

## Module - 5

### Density of states in 2D, 1D & 0D Systems

Density of states gives the number of allowed energy state for electron/hole in the given Energy (E) per unit volume of given system.

We know that density of states in 2D system =  $\frac{8\pi^2}{h^3} (m)^{3/2} E^{1/2}$

But most of the Semiconductors device today were based on 2D, 1D & 0D systems

Example for 2D system = Quantum well were electrons are confined in 1 Dimension

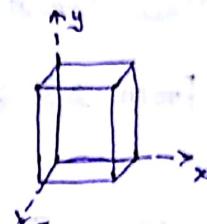
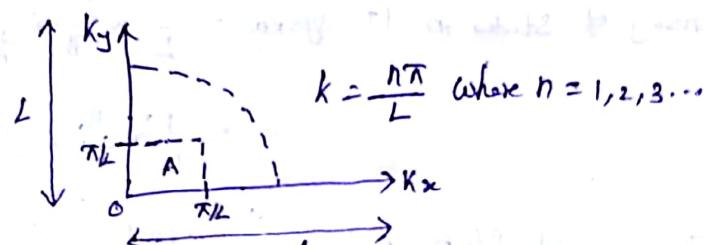
Example for 1D system = Quantum wire were electrons are confined in 2 Dimensions

Example for 0D system = Quantum dot were electrons are confined in 3 Dimensions

#### (i) Density of states in 2D dimension

Consider a 2D system of Quantum well.

Let the k-spacing for 2D system is given by



In k space diagram - Each Energy state occurs at  $\pi/L$   
Then Area =  $(\pi/L)^2$

Let us first find the number of states in k space by considering circle with radius 'k' than

$$N = \frac{[1^{\text{st}} \text{ Area of circle}]}{\text{Area of Energy State}} \times \text{Electron spin}$$

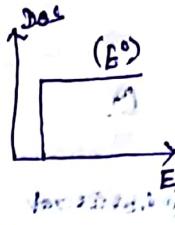
$$N = \frac{1}{4} \pi k^2 \times \left(\frac{L}{\pi}\right)^2 \times 2$$

$$\text{Diff w.r.t. } k \quad \frac{dN}{dk} = \frac{L^2}{\pi} k$$

Then Density of states in 2D Systems =  $\frac{dN/dE}{A} = \frac{1}{A} \cdot \frac{dk}{dx} \cdot \frac{dk}{dE}$

To find  $dk/dE$  we know that  $E = \frac{\hbar^2 k^2}{2m}$

$$\frac{dE}{dk} = \frac{\hbar^2 k}{m} \Rightarrow \frac{dk}{dE} = \frac{m}{\hbar^2 k}$$



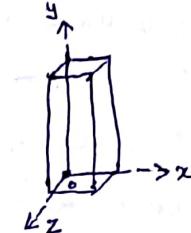
$$\therefore \text{Density of States in 2D System} = \frac{1}{L^2} \times \frac{L^2 k}{\pi} \times \frac{m}{\hbar^2 k} = \frac{m}{\hbar^2 \pi}$$

$$\text{Density of States in 2D System} = \frac{4\pi^2 m}{h^2 \pi} = \boxed{\frac{4\pi m}{h^2}} \quad \left[ \because \hbar^2 = \frac{\lambda^2}{4\pi^2} \right]$$

### (ii) Density of states in 1D Systems

Consider 1D system of Quantum wire.

Let the  $k$ -spacing for 1D system is given by



$$\text{Number of energy states is given by } N = 2 \times k \times \left( \frac{L}{\pi} \right)$$

$$\text{Diff. w.r.t } dk \left( \frac{dN}{dk} \right) = \frac{2L}{\pi}$$



$$\text{Then Density of states in 1D Systems} = \frac{dN/dE}{A} = \frac{1}{A} \cdot \frac{dk}{dx} \cdot \frac{dk}{dE}$$

$$\text{From 2D systems, we know } \frac{dE}{dk} = \frac{m}{\hbar^2 k} \text{ where } k = \frac{\sqrt{2mE}}{\hbar}$$

$$\text{Then Density of states in 1D system} = \frac{1}{L} \times \frac{2L}{\pi} \times \frac{m}{\hbar^2 \left[ \frac{\sqrt{2mE}}{\hbar} \right]}$$

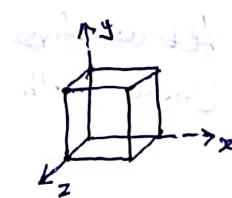
$$= \frac{1}{4} \times \frac{2k}{\pi} \times \frac{m \times 2k}{h \sqrt{2mE}}$$

$$\text{Density of states in 1D system} = \boxed{\frac{2\sqrt{2} (m)^{1/2} (E)^{1/2}}{h}}$$

### (iii) Density of states in 0D Systems

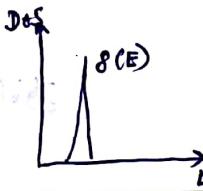
Consider 0D system of Quantum dot.

