

5.1 Dielectrics

5.1.1 Introduction

Dielectrics are essentially *insulating materials*. Dielectric materials are used to store electric energy. The basic function of an insulating material is to resist the flow of electric current and at the same time the dielectric material stores electric energy. For a material to be a good dielectric, it must behave as an insulator.

They are *non metallic materials* having *high specific resistance* and *negative temperature coefficient*. In a dielectric, all the electrons are bound to their parent molecules and there are no free charges and electrons are not released under the action of applied electric field or thermal energy.

5.1.2 Fundamental definitions

1. Electric field and electric lines of force

The space around a charge, where the influence of electricity is felt (or) in which it exerts a force on another charge. The electric field is assumed to consist of electric lines of force. These lines of force start from positive charge and end on the negative charge. It is a line along which a unit positive charge is free to move.

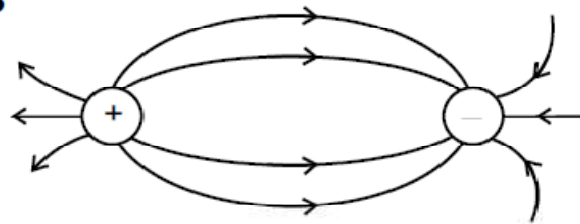


Fig.21

The tangent at any point on the electric line of force gives the direction of electric at that point.

2. Electric field strength (or) electric field intensity (I)

Electric field strength at a point in an electric field is the force experienced by a unit positive charge placed at that point. It is represented by the letter E.

If q is the magnitude of charge in coulomb and F is the force experienced by the charge in Newton, then

Electric field strength

$$E = \frac{F}{q}$$

Also

$$E = \frac{V}{d}$$

V = Voltage applied

d = Distance between the plates

unit E is N/C (or) V/m .

3. Electric flux (ψ)

It represents the total number of electric lines of force starting from a positive charge. It is numerically equal to the charge. It has the same unit as charge.

Unit of ψ is coulomb.

4. Electric flux density (or) electric displacement vector (D)

Electric flux density at a point is defined as the flux (ψ) (or) electric lines of force passing normally through the unit area of cross section at that point. It is represented by the letter D.

If ψ is the total flux in Coulomb

A = Area of cross section in metre²

then Electric flux density

$$D = \frac{\psi}{A}$$

unit of D is C/m^2 .

5. Permittivity (ϵ)

It represents the effectiveness (or) easiness of a medium (or) substance to allow the electric flux through it. It is defined as the ratio of electric displacement (D) in a dielectric medium to the applied field strength (E). Permittivity is represented by the latter ϵ ,

$$\text{Permittivity } \epsilon = \frac{D}{E}$$

Permittivity can also be defined as the degree up to which a medium can restrict the flow of charge through it and it is always greater than 1.

If ϵ_0 = absolute permittivity of free space

$$= 8.854 \times 10^{-12} F/m \text{ and}$$

ϵ_r = Relative permittivity (or) dielectric constant of a medium

then permittivity ϵ of a medium is given by

$$\epsilon = \epsilon_0 \times \epsilon_r$$

unit of ϵ is Farad/metre (F/m).

6. Dielectric constant (ϵ_r)

The dielectric characteristic of a material can be determined by the dielectric constant (or) relative permittivity (ϵ_r) of the material.

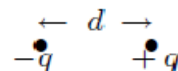
It is defined as the ratio of the permittivity of the medium (ϵ) to the permittivity of free space (ϵ_0) and is represented by ϵ_r .

Dielectric constant (or) relative permittivity $\epsilon_r = \frac{\epsilon}{\epsilon_0}$.

Since it is ratio, it has no unit. It also gives the measure of polarisation (alignment of charges) in the dielectric material under external electric field.

7. Dipole

Two charges of equal magnitude but of opposite polarity separated by a small distance form a dipole. It is represented in the following figure



8. Dipole moment (μ)

The product of either charge (one of the charge) on the dipole and distance between the charges is defined as the dipole moment represented by μ and it is directed from $-q$ to $+q$.

The dipole moment $\mu = q \times d$

unit of dipole moment is coulomb metre (C m).

9. Electric polarisation (\vec{P}) (or) polarisation vector

The dipole moment (μ) per unit volume of dielectric material is known as polarisation. It is represented by the letter P

$$P = \frac{\mu}{V} \quad \text{where } V = \text{volume of dielectric in } m^3.$$

If $\vec{\mu}$ is the average dipole moment per molecule and N is the number of molecular per unit volume then

$$\vec{P} = N \vec{\mu}$$

Explanation

Consider an atom of dielectric material placed inside an electric field. The centre of positive charge is displaced along the direction of electric field (+ve polarity to -ve polarity) and the centre of negative charge is displaced in opposite direction. Thus a **dipole is produced**.

Hence when a dielectric material is kept in an electric field, dipoles are created in

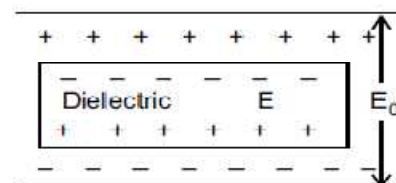


Fig. 22

all the atoms of the material. The process of producing electric dipoles in an electric field which are oriented along the field direction is known as *polarisation* in dielectrics. But the field produced in dielectric (E) is opposite to the applied field (E_0).

