-side of diodes.

During the positive half cycle D_1 is forward biased and diode D_2 is reverse biased. Hence this half cycle drives the diode D_1 and current appears at R_L for negative half cycle. D_1 become reverse biased and D_2 is forward biased. Hence this half cycle drives the diodes D_2 and current appears for two half cycles (i.e.), for full cycle. Using proper filter eKt current is made constant.
The efficiency of full wave rectifier = 81.2%

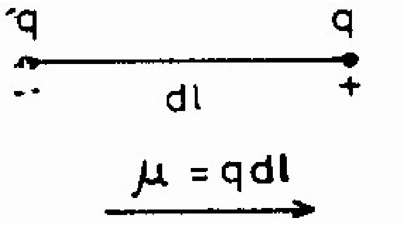
UNIT - III

DIELECTRIC PROPERTIES

Introduction:

Dielectrics are insulating materials. In dielectrics, all the electrons are bound to their parent molecules and there are no free charges. Even with normal voltage or thermal energy, electrons are not released.

Electric Dipole: A system consisting of two equal and opposite charges separated by a distance is called electric dipole.



Dipole moment: The product of charge and distance between two charges is called dipole moment.

i e, $\mu = q \times dl$

Permittivity: It is a quantity, which represents the dielectric property of a medium. Permittivity of a medium indicates the easily Polarisable nature of the material.

Units: Faraday / Meter or Coulomb / Newton-meter .

Dielectric constant: The dielectric characteristics are determined by the dielectric constant. The dielectric constant or relative permittivity of a medium is defined as the ratio between the permittivity of the medium to the permittivity of the free space.

$\varepsilon_r = \varepsilon / \varepsilon_0 = C / C_0$ where

ε is permittivity of the medium
ε_0 is permittivity of the free space
C is the capacitance of the capacitor with dielectric
C_0 is the capacitance of the capacitor without dielectric

Units: No Units.

Capacitance: The property of a conductor or system of conductor that describes its ability to store electric charge.

$C = q / V = A \varepsilon / d$ where

C is capacitance of capacitor
q is charge on the capacitor plate
V is potential difference between plates
A is area of capacitor plate
ε is permittivity of medium
d is distance between capacitor plates

Units: Farad.

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.

$\boldsymbol{\mu} = \alpha E$
where α the constant of proportionality is called polarizability
.It can be defined as induced dipole moment per unit electric field.

$\alpha = \boldsymbol{\mu} / E$

Units: Farad – meter^2

Polarization Vector (P) : The dipole moment per unit volume of the dielectric material is called polarization vector **P** .if **μ** is the average dipole moment per molecule and N is the number of molecules per unit volume then polarization vector

$\mathbf{P} = \mathbf{N} \boldsymbol{\mu}$

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

Electric Flux Density or Electric Displacement (D): The Electric Flux Density or Electric Displacement at a point in the material is given by

$D = \varepsilon_r \varepsilon_0 E$ -------------(1) where

E is electric field strength
ε_r is relative permittivity of material
ε_0 is permittivity of free space

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

Hence $D = \varepsilon_0 E + \mathbf{P}$ -----------(2) Since D

$= \varepsilon_0 \varepsilon_r E$

$\varepsilon_0 \varepsilon_r E = \varepsilon_0 E + \mathbf{P}\,\mathbf{P} =$

$\varepsilon_0 \varepsilon_r E - \varepsilon_0 E$

$\mathbf{P} = \varepsilon_0(\varepsilon_r - 1) E.$

Electric Susceptibility (χ_e) : The polarization **P** is proportional to the total electronic flux density E and is in the same direction of E . Therefore, the polarization vector can be written as

$\mathbf{P} = \varepsilon_0 \chi_e E$

Therefore $\chi_e = \mathbf{P} / \varepsilon_0 E = \varepsilon_0(\varepsilon_r - 1) E / \varepsilon_0 E$

$\chi_e = (\varepsilon_r - 1)$

Dielectric Strength: It can be defined as the minimum voltage required for producing dielectric breakdown. Dielectric strength decreases with raising the temperature, humidity and age of the material.

Various polarization Process: polarization occurs due to several atomic mechanisms. When a specimen is placed in a d.c. electric field, polarization is due to four types of processes. They are

(1) electronic polarization
(2) ionic polarization
(3) orientation polarization and
(4) space charge polarization

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

Consider an atom placed inside an electric field. The centre of positive charge is displaced along the applied field direction while the centre of negative charge is displaced in the opposite direction .thus a dipole is produced.

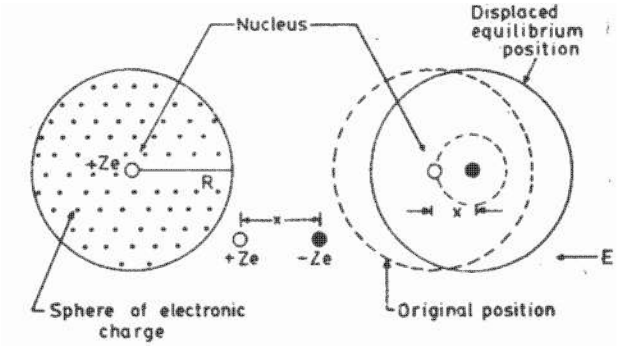
The displacement of the positively charged nucleus and the negative electrons of an atom in opposite directions, on application of an electric field, result in electronic polarization.

Induced dipole moment

$\mu \propto E$ or $\mu = \alpha_e E$ where α_e is electronic polarizability

Electronic polarizability is independent of temperature.

***Derivation**:* Consider the nucleus of charge Ze is surrounded by an electron cloud of charge -Ze distributed in a sphere of radius R.



Charge density ρ is given by

$$\rho = -Ze \,/\, ({}^{4}/_{3}\, \Pi R^{3}) = -(3/4)\,(Ze \,/\, \Pi R^{3}) \quad \text{----------(1)}$$

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

Then Coulomb force develops between them, which tends to oppose the displacement. When Lorentz and coulomb forces are equal and opposite, equilibrium is reached.

Let x be the displacement

Lorentz force = -Ze E (since = charge x applied field)

Coulomb force = Ze x [charge enclosed in sphere of radius ‘x’ / $4 \Pi \varepsilon_0 x^2$]

Charge enclosed $= (4/3)\, \Pi x^3 \rho$

$$= (4/3)\, \Pi x^3 [(-3/4)\,(Ze \,/\, \Pi R^3)]$$

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

Therefore Coulomb force $= (Ze)(-Zex^3 / R^3) / 4 \Pi \varepsilon_0 x^2 = -Z^2 e^2 x / 4 \Pi \varepsilon_0 R^3$

At equilibrium, Lorentz force = Coulomb force

$$\Rightarrow -ZeE = -Z^2 e^2 x / 4 \Pi \varepsilon_0 R^3$$

 $E = -Ze\, x / 4 \Pi \varepsilon_0 R^3$

 or $x = 4 \Pi \varepsilon_0 R^3 E / Ze$

Thus displacement of electron cloud is proportional to applied field.

The two charges +Ze and -Ze are separated by a distance ‘x‘ under applied field constituting induced electric dipoles .

Induced dipole moment $\mu_e = Ze\, x$

Therefore $\mu_e = Ze (4 \Pi \varepsilon_0 R^3 E / Ze) = 4 \Pi \varepsilon_0 R^3 E$

Therefore $\mu_e \; \alpha \; E$, $\mu_e = \alpha_e E$ where $\alpha_e = 4 \Pi \varepsilon_0 R^3$ is electronic polarizability

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

$P = N \mu_e = N \alpha_e E$ where

N is Number of atoms / m^3

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

R is radius of atom

Electric Susceptibility $\chi = P / \varepsilon_0 E$

Therefore $P = \varepsilon_0 E \chi$

$P = (4 \Pi R^3 N) \varepsilon_0 E$ where $\chi = 4 \Pi R^3 N$

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

Or $\varepsilon_r - 1 = N \alpha_e / \varepsilon_0$

Hence $\alpha_e = \varepsilon_0 (\varepsilon_r - 1) / N$.

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

Consider a NaCl molecule. Suppose an electric field is applied in the positive direction . The positive ion moves by x_1 and the negative ion moves by x_2

Let M is mass of positive ion

M is mass of negative ion

x_1 is displacement of positive ion

x_2 is displacement of negative

ion

Total displacement $x = x_1 + x_2$ --------------(1)

Lorentz force on positive ion $= + e E$ ----------(2)

Lorentz force on negative ion $= - e E$ ----------(3)

Restoring force on positive ion $= -k_1 \ x_1$ ----------(2 a)

Restoring force on negative ion $= +k_2 \ x_2$ ----------(3 a)

where k_1, k_2 Restoring force constants

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

For positive ion, $e E = k_1 \ x_1$

For negative ion, $e E = k_2 \ x2$] ---------- (4)

Where $k_1 = M \omega_0^2$ & $k_2 = m \omega_0^2$

where ω_0 is angular velocity of ions

Therefore $x = x_1 + x_2 = (e E / \omega_0^2) \ [1/M + 1/m]$ ----------(5)

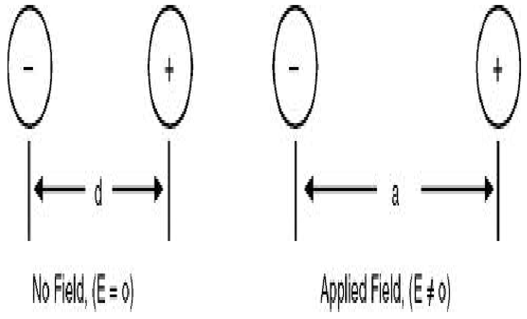
From definition of dipole moment

μ = charge x distance of separation

$$\mu = e x = (e^2 E / \omega_0^2) \ [1/M + 1/m] \quad \text{------------(6)}$$

But $\mu \propto E$ or $\mu = \alpha_i E$

Therefore $\alpha_i = (e2 / \omega_0^2) \ [1/M + 1/m]$ This is ionic polarizability.