We cannot plot  $k$ -spacing for 0D as all three dimensions are reduced. Hence Energy States cannot be determined exactly.



But considering a function, Energy of conduction band ( $E_c$ ) and the total energy of system as ( $E$ ) we write

$$\text{Density of states in 0D Systems} = \boxed{2 \times f(E - E_c)}$$



## Introduction to Low dimensional systems

Refers to development and Production of Components at small scale ( $1 - 100 \text{ nm}$ ). It refers one billionth of something or  $1 \text{ nm} = 10^{-9} \text{ m}$ . The technology used to manipulate matters at atomic level to produce low dimensional systems to achieve some properties is called Nanotechnology.

When Surface to volume ratio increases for low dimensional systems it results better chemical, electronic, magnetic, catalytic, optical & mechanical properties

(Eg) For bulk matter - Gold - melting point is  $1064^\circ\text{C}$

For Nano meter  $\rightarrow (2 \text{ nm})$  Gold particle - melting point is  $680^\circ\text{C}$

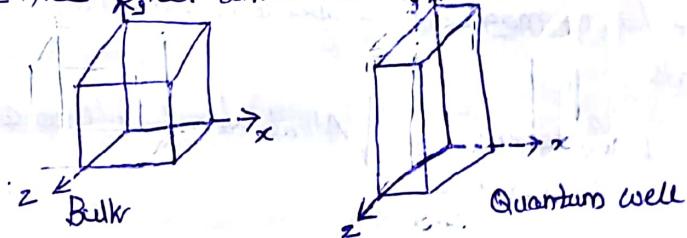
For bulk CdSe crystal - Eg is  $2.52 \text{ eV}$

For  $4 \times 4 \text{ nm}^2$  CdSe crystal - Eg is  $2.14 \text{ eV}$

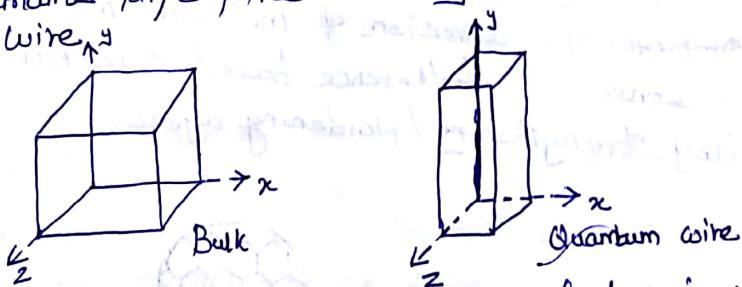
## Types of Low dimension System

Classified as Quantum well, Quantum wire and Quantum dot

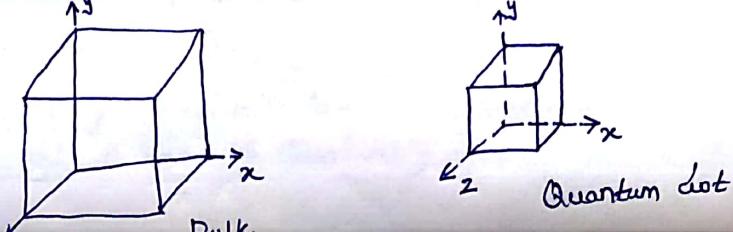
1) Quantum well - If one dimension is reduced to nanometer range while the other dimensions remain large is called Quantum well.



2) Quantum wire - If two dimensions are so reduced and one dimension remains large, the resulting structure is referred as quantum wire.



3) Quantum dot - The process in which size reduction in which all three dimensions reach the low nanometer range is called Quantum dot.



In Quantum well, exciton can move freely in 2-dimensions. In Quantum wire the exciton can move freely in 1-dimension & in Quantum dot exciton cannot move freely in any direction

Two common approaches to synthesis Low dimensional systems

Top down approach - Large scale object in which atoms are vaporized and are coated on substrate

Bottom up approach - The individual atoms and molecules are collected through controlled chemical reactions and structures formed.

