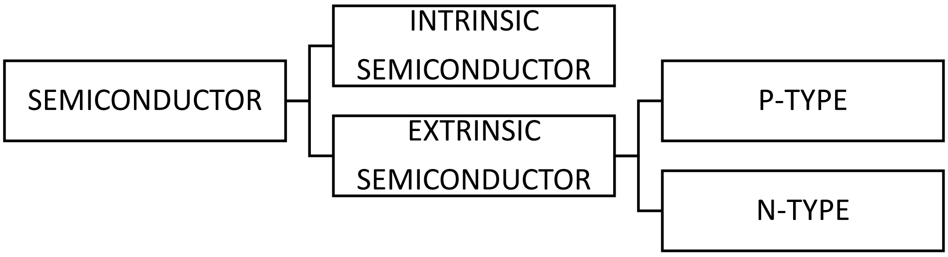
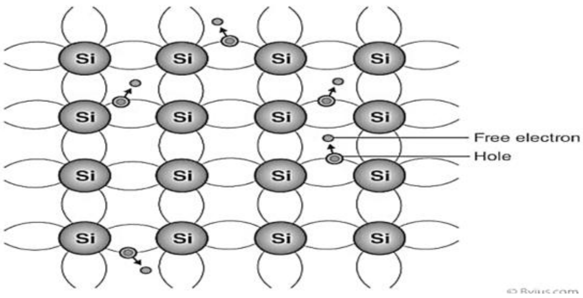
Unit 4
Physics Of Advanced Materials

TYPES OF SEMICONDUCTORS



1. **Intrinsic Semiconductor**

- Pure form of semiconductor materials without any significant impurities.
- Free Electron moves from valence band to conduction band.
- When we increase temperature, the conductivity also increases.
- In Intrinsic semiconductor flow of electricity is low as comparison to extrinsic semiconductor.



Properties Of Intrinsic Semiconductor

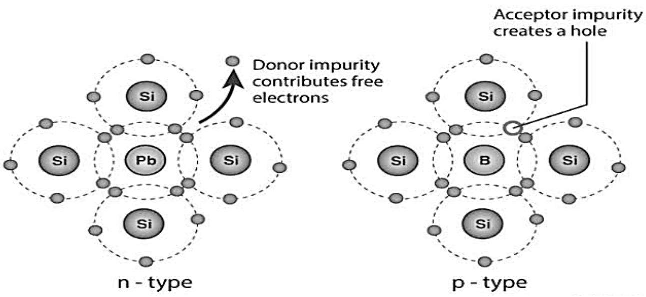
- Semiconductor are made of atoms with four outer electrons (tetravalent), like silicon.
- No. of free electron in conduction band = No. of holes in valence band.
- The no. Of electron and holes depend on the material properties and the temperature.
- At 0°C no electron moves from conduction band.

2. **Extrinsic Semiconductor**

- Doped semiconductor where impurities are added to modify their electrical properties.
- Doping = Pure + Impure
  E.g. Si + Al

(a) *N-type:* Doping with elements that have more valence electrons than the host semiconductor (e.g. P in Si) adding extra free electron.

(b) *P-type:* Doping with elements that have few valence electron than the host semiconductor (e.g. B in Si) creating holes.



MOBILITY AND CONDUCTIVITY IN SEMICONDUCTORS

Mobility: The electron mobility characterises how quickly an electron move through a metal or semiconductor.

$$V_d \propto E$$

$$V_d = \mu E$$

$$\boxed{\mu = \frac{V_d}{E}}$$

μ depends upon: Temperature, Material, Motion of electrons or holes

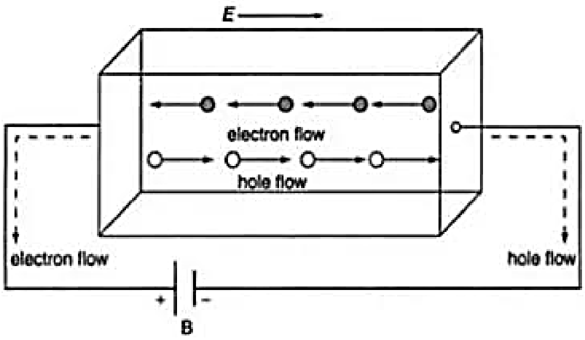
Conductivity:
Consider a semiconductor having an electron density in the conduction band in n per unit volume.