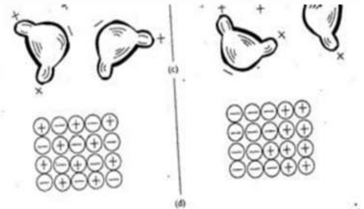


Fig. Various polarization processes: (a) electronic polarization, (b) ionic pol
(c) orientation polarization, and (d) space charge polarization.

Orientational Polarization :

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

Orientational polarization $P_o = N\mu = N\mu^2E / 3kT$

$= N \alpha_0 E$

Therefore Orientational polarizability $\alpha_0 = P_o / NE = \mu^2 / 3kT$

Thus orintational polarizability α_0 is inversely proportional t absolute temperature of material.

Internal field or Local field or Lorentz field: Internal field is the total electric field at atomic site.

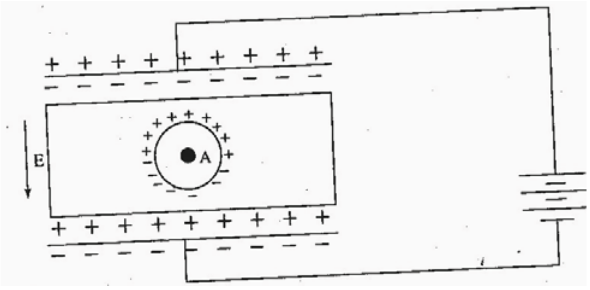
Internal field $A = E_1 + E_2 + E_3 + E_4$ ------- (I) where

E_1 is field intensity due to charge density on plates

E_2 is charge density induced on two sides of dielectric

E_3 is field intensity due to other atoms in cavity and

E_4 is field intensity due to polarization charges on surface of cavity



Field E1: E_1 is field intensity due to charge density on plates

From the field theory

$$E_1 = D / \varepsilon_0$$

$$D = P + \varepsilon_0 E$$

Therefore $E_1 = P + \varepsilon_0 E / \varepsilon_0 = E + P / \varepsilon_0$ ----------(1)

Field E2: E_2 is the field intensity at A due to charge density induced on two sides of dielectric

Therefore $E_2 = - P / \varepsilon_0$ -----------(2)

Field E3: E_3 is field intensity at A due to other atoms contained in the cavity and for a cubic structure,

$E_3 = 0$ because of symmetry. ----------- (3)

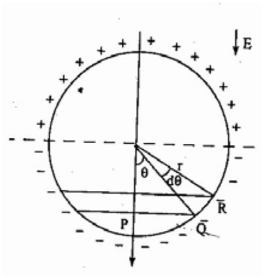
Field E4: E_4 is field intensity due to polarization charges on surface of cavity and was calculated by Lorentz in the following way:

If dA is the surface area of the sphere of radius r lying between θ and θ + dθ, where θ is the direction with reference to the direction of applied force.

Then $dA = 2 \Pi (PQ) (QR)$

But $\sin \theta = PQ / r$ => $PQ = r \sin \theta$

And $d\theta = QR / r$ => $QR = r\, d\theta$



Hence $dA = 2\Pi (r \sin\theta)(r\, d\theta) = 2\Pi r^2 \sin\theta\, d\theta$

Charge on surface dA is $dq = P\cos\theta\, dA$ (cos θ is normal component)

$dq = P\cos\theta\,(2\Pi r^2 \sin\theta\, d\theta) = P\,(2\Pi r^2 \sin\theta \cos\theta\, d\theta)$

The field due to the charge dq at A, is denoted by dE_4 in direction $\theta = 0$

$$dE_4 = dq\cos\theta / 4\Pi\varepsilon_0 r2 = P\,(2\Pi r^2 \sin\theta\cos\theta\, d\theta)\cos\theta$$

$$dE_4 = P\sin\theta\cos^2\theta\, d\theta / 2\varepsilon_0$$

$$\int dE_4 = P/2\varepsilon_0 \int_0^{\Pi} \sin\theta\cos^2\theta\, d\theta = P/2\varepsilon_0 \int_0^{\Pi} \cos^2\theta\, d(-\cos\theta)$$

Let $\cos\theta = x$

$$\int dE_4 = -P/2\varepsilon_0 \int_0^{\Pi} x^2\, dx$$

Therefore $E_4 = -P/2\varepsilon_0\ [x3/3]_0^{\Pi}$

$$= -P/2\varepsilon_0\ [\cos 3\theta/3]_0^{\Pi} = -P/6\varepsilon_0\ [-1-1] = P/3\varepsilon_0 \quad \text{------- (4)}$$

Local field $E_i = E1 + E_2 + E_3 + E_4$

$$= E + P/\varepsilon_0 - P/\varepsilon_0 + 0 + P/3\varepsilon_0$$

$$= E + P/3\varepsilon_0$$

Clausius – Mosotti Relation:

Let us consider the elemental dielectric having cubic structure. Since there are no ions and perment dipoles in these materials, them ionic polarizability α_i and orientational polarizability $\boldsymbol{\alpha_0}$ are zero.

i.e. $\alpha_i = \alpha_0 = 0$

Hence polarization $P = N\alpha_e E_i$

$$= N\alpha_e\,(E + P/3\varepsilon_0)$$

i.e. $P\,[1 - N\alpha_e/3\varepsilon_0] = N\alpha_e E$

$P = N\alpha_e E/\ P\,[1 - N\alpha_e/3\varepsilon_0]$ -------------→ **1**

$$D = P + \varepsilon_0 E$$

$$P = D - \varepsilon_0 E$$

Dividing on both sides by E

$P / E = D / E - \varepsilon_0 = \varepsilon - \varepsilon_0 = \varepsilon_0 \varepsilon_r - \varepsilon_0$

$P = E \varepsilon_0 (\varepsilon_r - 1)$ ----------------------- **2**

From eqn **1** and **2** , we get

$P = E \varepsilon_0 (\varepsilon_r - 1) = N \alpha_e E / [1 - N \alpha_e / 3 \varepsilon_0] [1 - N \alpha_e / 3 \varepsilon_0] = N \alpha_e / \varepsilon_0 (\varepsilon_r - 1)$

$1 = N \alpha_e / 3 \varepsilon_0 + N \alpha_e / \varepsilon_0 (\varepsilon_r - 1)$

$1 = (N \alpha_e / 3 \varepsilon_0) (1 + 3 / (\varepsilon_r - 1))$

$1 = (N \alpha_e / 3 \varepsilon_0)[(\varepsilon_r - 1 + 3) / (\varepsilon_r - 1)]$

$1 = (N \alpha_e / 3 \varepsilon_0)[(\varepsilon_r + 2) / (\varepsilon_r - 1)]$

$(\varepsilon_r + 2) / (\varepsilon_r - 1) = N \alpha_e / 3 \varepsilon_0$ Where N – no of molecules per unit volume

This is Clausius – Mosotti Relation.

Dielectric Breakdown : The dielectric breakdown is the sudden change in state of a dielectric material subjected to a very high electric field , under the influence of which , the electrons are lifted into the conduction band causing a surge of current , and the ability of the material to resist the current flow suffers a breakdown .

Or

When a dielectric material loses its resistivity and permits very large current to flow through it, then the phenomenon is called dielectric breakdown.

There are many factors for dielectric breakdown which are (1) Intrinsic breakdown (2) Thermal breakdown (3) Discharge breakdown (4) Electro Chemical breakdown (5) Defect breakdown.

(1) **Intrinsic breakdown**: The dielectric strength is defined as the breakdown voltage per unit thickness of the material. When the applied electric field is large, some of the electrons in the valence band cross over to the conduction band across the large forbidden energy gap giving rise to large conduction currents. The liberation or movement of electrons from valence band is called field emission of electrons and the breakdown is called the intrinsic breakdown or zener breakdown

The number of covalent bonds broken and the number of charge carriers released increases enormously with time and finally dielectric breakdown occurs. This type of breakdown is called Avalanche breakdown.

(2) **Thermal breakdown:** It occurs in a dielectric when the rate of heat

generation is greater than the rate of dissipation. Energy due to the dielectric loss appears as heat. If the rate of generation of heat is larger than the heat dissipated to the surrounding, the temperature of the dielectric increases which eventually results in local melting .once melting starts, that particular region becomes highly conductive, enormous current flows through the material and dielectric breakdown occurs.

Thus thermal breakdown occurs at very high temperatures. Since the dielectric loss is directly proportional to the frequency, for a.c fields, breakdown occurs at relatively lower field strengths.

(3) **Discharge breakdown**: Discharge breakdown is classified as external or internal. External breakdown is generally caused by a glow or corona discharge .Such discharges are normally observed at sharp edges of electrodes. It causes deterioration of the adjacent dielectric medium. It is accompanied by the formation of carbon so that the damaged areas become conducting leading to power arc and complete failure of the dielectric. Dust or moisture on the surface of the dielectric may also cause external discharge breakdown. Internal breakdown occurs when the insulator contains blocked gas bubbles .If large number of gas bubbles is present, this can occur even at low voltages.

(4) **Electro Chemical breakdown:** Chemical and electro chemical breakdown are related to thermal breakdown. When temperature rises, mobility of ions increases and hence electrochemical reaction takes place. When ionic mobility increases leakage current also increases and this may lead to dielectric breakdown. Field induced chemical reaction gradually decreases the insulation resistance and finally results in breakdown.

(5) **Defect breakdown:** if the surface of the dielectric material has defects such as cracks and porosity, then impurities such as dust or moisture collect at these discontinuities leading to breakdown. Also if it has defect in the form of strain in the material, that region will also break on application of electric field.