### Introduction to Novel low dimensional systems

1) Fullerenes - New allotropy of carbon in which atoms are arranged in closed shell and was discovered in year 1985. It was initially named as Buckminsterfullerene (as Buckminster fuller who designed geodesic domes in 1960)

Different forms of fullerenes are  $C_{60}$ ,  $C_{70}$ ,  $C_{76}$ ,  $C_{84}$  and most abundant form is  $C_{60}$  having 32 facets (12 pentagons and 20 hexagons) resembles soccer ball.  $C_{60}$  are chemically stable and having variety of unusual properties. It can be stretched into rod and tubes. They are having magnetic, superconducting properties and serves as lubricants

Species of fullerenes - Alkali doped fullerenes, endohedral fullerenes, exohedral fullerenes

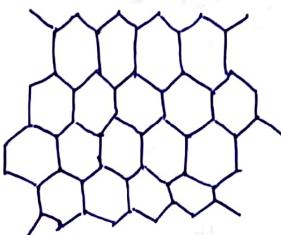
Applications of fullerenes - Used for hydrogen or oxygen storage (hydrogenation of fullerenes produces hydrides), as catalyst (promotes the conversion of methane into higher hydrocarbons), as sensors (fullerene based capacitors detect ppm of  $H_2S$  in  $N_2$ ), Alloy strengthening / Hardening agent.



Structure of fullerenes

2) Graphene - Another allotrope of Carbon discovered in 2004. It is a two dimensional building block for carbon-based materials. Also called as atomic-scale honeycomb lattice made of carbon atoms with  $sp^2$  hybridization.

Graphene is million times thinner than paper ( $0.33 \times 0.36\text{ nm}$ ) stronger than diamond ( $\gamma = 1.3\text{ TPa}$ ). Better than Copper in electrical conduction ( $\rho = 10^{-6}\Omega\text{m} \geq \gamma = 2 \times 10^5\text{ cm}^2\text{V}^{-1}\text{s}^{-1}$ )



2D Dimensional Graphene

### Properties of Graphene

- 1) Perfect thermal conductor ( $> 5000\text{ W/m/K}$ ) & thermal conductivity is isotropic. This helps to fabricate graphene-based electronic device more cool.
- 2) Harder than diamond. (Tensile strength exceeds  $1\text{ TPa}$ )
- 3) Graphene can absorb / deabsorb various atoms and molecules ( $\text{NO}_2, \text{NH}_3, \text{K} \& \text{OH}$ )
- 4) High conducting nature helps to use Graphene as Sensors
- 5) Graphene can be functionalized by several chemical group forming Graphene Oxide & Fluorinated Graphene
- 6) Edge of Graphene has more reactivity than surface

Applications of Graphene - used to detect single molecule gas, fabrication of low switching time transistors, Transparent Conducting electrodes, Ultra capacitors, Thermally Conductive nano-Composites, As Reinforcement layer for polymer nanoComposites

### Carbon Nanotubes (CNT)

CNT was discovered in 1991 by Japanese Electron microscopist Sumio Iijima. While studying the material deposited on the cathode through arc-evaporation synthesis of fullerenes, found that central core of cathode deposit contained a variety of closed graphite structures called Carbon Nano Tube (CNT).

CNT are sheet of graphite rolled in cylindrical form (Ø) constructed from hexagonal rings of covalently bonded carbon/graphene layer.

CNT are constructed with one or multiple graphene layer. If CNT is observed with one graphene layer, it is called single walled CNT and observed with more than one graphene layer (r) multiple graphene layer, it is called multiwalled CNT. CNT's are also having three unique geometries (a) structure. They are (1) Armchair- $(n,n)$  Tube, (2) Zig-Zag -  $(n,0)$  tube and (3) Chiral- $(n,m)$  Tube. These geometries can be classified by how the carbon sheets is wrapped into a tube & method prescribed is called Hamada method.

### Properties of CNT

- 1) Chemical Reactivity - The chemical reactivity of CNT is compared with graphene sheet, enhanced as a direct result of the curvature of CNT surface. Reactivity is directly related to the pi-orbital mismatch caused by an increased curvature. Therefore side walls and end caps are having different reactivity. Also covalent chemical modification on side walls/end caps gives different solubility limit for CNT in solvents.
- 2) Electrical Conductivity - Depending on geometry, CNT with smaller diameter are either semi-conducting or metallic. The difference in conducting property are caused by the molecular structure that results in different band structure and thus a different ( $E_g$ ).
- 3) Mechanical Strength - CNT have a very large Young's modulus in their axial direction. The Young's modulus is over 1 TPa & estimated tensile strength is 200 GPa. These properties are ideal for reinforced composites.
- 4) Optical activity - Theoretical studies have revealed that the optical activity of chiral nanotubes ( $n,m$ -tubes) disappears if the nanotubes become large. It is expected that other properties are influenced by these parameters too.

