Engineering Physics: PHY110

Introduction to engineering materials
UNIT-6

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Dielectric Materials:

- A dielectric is an insulating material which can be polarised by an external electric field.

  Examples: Glass, Ceramics, Polymers, Paper etc.

- A dielectric has to be an insulator but an insulator need not to be dielectric. The main function of dielectric is to store electric energy while the insulator is to obstruct the flow of current.

- To what extent a dielectric material can be polarised is measured by dielectric constant.

Dielectric Constant

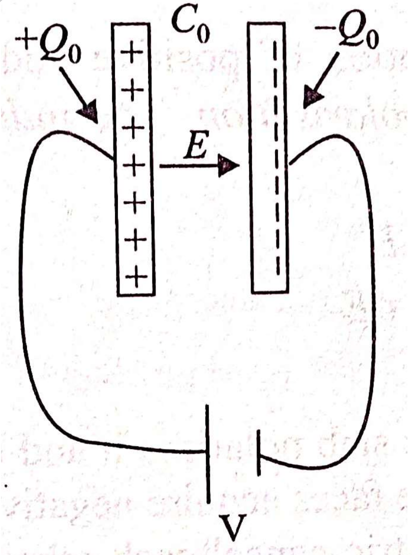
- Dielectric constant (ε_r) is defined as the ratio of permittivity of the material (ε) to the permittivity of free space (ε_0). It is also know as relative permittivity.

$$\boxed{K = \varepsilon_r = \frac{\varepsilon}{\varepsilon_0}}$$

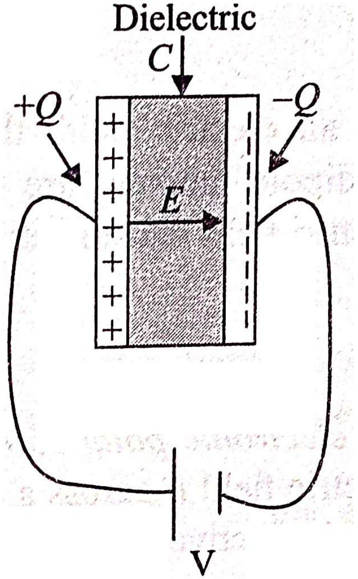
- For a parallel plate capacitor,

$$C_0 = \frac{Q_o}{V} = \frac{\varepsilon_0 A}{d} \quad \text{and} \quad C = \frac{Q}{V} = \frac{\varepsilon A}{d}$$

$$\boxed{\varepsilon_r = \frac{\varepsilon}{\varepsilon_0} = \frac{Q}{Q_0} = \frac{C}{C_0}}$$



(a)

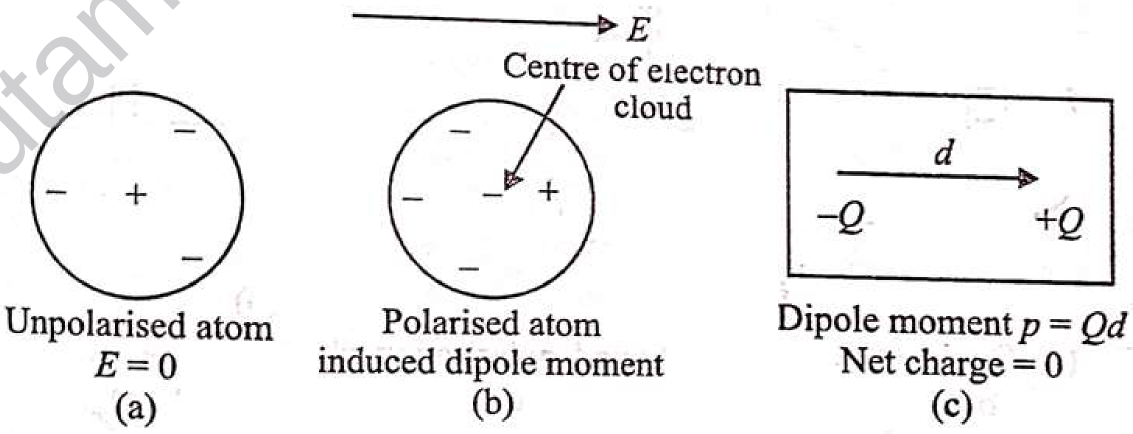


(b)

Dipole and Dipole moment

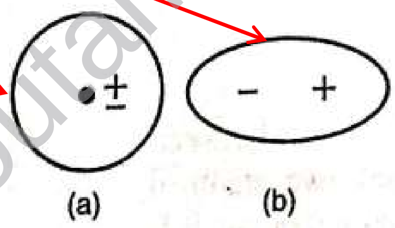
- An electric dipole is a pair of equal and opposite charges separated by a considerably short distance.
- The dipole moment definition is given as the product of the magnitude of charges and the separation between them. It is denoted by *p* and it is a vector quantity.

$$\boxed{p = Q \times d}$$



Polar and Non-polar Dielectric

- We know that most of the matter made up of atoms and molecules will be electrically neutral. Based on the dipole moment, the dielectrics are polar and non polar.
  - Polar: If the centre of gravity of positive charge doesn't coincide with the centre of gravity of negative charge then it is known as a polar molecule. Example: H_20, HCl, N_2O, CO etc.-→ Asymmetrical structure and Permanent dipole moment
  - Non-polar: If the centre of gravity of positive charge coincides with the centre of gravity of negative charge then it is known as a non-polar molecule. Example: H_2, N_2, CO_2 etc. → Symmetrical structure and No permanent dipole moment



- Dielectric having polar molecule is called polar dielectric, however, dielectric having non-polar molecule is called non-polar dielectric.

Polarisation of dielectric

- Dielectric Polarization occurs when an external electric field is applied to a dielectric substance. When an electric field is applied, it causes charges (both positive and negative) to be displaced.
- The dipole moment per unit volume is called polarisation and is denoted by P
- Polarization is actually the alignment of the dipole moments of the fixed or induced dipole in the direction of the external electric field.

Types of Polarisation:

- There are four main polarisation mechanisms that can occur within a dielectric material
  - ✓ Electronic Polarisation
  - ✓ Ionic Polarisation
  - ✓ Orientational Polarisation
  - ✓ Space-Charge Polarisation

Electronic Polarisation

- The displacement of +ve and –ve charges of an atom in the presence of external electric field.
- As the nucleus and centre of electron cloud are separated by a certain distance, dipole moment is created in each atom. Then induced dipole moment is proportional to external electric field.

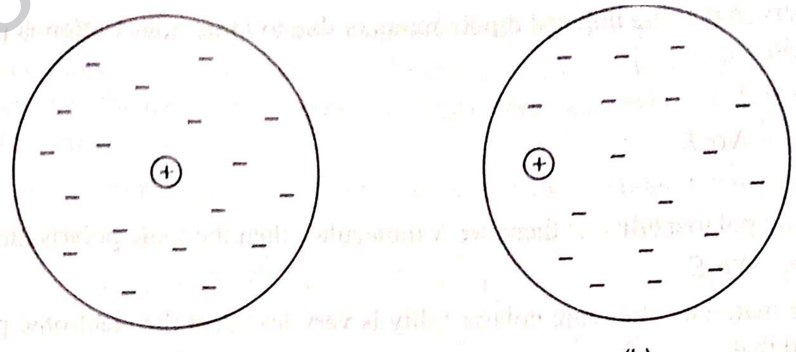
$$\vec{p}_e \propto \vec{E}$$

If there are N atoms in the dielectric, then

$$\vec{p}_e \propto N\vec{E}$$

or $$\vec{p}_e = \alpha_e N\vec{E}$$

where α_e is the electronic polarisability.