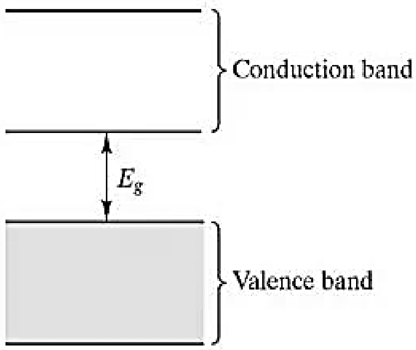
$$q = ne$$

The charge which is available for conductor per unit volume is ne.

If this charge will move with a velocity V_e in the field E, then the current density is given by

$$J_e = n_e e V_e$$





Similarly, for holes $\qquad J_h = n_h e V_h$

Now, conductivity $\qquad \frac{V_d}{E} = \mu$

For electron: $\qquad \sigma_e = \frac{J_e}{E} = \frac{n_e e V_e}{E} \qquad \boxed{\sigma_e = n_e e \mu_e}$

For holes: $\qquad \sigma_e = \frac{J_e}{E} = \frac{n_e e V_e}{E} \qquad \boxed{\sigma_h = n_h e \mu_h}$

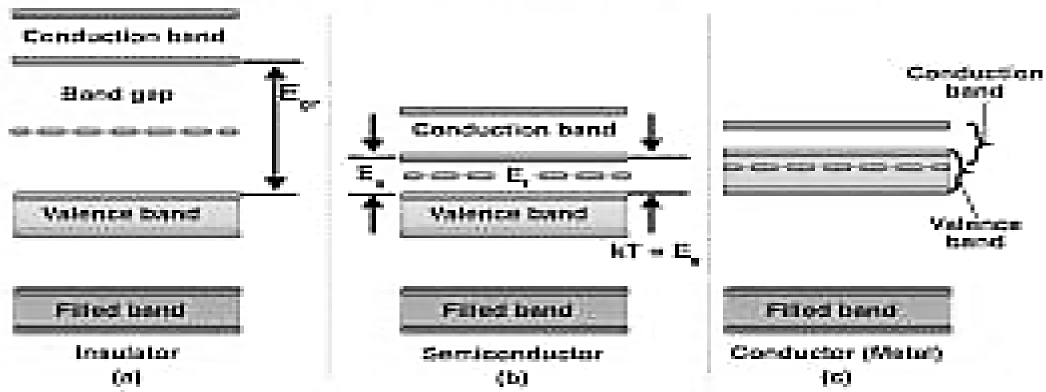
Total conductivity, $\qquad \sigma = \sigma_e + \sigma_h = n_e e \mu_e + n_h e \mu_h$

$$\boxed{\sigma = e(n_e \mu_e + n_h \mu_h)}$$

ENERGY BAND GAP

Bands In Solids

- *Valence Bands:* The electrons in the outermost shell are known as valence electrons. These valence electrons contain a series of energy levels and form an energy band known as the valence band.
- *Conduction Bands:* The valence electrons are not tightly held to the nucleus due to which a few of these valence electrons leave the outermost orbit even at room temperature and become free electrons move towards the conduction band.
- *Forbidden Energy Gap:* The gap between the valence band and the conduction band is referred to as the forbidden gap.