Frequency dependence of polarizability:

On application of an electric field, polarization process occurs as a function of time. The polarization P(t) as a function of time. The polarization P(t) as a function of time t is given by

$P(t) = P[\ 1- \exp\ (\ - t\ /\ t_r\ )]$

Where P – max. Polarization attained on prolonged application of static

field. t_r - relaxation time for particular polarization process

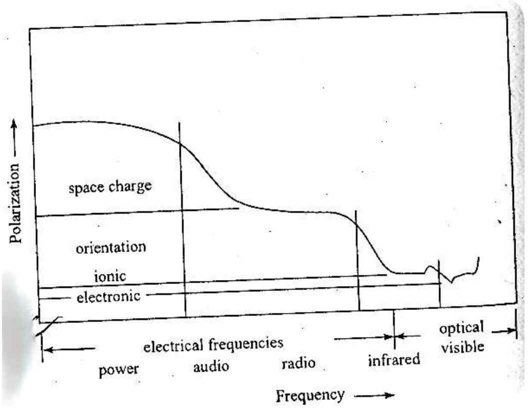
The relaxation time t_r is a measure of the time scale of polarization process. It is the time taken for a polarization process to reach 0.63 of the max. value.

Electronic polarization is extremely rapid. Even when the frequency of the applied voltage is very high in the optical range ($\approx 10^{15}$ Hz), electronic polarization occurs during every cycle of the applied voltage.

Ionic polarization is due to displacement of ions over a small distance due to the applied field. Since ions are heavier than electron cloud, the time taken for displacement is larger. The frequency with which ions are displaced is of the same order as the lattice vibration frequency (≈1013Hz). Hence, at optical frequencies, there is no ionic polarization. If the frequency of the applied voltage is less than 1013 Hz, the ions respond.

Orientation polarization is even slower than ionic polarization. The relaxation time for orientation polarization in a liquid is less than that in a solid. Orientation polarization occurs, when the frequency of applied voltage is in audio range (1010 Hz).

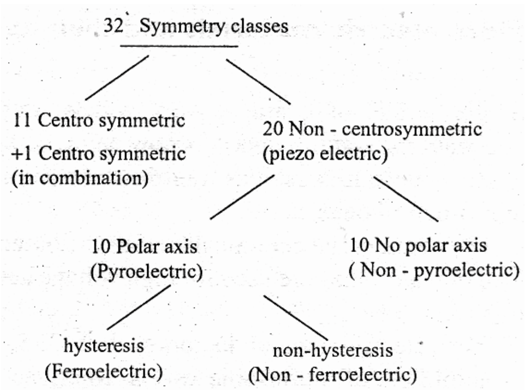
Space charge polarization is the slowest process, as it involves the diffusion of ions over several interatomic distances. The relaxation time for this process is related to frequency of ions under the influence of applied field. Space charge polarization occurs at power frequencies (50-60 Hz).



Piezo – Electricity: These materials have the property of becoming electrically polarized when mechanical stress is applied. This property is known as Piezo – electric effect has an inverse

.According to inverse piezo electric effect, when an electric stress or voltage is applied, the material becomes strained. The strain is directly proportional to the applied field E.

When piezo electric crystals are subjected to compression or tension, opposite kinds of charges are developed at the opposite faces perpendicular to the direction of applied force. The charges produced are proportional to the applied force.



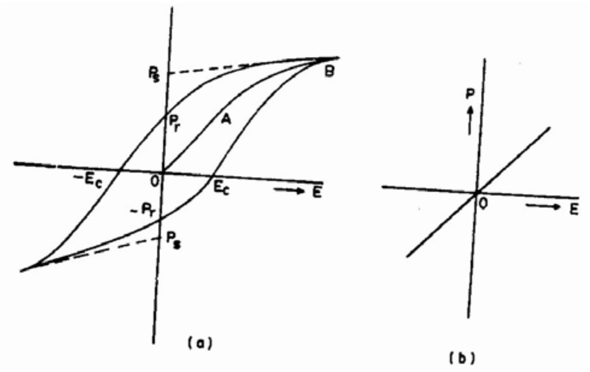
Piezo – Electric Materials and Their Applications: Single crystal of quartz is used for filter, resonator and delay line applications. Natural quartz is now being replaced by synthetic material.

Rochelle salt is used as transducer in gramophone pickups, ear phones,

hearing aids, microphones etc. the commercial ceramic materials are based on barium titanate, lead zirconate and lead titanate. They are used for high voltage generation (gas lighters),

accelerometers, transducers etc.

ultrasonic waves.Piezo electric semiconductors such as GaS, ZnO & CdS are used as amplifiers



Ferro electricity: Ferro electric materials are an important group not only because of intrinsic Ferro electric property, but because many possess useful piezo electric, birefringent and electro optical properties.

The intrinsic Ferro electric property is the possibility of reversal or change of orientation of the polarization direction by an electric field. This leads to hysteresis in the polarization P, electric field E relation , similar to magnetic hysteresis. Above a critical temperature, the Curie point T_C, the spontaneous polarization is destroyed by thermal disorder. The permittivity shows a characteristic peak at T_C.

Pyroelectricity: It is the change in spontaneous polarization when the temperature of specimen is changed.

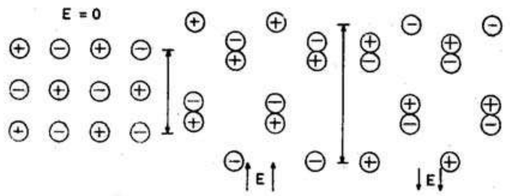


Fig Displacements of the ions under an electric field

Pyroelectric coefficient ‘λ’ is defined as the change in polarization per unit temperature change of specimen.

$$\lambda = dP / dT$$

change in polarization results in change in external field and also changes the surface.

Required Qualities of Good Insulating Materials: The required qualities can be classified as under electrical, mechanical, thermal and chemical applications.

Electrical: 1. electrically the insulating material should have high electrical resistivity and high dielectric strength to withstand high voltage.
2 .The dielectric losses must be minimum.
3. Liquid and gaseous insulators are used as coolants. For example transformer oil, hydrogen and helium are used both as insulators and coolant.
ii) Mechanical: 1. insulating materials should have certain mechanical properties depending on the use to which they are put.
2. When used for electric machine insulation, the insulator should have sufficient mechanical strength to withstand vibration.
iii) Thermal: Good heat conducting property is also desirable in such cases. The insulators should have small thermal expansion and it should be non-ignitable.
iv) Chemical: 1. chemically, the insulators should be resistant to oils, liquids, gas fumes, acids and alkali’s.
2. The insulators should be water proof since water lowers the insulation resistance and the dielectric strength.

MAGNETIC PROPERTIES

Introduction: The basic aim in the study of the subject of magnetic materials is to understand the effect of an external magnetic field on a bulk material ,and also to account for its specific behavior. A dipole is an object that a magnetic pole is on one end and a equal and opposite second magnetic dipole is on the other end.

A bar magnet can be considered as a dipole with a north pole at one end and South Pole at the other. If a magnet is cut into two, two magnets or dipoles are created out of one. This sectioning and creation of dipoles can continue to the atomic level. Therefore, the source of magnetism lies in the basic building block of all the matter i.e. the atom.

Consider electric current flowing through a conductor. When the electrons are flowing through the conductor, a magnetic field is forms around the conductor. A magnetic field is produced whenever an electric charge is in motion. The strength of the field is called the **magnetic moment.**

Magnetic materials are those which can be easily magnetized as they have permanent magnetic moment in the presence of applied magnetic field. Magnetism arises from the magnetic dipole moments. It is responsible for producing magnetic influence of attraction or repulsion.

Magnetic dipole : it is a system consisting of two equal and opposite magnetic poles separated by a small distance of ‘2l’metre.

Magnetic Moment (μ_m) :It is defined as the product of the pole strength (m) and the distance between the two poles (2l) of the magnet.

i . e . . $\mu_m = (2l)\,m$

Units: Ampere – metre^2

Magnetic Flux Density or Magnetic Induction (B): It is defined as the number of magnetic lines of force passing perpendicularly through unit area.

i . e . . **B** = magnetic flux / area = Φ /

A Units: Weber / metre^2 or Tesla.

Permeability:
Magnetic Field Intensity (H): The magnetic field intensity at any point in the magnetic field is the force experienced by a unit north pole placed at that point.

Units: Ampere / meter

The magnetic induction B due to magnetic field intensity H applied in vacuum is related by

B = μ_0 **H**where μ_0 is permeability of free space = 4 Π x 10^{-7} H / m

If the field is applied in a medium, the magnetic induction in the solid is given by

$\mathbf{B} = \mu \mathbf{H}$ where μ is permeability of the material in the medium

$\mu = B / H$

Hence magnetic Permeability μ of any material is the ratio of the magnetic induction to the applied magnetic field intensity. The ratio of μ / μ_0 is called the relative permeability (μ_r).

$$\mu_r = \mu / \mu_0$$

Therefore $\mathbf{B} = \mu_0 \mu_r \mathbf{H}$

Magnetization: It is the process of converting a non – magnetic material into a magnetic material. The intensity of magnetization (M) of a material is the magnetic moment per unit volume. The intensity of magnetization is directly related to the applied field H through the susceptibility of the medium (χ) by

$$\chi = M / H \quad \text{------------(1)}$$

The magnetic susceptibility of a material is the ratio of the intensity of magnetization produced to the magnetic field intensity which produces the magnetization. It has no units.

We know

$$\mathbf{B} = \mu \mathbf{H}$$

$$= \mu_0 \mu_r \mathbf{H}$$

i.e $\mathbf{B} = \mu_0 \mu_r \mathbf{H} + \mu_0 \mathbf{H} - \mu_0 \mathbf{H}$

$$= \mu_0 \mathbf{H} + \mu_0 \mathbf{H} (\mu_r - 1)$$

$= \mu_0 \mathbf{H} + \mu_0 \mathbf{M}$ where M is magnetization $= \mathbf{H} (\mu_r - 1)$

i.e $\mathbf{B} = \mu_0 (\mathbf{H} + \mathbf{M})$ ----------(2)

The first term on the right side of eqn (2) is due to external field. The second term is due to the magnetization.