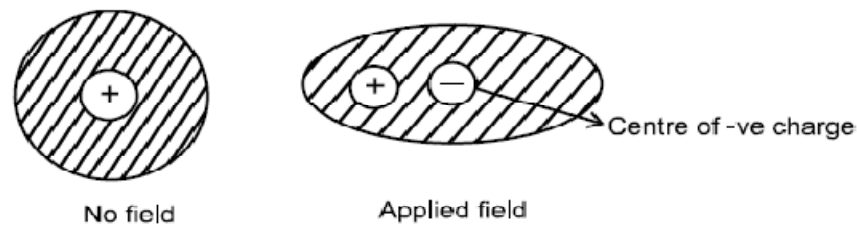


Fig. 23

10. Polarizability (α)

When a dielectric material is kept in an electric field and if the strength of electric field is increased the strength of induced dipoles also increases. Thus the induced dipole moment (μ) is directly proportional to the strength of the applied field (E).

that is $\mu \propto E$

$$\mu = \alpha E$$

Where α is a constant of proportionality known as *polarizability*

$$\alpha = \frac{\mu}{E} = \frac{\text{Induced dipole moment}}{\text{Strength of applied field}}$$

Unit of α is F/m^2

Relation between P , ϵ_0 , ϵ_r and E is

$$P = \epsilon_0(\epsilon_r - 1)E$$

11. Electric flux (D) in terms of field strength

Since the electric flux density (D) of a dielectric material is directly proportional to the field strength (E), then D can be written as

$$D = \epsilon_0 \epsilon_r E \quad (15)$$

Since polarisation measures the additional field density in the presence of material as compared to the vacuum, D can be written as

$$D = \epsilon_0 E + P$$

Sub for D from (15), we have

$$\begin{aligned} \epsilon_0 \epsilon_r E &= \epsilon_0 E + P \\ \therefore P &= \epsilon_0 \epsilon_r E - \epsilon_0 E \end{aligned}$$

$$P = \epsilon_0(\epsilon_r - 1)E$$

Hence flux density (D) is similar to the magnetic induction (B).

12. Electric susceptibility (χ_e)

Since polarisation vector \vec{p} is proportional to the applied field E and is in the direction of E , the polarisation vector \vec{p} can be written as

$$p = \epsilon_0 \chi_e E$$

$$\therefore \chi_e = \frac{p}{\epsilon_0 E}$$

Sub for p

$$\chi_e = \frac{\epsilon_0(\epsilon_r - 1)E}{\epsilon_0 E}$$

$$\chi_e = \epsilon_r - 1$$

It is a measure of a substance to get electrified.

5.2

Dielectric breakdown

5.2.1

Definition of dielectric breakdown

When electric field is applied to a dielectric and if it exceeds the critical value, the dielectric material loses its resistivity (insulating property) and permits a very large current to flow through it. This phenomenon is known as *dielectric breakdown*. The electric field strength at which the breakdown takes place is known as *dielectric strength* and the voltage corresponding to this is known as *breakdown voltage*. This breakdown produces a devastating effect like firing.

5.2.2

Definition of dielectric strength

The dielectric strength is defined as the *breakdown voltage per unit thickness* of the dielectric material. Unit is Vm^{-1} .

The failure (or) breakdown of a dielectric material is of great important for electronic engineers. There are many reasons for this breakdown to occur.

Let us now discuss the different types of dielectric breakdown and their mechanism briefly.

5.2.3 Types of dielectric breakdown

The different types of dielectric breakdown are

- (a) Intrinsic breakdown
- (b) Thermal breakdown
- (c) Discharge breakdown
- (d) Electrochemical breakdown
- (e) Defect breakdown.

(a) Intrinsic breakdown

In a perfect dielectric, there are *no free electrons* and the *conductivity is almost zero*.

When the applied voltage is large, some of the electrons in the valence band cross over to the conduction band after crossing through the large forbidden energy gap, thereby giving rise to large conduction currents. The liberation (or) movement of electrons from the valence band is known as *field emission*. This process of crossing of electrons from valence band to conduction band is a *chain reaction*. As a result, a large amount of current flows through the dielectric material causing dielectric breakdown (losing the resistive property). The breakdown produced in this manner is known as *intrinsic breakdown* (or) *avalanche breakdown*. This breakdown occurs may be due to the presence of imperfections, vacancies at the intensities or filled with ions and some extra atoms present at the lattice other than normal ones.

Characteristics of this breakdown:

1. It can take place even at *low temperature*.
2. It requires relatively *large electric field*.
3. It does not depend on the *electrode configuration* and the *shape of the material*.
4. This kind of breakdown mostly occurs in *thin samples*.

(b) Thermal breakdown

If an electric field is applied to a dielectric material, some amount of heat is produced. This *heat produced* in the material *should be dissipated*. In some cases, the amount of *heat generated* is *larger* than the heat *dissipated* in it, then this excess of heat results in local melting. Once the melting starts, that particular region becomes more conductive and allows a very large current flow through it thereby causing dielectric breakdown. This type of breakdown is known as *thermal breakdown*.