(a) (b)

- Electronic polarisability is temperature independent.

Ionic Polarisation

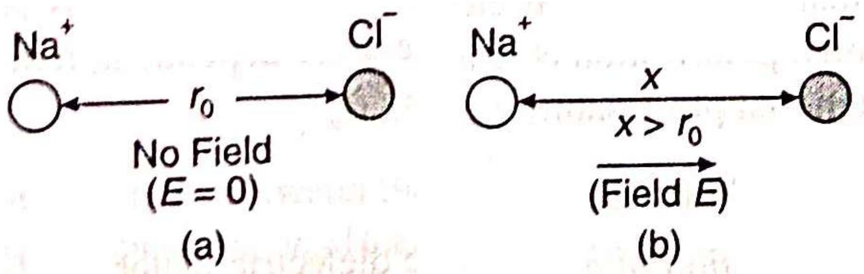
- It happens due to displacement of ions from their equilibrium position in the presence of applied electric field.
- The dielectric materials having ionic bonds, such as, NaCl shows ionic polarisation.
- The displacement of ions causes an increase or decrease of distance between atoms and this leads to net dipole moment.

$$\vec{p}_i \propto \vec{E}$$

If there are N atoms in the dielectric, then

$$\vec{p}_i \propto N\vec{E}$$

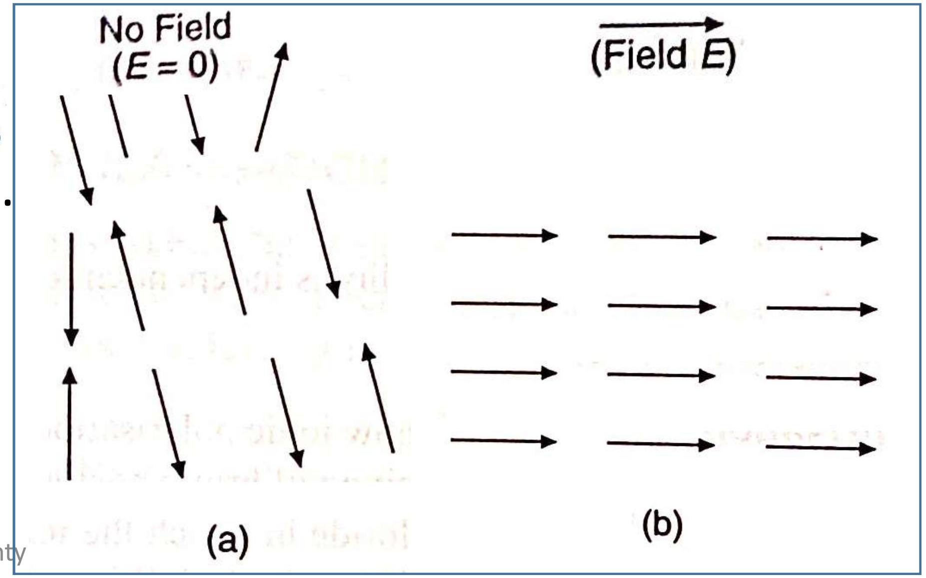
or $$\vec{p}_i = \alpha_i N\vec{E}$$



- Ionic polarisation is temp independent and $\boxed{\alpha_i = 0.1\alpha_e}$

Orientational Polarisation

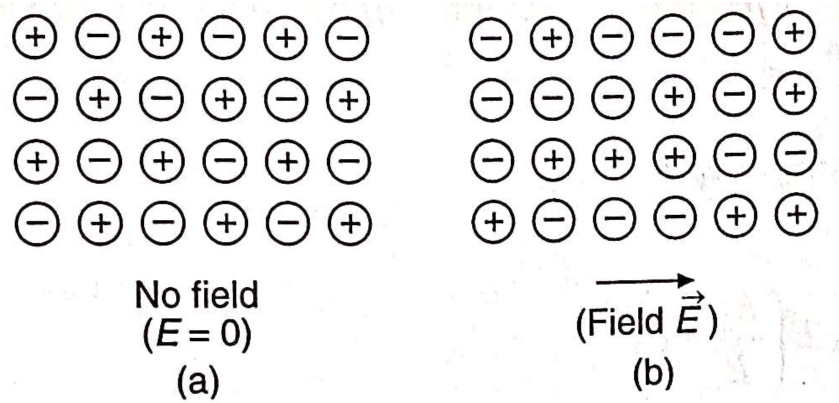
- Orientational polarisation occurs in polar substances. These substances exhibit dipole moment even in absence of external electric field but the net dipole moment is zero.
- When such materials subjected to an external electric field, the permanent molecular dipoles rotate about their axis of symmetry to align with the applied field, which exerts a torque on them. This type of polarisation is called orientational polarisation.
- Orientational polarisability is denoted by α_0
- This polarisation is inversely related to temp.



Space-Charge Polarisation

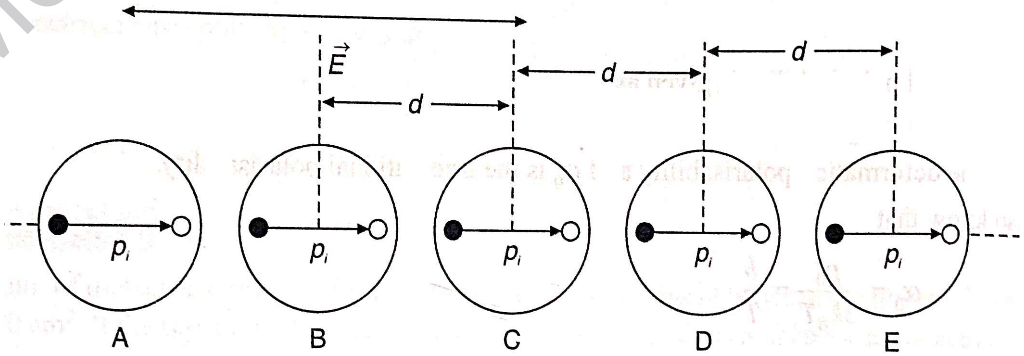
- Under the influence of applied electric field, the ions are diffused over appreciable distance, due to which redistribution of charges in the dielectric medium takes place.
- The tendency of redistribution of charges in the dielectric medium in the presence of an external electric field is known as space-charge polarisation.
- The space-charge polarisation is not an important factor in most common dielectrics.