Fermi-Distribution Function

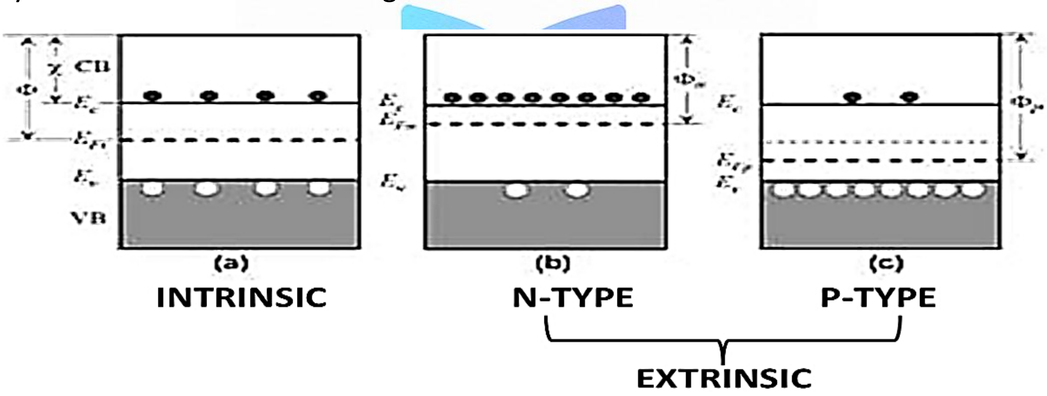
$$\boxed{f(E) = \frac{1}{1 + e^{\frac{(E-E_F)}{kT}}}}$$

EF = Fermi energy or Fermi level

K = Boltzmann Constant = 1.38 x 10-23 J/K = 8.6 x 105 eV/K

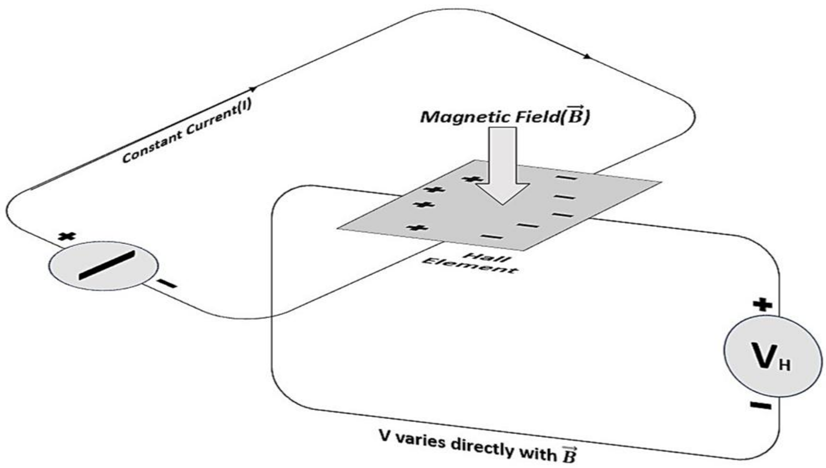
T = Absolute Temperature in K

- Fermi distribution function gives the probability of occupation of an energy states E for electron at a certain temperature.
- ***Fermi energy*** is the energy of the highest occupied state at absolute zero temperature, and it serves as a key reference for understanding the behaviour of electron in materials.



HALL EFFECT: THEORY AND APPLICATIONS

The Hall Effect is the production of a voltage difference (The Hall Voltage) across an electrical conductor, transverse to an electric current in the conductor and to an applied Magnetic field.



Now, let us talk about force due to Electric field
If Magnetic force and Electric force are equal

$$\overrightarrow{F_{Magnetic}} = \overrightarrow{F_{Electric}}$$
$$q\overrightarrow{V_d}\vec{B} = q\overrightarrow{E_H}$$
$$\overrightarrow{E_H} = \overrightarrow{V_d}\vec{B}$$

As we know,

$$V_H = E_H d$$

Hall voltage, $\boxed{V_H = \overrightarrow{V_d}\vec{B}d}$ OR $\boxed{V_H = \frac{I\vec{B}d}{neA}}$ [I=nAeV$_d$]