Characteristics of this breakdown:

1. It occurs at *high temperatures*.

2. The breakdown strength depends on the *size and shape* of the *dielectric material*.
3. It also depends on the *geometry* and thermal property of electrodes.
4. The breakdown time is of the *order of milliseconds* or much longer.
5. The *breakdown strength* is lower in a.c. fields than in D.C., since the power loss increases with the *frequency* (frequency of a.c).

(c) Discharge breakdown

This breakdown is classified in two types

1. External breakdown.
2. Internal breakdown.

The *external breakdown* caused by a glow (or) corona discharge and such a discharge occurs at the sharp edges of the electrodes. The large electric field due to this glow (discharge) causes a damage on the adjacent solid dielectric medium. The carbon formed due to this damage makes the dielectric more conducting and there by causing dielectric breakdown. Dust or moisture present on the surface of the dielectric may also produce this external discharge breakdown.

Internal breakdown occurs when the insulator contains occluded (hiding) gas bubbles. If these dielectric materials are subjected to *high voltage*, the *gaseous substances* are *dissociated* into ions and there by producing a large *ionisation current*. This large ionisation current may produce an electric breakdown known as discharge breakdown.

Characteristics:

When a large number of *occluded gas bubbles are present* in a dielectric materials, the breakdown takes place even at low voltages.

(d) Electrochemical breakdown

The chemical and electrochemical breakdown are closely related to thermal breakdown. If the temperature of the dielectric material increases, it will increase the mobility of the ions and hence the electrochemical reaction takes place. When the ionic *mobility increases*, large current will flow there by *decreasing the insulation* resistance and this will result in *dielectric breakdown*. Due the chemical reaction, the electrical and mechanical properties of the dielectric materials are changed and finally these will lead to breakdown. Insulating materials become oxides and thereby decreasing the dielectric properties. For example in the case of rubber in *air* the oxide forms on the surface and, produce cracks on the surface. Organic materials working at high temperatures have lost their stability towards chemical properties.

Characteristics of this breakdown

1. Electrochemical breakdown is determined by the leakage current, density of ions, temperature and permanent dipoles present in the materials.
2. To avoid the electrochemical breakdown, the impurities should not be mixed with the pure dielectric materials.
3. Electrochemical breakdown are accelerated by the increase of temperature. Hence to avoid electrochemical breakdown, the dielectric materials should not be operated at high temperature (or) heat dissipation facilities should be provided.

(e) Defect breakdown

Some dielectric materials may have defects *like cracks, and pores* etc. *Moisture and other impurities* can be get filled up in these places leading to the breakdown. This is known as *defect breakdown*.

5.2.4 Dielectric loss

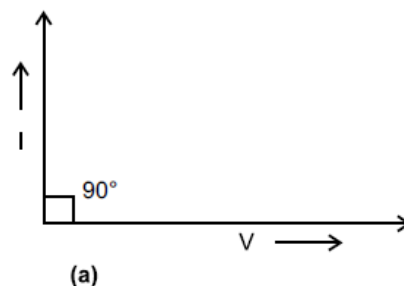
Definition

When a dielectric is subjected to an a.c. voltage, the electric energy is absorbed by the material and is dissipated in the form of heat. This *dissipation of energy* is called as *dielectric loss*. Since this involves *heat generation* and *heat dissipation*, the dielectric loss plays an important role in high voltage applications.

(a) Expression for dielectric loss

When the period of applied voltage is *greater than relaxation process*, the polarisation is completed at any time within a cycle. Here the *charging current leads the voltage* as in capacitor. Hence electric energy is lost during charging. This is applicable for a perfect insulator like vacuum or purified gas.

When the period of the applied voltage is in the *same range as relaxation time of polarisation process*, the *resonance occurs*. Here the *current leads the voltage by $(90 - \delta)$* where δ is called as the *loss angle* and $\tan \delta$ is taken as a measure of electrical loss due to resonance and is known as *loss tangent*. Here the charging current can be resolved in to two components, one is parallel and another is perpendicular (90°) to the applied voltage as in capacitor. This is shown in Fig.32.



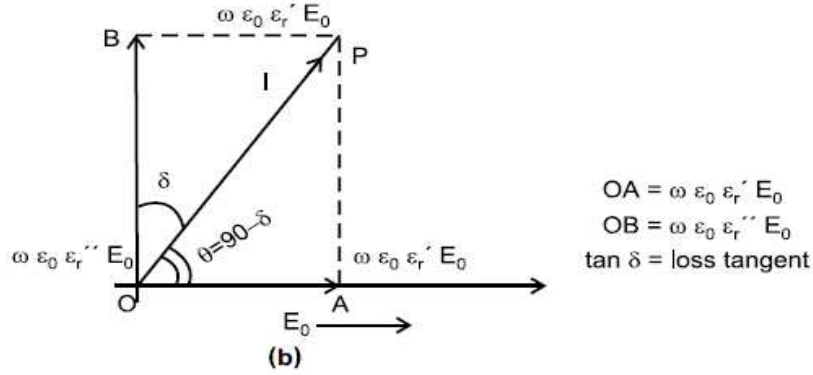


Fig. 32

The parallel component is the real part (OP is charging current) and results in $I^2 R$ loss (power loss).