➢ Total polarisability can be given as the sum of electronic, ionic, and orientational polarisability, i.e., $\boxed{\alpha = \alpha_e + \alpha_i + \alpha_o}$



Internal Field

- When solid or liquid dielectric material is subjected to an external electric field, the atoms experiences two field i.e. external applied field and field due to dipole moment.
- Thus, the resultant field is the sum of the above two files and is known as internal field (or) local filed.
- For a linear array of atoms in an external filed, the internal filed at C due to all atomic dipoles will be,



$$\vec{E}_i = \vec{E} + \frac{\vec{p}_i}{\pi \epsilon_0 d^3} + \frac{\vec{p}_i}{\pi \epsilon_0 (2d)^3}$$

$$= \vec{E} + \frac{\vec{p}_i}{\pi \epsilon_0 d^3}\left[1 + \frac{1}{2^3} + \frac{1}{3^3} + \right]$$

$$= \vec{E} + \frac{\vec{p}_i}{\pi \epsilon_0 d^3}\left[\sum_{n=1}^{\infty} \frac{1}{n^3}\right] = \vec{E} + \frac{1.2\, \vec{p}_i}{\pi \epsilon_0 d^3}$$

- In 3D, internal field of dielectric is $\boxed{\vec{E}_i = \vec{E}_L = \vec{E} + \frac{\vec{P}}{3\epsilon_0}}$ Also called Lorentz field

Clausius-Mossotti Relation

- When dielectric subjected to an external electric field. then the induced dipole moment of an atom is $\vec{p}_i = \alpha \vec{E}_L$,Where is polarisability of the atom.
- It dielectric material have N molecule per unit volume, then electric polarisation is given by,

$$\vec{P} = N\vec{p}_i = N\alpha\vec{E}_L$$

$$\text{or} \quad \alpha = \frac{\vec{P}}{N\vec{E}_L}$$

- But in 3D internal field of dielectric is,

$$\vec{E}_i = \vec{E}_L = \vec{E} + \frac{\vec{P}}{3\epsilon_0}$$

- Then,

$$\alpha = \frac{\vec{P}}{N\left[\vec{E} + (\vec{P}/3\epsilon_0)\right]}$$

But we know

$$\vec{P} = \epsilon_0 (\epsilon_r - 1)\vec{E}$$

$$\text{or} \quad \vec{E} = \frac{\vec{P}}{\epsilon_0 (\epsilon_r - 1)}$$

- By putting E in the above equation, we get,

$$\alpha = \frac{\vec{P}}{N\left[\left\{\vec{P}/\epsilon_0 (\epsilon_r - 1)\right\} + (\vec{P}/3\epsilon_0)\right]}$$

$$\text{or} \quad \frac{N\alpha}{\epsilon_0} = \frac{1}{\left[\left\{1/(\epsilon_r - 1)\right\} + (1/3)\right]}$$

$$= \frac{1}{\left[\left\{(\epsilon_r + 2)/3(\epsilon_r - 1)\right\}\right]} = \frac{3(\epsilon_r - 1)}{\epsilon_r + 2}$$

$$\text{or} \quad \boxed{\frac{N\alpha}{3\epsilon_0} = \frac{(\epsilon_r - 1)}{(\epsilon_r + 2)}}$$

This is Clausius-Mossotti Relation

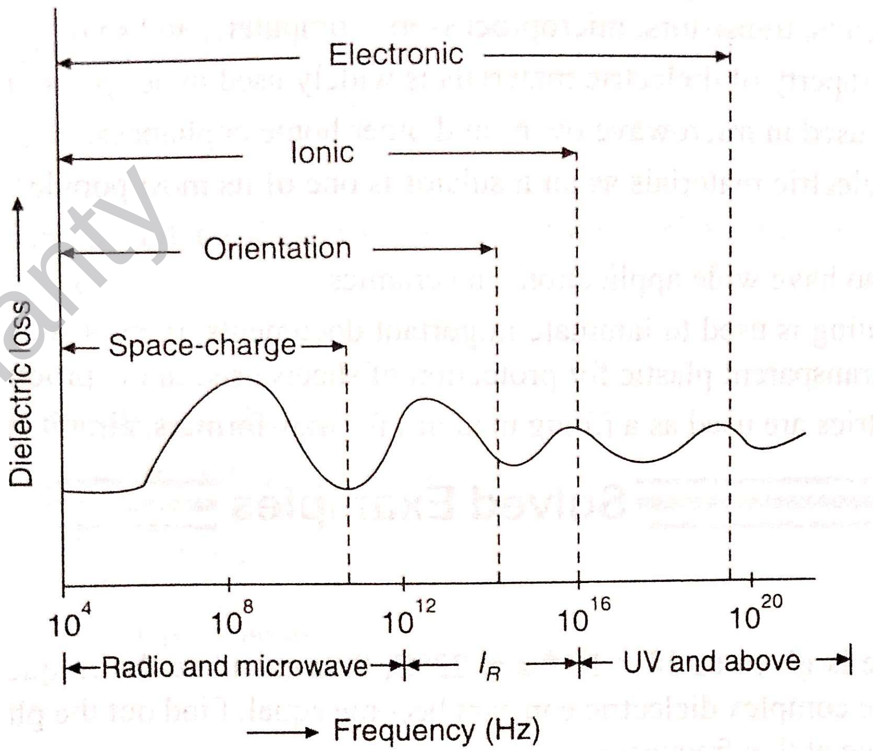
Dielectric Breakdown

- Dielectric materials are not perfect insulators. When the externally applied voltage to the dielectrics exceeds a certain maximum level, then the dielectrics break down. This value of voltage is known breakdown voltage.
- Dielectric breakdown can be explained on the basis of band theory of solids. In insulators (dielectrics), there is a large gap between the conduction band and valance band.
- When applied voltage exceeds a certain maximum value, then the electrons of valance band get sufficient energy to jump to the conduction band. Due to the availability of sufficient number of electrons in conduction band, the insulating properties of dielectric material break down.
- This mechanism of dielectric material is known as dielectric breakdown.

Dielectric Loss

- ✓In case of a capacitor charging and discharging takes place.
- ✓If capacitor is charged by a potential V , then the amount of energy stored to the capacitor is ½ CV^2. This energy stored as electrostatic P.E.
- ✓This energy is stored as polarisation energy in dielectric medium placed between plates.
- ✓During discharging the same amount of energy should be released but it is observed that a part of energy is released while rest is dissipated in the form of heat. This is called dielectric loss.
- ✓Sometimes, it is called relaxation loss.

(Dielectric Loss Spectrum)



Below 10^6 Hz: $P_o + P_i + P_e$

Audio/ Micro, 10^6 - 10^{11} Hz: $P_i + P_e$

At IR, 10^{11} - 10^{14} Hz: P_e

At Optical = 10^{15} Hz: P_e

At UV: $>10^{15}$ Hz, $P = 0$, $\varepsilon_r = 1$

Magnetic Materials

Introduction to magnetic material

- The materials which strongly attract apiece of iron are known as magnetic materials or magnets.
- The magnetic property of a material arises due to the magnetic moment or magnetic dipole of materials.
- Materials which are magnetised by the application of an external magnetic field are known as magnetic materials.
- Magnetic materials play an important role in modern technology as they are used frequently used in industrial electronics and computer industry etc.
- Magnetic materials are two types hard and soft material.

Magnetic terminology

- When a solid is placed in a magnetic field, it gets magnetised. The magnetic moment unit volume developed inside a material is called magnetization and is denoted by **M**.

- Magnetic susceptibility, which is a measure of the quality of the magnetic material and is defined as the magnetization produced per unit magnetic field, i.e. $\chi = \mathbf{M}/\mathbf{H}$, Where **H** is the strength of the applied magnetic field, also referred to as the *magnetic field intensity*. Here **M** and **H** are measured in amperes per meter.