$$V_H = \frac{I\vec{B}d}{newd}$$
$$V_H = R_H \frac{I\vec{B}}{w}$$

Hall coefficient, $\boxed{R_H = \frac{1}{ne}}$

Applications Of Hall Effect

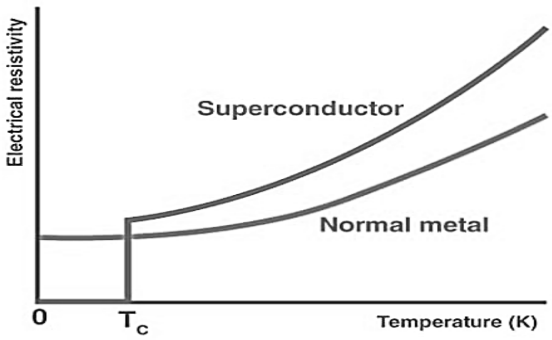
- Hall effect used to find whether a semiconductor is n-type or p-type.
- Hall effect is used to find carrier concentration.
- Hall effect is used to calculate the mobility of charge carries (free electron and holes).
- Hall effect is used to measure conductivity.
- Hall effect is used to measure A.C. power and the strength of magnetic fields.
- Hall effect is used in an instrument called hall effect multiplier which gives the output proportional to the product of two input signals.

SUPERCONDUCTOR AND ITS PROPERTIES

- The phenomena of attaining 'Zero Resistivity' or 'Infinite Conductivity' at low temperature is known as 'Super Conductivity'. The materials are called superconductors.
- In another way, certain metals alloys exhibit almost zero resistivity when they cooled to low temperature is known as Super Conductivity.

They are two important properties of superconductors are:

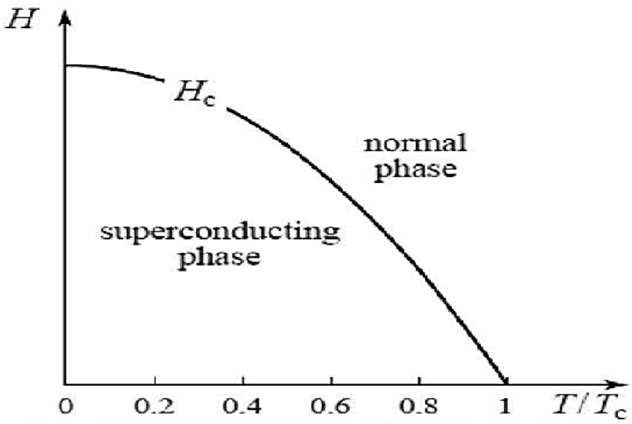
1. *Transition Or Critical Temperature (Zero Resistivity*)
    - The temperature at which the materials undergo a transition from normal state to superconducting state is known as transition or critical temperature.
    - At which temperature resistivity is 0 or conductivity is ∞.
    - It is not a very sensitive to the small amount of impurities.
    - E.g. Mercury: -4.15K
      Aluminium: -1.19K
      Tin: -3.7K



2. *Critical Magnetic Field (Diamagnetism)*
    - The minimum applied field necessary to destroy superconductivity and further restore the normal resistivity is called the critical magnetic field.
    - It is that magnetic field in which superconductors lost its super conductivity.
    - If H_C is the critical magnetic field at absolute 0 temperature, then

$$H_C = H_C\left[1 - \left(\frac{T}{T_c}\right)\right]^2$$

Where, T_c is the transition temperature

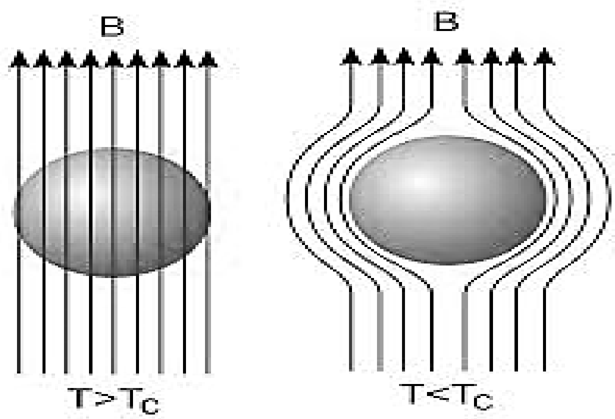


General Properties of Superconductors

- Super conductivity is a low temperature phenomenon.
- The transition from normal state to Super conducting state occurs below the Critical temperature.
- Different metals will show different critical temperatures.
- The current once set up in a superconductor persists for a long due to Zero Resistivity.
- Super conductors do not allow magnetic lines thorough them and behave as a diamagnetic nature. This property of as expulsion is known as Meissner Effect.
- The magnetic field at which a super conductor loses its super conductivity and becomes normal is known as conductor Critical magnetic field.