Other unique properties of CNT are :

- High electrical conductivity, highly flexible, very elastic, high thermal conductivity, low thermal expansion coefficient, highly absorbent, Good field emission of electrons

Synthesis of CNT - There are three commonly used methods are considered

- 1) Laser ablation - A high power laser is rastered across a carbon target. In the plasma plume created with appropriate conditions, SWNT are formed downstream from the plasma plume on a cold substrate. Usually graphite is used as carbon source & atmospheric condition is maintained with Argon/Helium.
- 2) Arc-discharge method - CNT are synthesized by using a fairly low voltage power supply to strike an electric arc between two carbon electrodes. The carbon anode is enriched with particles of a transition metal in order to aid synthesis. This method provides very & multiwalled CNT.
- 3) Chemical vapour deposition (CVD) - This method uses carbon species in the gas phase and an energy source such as plasma (or) a resistively heated coil, to impart energy to a gaseous carbon molecule. Commonly used carbon source in CVD method are methane, carbon monoxide & acetylene. The energy source is used to crack the molecule into a reactive radical species. These reactive species then diffuse down to the substrate which is heated and already coated with catalyst (transition metals - Ni, Fe, Co).

### Applications of CNT

- 1) Hydrogen storage - Hydrogen is a combustion product in water and can be easily regenerated. For this reason, a suitable hydrogen storage system is necessary for energy extraction. The hydrogen storage can be done either in gas phase and electrochemical adsorption. It has been predicted that carbon nanotubes can store gas/liquid in their inner cores through capillary effect because of cylindrical geometry and nanometre-scale diameter.
- 2) Lithium intercalation - The basic principle of rechargeable lithium batteries is electrochemical intercalation and deintercalation of lithium in both electrodes. Single-walled CNT shown to possess both highly reversible / irreversible capacities. But high observed voltage hysteresis still limits the use of CNT for battery applications.

3) Transistors - FET a three terminal switching device - can be constructed of only one semiconducting SWNT. By applying voltage to the gate electrode, the nanotube can be switched from a conducting to an insulating state. Such CNT can be coupled together, working as a logical switch which is the basic component of computer

4) Field Emitting devices - An ideal emitter is required to have a nanometer size diameter, a structural integrity, a high electrical conductivity, a small energy spread and large chemical stability. CNT possess all these properties if the fabrication process and synthesis conditions are optimized.

5) Nanoprobes - Nanotubes can be used in scanning probe instruments. Multiswalled Nanotubes are Conducting, they can be used in STM and AFM instruments. Advantages are the improved resolution in comparison with conventional Si or metal tips.

6) Sensors - Single walled Nanotubes may be used as miniaturised chemical sensor. On exposure to environments which contain  $\text{NO}_2$ ,  $\text{NH}_3$  (or)  $\text{O}_2$ , the electrical resistance changes.

7) Composite materials - Theoretically single walled CNT's could have Young's modulus of 1TPa. Multiwalled CNT's are weaker because the individual cylinders slide with respect to each other. Single walled CNT's are highly flexible & sustain large strains in tension without fracture. Therefore used as reinforcement material for composites.

### Fabrication technique for low dimensional systems

#### D) Chemical Vapour deposition (CVD)

Involves depositing a solid material from a gaseous phase. Microfabrication processes widely use CVD to deposit materials in monocrystalline/poly-crystalline/Amorphous/Epitaxial form.

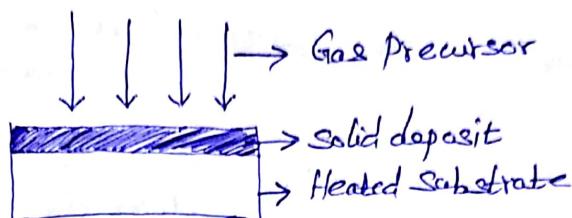
Working concept - results from the chemical reaction of gaseous precursor (source) at a heated substrate to yield a fully dense deposit. Thermodynamics and kinetics drive both precursor generation and de-lagocification, (i.e) control through temperature, pressure & concentration yields the desire deposit.

for Metal deposition      Metal halide (gas)  $\rightarrow$  metal (solid) + by product (gas)

for Ceramic deposition      Metal halide (gas) +  $\text{O}_2/\text{C}_2/\text{N}_2/\text{B}_2$  (gas)  $\rightarrow$  Ceramic (solid) + by product (gas)

## Steps involved in CVD System for material process / deposition

- 1) A predefined mix of reactant gas & diluent inert gas are introduced at a specified flow rate into the reaction chamber
- 2) Gas species move to the substrate
- 3) Reactants get absorbed on the surface of the substrate
- 4) Reactants undergo chemical reaction with substrate to form the film
- 5) Gaseous by product of reaction are desorbed & evacuated from the reaction chamber



During deposition process, the reactant gases undergoes two types of reaction.