Loss tangent can be expressed as

$$\tan \delta = \frac{\epsilon_r''}{\epsilon_r'} \quad (77)$$

Where ϵ_r' , ϵ_r'' are real and imaginary parts of relative permittivity for a dielectric in a capacitor having capacitance C and f is the frequency of the applied voltage V , then the *dielectric power loss* is given by

$$P = VI \cos \theta \quad (78)$$

But $V = I X_C$ (79)

where X_C is the capacitive reactance

$$\therefore X_C = \frac{1}{2\pi f C}$$

$$I = \frac{V}{X_C} \quad (80)$$

Also $\cos \theta = \cos(90 - \delta) = \sin \delta$ (81)

Where δ is the angle made by the charging current with the applied voltage sub in (78)

$$P = \frac{V^2}{X_C} \sin \delta \quad (82)$$

Since δ is very small, $\sin \delta = \tan \delta$. Hence Eq.(82) can be written as

$$P = \frac{V^2}{X_C} \tan \delta \quad (83)$$

Sub for X_C we get

$$P = \frac{V^2 \tan \delta}{2\pi f C} \quad (84)$$

Here $\tan \delta$ is called as the *power factor of the dielectric*. Hence power loss depends on $\tan \delta$ only. Since other factors like voltage (V) frequency of applied voltage (f) and capacitance are constants.

(b) Frequency regions of dielectric losses

1. The dielectric losses in *radio frequency* region are usually due to the *dipole rotation* or due to ions jumping from one equilibrium position to another.
2. The dielectric losses in the *lower frequencies* are mainly due to d.c. resistivity (P).
3. The dielectric losses in the *optical region* are associated with electrons and this loss is known as *optical absorption*. Hence the *electronic polarisation* produces power loss at optical region and at lower frequencies electronic polarisation produces no power loss.
4. The dielectric losses associated with ionic vibrations the frequencies fall in *Infrared region* and is known as *Infrared absorption*.

(c) Dependence of dielectric loss

Factor affecting dielectric loss. Increase in values of the following factors will increase the dielectric loss.

- (a) Temperature
- (b) Humidity
- (c) Applied voltage
- (d) Frequency of the applied voltage.

(d) Significance of dielectric loss

Dielectric loss plays a dominating role in high voltage applications. Dielectric loss is an engineering problem involving *heat generation and heat dissipation*. Hence for the usage of insulating materials, the proper understanding of balance between heat generation and heat dissipation is a must.

The dielectric materials having very large value of dielectric loss is said to be *lossy dielectric*.

5.2.5 Expression for Internal field (Lorentz method) and Clausius - Mosotti equation

Consider a dielectric material (a slab) placed between the plates of a parallel plate capacitor. Let an external electric field is applied across the plates of the capacitor.

Let us imagine a spherical cavity is formed around the atom A inside the dielectric slab. It is also assumed that the radius (size) of the cavity is large when compared to the radius (size) of the atom.

The internal field at the atom site A can be considered to be made up of four components of electric field intensities namely E_1 , E_2 , E_3 and E_4 which are discussed as follows:

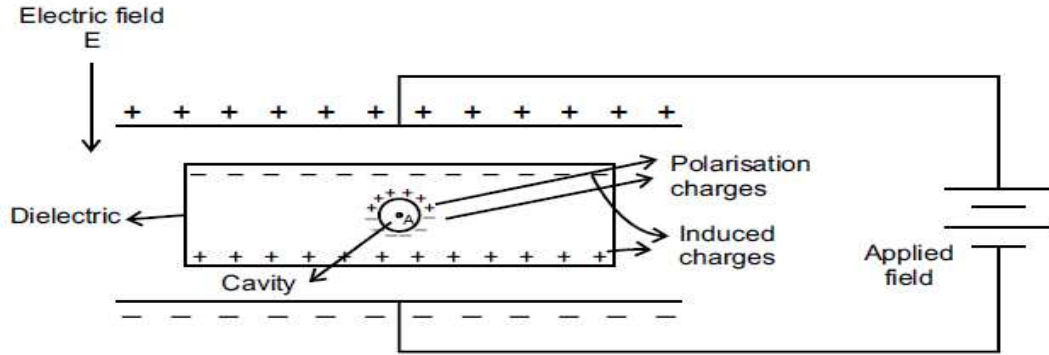


Fig. 30

(a) Electric field intensity E_1

This *field intensity* E_1 at A is due to the *charge density on the plates of capacitor* (across which an external field is applied).

From theory we can write

$$D = \epsilon_0 E_1 \quad (53)$$

where D = Electric flux density in vacuum (due applied field)

ϵ_0 = permittivity of air (or) vacuum,

$$\therefore E_1 = \frac{D}{\epsilon_0} \quad (54)$$

$$\text{But } D = D + \epsilon_0 E \quad (55)$$

When the polarisation takes place additional flux density (P) arises due to the presence of dielectric material along with air or free space.

Hence P = Flux density due to dielectric material present.

$\epsilon_0 E$ = Flux density in vacuum (or) air.