MEISSNER EFFECT

- The Meissner effect is the expulsion of magnetic fields from a material when it becomes superconductor.
- The materials lose its resistance to electrical currents and becomes a superconductor.
- It is perfect diamagnetic material.



For superconductor, below T_c $\boxed{\vec{B} = 0}$

$$B = \mu_0(\vec{H} + \vec{M})$$

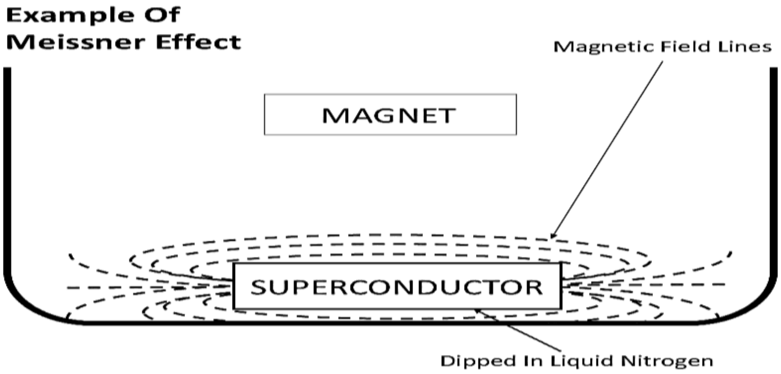
$$\mu_0(\vec{H} + \vec{M}) = 0$$

Now, $\boxed{\frac{\vec{M}}{\vec{H}} = -1}$

Magnetic Susceptibility = $\frac{\vec{M}}{\vec{H}}$

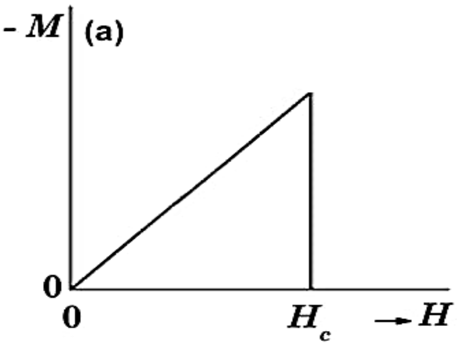
$$\boxed{x_m = -1}$$

It shows the property of perfect Diamagnetic.

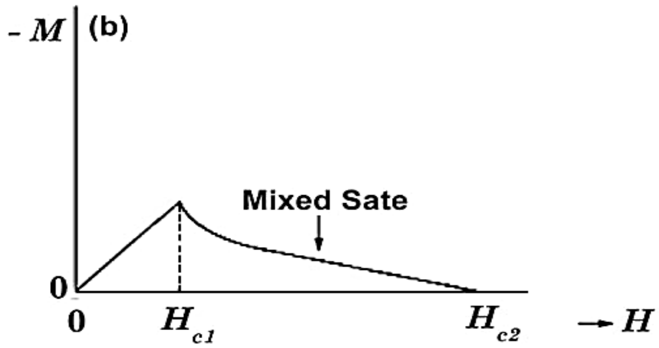


TYPE I AND II SUPERCONDUCTORS

1. **Type I Superconductors / Soft Superconductors**
    - These superconductors which can tolerate impurities without affecting the superconductivity properties.
    - It exhibits perfect & complete Meissner Effect.
    - Behave like a perfect Diamagnetic material
    - There is only one H_c. ⟵ Critical Magnetic Field.
    - Sudden loss of Magnetisation.
    - E.g. Ph, Sn, Hg



2. **Type II Superconductors / Hard Superconductors**
    - Those superconductors which cannot tolerate impurities, impurity affects the superconductivity properties.
    - Don't exhibit complete Meissner Effect.
    - Does not behave as a perfect diamagnetic materiel.
    - There are too critical magnetic fields.
    - $H_{c1} \longrightarrow$ Lower C.M.F.
    - $H_{c2} \longrightarrow$ Upper C.M.F.
    - Gradual loss of magnetisation.
    - E.g. Nb-Sn, Nb-Ti



APPLICATION OF SUPERCONDUCTORS

- Energy Production and Transport.
- Current Limiters.
- Transports: Magnetic Lavation, Trains Motors.
- Medicine: MRI, Bio-Magnetic Measurements.
- Research: Laboratory Magnets.
- Fast Electrical Switching.
- Electronic Power Transmission Lines.