Homogeneous Reaction - Reaction that takes place in gas phase which results low density films with lot of defects

Heterogeneous Reaction - Reaction that takes place at the substrate surface thereby helps to create good-quality film.

In short heterogeneous reaction are much more desirable than homogeneous reaction during CVD.

### Type of CVD

- 1) Based on chemical reaction & Processing Condition classified as hot wall & cold wall reactor.
- 2) Based on Operating pressure classified as Atmospheric Pressure CVD, Low pressure CVD, Plasma Enhanced CVD.

Advantages of CVD - Used to coat wide range of metals / ceramics, coating free standing structures, to fabricate complex shapes, controllable thickness & morphology, Coats multiple components & powders.

Applications - Wide range of industrial components like aircraft & land gas turbine blades, chemical implant items, parts of automotive industry. Apart from this

- 1) Used to do surface modification to prevent adhesion
- 2) Photoresist adhesion for Semiconductor wafer
- 3) Copper plating & Anti Corrosive Coatings
- 4) Promote biocompatibility between natural and synthetic materials

## 2) Physical Vapour deposition - (PVD)

- It is a vaporisation coating technique involving transfer of material on an atomic level. It is an alternative process of electroplating. Here the starting material is taken in solid form whereas in CVD, the starting material is in gaseous state.

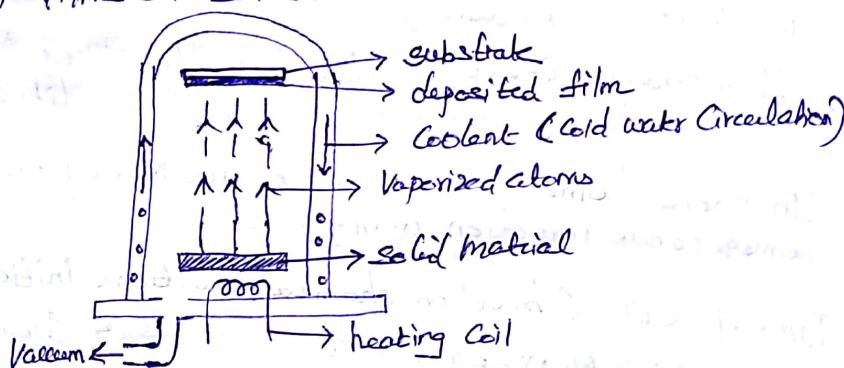
Working concept - Process is carried out under vacuum condition which involves four steps

1) Evaporation - Target material to be deposited is vaporized by high energy source using electron beam or beam of ions.

2) Transport - The vaporized atoms are moved from target material to the substrate in straight line affair.

3) Reaction - In some cases like metal oxide, nitrides, carbides coating, the vaporized atoms are reacted with appropriate gas during transport stage.

4) Deposition - Here the vaporized atom reacts on surface and builds up thin films on substrate.



Types of PVD (in the order of increasing hardness)

- 1) Evaporation Deposition
- 2) Electron beam PVD
- 3) Sputter Deposition
- 4) Cathodic Arc Deposition
- 5) Pulsed Laser Deposition

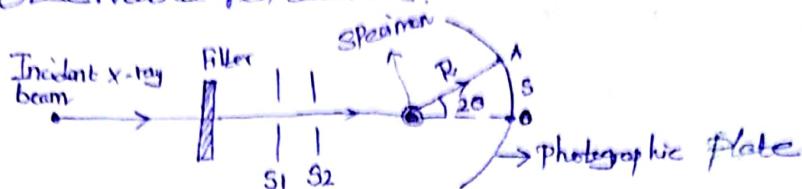
Advantages - Improved properties can be achieved, Any type of inorganic and organic material coating, process is environmentally friendly than electroplating, used to improve oxidation/wear resistance.

Applications - Coating used in Aerospace, Automotive, medical, cutting tools, Die and mould industries.

Disadvantages - High Capital cost, operates at high vacuums, requires large heat & appropriate cooling systems.

## Characterization techniques for low dimensional materials

D) Powder X-ray diffraction technique - This method employs powdered samples in which the crystals are oriented in all directions so that some of the crystals will be properly oriented for all observable reflections.



In this method, finely powdered specimen in thin walled glass capsule, X-ray from source are made approximately monochromatic by filter 'F' (usually Zirconium oxide). The narrow beam of monochromatic X-rays is suitably collimated by the two lead sheets  $S_1$  &  $S_2$ . Then the beam is made to fall on specimen (powdered form) which is suspended vertically on the axis of a cylindrical camera is fitted with photographic plate. The film covers nearly the whole circumference in order to record the beam's diffraction upto  $180^\circ$ .