- Magnetic induction or magnetic flux density **B** (measured in Wb/mt^2 or Tesla (T)) produced inside the medium as a consequence of the applied magnetic field **H** is given by $\mathbf{B} = \mu_o (\mathbf{H} + \mathbf{M})$ (or) $\mathbf{B} = \mu_o (1 + \chi) \mathbf{H}$

- Relative permeability of the material, $\mu_r = \mu/\mu_o$
- Relation between magnetic permeability and susceptibility, $\mu_r = 1 + \chi$

Classification:

- According to the modern theories, the magnetism in solids arises due to orbital and spin motions of electrons as well as spins of the nuclei.
- The major contribution comes from the spin of unpaired valence electrons which produces permanent electronic magnetic moments.
- The magnetism in solids has been classified into the following five categories :
  - ✓ Diamagnetism
  - ✓ Paramagnetism
  - ✓ Ferromagnetism
  - ✓ Antiferromagnetism
  - ✓ Ferrimagnetism

Diamagnetic Material

- In the presence of a field, dipoles are induced and aligned opposite to the field direction. Examples: Copper, Gold, Mercury, Silver and Zinc.

Properties:

✓ They repel the magnetic lines of force. The existence of this behaviour in a diamagnetic material is shown in Figure 2.

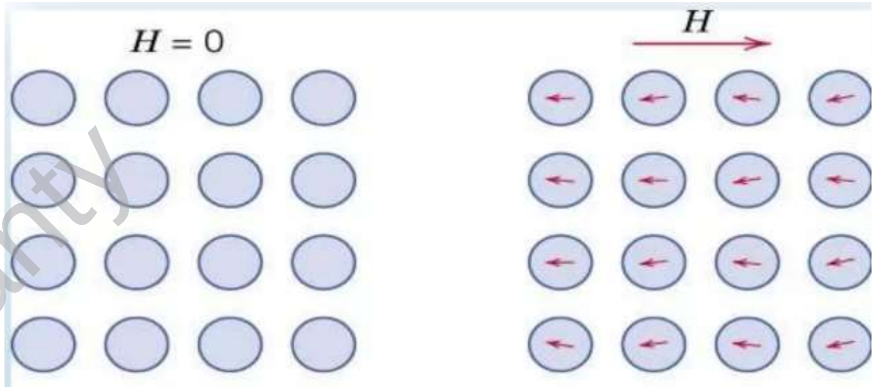
✓ They do not have a permanent dipoles moment and μ < 1

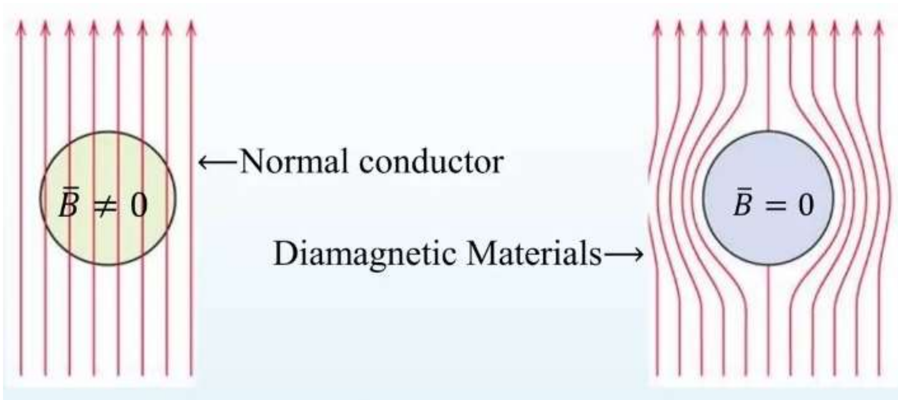
✓ The magnetisation becomes zero on removal of the external field.

✓ A diamagnetic liquid in a U-shaped tube is depressed when subjected to a magnetic field.

✓ The susceptibility of a diamagnetic material is negative.

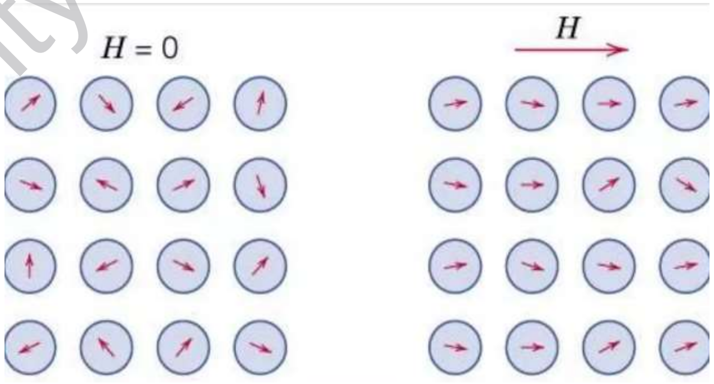
✓ The susceptibility is independent of temperature and external field.





Paramagnetic Material

- The behaviour of a paramagnetic material under the influence of an external field is shown in figure.
- Examples: Aluminum, chromium, sodium, titanium, zirconium, oxygen molecule etc.



Properties:

✓ Paramagnetic material possess a permanent dipole moment.

✓ The attract the magnetic lines of force and $\mu > 1$

✓ A paramagnetic liquid in a U-shaped tube is elevated when subjected to a magnetic field.

✓ The susceptibility is positive and depends on temperature.

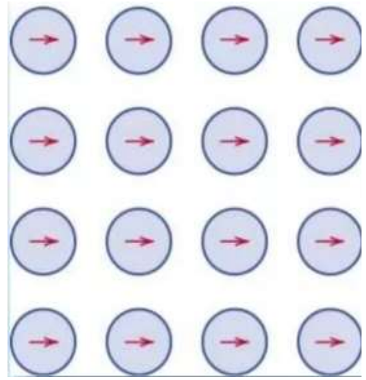
✓ Paramagnetic susceptibility is inversely proportional to temperature.

$$\boxed{\chi = \frac{C}{T}}$$

This is known as the Curie law of paramagnetism.

Ferromagnetic Material

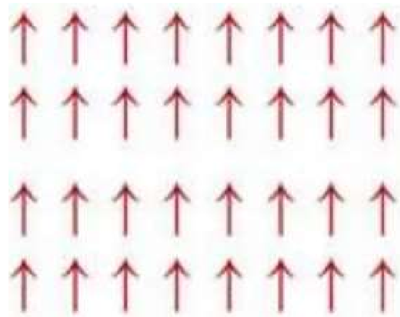
- Mutual alignment of atomic dipoles even in the absence of an external magnetic field. coupling forces align the magnetic spins. Examples: Iron, Cobalt, Nickel, Gd



Properties:

✓The magnetic dipoles are arranged parallel to each other. The spin arrangement is shown in figure.

✓They have characteristic temperature, namely, ferromagnetic Curie temperature(T_c). Materials below T_c behave as ferromagnetic materials and obey hysteretic curve. A material behave as a paramagnetic when it is above T_c.



✓They possess permanent dipole moment and $\mu > 1$

✓A paramagnetic liquid in a U-shaped tube is elevated when subjected to a magnetic field.

✓The susceptibility of a ferromagnetic material is $\chi = \dfrac{C}{T - T_c}$

This is known as Curie-Weiss law.