Sub for D in (54)

$$E_1 = \frac{P + \epsilon_0 E}{\epsilon_0} = \frac{P}{\epsilon_0} + E$$

$$E_1 = E + \frac{P}{\epsilon_0} \quad (56)$$

(b) Electric field intensity E_2

This *field intensity* E_2 at A is due to the *charge density induced on two sides of the dielectric material* (kept between plates of a charged capacitor).

$$\text{Hence } E_2 = -\frac{P}{\epsilon_0} \quad (P = \text{flux density in the slab})$$

Negative sign shows that this field is opposite to external field (E) [acts up] in Figure.

(c) Electric field intensity E_3

This *field intensity* at A is due to the other *atoms present in the cavity*. If we assume a cubic structure, $E_3 = 0$ due to the symmetric structure (fields due to atoms surrounding the considering atom cancel each other).

(d) Electric field intensity E_4

This *field intensity* E_4 at A is due to the *polarisation charges on the surface of cavity* around the atom A. This can be calculated by Lorentz method as given below.

In the Fig.31 if dA is the surface area of the sphere of radius r lying between θ and $\theta + d\theta$. Where θ is the angle made by the element of sphere with reference to the applied force (field E).

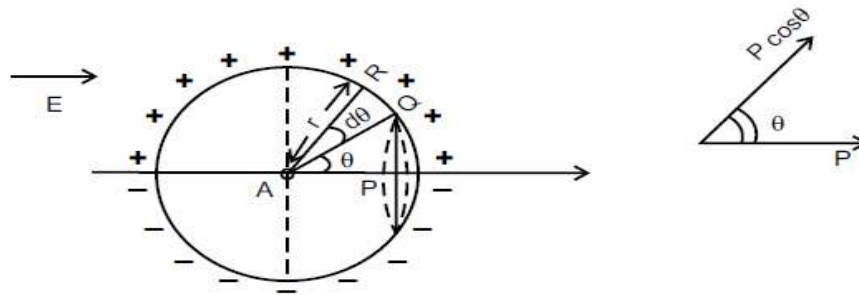


Fig.31 Enlarged view of cavity around the atoms

Circumference of element of sphere (in the form of circle of radius PQ).

$$= 2\pi (PQ)$$

Surface area of the element = circumference \times thickness

$$dA = 2\pi(PQ) \times (QR) \quad (57)$$

In fig $\sin \theta = \frac{PQ}{r}$

$$\boxed{PQ = r \sin \theta} \quad (58)$$

$$d\theta = \frac{QR}{r}$$

$$\boxed{QR = r d\theta} \quad (59)$$

Sub in (57)

$$dA = 2\pi \times r \sin \theta \times r d\theta$$

$$\boxed{dA = 2\pi r^2 \sin \theta d\theta} \quad (60)$$

If dq is the charge on the element and is equal to the product of the normal component of the *polarisation* (P) by the surface area.

$$\boxed{dq = P \cos \theta \times dA} \quad (61)$$

Sub for in (61) from Eq.(60)

$$dq = P \cos \theta \times 2\pi r^2 \sin \theta d\theta$$

$$\boxed{dq = P \times 2\pi r^2 \sin \theta \cos \theta d\theta} \quad (62)$$

The field due to this at A is denoted by dE_4 in the direction $\theta = 0$ is given by

By coulomb's law

$$dE_4 = \frac{q_1 \times q_2}{4\pi \epsilon_0 r^2}$$

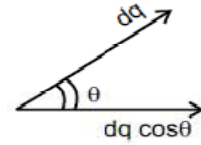
$$\text{where } q_1 = dq \cos \theta$$

$$q_2 = 1$$

$$dE_4 = \frac{dq \cos \theta \times 1}{4\pi \epsilon_0 r^2} \quad (63)$$

Sub for dq

$$\begin{aligned} dE_4 &= \frac{P \times 2\pi r^2 \sin \theta \cos \theta d\theta \times \cos \theta}{4\pi \epsilon_0 r^2} \\ dE_4 &= \frac{P \times 2\pi r^2 \cos^2 \theta \sin \theta d\theta}{4\pi \epsilon_0 r^2} \end{aligned} \quad (64)$$



The total field E_4 due to the charges on the entire (full) surface of cavity is obtained by integrating (64) between limits 0 to π .

$$\begin{aligned} \int dE_4 &= \frac{2\pi r^2 P}{4\pi \epsilon_0 r^2} \int_0^\pi \cos^2 \theta \sin \theta d\theta \\ E_4 &= \frac{P}{2\epsilon_0} \int_0^\pi \cos^2 \theta \sin \theta d\theta \end{aligned} \quad (65)$$

$$\text{Put } x = \cos \theta$$

$$dx = -\sin \theta d\theta$$

$$\therefore -dx = \sin \theta d\theta$$

Integrating Eq.(65) without limits,

$$\therefore E_4 = \frac{P}{2\epsilon_0} \int x^2(dx) = \frac{P}{2\epsilon_0} \left[\frac{x^3}{3} \right]$$

Substituting the value of x and applying the limits

$$\begin{aligned} E_4 &= \frac{-P}{3\epsilon_0} \left[\frac{(\cos \theta)^3}{3} \right]_0^\pi \\ &= -\frac{P}{2\epsilon_0} \times \frac{1}{3} [(\cos \pi)^3 - (\cos 0)^3] \\ &= -\frac{P}{6\epsilon_0} [-1 - 1] \\ E_4 &= \frac{2P}{6\epsilon_0} = \frac{P}{3\epsilon_0} \\ \boxed{E_4 = \frac{P}{3\epsilon_0}} \end{aligned} \tag{66}$$

\therefore The internal field E_i is given by

E_i = Intensity of the applied field + field due to polarisation

$$\boxed{E_i = E + \frac{P}{3\epsilon_0}} \tag{67}$$

Here E_i is called as *internal field or Lorentz field*.