NANOMATERIALS

Materials having any one or more than one dimension in Nano-Scale.

Nanomaterials

1D
Only One Dimension Nano-scale.
Eg-Quantum Well, Thin Fibres

2D
Two Dimensions Are In Nano-scale.
Eg-Quantum Wire, Nano Tubes, Nano Fibres

3D
All Three Dimensions In Nano-scale.
Eg-Quantum Dots, Nano Rings

Significance Of the Nanoscale

- *Quantum Effects:* At the nanoscale, quantum mechanical phenomena become significant, altering the electronic, optical, and magnetic behaviours of materials.
- *Surface Area to Volume Ratio:* Nanomaterials have a high surface area to volume ratio, enhancing their chemical reactivity and interaction with other substances.

Properties Of Nanomaterials

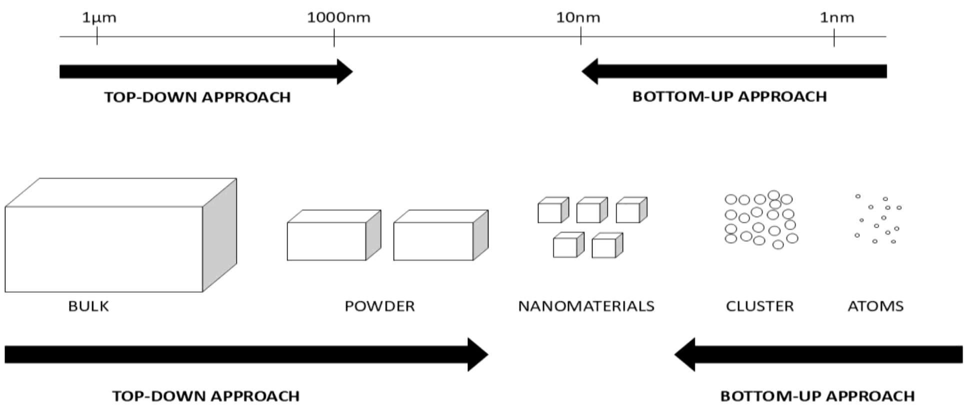
- *Mechanical Properties:* Nanomaterials can exhibit increased strength and flexibility compared to bulk materials.
- *Electrical Properties:* They may show enhanced electrical conductivity or, conversely, act as insulators, depending on their structure and composition.

- *Optical Properties:* Nanomaterials can have unique optical properties, such as fluorescence or the ability to absorb specific wavelengths of light, making them useful in imaging and sensor applications.
- *Magnetic Properties:* At the nanoscale, materials can display superparamagnetic, which is valuable in data storage technologies.

BASICS OF SYNTHESIS OF NANOMATERIALS

Top-Down & Bottom-Up Approach

There are two general approaches for synthesis of nanomaterials are:



1. *Top-Down Approach*
    - Breaking down of bulk material into nanomaterial.
    - E.g. E-Beam Lithography, Atomic-Force Manipulation, Aerosol Spray Method.
    - Drawbacks: (I) Imperfection surface of nanomaterials (Crystal Defects).
      (II) Produce large amount of waste.
2. *Bottom-Up Approach*
    - Combination of atoms and cluster into nanomaterials.
    - E.g. Organometallic Chemical Route, Cluster-Beam Evaporation, Colloidal Precipitation.

Applications Of Nanomaterials

1. In Medicines
    - Targeted Drug Delivery
    - Reduces Side Effect
    - Early Diagnosis of Decease
2. In Electronics
    - Reduced Power Consumption
    - Less Size and Weight of Components
    - Smaller And Faster Processors
3. In Energy
    - Reduce Cost of Catalysts in Fuel Cells
    - Can Increase Efficiency of Solar Cells
    - Increased Energy Density of Batteries
4. In Automobiles
    - High Strength of Metal
    - Increased Fuel Efficiency
    - Quality Of Paints

5. In Space Technology's
    - Light Weight Spacecraft
    - Reduction In Rocket Fuel
    - Larger Material Strength

X-RAY DIFFRACTION METHOD

It is a method used to study the atom structure of crystalline materials by analysing the patterns produced when X-Rays are diffracted by the crystal's atomic planes.