Hence $\mu_0 = \mathbf{B / H + M}$

Relative Permeability ,

$$\mu_r = \mu / \mu_0 = (B / H) / (B / H + M) = H + M / H = 1 + M / H$$

$$\mu_r = 1 + \chi \text{ ---------(3)}$$

The magnetic properties of all substances are associated with the orbital and spin motions of the electrons in their atoms. Due to this motion, the electrons become elementary magnets of the substance. In few materials these elementary magnets are able to strengthen the applied magnetic field , while in few others , they orient themselves such that the applied magnetic field is weakened.

Origin of Magnetic Moment : In atoms , the permanent magnetic moments can arise due to the following :

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

Orbital magnetic moment of the electrons: In an atom, electrons revolve round the nucleus in different circular orbits.

Let m be the mass of the electron and r be the radius of the orbit in which it moves with angular velocity ω.

The electric current due to the moving electron I = - (number of electrons flowing per second x charge of an electron)

Therefore $I = - e\omega / 2\Pi$ --------------(1)

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

$$\mu_m = I.A$$

$$= (-e\omega / 2\Pi)(\Pi r^2)$$

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

where $L = m\omega r^2$ is the orbital angular momentum of electron. The minus sign indicates that the magnetic moment is anti – parallel to the angular momentum L. A substance therefore possesses permanent magnetic dipoles if the electrons of its constituent atom have a net non- vanishing angular momentum. The ratio of the magnetic dipole moment of the electron due to its orbital motion and the angular momentum of the orbital motion is called orbital gyro magnetic ratio , represented by γ.

Therefore γ = magnetic moment / angular momentum = $e / 2m$

The angular momentum of an electron is determined by the orbital quantum number 'l' given by l = 0 , 1 , 2 , ……(n – 1) where n is principal quantum number n = 1 , 2 , 3 , 4 , …… ……corresponding to K , L , M , N……shells .

The angular momentum of the electrons associated with a particular value of l is given by l(h / 2

Π
)

The strength of the permanent magnetic dipole is given by

$$\mu_{el} = -(e/2m)(lh/2\Pi)$$

i.e $\mu_{el} = -(ehl/4\Pi m) = -\mu_B\, l$ ---------------(3)

The quantity $\mu_B = eh/4\Pi m$ is an atomic unit called Bohr Magneton and has a value 9.27 x 10^{-24} ampere metre^2

In an atom having many electrons, the total orbital magnetic moment is determined by taking the algebraic sum of the magnetic moments of individual electrons. The moment of a completely filled shell is zero. An atom with partially filled shells will have non zero orbital magnetic moment.

Magnetic Moment Due to Electron Spin : The magnetic moment associated with spinning of the electron is called spin magnetic moment μ_{es} .Magnetic moment due to the rotation of the electronic charge about one of the diameters of the electron is similar to the earth's spinning motion around it's north – south axis.

An electronic charge being spread over a spherical volume ,the electron spin would cause different charge elements of this sphere to form closed currents, resulting in a net spin magnetic moment. This net magnetic moment would depend upon the structure of the electron and its charge distribution.

$\mu_{es} = \gamma(e/2m)S$ -------------------(1)where $S = h/4\Pi$ is spin angular

momentum therefore $\mu_{es} \approx 9.4 \times 10^{-24}$ ampere metre^2

Thus, the magnetic moments due to the spin and the orbital motions of an electron are of the same order of magnitude. The spin and electron spin magnetic moment are intrinsic properties of an electron and exist even for a stationary electron. Since the magnitude of spin magnetic moment is always same, the external field can only influence its direction. If the electron spin moments are free to orient themselves in the direction of the applied field B. In a varying field ,it experiences a force in the direction of the increasing magnetic field due to spin magnetic moments of its various electrons.

Magnetic Moment due to Nuclear Spin : Another contribution may arise from the nuclear magnetic moment. By analogy with Bohr Magneton, the nuclear magneton arises due to spin of the nucleus. It is given by

$$\mu_{ps} = eh/4\Pi M_p$$

$\mu_{ps} = 5.05 \times 10^{-27}$ ampere $\text{metre}^2$where M_p is mass of

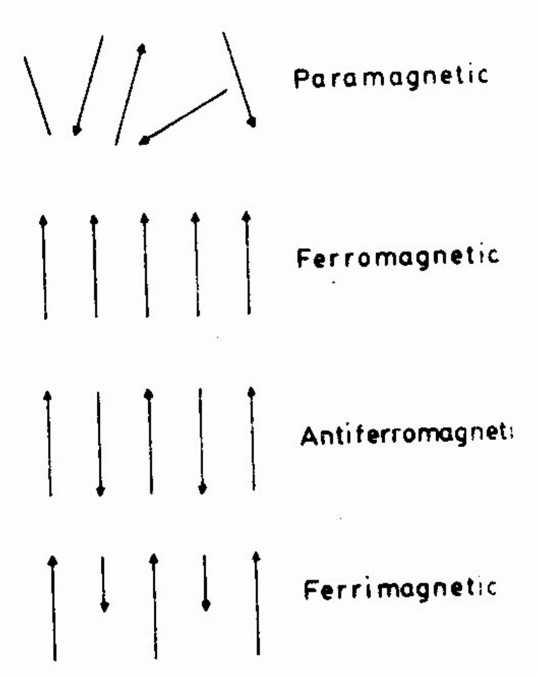
proton. The nuclear magnetic moments are smaller than those associated with

electrons.

Classification Of Magnetic Materials :All matter respond in one way or the other when subjected to the influence of a magnetic field. The response could be strong or weak, but there is none with zero response ie, there is no matter which is non magnetic in the absolute sense. Depending upon the magnitude and sign of response to the applied field , and also on the basis of effect of temperature on the magnetic properties, all materials are classified broadly under 3 categories.

1. Diamagnetic materials 2. Paramagnetic materials, 3. Ferromagnetic materials

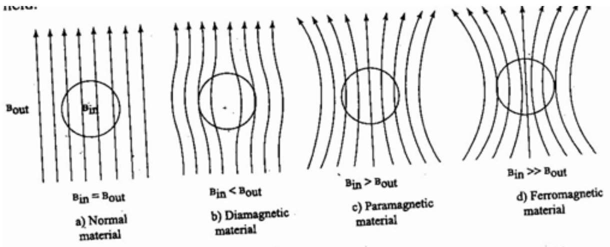
two more classes of materials have structure very close to ferromagnetic materials but possess quite different magnetic effects. They are i. Anti ferromagnetic materials and ii . Ferri magnetic materials



1. ***Diamagnetic materials: Diamagnetic*** materials are those which experience a repelling force when brought near the pole of a strong magnet. In a non uniform magnetic field they are repelled away from stronger parts of the field.

   In the absence of an external magnetic field , the net magnetic dipole moment over each atom or molecule of a diamagnetic material is zero.

   Ex: Cu, Bi , Pb .Zn and rare gases.



$B_{in} = B_{out}$ a) Normal material

$B_{in} < B_{out}$ b) Diamagnetic material

$B_{in} > B_{out}$ c) Paramagnetic material

$B_{in} >> B_{out}$ d) Ferromagnetic material

Fig. The behaviour of magnetic materials in the presence of magnetic field.

Paramagnetic materials: Paramagnetic materials are those which experience a feeble attractive force when brought near the pole of a magnet. They are attracted towards the stronger parts of magnetic field. Due to the spin and orbital motion of the electrons, the atoms of paramagnetic material posses a net intrinsic permanent moment.

Susceptibility **χ** is positive and small for these materials. The susceptibility is inversely proportional to the temperature T.

$$\chi \alpha \ 1/T$$

$\chi = C/T$ where C is Curie's temperature.

Below superconducting transition temperatures, these materials exhibit the Para magnetism.

Examples: Al, Mn, Pt, $CuCl_2$.

Ferromagnetic Materials: Ferromagnetic materials are those which experience a very strong attractive force when brought near the pole of a magnet. These materials, apart from getting magnetized parallel to the direction of the applied field, will continue to retain the magnetic property even after the magnetizing field removed. The atoms of ferromagnetic materials also have a net intrinsic magnetic dipole moment which is due to the spin of the electrons.

Susceptibility is always positive and large and it depends upon temperature.

$\chi = C / (T- \theta)$ (only in paramagnetic region i.e., $T > \theta$)

θ is Curie's temperature.

When the temperature of the material is greater than its Curie temperature then it converts into paramagnetic material.

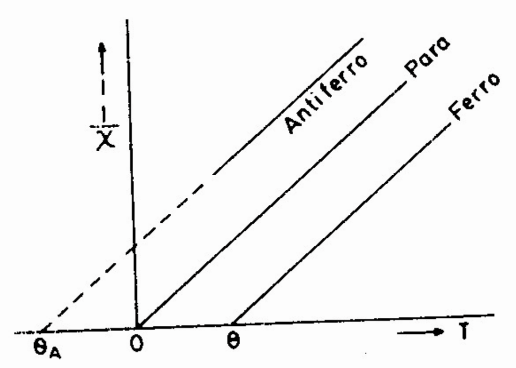
Examples: Fe, Ni, Co, MnO.

Antiferromagnetic matériels : These are the ferromagnetic materials in which equal no of opposite spins with same magnitude such that the orientation of neighbouring spins is in antiparallel manner are present.

Susceptibility is small and positive and it is inversely proportional to the temperature.

$$\chi=C /(T+\theta)$$

the temperature at which anti ferromagnetic material converts into paramagnetic material is known as Neel's temperature.Examples:FeO, Cr_2O_3.



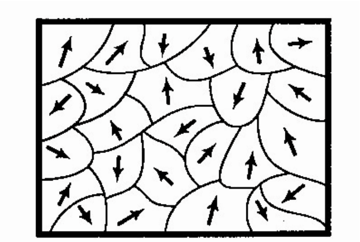
Ferrimagnetic materials: These are the ferromagnetic materials in which equal no of opposite spins with different magnitudes such that the orientation of neighbouring spins is in antiparallel manner are present.