Classius - Mosotti relation

Let us consider an elemental dielectric having cubic structure. Since there are *no ions and permanent dipoles* in these materials, the ionic polarizability α_i and orientation polarizability α_0 are zero that is

$$\alpha_i = \alpha_0 = 0 \tag{68}$$

Since only *electronic polarizability* occurs, the polarisation P is given by

$$P = N \alpha_e E_i \tag{69}$$

Sub for E_i

$$\begin{aligned} P &= N \alpha_e \left[E + \frac{P}{3\epsilon_0} \right] \\ P &= N \alpha_e E + N \alpha_e \frac{P}{3\epsilon_0} \\ P \left[1 - \frac{N \alpha_e}{3\epsilon_0} \right] &= N \alpha_e E \end{aligned} \tag{70}$$

$$P = \left(\frac{N \alpha_e E}{1 - \frac{N \alpha_e}{3\epsilon_0}} \right) \quad (71)$$

We know electric flux density in the material in the presence of external field is given by

$$D = P + \epsilon_0 E \quad (72)$$

$$P = D - \epsilon_0 E \quad (73)$$

Divide by E

$$\frac{P}{E} = \frac{D}{E} - \epsilon_0$$

$$\text{But } \frac{P}{E} = \epsilon = \epsilon_0 \epsilon_r \quad (74)$$

$$\begin{aligned} \frac{P}{E} &= \epsilon - \epsilon_0 \\ &= \epsilon_0 \epsilon_r - \epsilon_0 \end{aligned}$$

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

$$P = E \epsilon_0(\epsilon_r - 1) \quad (75)$$

Comparing (75) and (71) we can write

$$E \epsilon_0(\epsilon_r - 1) = \frac{N \alpha_e E}{1 - \frac{N \alpha_e}{3\epsilon_0}}$$

$$1 - \frac{N \alpha_e}{3\epsilon_0} = \frac{N \alpha_e}{\epsilon_0(\epsilon_r - 1)}$$

$$1 = N \alpha_e \left[\frac{1}{3\epsilon_0} + \frac{1}{\epsilon_0(\epsilon_r - 1)} \right]$$

$$1 = \frac{N \alpha_e}{3\epsilon_0} \left[1 + \frac{3}{\epsilon_r - 1} \right]$$

$$\frac{N \alpha_e}{3\epsilon_0} = \frac{1}{1 + \frac{3}{\epsilon_r - 1}} = \frac{\epsilon_r - 1}{\epsilon_r - 1 + 3}$$

$$\boxed{\frac{N \alpha_e}{3\epsilon_0} = \frac{\epsilon_r - 1}{\epsilon_r + 2}} \quad (76)$$

Where N = number of molecules per unit volume. The equation (76) is known as *Classius-Mosotti equation*. This equation is used to calculate α_e (*Electronic polarizability*), knowing the value of ϵ_r .

5.3

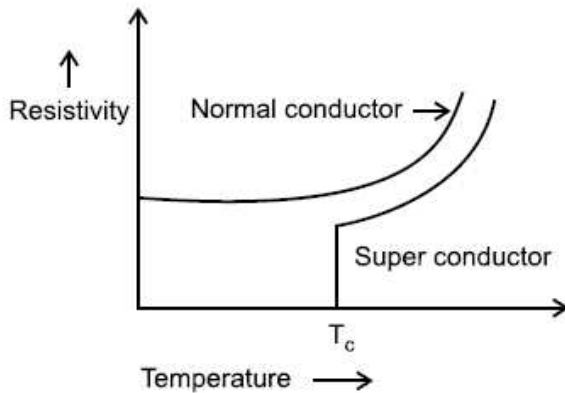
Superconductivity

Superconductivity was discovered by Heike Kanerlingh Onnes in 1911, while investigating the effect of impurity on the resistivity of a metal he found superconductivity for the case of mercury(Hg). The resistivity of Hg is decreasing with temperature and at the temperature $T = 4.12k$, the specific resistance suddenly become equal to zero. This phenomenon of normal metal exhibiting the property of ideal is perfect conductor is called a new state of matter as “superconductivity”.

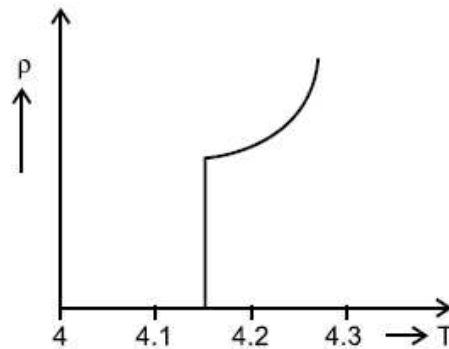
The temperature at which a normal conductor is converted into a superconductor is known as critical temperature or transition temperature (T_o).