For a given wavelength and given value of  $d$ , there can be only one ' $\theta$ ' value which satisfies the equation  
$$2d \sin \theta = n\lambda \text{ where } n=1 \text{ (Bragg's law)}$$

Such reflected beam emerges out from the specimen in all direction inclined at an angle  $2\theta$  with the direction of the incident beam. Therefore there will be a cone for each set of diffracted X-rays. These cones produce a series of concentric arcs of the photographic plate.



Structure determination of crystal:

Let 's' be the distance between the symmetrical lines on a stretched photograph and 'R' be the radius of cylindrical film then

$$2\theta = \frac{s}{R} \text{ radian (ie)} \quad 2\theta = \left(\frac{s}{R}\right) \times \left(\frac{180}{\pi}\right) \text{ degree}$$

Thus using Bragg's law condition, 'd' is calculated and crystal structure is identified

Applications: employed to study microcrystalline substance like metals, alloys, carbons and other forms where single crystals are not available.

## 2. Electron Microscopy Technique

An scientific instrument that use a beam of highly energetic electrons to examine objects on a very fine scale. The main advantage is unusual short wavelength of electron beam which is shorter than light wave. The wavelength of about 0.0001 nm increases the resolving power of instruments to fractions of a nanometer.

The examination yields following informations

- D) Topography - Surface feature of specimen
- 2) Morphology - shape and size of particle making up object
- 3) Composition - Elements and compounds that the object is composed
- 4) Crystallographic Information - Atomic arrangement, d-spacing etc.

Two types of Electron microscopy technique

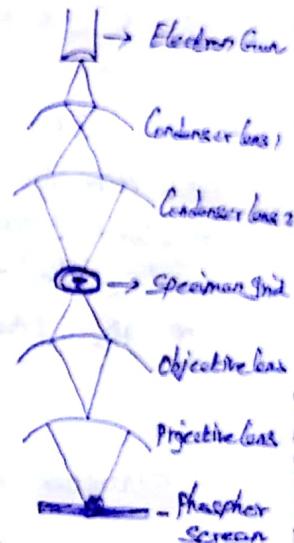
- D) Transmission Electron microscopy (TEM)
- 2) Scanning Electron microscopy (SEM)

### D) Transmission Electron microscopy (TEM)

Working Concept - Much like slide projector, TEM shine a beam of electrons (like the light in slide projector) through the specimen and transmitted beam is projected on phosphor screen for analysis.

Construction :

- D) The virtual source at the top represents the electron gun, producing a stream of monochromatic electron.
- 2) This stream is focused to a small, thin coherent beam by condenser lens 1 & 2. First one decides the size & second one decides the brightness.
- 3) The beam strikes the specimen & parts are transmitted. The transmitted portion is focused by objective lens into a image.
- 4) The image is passed down the column through the projector lenses being enlarged and finally strikes the phosphor screen where light is generated, allowing the user to see image.



Specimen Interaction with electron beam & uses

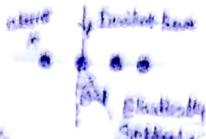
- D) Unscattered Electrons - Incident electrons which are transmitted through the thin specimen without any interaction occurring inside the specimen.

use : unscattered electrons is inversely proportional to specimen thickness

- (e) for thicker specimen - fewer unscattered electrons appear (dark)  
 for thinner specimen - more unscattered electrons appear (bright)

2) Elastically scattered electrons - Incident electrons that are scattered by atoms in the specimen in an elastic fashion without energy loss

Uses : All incident electron that are scattered by the same atomic spacing will be scattered by the same angle. When recorded, each spot on photographic plates represents atomic spacing & crystal phase.



3) Inelastically scattered electrons - Incident electron that interacts with specimen atom in inelastic fashion, losing energy during interaction & transmitted

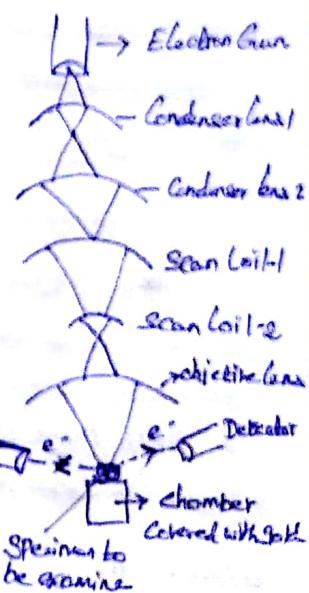
Uses : Inelastic loss of energy by the incident electrons is characteristic of the elements of specimen, thus gives compositions of elements in specimen. Also bands of alternating bright and dark lines formed by inelastic scattering relates the atomic spacing in specimen.