Susceptibility positive and large, it is inversely proportional to temperature

$\chi = C/(T \pm \theta)$ $T > T_N$ (Neel's temperature)

Examples : $ZnFe_2O_4$, $CuFe_2O_4$

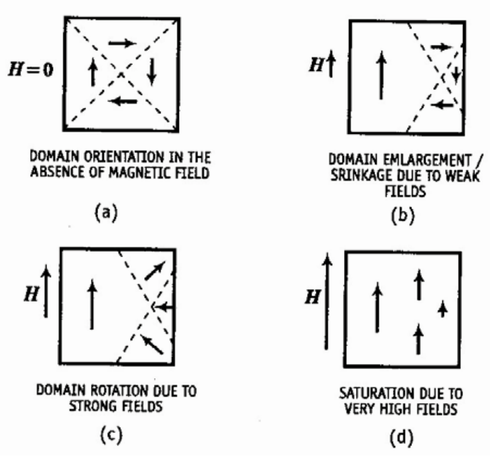
Domain theory of ferromagnetism: According to Weiss, a virgin specimen of ferromagnetic material consists of a no of regions or domains (≈ 10-6 m or larger) which are spontaneously magnetized. In each domain spontaneous magnetization is due to parallel alignment of all magnetic dipoles. The direction of spontaneous magnetization varies from domain to domain. The resultant magnetization may hence be zero or nearly zero. When an external field is applied there are two possible ways of alignment fo a random domain.



RANDOM ORIENTATION OF MAGNETIC MOMENTS OF THE DOMAINS

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

ii) **By rotation of domains**: When the applied magnetic field is strong, rotation of the direction of magnetization occurs in the direction of the field.



Hysteresis curve (study of B-H curve): The hysteresis of ferromagnetic materials refers to the lag of magnetization behind the magnetization field. when the temperature of the ferromagnetic substance is less than the ferromagnetic Curie temperature ,the substance exhibits hysteresis. The domain concept is well suited to explain the phenomenon of hysteresis. The increase in the value of the resultant magnetic moment of the specimen by the application of the applied field , it attributes to the 1. motion of the domain walls and 2. rotation of domains.

When a weak magnetic field is applied, the domains that are aligned parallel to the field and in the easy direction of magnetization , grow in size at the expense of less favorably oriented ones. This results in Bloch wall movement and when the weak field is removed, the domains reverse back to their original state. This reverse wall displacement is indicated by OA of the magnetization curve. When the field becomes stronger ,the Bloch wall movement continues and it is mostly irreversible movement. This is indicated by the path AB of the graph. The phenomenon of hysteresis is due to this irreversibility.

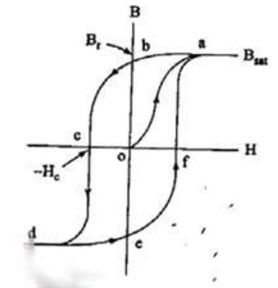
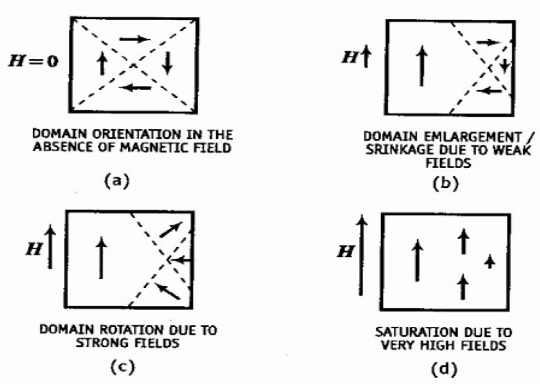


Fig. Schematic representation of the hysteresis loop for a ferromagnetic material.



DOMAIN ORIENTATION IN THE ABSENCE OF MAGNETIC FIELD (a)

DOMAIN EMLARGEMENT / SRINKAGE DUE TO WEAK FIELDS (b)

DOMAIN ROTATION DUE TO STRONG FIELDS (c)

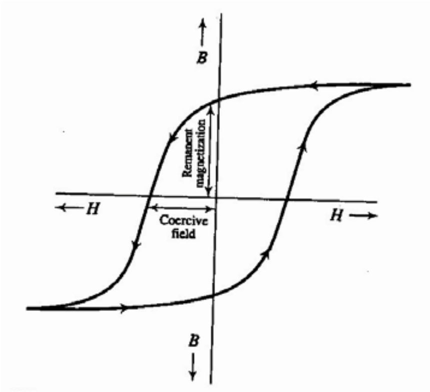
SATURATION DUE TO VERY HIGH FIELDS (d)

At the point B all domains have got magnetized along their easy directions. Application of still higher fields rotates the domains into the field direction which may be away from the easy direction. Once the domain rotation is complete the specimen is saturated denoted by C. on removal of the field the specimen tends to attain the original configuration by the movement of Bloch walls. But this movement is hampered by the impurities, lattice imperfections etc, and so more energy must be supplied to overcome the opposing forces. This means that a coercive field is required to reduce the magnetization of the specimen to zero. The amount of energy spent in this regard is a loss. Hysteresis loss is the loss of energy in taking a ferromagnetic body through a complete cycle of magnetization and this loss is represented by the area enclosed by the hysteresis loop.

A hysteresis curve shows the relationship between the magnetic flux density B and applied magnetic field H. It is also referred to as the B-H curve (loop).

Hard and Soft Magnetic Materials:

Hysteresis loop of the ferromagnetic materials vary in size and shape. This variation in hysteresis loops leads to a broad classification of all the magnetic materials into hard type and soft type.



HYSTERESIS CURVE FOR HARD MAGNETIC MATERIAL

HardMagneticMaterials:

Hard magnetic materials are those which are characterized by large hysteresis loop because of which they retain a considerable amount of their magnetic energy after the external magnetic field is switched off. These materials are subjected to a magnetic field of increasing intensity, the domain walls movements are impeded due to certain factors. The cause for such a nature is attributed to the presence of impurities or non-magnetic materials, or the lattice imperfections. Such defects attract the domain walls thereby reducing the wall energy. It results in a stable state for the domain walls and gives mechanical hardness to the material which increases the electrical resistivity. The increase in electrical resisitivity brings down the eddy current loss if used in a.c conditions. The hard magnetic materials can neither be easily magnetized nor easily demagnetized.

Properties:

1. High remanent magnetization
2. High coercivity
3. High saturation flux density
4. Low initial permeability
5. High hysteresis energy loss
6. High permeability
7. The eddy current loss is low for ceramic type and large for metallic type.

Examples of hard magnetic materials are, i) Iron- nickel- aluminum alloys with certain amount of cobalt called Alnico alloy. ii) Copper nickel iron alloys. iii) Platinum cobalt alloy.

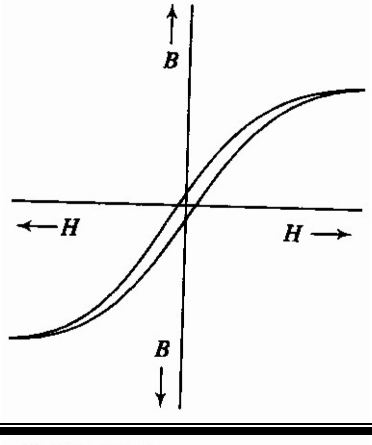
Applications of hard magnetic materials: For production of permanent magnets, used in magnetic detectors, microphones, flux meters, voltage regulators, damping devices and magnetic separators.

Soft Magnetic Materials:

Soft magnetic materials are those for which the hysteresis loops enclose very small area. They are the magnetic materials which cannot be permanently magnetized. In these materials,the domain walls motion occurs easily. Consequently, the coercive force assumes a small value and makes the hysteresis loop a narrow one because of which, the hysteresis loss becomes very small. For the same reasons, the materials can be easily magnetized and demagnetized.

Properties:

1. Low remanent magnetization
2. Low coercivity



HYSTERESIS CURVE FOR SOFT MAGNETIC MATERIAL

3. Low hysteresis energy loss
4. Low eddy current loss
5. High permeability
6. High susceptibility

Examples of soft magnetic materials are
i)Permalloys (alloys of Fe and Ni)
ii)Si – Fe alloy
iii)Amorphous ferrous alloys (alloys of Fe, Si, and B)
iv)Pure Iron (BCC structure)

Applications of soft magnetic materials: Mainly used in electro- magnetic machinery and transformer cores. They are also used in switching circuits, microwave isolators and matrix storage of computers.

SUPERCONDUCTIVITY

Introduction : Certain metals and alloys exhibit almost zero resistivity(i.e. infinite conductivity) when they are cooled to sufficiently low temperatures. This phenomenon is called superconductivity. This phenomenon was first observed by H.K. Onnes in 1911. He found that when pure mercury was cooled down to below 4K, the resistivity suddenly dropped to zero. Since then hundreds of superconductors have been discovered and studied. Superconductivity is strictly a low temperature phenomenon. Few new oxides exhibited superconductivity just below 125K itself. This interesting phenomena has many important applications in many emerging fields.

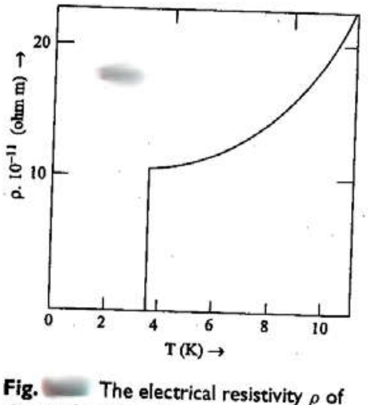


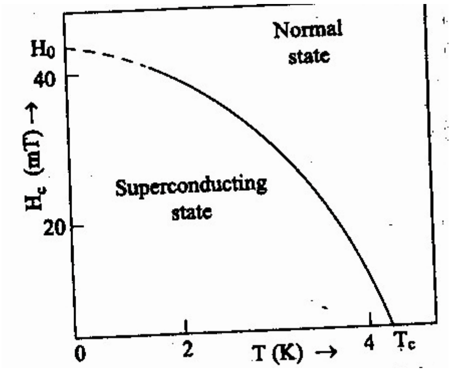
Fig. [redacted] The electrical resistivity ρ of tin, as a function of temperature near 0K.