Example:

GeTe	-	0.3 K
Hafnium	-	0.35 K
NbO	-	1.25 K
Niobium	-	9.22 K



Resistivity of a conductor and superconductor



Resistance of a Hg

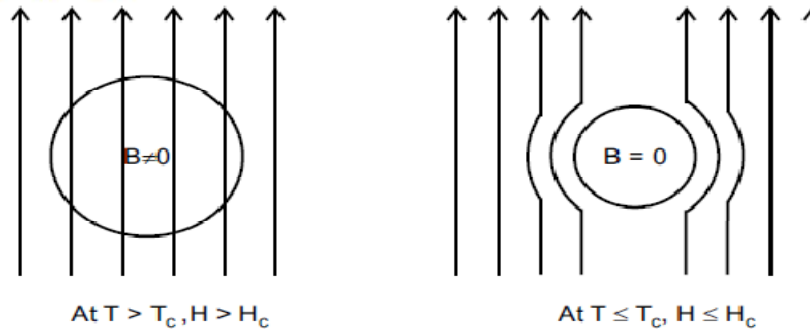
5.3.1

Superconducting transition temperature T_C

Superconducting transition temperature T_C is the temperature to which or below which if a normal conductor is cooled, it starts conducting current fully due to enormous conductivity with almost zero resistivity and behave as a superconductor.

5.3.2 Meissner effect

Meissner and Ochenteld, while investigating the properties of superconductor in the presence of magnetic field observed that when a specimen is placed in magnetic field and cooled (i.e., the temperature is lowered to T_c), the magnetic flux originally present in the bulk of the conductor, is expelled out from the specimen. Thus implies that superconductor behaves like a Local diamagnetic material. The phenomenon is known as Meissner effect.



The magnetic induction inside the substance is given by

$$B = \mu_o (H + M)$$

where,

B - flux density

H - applied magnetic field

M - magnetization in the medium

But in superconducting material $B = 0$

$$\mu_o (H + M) = 0$$

$$H = -M$$

$$\frac{M}{H} = -1$$

We know that $\frac{M}{H} = \chi$ (superconductivity)

Therefore, the above equation can be written as

$$\chi = -1$$

\therefore Superconducting material is a perfect diamagnetic material.

5.3.3 Properties of superconductor

1. Effect of magnetic field

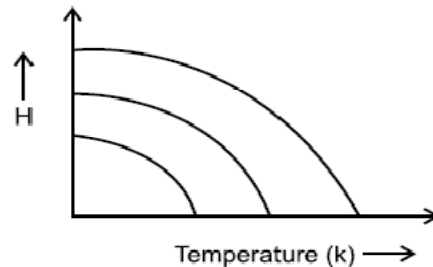
The superconducting state can be destroyed by the application of an external magnetic field. The minimum magnetic field required to destroy superconductor is called

critical field H_c . The H_c depends on temperature being at $T = T_c$ and increases with decrease in temperature. The critical field attains maximum at $T = 0^\circ K$. The following expression and graph explains the of magnetic field

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

where,

- H_c - maximum critical field strength at the temperature T
- H_o - maximum critical field strength occurring at $0^\circ K$
- T_c - critical temperature i.e., the highest temperature by superconductor



2. Effect of specific heat

The specific heat of a material shows an abrupt change at $T = T_c$ jumping to a large value for $T < T_c$.

3. Effect of heavy current

The superconducting state can be destroyed when a sufficient heavy current is passed through them. According to the for superconducting material the induced electric current (I_c) required to destroy the superconductivity is,

$$I_c = 2\pi r H_c$$

- I_c - critical current (or) induced electric current
- where, r - radius of the material (superconductor)
- H_c - critical magnetic field

4. Effect of pressure

By applied very high pressure critical temperature T_c also increases. T_c is directly proportional to pressure at very

A superconducting material is possible by applying very high pressure.

5. Isotope effect

The critical temperature T_c is inversely proportional to the square root in atomic weight of the isotopes of a

$$T = \frac{1}{\sqrt{M^\alpha}}$$
$$T_c M^\alpha = \text{constant}$$

where,

- α - constant equal to $\frac{1}{2}$
 M - the atomic weight

5.3.4 Types of superconductors

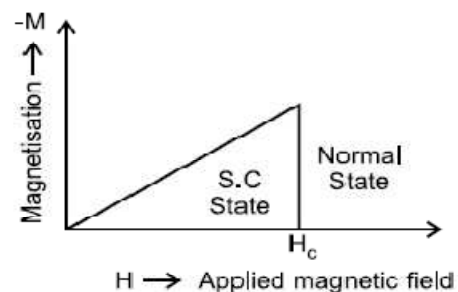
Superconductors are divided into two categories depending on the way in which transition from the superconducting in normal state proceeds when the applied magnetic field exceeds the critical field H_c . They are

1. Type I or soft superconductors.
2. Type II or hard superconductors.

1. Type I or soft superconductors.

This type of superconductors delays the Meissner effect i.e., behave as perfect diamagnetic material.