## 2) Scanning Electron Microscopy (SEM)

SEM allows surfaces of objects to be seen in their natural state without staining. As electron strikes the object, they knock loose showers of electrons that are captured by a detector to form the image.

### Construction

- 1) The virtual source at the top represents Electron gun producing monochromatic electrons.
- 2) The beam strikes Condenser lens 1 & 2 where size and brightness is controlled. The beam falls on scan coils 1 & 2 then which sweep the beam dwelling on points for a period of time.



- 3) Then objective lens focuses the scanned beam onto the part of specimen. When electrons interact with specimen and are detected by detectors (1 & 2). The process is repeated to scan entire area. (Entire pattern is scanned 30 times per second)

## Specimen interaction with electron beam and uses

D) Backscattered electrons - Incident electron colliding with an atom in specimen is then scattered backward 180°

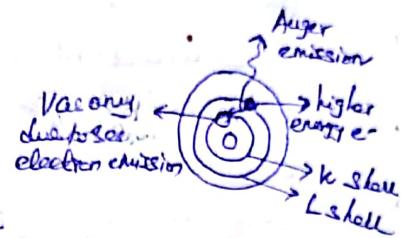
uses : Backscattered electron varies with specimen's atomic number. Different backscattering causes higher atomic number elements to appear bright for lower atomic number elements. Thus interaction in different parts helps to find average atomic number.

2) Secondary electrons - Incident electron passing near the atom imparts energy to lower K-shell electrons of atom. These ionized electron then leaves the atom with small kinetic energy and is termed as secondary electrons.

uses : Secondary electron take relates the topography. Any change in surface <sup>depth</sup> changes the secondary electron collection rate.



3) Auger electrons - Caused by de-energization of the specimen atom after the secondary electrons are produced. To fill the vacancy, higher energy electron from the same atom can fall to lower energy filling the vacancy, thus create energy surplus to release from atom called Auger electrons.



uses : Auger electron energy have a characteristic energy unique to each element from which it was emitted from and thus gives compositional information about specimen.

## Atomic Force Microscopy (AFM)

Also called Scanning force microscope (SFM). AFM raster scans a sharp probe over the surface of a sample and measure the changes in force between the probe tip and the sample.

### Working Concept

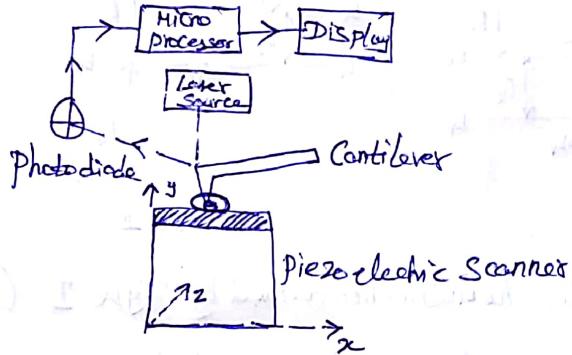
The physical parameter probed is a force resulting from different interactions. The origin of these interactions can be ion-ion repulsion, van der waals, capillary, electrostatic & magnetic force. The AFM image is generated by recording the force changes as the probe is scanned in the x & y directions.

### Construction

AFM consists of cantilever with a sharp tip. The tip should have radius of curvature less than 20-50 nm. The movement of the tip (or) sample in x, y & z direction is controlled by a piezo

electric tube scanner. The typical scanner range is  $80\text{nm} \times 80\text{nm}$  in  $x-y$  plane &  $5\text{nm}$  in  $z$ -direction. The force that are exerted between tip and sample are measured by the amount of bending of the cantilever.

Working - The sample is mounted on a piezoelectric scanner, which ensures three-dimensional positioning with high resolution. The force is monitored by attaching the probe to a pliable cantilever, which acts as spring & measuring the bending or deflection of the cantilever. Larger the deflection, higher the force experienced by the probe. The deflection is measured by focussing laser beam on the free end of cantilever. The reflected beam is detected by photodiode which give electric signals to microprocessor to form surface image.



Applications - Useful to obtain three dimensional topographic information of insulating & conducting structures with lateral resolution down to  $1.5\text{nm}$  and vertical resolution to  $0.05\text{nm}$ .

To study powder catalysts; aggregate structural determinations, Metal - tooling studies, roughness, corrasions etc,

Advantages - provides 3D surface images, no special treatment for sample is required, works in ambient air (or) liquid environment, tests biological macromolecules and living organisms.

Disadvantages - AFM scanning depth is less ( $\text{nm}$ ) and scanning area is ( $150 \times 150\text{ nm}$ ). Quality of image is limited by radius of curvature of probe. Scanning time is slow compared to SEM.