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

The following are the general properties of the superconductors:

1. The transition temperature is different to different substances.
2. For a chemically pure and structurally perfect specimen, the superconducting transition is very sharp.
3. Superconductivity is found to occur in metallic elements in which the number of valence electrons lies between 2 and 8.
4. Transition metals having odd number of valence electrons are favourable to exhibit superconductivity while metals having even number of valence electrons are unfavourable.
5. Materials having high normal resistivities exhibit superconductivity.
6. Materials for which Zρ > 106 (where Z is the no. of valence electrons and ρ is the resistivity) show superconductivity.
7. Ferromagnetic and antiferromagnetic materials are not superconductors.
8. The current in a superconducting ring persists for a very long time.

Effect of Magnetic Field: Superconducting state of metal depends on temperature and strength of the magnetic field in which the metal is placed. Superconducting disappears if the temperature of the specimen is raised above Tc or a strong enough magnetic field applied. At temperatures below Tc, in the absence of any magnetic field, the material is in superconducting state. When the strength of the magnetic field applied reaches a critical value Hc the superconductivity disappears.



At T= Tc, Hc = 0. At temperatures below Tc, Hc increases. The dependence of the critical field upon the temperature is given by

$$H_C(T) = H_C(0)\,[1 - (T/T_c)^2] \text{-----------------------------}(1)$$

Where Hc(0) is the critical field at 0K. Hc(0) and Tc are constants of the characteristics of the material.

Meissner effect: When a weak magnetic field applied to super conducting specimen at a temperature below transition temperature Tc , the magnetic flux lines are expelled. This specimen acts as on ideal diamagnet. This effect is called meissner effect. This effect is reversible, i.e. when the temperature is raised from below Tc , at T = Tc the flux lines suddenly start penetrating and the specimen returns back to the normal state. Under this condition, the magnetic induction inside the specimen is given by

$$B = \mu_0 (H + M) \qquad \text{-------------------------------------}(2)$$

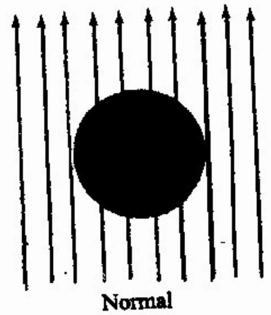
Where H is the external applied magnetic field and M is the magnetization produced inside the specimen.

When the specimen is super conducting, according to meissner effect inside the bulk semiconductor B= 0.

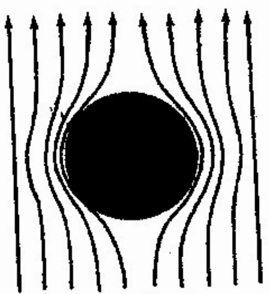
Hence $\mu_0 (H + M) = 0$

Or $M = - H$ --- (3)

Thus the material is perfectly diamagnetic.



Normal
$T > T_c$ or $H > H_c$



Superconducting
$T < T_c$ or $H < H_c$
(b)

Magnetic susceptibility can be expressed as

$\chi = M/H = -1$-- (4)

Consider a superconducting material under normal state. Let J be the current passing through the material of resistivity ρ. From ohm's law we know that the electric field

$$E = J\rho$$

On cooling the material to its transition temperature, ρ tends to zero. If J is held finite. E must be zero. Form Maxwell's eqn, we know

$\nabla \times E = - dB/dt$ ---------------------------- (5)

Under superconducting condition since $E = 0$, $dB/dt = 0$, or $B = \text{constant}$.

This means that the magnetic flux passing through the specimen should not change on cooling to the transition temperature. The Meissner effect contradicts this result.

According to Meissner effect perfect diamagnetism is an essential property of defining the superconducting state. Thus

From zero resistivity

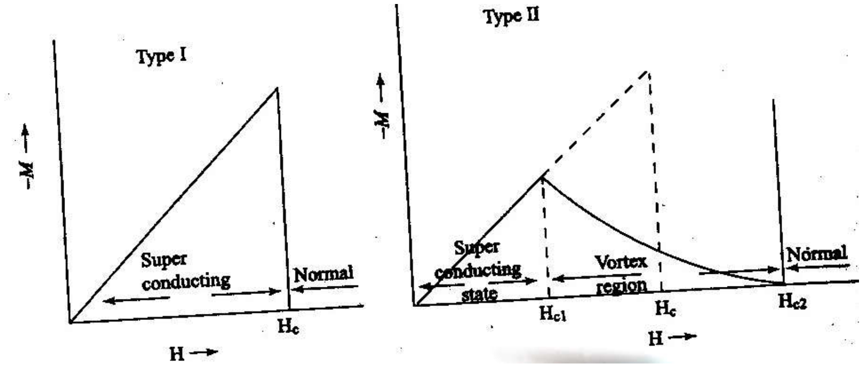
$E = 0$, From Meissner

effect $B = 0$.

***Type- I , Type- II superconductors*:** Based on diamagnetic response Superconductors are divided into two types, i.e type-I and type-II.

Superconductors exhibiting a complete Meissner effect are called type-1, also called

Soft Superconductors. When the magnetic field strength is gradually increased from its initial value H< HC, at HC the diamagnetism abruptly disappear and the transition from superconducting state to normal state is sharp. Example Zn, Hg, pure specimens of Al and Sn.



In type-2 Superconductors, transition to the normal state takes place gradually. For fields below HC1 , the material is diamagnetic i.e., the field is completely excluded HC1 is called the lower critical field. At HC1 the field begins to penetrate the specimen. Penetration increases until HC2 is reached. At HC2 , the magnetizations vanishes i.e., the material becomes normal state. HC2 is the upper critical field. Between HC1 and HC2 the state of the material is called the mixed or vortex state. They are also known as hard superconductors. They have high current densities. Example Zr , Nb etc.

Questions:

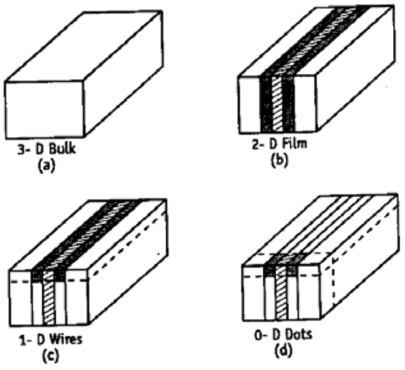
1. Describe how polarization occurs in a dielectric material.
2. Define dielectric constant of a material.
3. Explain the origin of different kinds of polarization.
4. Describe in brief various types of polarization.
5. Obtain an expression for the internal field.
6. Derive Clausius - Mossotti equation.
7. Describe the frequency dependence of dielectric constant.
8. Write note on Dielectric loss.
9. Explain the properties of ferroelectric materials.
10. What is piezoelectricity?
11. Distinguish between dia, para, ferro, antiferro,and ferromagnetic materials.
12. what is meant by Neel temperature
13. Define magnetization and show that $B = \mu_0 (H + M)$.
14. Explain the origin of magnetic moment.

15. Decribe the domain theory of ferromagnetism.
16. What is Bhor Magneton.
17. Draw and explain the hysteresis curve.
18. Discuss the characteristic features of soft and hard magnetic materials.
19. What are the applications of soft and hard magnetic materials?

NANOTECHNOLOGY

Introduction

In 1959, Richard Feynman made a statement ‘there is plenty of room at the bottom’. Based on his study he manipulated smaller units of matter. He prophesied that “we can arrange the atoms the way we want, the very atoms, all the way down”. The term ‘nanotechnology’ was coined by Norio Taniguchi at the University of Tokyo. Nano means 10^{-9}. A nano metre is one thousand millionth of a metre (i.e. 10^{-9} m). Nanomaterials could be defined as those materials which have structured components with size less than 100nm at least in one dimension. Any bulk material we take, its size can express in 3-dimensions. Any planer material, its area can be expressed in 2-dimension. Any linear material, its length can be expressed in 1-dimension.



3- D Bulk (a)

2- D Film (b)

1- D Wires (c)

0- D Dots (d)

SCHEMATIC DIAGRAM OF QUANTUM STRUCTURES

Materials that are nano scale in 1-dimension or layers, such as thin films or surface coatings. Materials that are nano scale in 2-dimensions include nanowires and nanotubes.

Materials that are nano scale in 3- dimensions are particles like precipitates, colloids and quantum dots.

Nanoscience: it can be defined as the study of phenomena and manipulation of materials at atomic, molecular and macromolecular scales, where properties differ significantly from those at a larger scale.

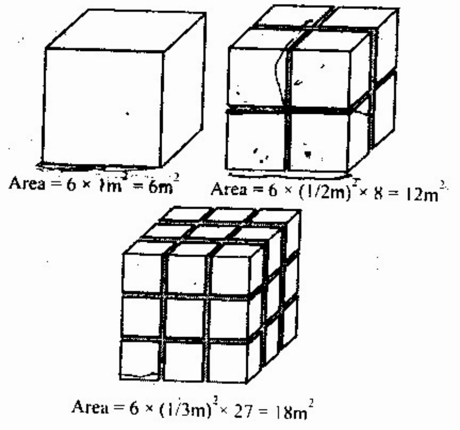
Nanotechnology: It can be defined as the design, characterization, production and application of structures, devices and systems by controlling shape and size at the nano metre scale. It is also defined as “A branch of engineering that deals with the design and manufacture of extremely small electronic circuits and mechanical devices built at molecular level of matter. Now nanotechnology crosses and unites academic fields such as Physics, Chemistry and Computer science.

Properties of nano particles:

The properties of nano scale materials are very much different from those at a larger scale. Two principal factors that cause that the properties to differ significantly are increased relative surface area and quantum effects. These can enhance or change properties such as reactivity, strength and electrical characteristics.

1. **Increase in surface area to volume ratio**

Nano materials have relatively larger surface area when compared to the volume of the bulk material.