Magnetic data storage

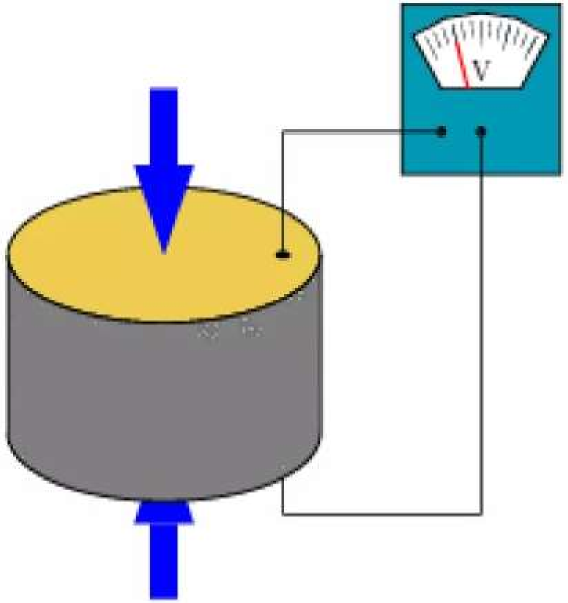
- In the Magnetic storage devices, all data are stored with using magnetized medium, and those types of data saved in that medium in the binary form like as 0 and 1.
- This magnetic storage has also non-volatile storage nature. Today’s, mostly people are preferred to magnetic medium because on the magnetic storage devices can be performed read/write activities very easily.
- It is also known as **Magnetic Media** or **Magnetic Memory** or **Magnetic Medium.**

Piezoelectric materials

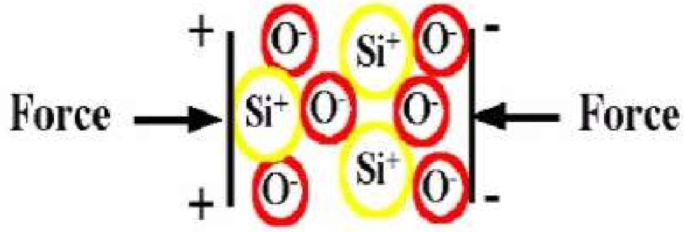
- The materials which can create electricity when subjected to a mechanical stress called Piezoelectric material.
- They will also work in reverse, generating a strain by the application of an electric field.
- The word originates from the greek word "piezein", which means "to press". This was discovered in 1880 by Pierre Curie in quartz crystals.

Examples:

- ✓ **<u>Natural Materials</u>:** Quartz, Rochelle Salt, Topaz, Sucrose, Tendon, Silk, Enamel, Dentin, DNA etc.
- ✓ **<u>Synthetic Materials</u>:** Lead zirconate titanate (PZT), Zinc oxide (ZnO), Barium titanate ($BaTi0_3$), Gallium orthophosphate ($GaP0_4$), Potassium niobate ($KNb0_3$), Lead titanate ($PbTi0_3$), Lithium tantalate ($LiTa0_3$), Langasite ($La_3Ga_5Si0_{14}$), Sodium tungstate (Na_2W0_3)



(A piezoelectric disk generates a voltage when deformed)

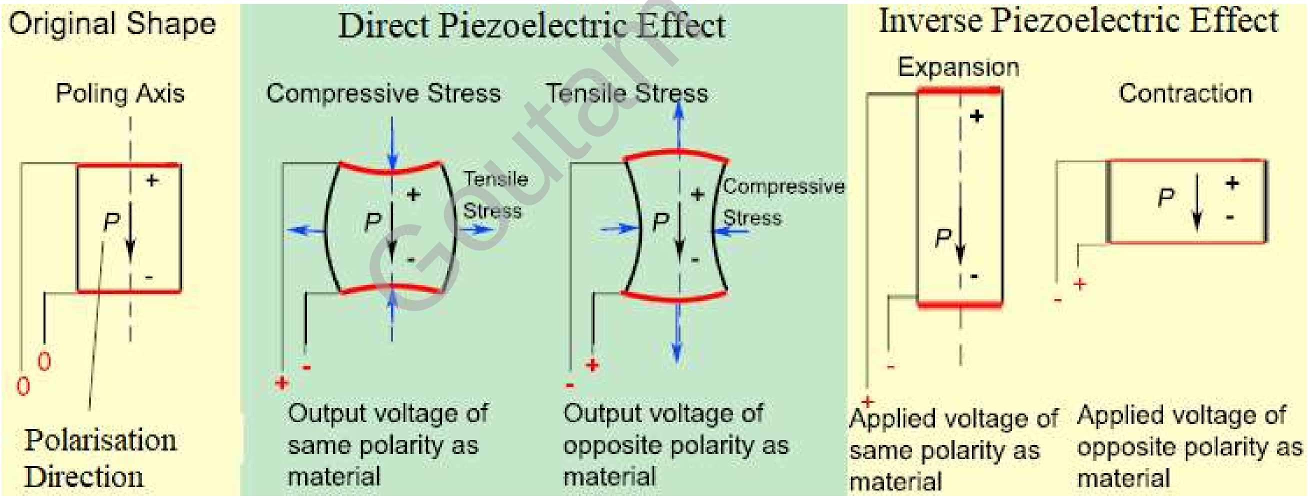


Piezoelectric effect and Types

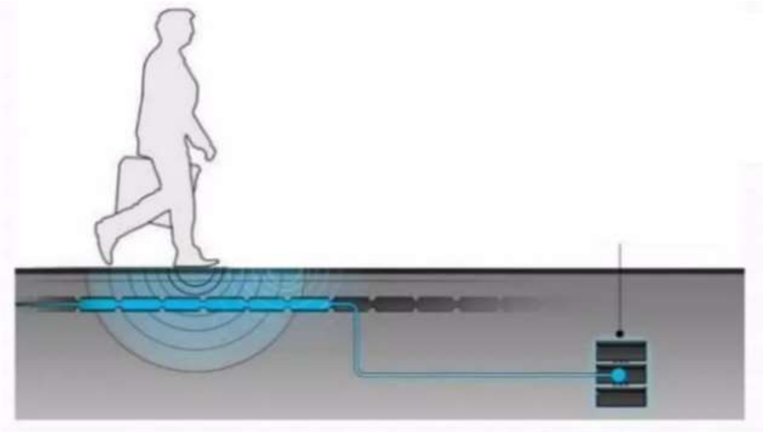
- The piezoelectric effect is the ability of certain materials to generate an electric field in response to applied mechanical stress.
- Piezoelectric behaviour can be manifested in TWO distinct ways:

✓ Direct Piezoelectric effect- Electrical response to Mechanical deformation

✓ Inverse Piezoelectric effect-Mechanical deformation to Electrical response



Application of Piezoelectric



(Power generating sidewalk)

- Charging pads under the cross walk collect energy from the vibrations.
- Piezoelectric charging panels channel energy to lithium ion batteries.