Heterojunctions - defined as junctions of two (or) more semiconductor materials, each with a different bandgap. In homo junction both sides of the junctions are made of same material.

Commonly used heterojunctions are  $nP$ ,  $Pn$ ,  $Nn$ ,  $PP$  heterojunctions. Here ( $n, P$ ) refers semiconductors with a relatively narrow forbidden band and ( $N, P$ ) refers semiconductors with a wider forbidden gap.

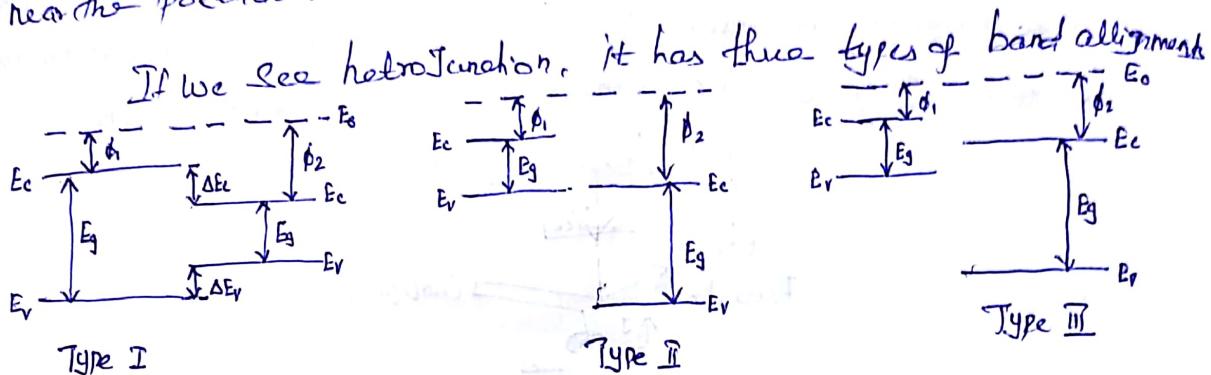
$nP$  &  $Pn$   $\rightarrow$  Anisotype heterojunction

$Nn$  &  $PP$   $\rightarrow$  Isotype heterojunction

Heterojunction can be formed based on Availability of Substrates and proper lattice matching. Most available substrates are GaAs, InP. GaAs provides relatively less cost and good lattice matching.

### Band diagram for heterojunction

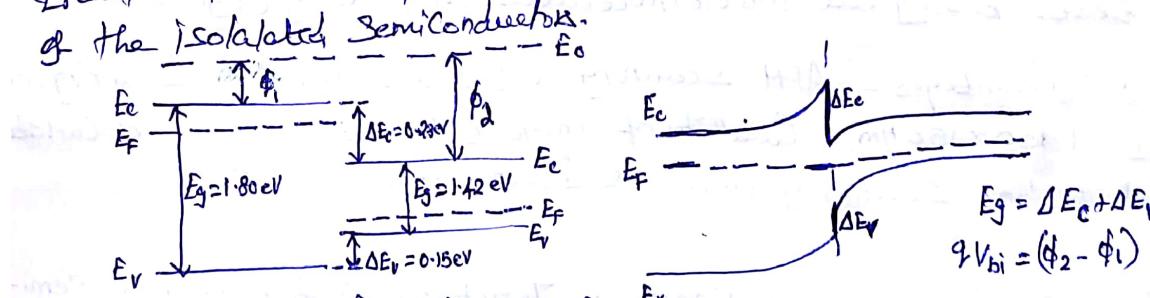
In normal p-n junction after placing the P-type & N-type material in contact, electron flows from region of higher Fermi level to region of lower Fermi level. As a result, a built-in potential is created near the potential barrier region.



If we consider heterojunction formed by Type I ( $N_p$  or  $n_p$ )

The band diagram ignore electrostatic potential due to re-arrangement of mobile carriers which occurs near the compositional Junction after the Semiconductors are placed in contact.

For Example, if energy band diagram of  $N_p$  Heterojunction [AlGaAs : GaAs] having the energy gap ( $N - E_g > P - E_g$ ). When the two materials are kept in contact, electrons moves from the Semiconductor with higher Fermi level to the other, and an electric field is produced to balance this transfer. The built-in potential is simply the difference in workfunction of the isolated Semiconductors.



After Contact -  $N_p$  heterojunction  
 $N_p$  denotes  $E_g$  of ( $N > P$ ) Semiconductor  
 Example - AlGaAs : GaAs

Similarly band diagram for  $PN$ ,  $nN$ ,  $Pp$  Heterojunctions are drawn.