Consider a sphere of radius r
Its surface area =$4\Pi r^2$
Its volume = $4\Pi r^3/3$

$$\frac{\text{Surface area}}{\text{Volume}} = \frac{4\Pi r^2}{4\Pi r^3/3} = \frac{3}{r}$$

Thus when the radius of sphere decreases, its surface area to volume ratio

increases. EX: For a cubic volume,

Surface area = $6x1m^2 = 6m^2$

When it is divided it 8 pieces
It surface area = $6x\ (1/2m)^{2x8} = 12m^2$
When the sane volume id divided into 27 pieces,

It surface area = $6x\ (1/3m)^{2x27} = 18m^2$
Therefore, when the given volume is divided into smaller pieces, the surface area increases. Hence as particle size decreases, greater proportions of atoms are found at the surface compared to those inside. Thus nano particles have much greater surface to volume ratio. It makes material more chemically reactive.

As growth and catalytic chemical reaction occur at surfaces, then given mass of material in nano particulate form will be much more reactive than the same mass of bulk material. This affects there strength or electrical properties.

2. Quantum confinement effects

When atoms are isolated, energy levels are discrete or discontinuous. When very large number of atoms is closely packed to form a solid, the energy levels split and form bands. Nan materials represent intermediate stage.

When dimensions of potential well and potential box are of the order of deBroglie wave length of electrons or mean free path of electrons, then energy levels of electrons changes. This effect is called Quantum confinement effect.

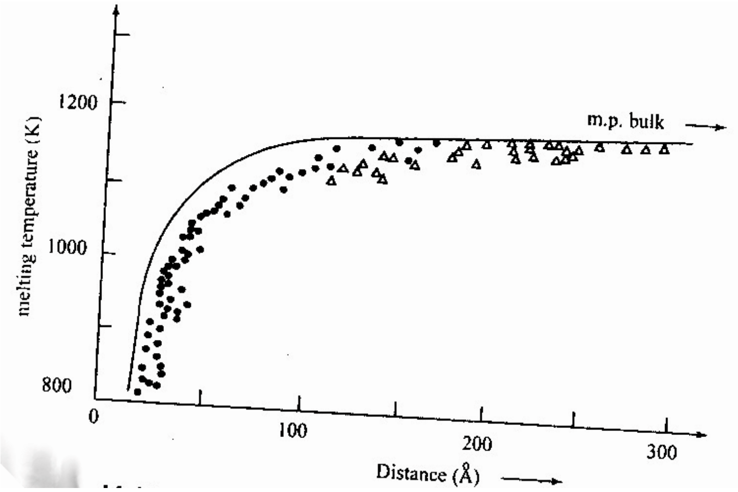
When the material is in sufficiently small size, organization of energy levels into which electrons can climb of or fall changes. Specifically, the phenomenon results from electrons and holes being squeezed into a dimension that approaches a critical quantum measurement called the exciton Bohr radius. These can affect the optical, electrical and magnetic behaviour of materials.

Variations of properties of nano materials

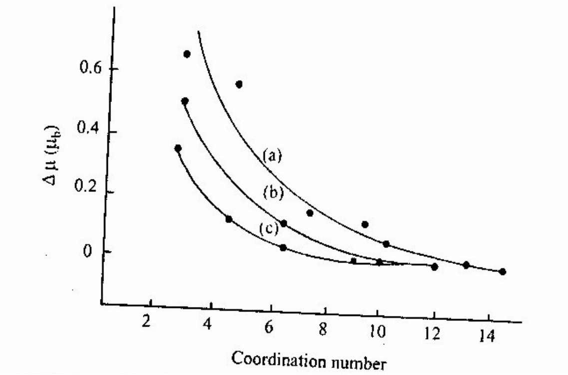
The physical, electronic, magnetic and chemical properties of materials depend on size. Small particles behave differently from those of individual atoms or bulk.

Physical properties: The effect of reducing the bulk into particle size is to create more surface sites i.e. to increase the surface to volume ratio. This changes the surface pressure and results in a change in the inter particle spacing. Thus the inter atomic spacing decreases with size.

The change in the inter particle spacing and the large surface to volume ratio in particle have a combined effect on material properties. Variation in the surface free energy changes the chemical potential. This affects the thermodynamic properties like melting point. The melting point decreases with size and at very small sizes the decrease is faster.



Chemical properties: the large surface to volume ratio, the variations in geometry and electronic structure has a strong effect on catalytic properties. The reactivity of small clusters increases rapidly even when the magnitude of the cluster size is changed only by a few atoms.



Another important application is hydrogen storage in metals. Most metals do not absorb, hydrogen is typically absorbed dissociatively on surfaces with hydrogen- to-metal atom ratio of one. This limit is significantly enhanced in small sizes. The small positively charged clusters of Ni, Pd and Pt and containing between 2 and 60 atoms decreases with increasing cluster size. This shows that small particles may be very useful in hydrogen storage devices in metals.

Electrical properties: The ionization potential at small sizes is higher than that for the bulk and show marked fluctuations as function of size. Due to quantum confinement the electronic bands in metals become narrower. The delocalized electronic states are transformed to more localized molecular bands and these bands can be altered by the passage of current through these materials or by the application of an electric field.

In nano ceramics and magnetic nano composites the electrical conductivity increases with reduction in particle size where as in metals, electrical conductivity decreases.

Optical properties: Depending on the particle size, different colours are same. Gold nano spheres of 100nm appear orange in colour while 50nm nano spheres appear green in colour. If semiconductor particles are made small enough, quantum effects come into play, which limits the energies at which electrons and holes can exist in the particles. As energy is related to wavelength or colour, the optical properties of the particles can be finely tuned depending on its size. Thus particles can be made to emit or absorb specific wavelength of light, merely by controlling their size.

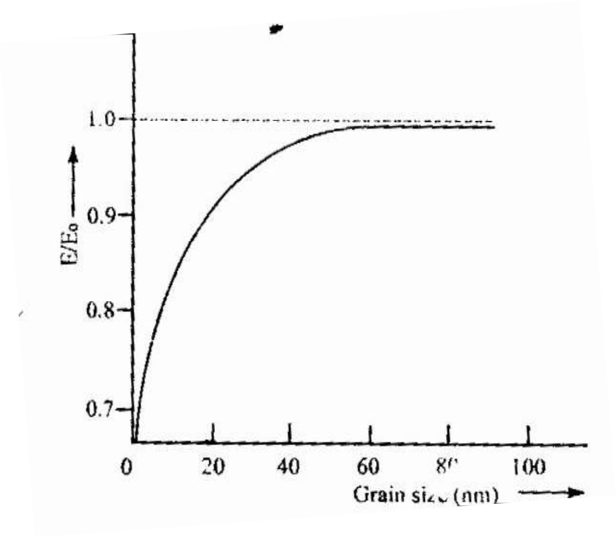
An electro chromic device consist of materials in which an optical absorption band can be introduced or existing band can be altered by the passage of current through the materials, or by the application of an electric field. They are similar to liquid crystal displays (LCD) commonly used in calculator and watches. The resolution, brightness and contrast of these devices depend on tungstic acid gel’s grain size.

Magnetic properties: The strength of a magnet is measured in terms of coercivity and saturation magnetization values. These values increase with a decrease in the grain size and an increase in the specific surface area (surface area per unit volume) of the grains.

In small particle a large number or fraction of the atoms reside at the surface. These atoms have lower coordination number than the interior atoms. As the coordination number decreases, the moment increases towards the atomic value there is small particles are more magnetic than the bulk material.

Nano particle of even non magnetic solids are found to be magnetic. It has been found theoretically and experimentally that the magnetism special to small sizes and disappears in clusters. At small sizes, the clusters become spontaneously magnetic.

Mechanical properties: If the grains are nano scale in size, the interface area within the material greatly increases, which enhances its strength. Because of the nano size many mechanical properties like hardness, elastic modulus, fracture toughness, scratch resistance, fatigue strength are modified.



The presence of extrinsic defects such as pores and cracks may be responsible for low values of E (young’s modulus) in nano crystalline materials. The intrinsic elastic modulli of nano structured materials are essentially the same as those for conventional grain size material until the grain size becomes very small. At lower grain size, the no. of atoms associated with the grain boundaries and triple junctions become very large. The hardness, strength and deformation behaviour of nano crystalline materials is unique and not yet well understood.

Super plasticity is the capability of some polycrystalline materials to exhibit very large texture deformations without fracture. Super plasticity has been observed occurs at somewhat low temperatures and at higher strain rates in nano crystalline material.

PRODUCTION OF NANOMATETIALS:

Material can be produced that are nanoscale in one dimension like thin surface coatings in two dimensions like nanowires and nanotubes or in 3 dimensions like nanoparticles

Nano materials can be synthesized by’ top down’ techniques producing very small structures from larger pieces of material. One way is to mechanical crushing of solid into fine nano powder by ball milling.

Nanomaterials may also be synthesized by ‘bottom up’ techniques, atom by atom or molecule by molecule. One way of doing this is to allow the atoms or molecules arranges themselves into a structure due to their natural properties

Ex: - Crystals growth

PERPARATION:

There are many methods to produce nanomaterials. They are

1). PLASMA ARCING:

Plasma is an ionized gas. To produce plasma, potential difference is applied across two electrodes. The gas yields up its electrons and gets ionized .Ionized gas (plasma) conducts electricity. A plasma arcing device consists of two electrodes. An arc passes from one electrode to the other. From the anode electrode due to the potential difference electrons are emitted. Positively charged ions pass to the other electrode (cathode), pick up the electron and are deposited to form nanoparticles. As a surface deposit the depth of the coating must be only a few atoms. Each particle must be nanosized and independent. The interaction among them must be by hydrogen bonding or Vander Waals forces. Plasma arcing is used to produced carbon nanotubes.

2). CHEMICAL VAPOUR DEPOSITION:

In this method, nanoparticles are deposited from the gas phase. Material is heated to from a gas and then allowed to deposit on solid surface, usually under vacuum condition. The deposition may be either physical or chemical. In deposition by chemical reaction new product is formed. Nanopowder or oxides and carbides of metals can be formed, if vapours of carbon or oxygen are present with the metal.