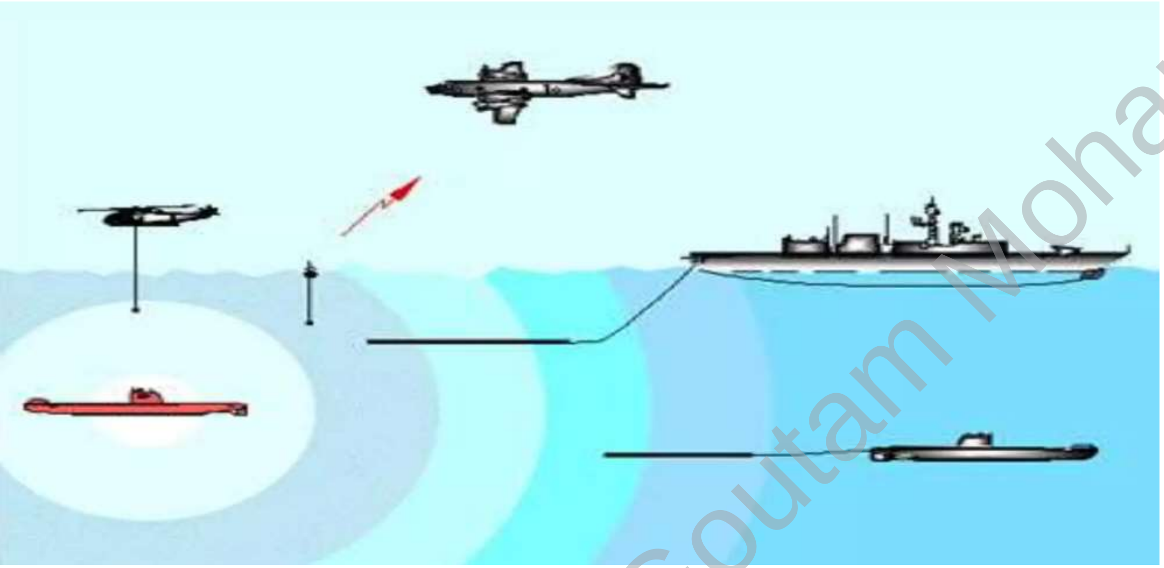
(Gyms and Workplace)

- Vibrations caused from machines in the gym.
- At workplaces, piezoelectric crystal are laid in the chairs for storing energy.
- Utilizing the vibrations in the vehicle like clutches, gears etc.

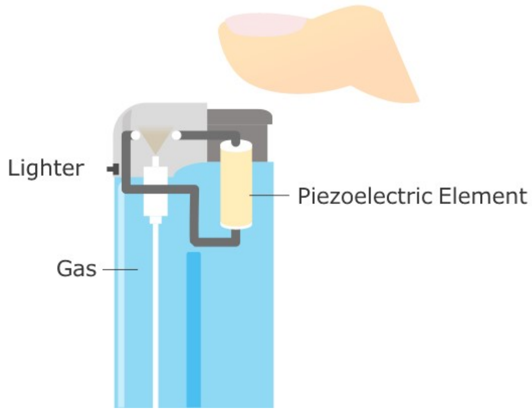
(Mobile keypads/ keyboards)

- Crystals laid down under keys of mobile unit and keyboard.
- For every key pressed vibrations are created.
- These vibrations can be used for charging purposes.

Application of Piezoelectric



SONAR - First application of piezoelectric device in World War-I in 1917



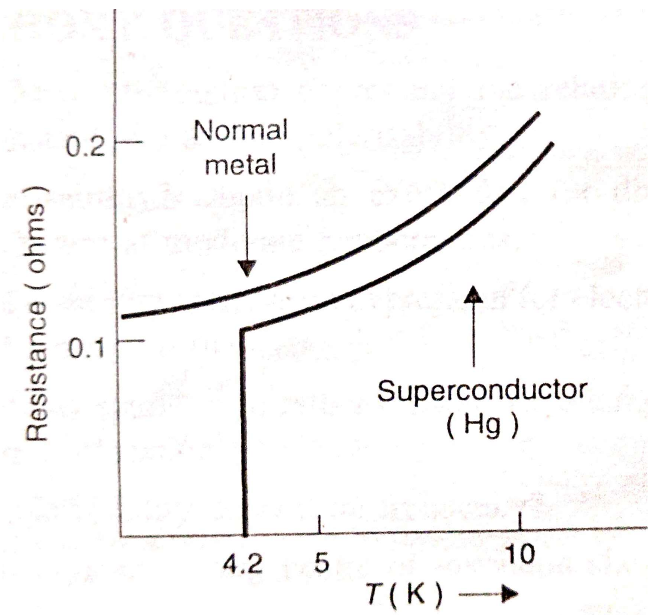
Piezoelectric Gas lighter

Superconductor

- The phenomenon of disappearance of electrical resistance of material below a certain temperature is called superconductor.

  Examples: Hg, Pb, Sn, In etc.

- This was first discovered by Kamerlingh Onnes in 1911.
- This idea was very helpful to fabricate powerful and economical devices which consumes very little electrical energy. Example: Electromagnet.
- In 1933, Nb_3Ge compound superconductor was discovered with maximum critical temperature 23 K.
- In 1968, $La_{1.85}Ba_{0.15}CuO_4$ ceramic superconductor was showed critical temp 34 K.(Bednorz and Muller, received Nobel prize in 1988)
- Thenafter, many compounds were discovered and one of them is Thallium Cuprate showed critical temp 125 K.



Meissner Effect

- The phenomenon of flux exclusion in a superconductor is called the Meissner Effect.(in 1933)
- Superconductor behaves perfect diamagnetism and also follows reversible effect.

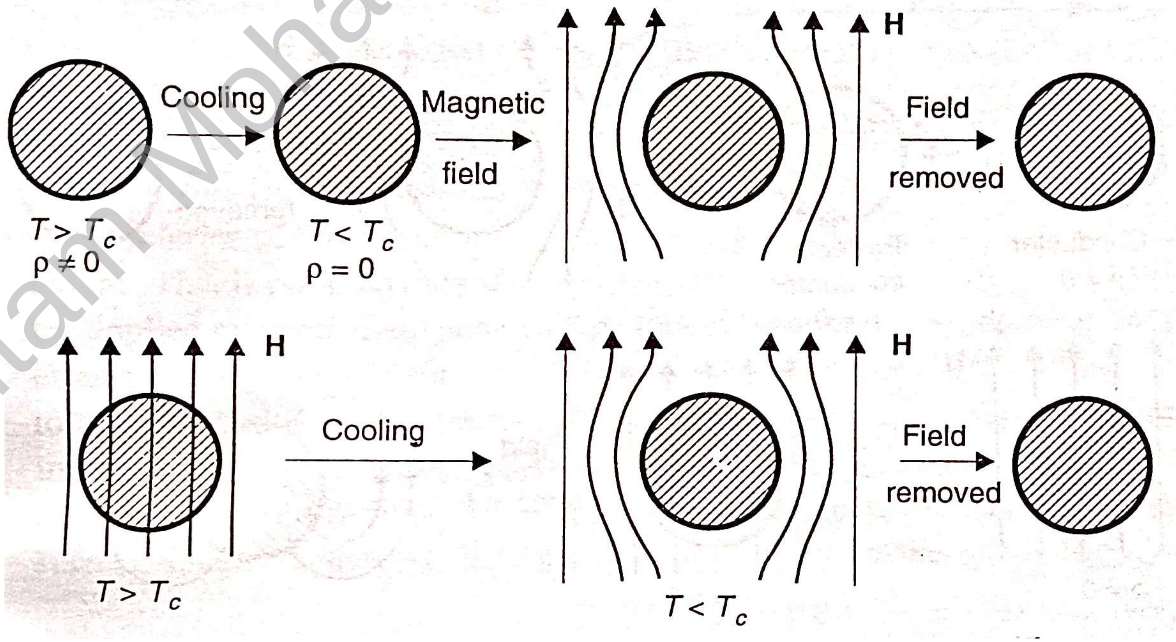
Since **B** = 0 inside superconductor, we can write

$$\mathbf{B} = \mu_o\,(\mathbf{H} + \mathbf{M}) = 0$$
$$\mathbf{H} = -\,\mathbf{M}$$