Principle

XRD is based on Bragg's law, which explains how X-rays are scattered atomic planes in a crystal lattice. The condition for constructive interference is given by

$$\boxed{n\lambda = 2\,d\,sin\,\theta}$$

Where, n = order of diffraction

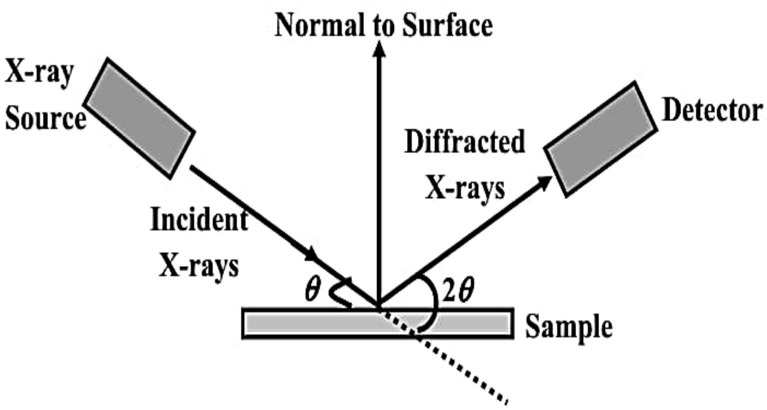
λ = wavelength of X-rays

d = spacing between atomic planes in the crystals

θ = angle of incidence reflection

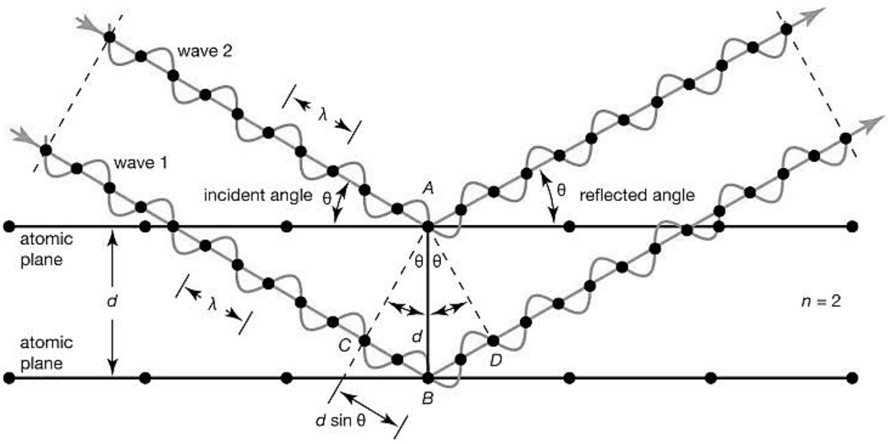
Construction

- X-Ray Tube: Produces X- rays by bombarding a target metal with high energies electron.
- Sample Holder: Holds the crystalline material in the path of X-Rays.
- Goniometer: Adjusts the angles for precise measurements.
- Detector: Detects the diffracted X-rays and converts them into a measurable signal.



Working

- X-Rays are generated using an X-ray tube and directed at the sample.
- The sample diffracted rays are detected by a detector as a series of spots or peaks.
- The angles and intensities of the diffraction pattern are analysed to determine the crystal structure.



According to Bragg's law,

$$n\lambda = 2\,d\,sin\,\theta \quad \text{(Bragg's Law)}$$

Bragg's Condition

$$\frac{n\lambda}{2d} = \sin\theta \qquad [\sin\theta = 1(Max)]$$

$$\boxed{\frac{n\lambda}{2d} \leq 1}$$

For n = 1

$\lambda \leq 2d$ wavelength of x-ray should be less than the double of interplanar spacing

$\boxed{\frac{2d}{\lambda} = n}$ as λ decreases, order of diffraction increases.