Production of pure metal powders is also possible using this method. The metal is meted exciting with microwave frequency and vapourised to produce plasma at 1500^0c . This plasma then enters the reaction column cooled by water where nanosized particles are formed.

CVD can also be used to grow surfaces. If the object to be coated is introduced inside the chemical vapour, the atoms/molecules coated may react with the substrate atoms/molecules. The way the atoms /molecules grow on the surface of the substrate depends on the alignment of the atoms /molecules of the substrate. Surfaces with unique characteristics can be grown with these techniques.

3. Sol – Gels:

Sol: - A material which when reacts with liquid converts in to a gelly or viscous fluid. Colloid:- A substance which converts liquid to semisolid or viscous or

cloudy.

Gel : Amore thicky substance.

Soot :- When a compound is brunt, it given black fumes called soot.

In solutions molecules of nanometer size are dispersed and move around randomly and hence the solutions are clear. In colloids, the molecules of size ranging from 20µm to100µm are suspended in a solvent. When mixed with a liquid colloids look cloudy or even milky. A colloid that is suspended in a liquid is called as sol. A suspension that keeps its shape is called a gel. Thus sol-gels are suspensions of colloids in liquids that keep their shape. Sol -gels formation occurs in different stages.

1) Hydrolysis
2) Condensation and polymerization of monomers to form particles
3) Agglomeration of particles. This is followed by formation of networks which extends throughout the liquid medium and forms a gel.

The rate of hydrolysis and condensation reactions are governed by various factors such as P_H, temperature, H_2O/Si molar ratio, nature and concentration of catalyst and process of drying. Under proper conditions spherical nanoparticles are produced.

3. *ELECTRODEPOSITION*:

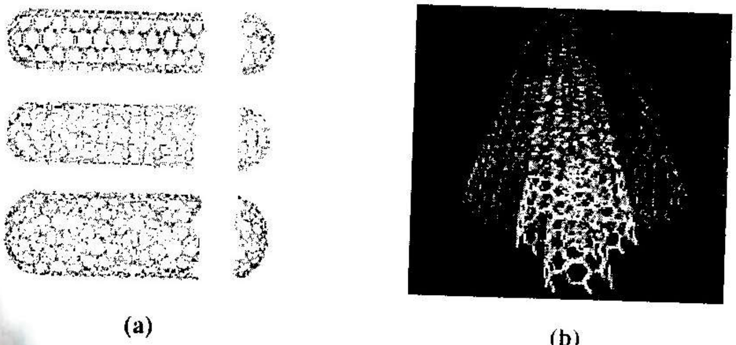
This method is used to electroplate a material. In many liquids called electrolytes (aqueous solutions of salts , acids etc) when current is passed through two electrodes immersed inside the electrolyte, certain mass of the substance liberated at one electrode gets deposited on the surface of the other. By controlling the current and other parameters, it is possible to deposit even a single layer of atoms. The films thus obtained are mechanically robust, highly flat and uniform. These films have very wide range of application like in batteries, fuel cells, solar cells, magnetic read heads etc.

5. BALL MILLING (MECHANICAL CRUSHING):

In this method, small balls are allowed to rotate around the inside of a drum and then fall on a solid with gravity force and crush the solid into nanocrystallites. Ball milling can be used to prepare a wide range of elemental and oxide powders. Ball milling is the preferred method for preparing metal oxides.

CARBON NANOTUBES (CNT'S):

We know three forms of carbon namely diamond graphite and amorphous carbon. There is a whole family of other forms of carbon known as carbon nanotubes, which are related to graphite. In conventional graphite, the sheets of carbon are stacked on top of one another .They can easily slide over each other. That's why graphite is not hard and can be used as a lubricant. When graphite sheets are rolled into a cylinder and their edges joined, they form carbon nanotubes i.e. carbon nanotubes are extended tubes of rolled graphite sheets.


(a) (b)

(a) Different types of single walled nanotubes (b) Multi walled nanotubes

TYPES OF CNT'S: A nanotube may consist of one tube of graphite, a one atom thick single wall nanotube or number of concentric tubes called multiwalled nanotubes.

There are different types of CNT'S because the graphite sheets can be rolled in different ways .The 3 types of CNT'S are ZigZag, Armchair and chiral. It is possible to recognize type by analyzing their cross sectional structures.

Multiwalled nanotubes come in even more complex array of forms. Each concentric single – walled nanotube can have different structures, and hence there are a variety of sequential arrangements. There can have either regular layering or random layering .The structure of the nanotubes influences its properties .Both type and diameter are important .The wider the diameter of the nanotube, the more it behaves like graphite.

The narrower the diameters of nanotube, the more its intrinsic properties depends upon its specific type. Nanotubes are mechanically very strong, flexible and can conduct electricity extremely well.

The helicity of the graphite sheet determines whether the CNT is a semiconductor of metallic.

PRODUCTION OF CNT'S: There are a number of methods of making CNT'S few method adopted for the production of CNT'S.

ARC MRTHOD: This method creates CNT'S through arc- vapourisation of two carbon rods placed end to end, separated by 1mm , in an enclosure filled with inert gas at low pressure .It is also possible to create CNT'S with arc method in liquid nitrogen. A direct current of 50-100A, driven by a potential difference of 20V apprx, creates a high temperature discharge between the two electrodes .The discharges vapourizes the surface of one of the carbon electrodes, and forms a small rod shaped deposit on the other electrode. Producing CNT'S in high yield depends on the uniformity of the plasma arc, and the temperatures of deposits forming on the carbon electrode.

LASER METHOD: CNT'S were first synthesized using a dual-pulsed laser. Samples were prepared by laser vapourizations of graphite rods with a 50:50 catalyst mixture of Cobalt & Nickel at 1200^{0}c in flowing argon. The initial layer vapourization pulse was followed by a second pulse, to vapourize the target more uniformly. The use of two successive laser pulses minimizes the amount of carbon deposited as soot. The second laser pulse breaks up the larger particles ablated by the first one and feeds then into growing nanotube structure. The CNT'S produced by this method are 10-20nm in diameter and upto 100m or more in length. By varying the growth temperatures, the catalyst composition and other process parameters the average nanotube diameter and size distribution can be varied.

CHEMICAL VAPOUR DEPOSITION (CVD)**:** Large amount of CNT"S can be formed by catalytic CVD of acetylene over Cobalt and Iron catalysts supported on silica or zeolite. The carbon deposition activity seems to relate to the cobalt content of the catalyst; where as the CNT'S selectivity seems to be a function of the P_H in catalyst preparation. CNT'S can be formed from ethylene. Supported catalysts such as iron cobalt and Nickel containing either a single metal or a mixture of metals, seem to induce the growth of isolated single walled nanotubes or single walled nanotubes, bundles in the ethylene atmosphere. The production of single walled nanotubes as well as double walled CNT'S, molybdenum and molylodenum-iron catalysts has also been demonstrated.

PROPERTIES OF CNT'S :

Few unique properties of CNT"S are

1) ELECTRICAL CONDUCTIVITY: CNT'S can be highly conducting , and hence can be said to be metallic. Their conductivity will be a function of chirality, the degree of twist and diameter. CNT'S can be either metallic or semi conducting in their electrical behaviour. Conductivity in multi walled CNT'S is more complex .The resistivity of single walled nanotubes ropes is of the order of 10^{-4} ohm –cm at 27^{0}c .This means that single walled nanotube ropes are most conductive carbon fibers. Individual single walled nanotubes may contain defects. These defects allow the single walled nanotubes to act as transistors. Similarly by joining CNT"S together forms transistor - like devices. A nanotube with natural junctions behaves as a rectifying diode.

2) Strength and elasticity: Because of the strong carbon bonds, the basal plane elastic modules of graphite, it is one of the largest of any known material. For this reason, CNT"S are the ultimate high strength fibers. Single walled nanotubes are stiffer than Steel, and are very resistant to damage from physical forces.

3)THERMAL CONDUCTIVITY AND EXPANSION: The strong in- plane graphite carbon- carbon bonds make them exceptionally strong and stiff against axial strains. The almost zero- in -plane thermal expansion but large inter - plane expansion of single walled nanotubes implies strong in plane coupling and high flexibility against non- axial strains. CNT'S show very high thermal conductivity. The nanotube reinforcements in polymeric materials may also significantly improve the thermal and thermo mechanical properties of composites.

4) HIGHLY ABSORBENT: The large surface area and high absorbency of CNT"S make them ideal for use in air, gas and water filteration. A lot of research is being done in replacing activated charcoal with CNT'S in certain ultra high purity application.

APPLICATION OF NANOMATERIALS:

1. **Engineering:** i).Wear protection for tools and machines (anti blocking coatings, scratch resistant coatings on plastic parts). ii) Lubricant – free bearings.
2. **Electronic industry:** Data memory(MRAM,GMR-HD), Displays(OLED,FED), Laser diodes, Glass fibres
3. **Automotive industry:** Light weight construction, Painting (fillers, base coat, clear coat), Sensors, Coating for wind screen and car bodies.
4. **Construction:** Construction materials, Thermal insulation, Flame retardants.

5. Chemical industry: Fillers for painting systems, Coating systems based on nano composites. Impregnation of papers, Magnetic Fluids.

6. Medicine: Drug delivery systems, Agents in cancer therapy, Anti microbial agents and coatings, Medical rapid tests Active agents.

7. Energy: Fuel cells, Solar cells, batteries, Capacitors.

8. Cosmetics: Sun protection, Skin creams, Tooth paste, Lipsticks.

Questions:

1. What are Nanomaterials? Why do they exhibit different properties?
2. How are optical, physical and chemical properties of nano particles vary with their size.
3. How are electrical, magnetic and mechanical properties of nano particles vary with their size?
4. How are nano materials produced?
5. What are carbon nano tubes? How are they produced?
6. What are the different types of carbon nano tubes? What are their properties?
7. What are the important applications of nano materials?