Therefore, the susceptibility is given by

$$\chi = \mathbf{M/H} = -1$$

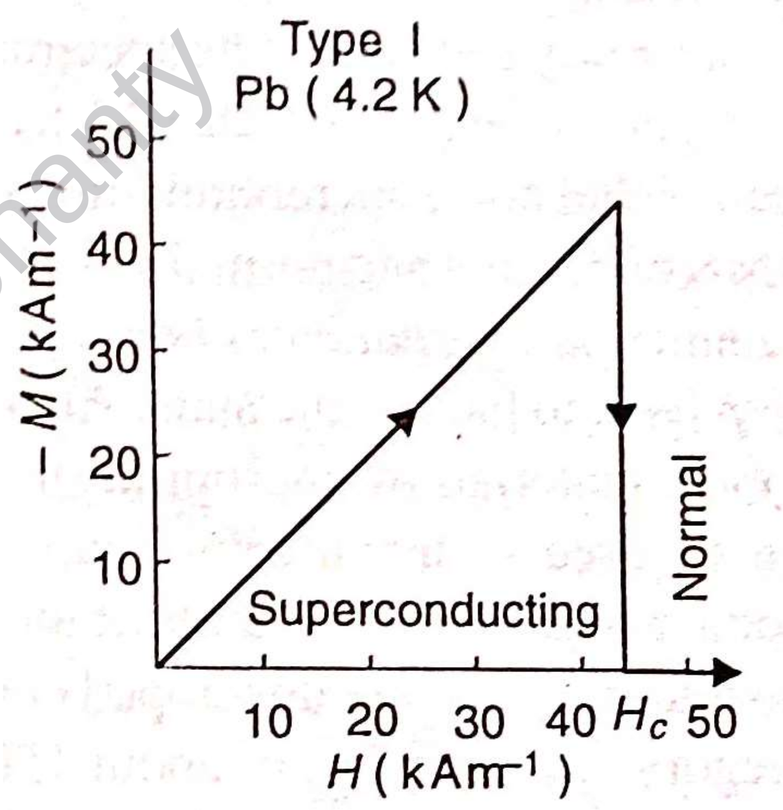
which is true for a perfect diamagnet.



Classification of superconductor

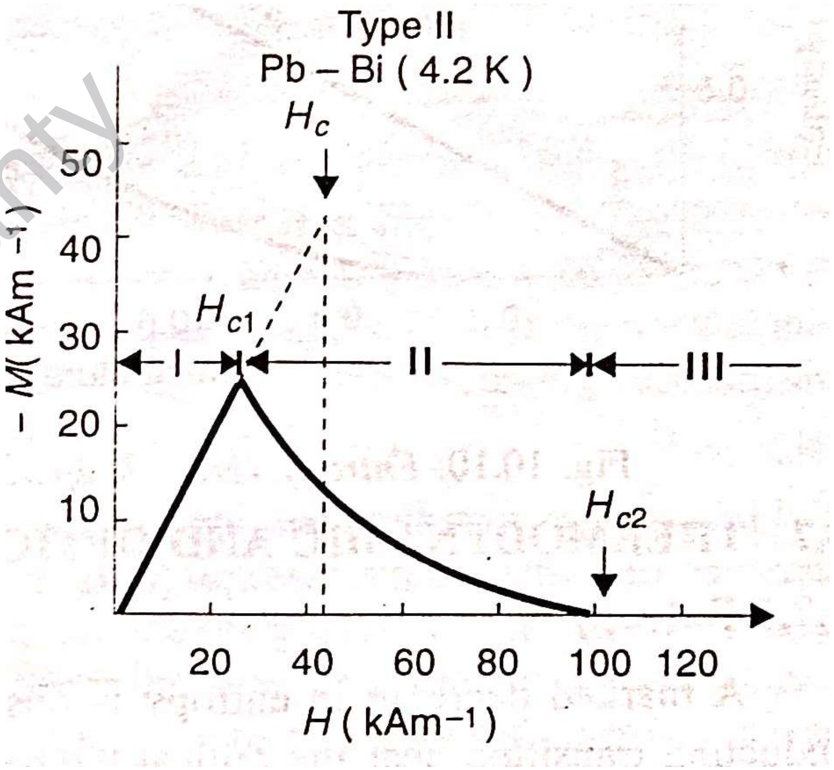
Type I superconductor:

- The superconductors which strictly follow the Meissner effect are called type-I superconductors.
- The typical magnetic behaviour of lead, a type I superconductor, is shown in figure.
- These superconductors exhibit perfect diamagnetism below a critical field H_c (~ 0.1 tesla)
- These materials give away their superconductivity at lower field are referred to as the soft superconductors.



Type II superconductor:

- The superconductors which don't follow the Meissner effect are called type-II superconductors.
- The typical magnetic behaviour of Pb-Bi alloy, is shown in figure.
- It exhibits perfect diamagnetism below a critical field H_{c1} and for above $H_{c1,}$ the flux begins to penetrate the specimen and at $H = H_{c1}$, it behaves as normal conductor.
- It is also called hard superconductor because relatively large field is required to bring them back to normal state. It is used to produce high magnetic field like 10 Tesla.



Nanomaterial

- Nanomaterial is a material in the order of nanometer scale.(1-100nm)
- In 1980, A physicist Sir Richard Feynman stated that "there are more rooms at the bottom" but the story of the real development of this field started in 1990s.
- It is an interdisciplinary domain in which physicist, chemist, material scientist, and engineers are working.
- It is found that physical phenomenon such as statistical mechanical effects and quantum mechanical effect become more pronounced as the size the system decreases.
- Furthermore, mechanical, electrical, and optical properties also change on moving from macroscopic to nanoscale.
- Nanomaterial is the structure of material with improved properties through controlled synthesis and assembly of materials at nanoscale level.

Top-Down Process

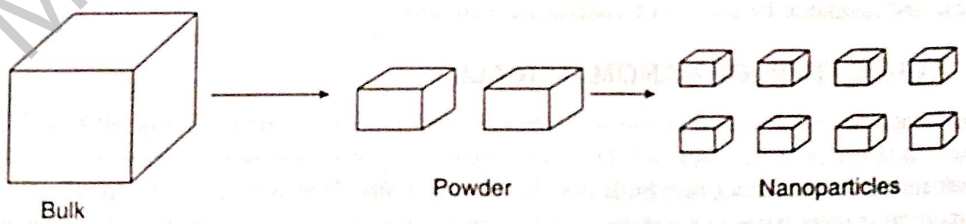
- Under this process of fabrication, bulk materials are broken into nano-sized particles.
- In this approach, there is no control over the size and the morphology of particles.
- There are many methods used in top-down approach to get nano-sized particles from bulk materials. Some common methods of top-down method are as follows:

✓ Ball milling method

✓ Plasma arcing

✓ Laser sputtering

✓ Vapour deposition method



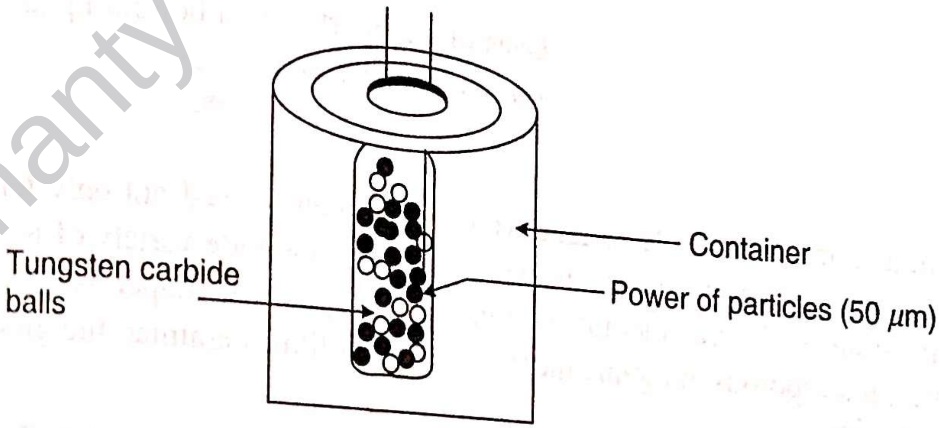
(Schematic representation of top-down method)

Advantages: Bulk production of nanomaterials.

Disadvantages: Imperfection in the surface structure and significant crystallographic damage to the processed patterns.

Ball Milling Method

- Principle: According to the basic principle of the ball milling method, small hard balls are allowed inside a container and then it is made to fall on a solid with high force to crush the solid into Nanoparticles.
- Construction and working: Hardened steel or tungsten carbide balls are put in a container along with powder of particles (50µm) of a desired material. The container is closed with tight lids (shown in figure). Tungsten carbide balls Container Power of particles (50 gm)
- When the container is rotated around the central axis, the material is forced to press against the walls. The milling balls impart energy on collision and produce smaller grain size of nanoparticles.



(Schematic diagram)

Application: This method is useful in the preparation of elemental and metal oxide nanocrystals such as Co, Cr, AlFe, AgFe and Fe. A variety of intermetallic compounds of Ni and A1 can be formed. This method is useful in producing new types of building materials, fireproof materials, glass- ceramics, etc.

Bottom-Up Process

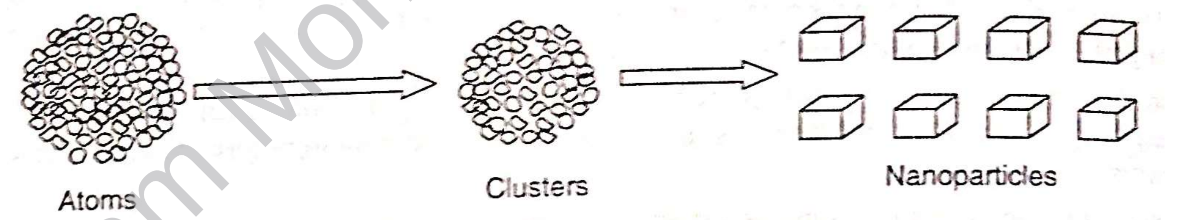
- This approach refers to the building up of a material from the bottom, i.e., atom by atom, molecule by molecule, or cluster by cluster. Some common methods of bottom-up method are as follows:

✓ Sol—gel method

✓ Colloidal method

✓ Electrodeposition

✓ Solution phase reductions



(Schematic representation of bottom-up method)

- The most important feature of this process is that the size and morphology of fabricated nanoparticles are well controlled.

Sol-Gel Method

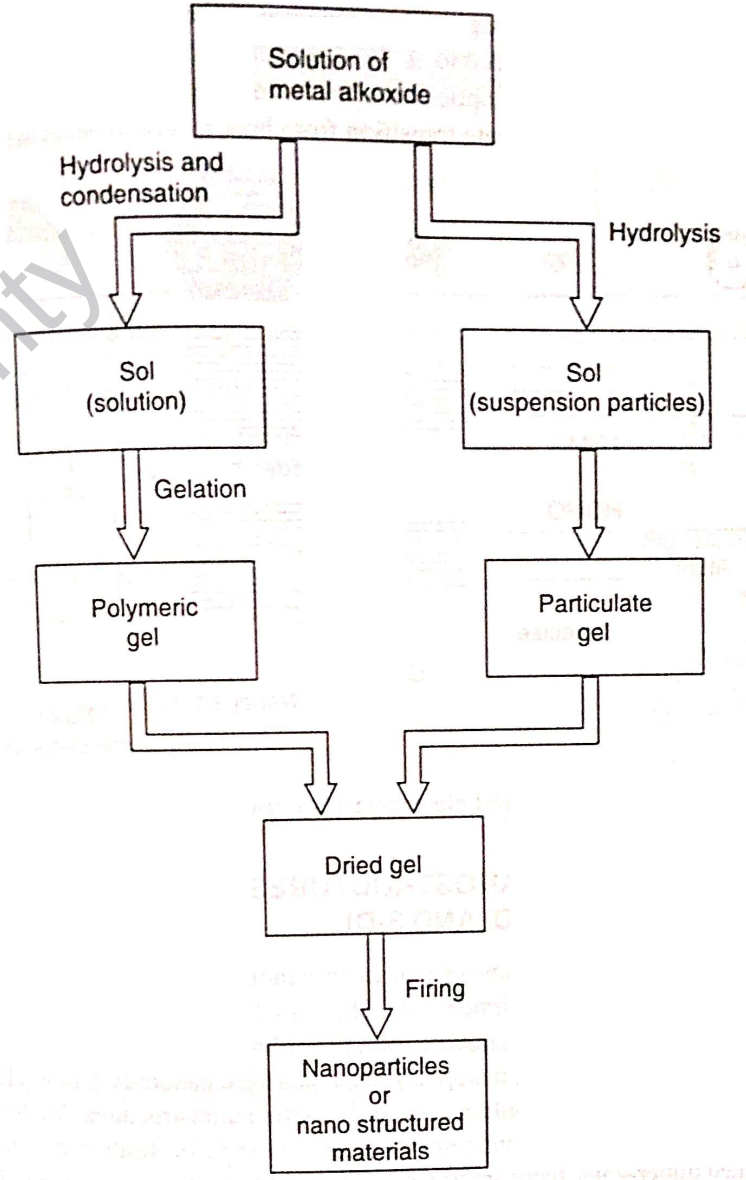
- The sol-gel method is an Important technique which is frequently used not only for the synthesis of nanoparticles but also to fabricate ceramic or glass materials in a wide variety of forms.
- Actually, a sol is a dispersion of the solid particles (0.1 to 1 mm) in a liquid. where only Brownian motions suspend the particles. A gel is a state where both liquids and solids are dispersed in each other, which presents a solid network containing liquid components The following are steps:

✓ Preparation of sol - preparation of the sol are usually inorganic metal salts or metal organic compounds such as metal alkoxides.

✓ Preparation of gel - the precursor is subjected to a series of hydrolysis and polymerisation reaction

✓ Drying and purification- heat treatment is given and mixture is refluxed and the washing is done several times.

✓ Product formation- Finally product is formed in different shapes.



Thank You !!!