The figure shows the relation between the magnetisation and applied magnetic field. The superconductivity is destroyed sharply at and with the critical field. It repels the magnetic lines of force, because it acts as a perfect diamagnetic. Such type of superconductors are called soft or Type - I superconductors. At H_c , the repulsive force is zero, and hence the material behaves as a normal conductor Nb, Hg, V, Sn are some examples of type - I superconductors.

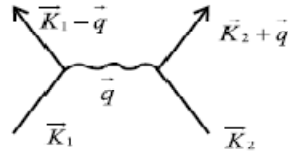


2. Type II or hard superconductors.

It does not obey the Meissner effect perfectly. These superconductors show the magnetisation property as shown in the figure.

In this type up to the field H_c , it will not allow the magnetic lines of force. The field H_{c1} and H_{c2} be the lower and upper critical fields. The region in between H_{c1} and H_{c2} is known as Vortex state or mixed state. Above H_{c2} the material behaves as a normal conductor. i.e., the magnetic field penetrates into the material.

The energy of pair of electrons in the bound state is less than the energy of the pair in the free state. The difference of the energy of the two states is the binding energy of the cooper pair and should. Therefore be supplied if the pair is to be broken or separated.



At temperature less than the critical temperature electron lattice interaction is stronger than electron coulomb interaction and so the electron tend pair up. Pairing is complete at $T = 0K$ and is complete broken at T_c .

The energy decrease between the free energy of the electron and the paired state appears as the energy gap at the fermi surface. the normal electrons stages are above the fermi energy gap and superconductor electron states in the superconducting cooper pairs. BCS theory thus predicts many electron ground states as well as excited states for the superconductor in the range 0 to T_c and in these states Cooper pair are supposes to be in condensed state with a definite phase. At T_c , this coherence disappears and the pairs are broken resulting in the transition of superconducting state to normal state.

5.3.5 High temperature superconductors(HTSC)

In the year between 1911 and 1986, with the help of liquid helium superconductors having T_c from 4k to 23k were observed. Later in the years 1983, 1987 & 1988 materials with high T_c upto 40k, 93k and 123k have been discovered respectively. To produce the superconductor with T_c greater than 77k liquid nitrogen was used instead of liquid helium. The above observations confirms that it might be possible to develop the superconductors at room temperature. The superconductors having high transition temperature (T_c) are known as high temperature superconductor(HTSC).

The oxide compound ($Ba_{1-x}Pb_xBi_{1-y}O_3$) having perovskite structure shows T_c at about 13k. Muller and Bendorz, tried to investigate the occurrence of superconductivity of other oxide compounds & found that the $La_{2-y}Ba_yCuO_2$ compound in solid solutions shows T_c of about 45k.

In 1987, Chu showed that $yBa_2Co_3O_{7-y}$ compound became superconducting at 90K. The high T_c oxide compounds of thallium and bismuth was found by in the year 1988. Later on, the HTSCs were also schieved by the substitution of Pb & TI compounds.

The HTSC compounds are generally represented by simplified notations such as 1212, 1234, etc., based on the number of atoms present on each metal element. For example, $yBa_2Co_3O_3$ compound is represented as 123. The HTSC components

along with transition temperature notations, chemical formula & structure are given in Table 1.

From this, it is evident that high T_c superconductors are formed by the oxides of copper in combination with other elements. They become brittle & it is easy to form wires & tapes which provides electrical power transmission over a long distances without resistance losses.

Structure T_c & properties of some superconductors chemical notations structure T.(1 c)

5.3.6 Applications of superconductors

The applications of superconductors are given below

I Superconducting quantum interface devices (SQUID)

1. It is a magnetometer, involving super current properties of Josephson junctions
2. The low temperature superconductors are used in the fabrication of this SQUID
3. They are suitably processed superconducting loops that can detect minute changes in magnetic flux, geological layers in different minerals, to detect NMR signals at low temperatures, etc.,
4. They are high-sensitivity magnetic flux and are used in precision instruments in frontier areas like advanced metrology.

II Magnetic levitation

Magnetic levitation is used to operate levitated trains when a superconducting material is placed in magnetic field electric currents are set up at its surface. This results in zero magnetic field inside the material. This diamagnetic property ensures the repulsion of magnet when brought near a superconductor. This repulsion can be used to float a magnet above a superconductor. This phenomenon is called magnetic levitation.

In the absence of any mechanical friction, it is possible to achieve extremely high speeds. Speeds up to 500 km/h have been already reported.

III Cryotron

It is a magnetic switch that utilizes superconductivity. It consists of two superconducting wires (e.g., tantalum and niobium) having different critical temperatures. The niobium wire (high T_c) is wrapped around a wire of tantalum (low T_c). A proper electrical insulation is provided between the two wires. The complete setup is immersed in a bath of liquid helium. Both the wires become superconducting & the tantalum wire is able to carry large amount of current in superconducting state no

current is passed through niobium wire. When a sufficient current passed through niobium wire. When a sufficient current passes through niobium wire, the resultant magnetic field destroys superconductivity V thus current flowing through tantalum wire.

Thus, the amount of current passing through the tantalum wire can be adjusted from high to low value with the help of current passing through niobium wire. Thus the tantalum acts as a gate niobium acts as a control.

Other applications

1. Superconductors are used as lossless power transmission lines
2. In Japan, superconductors are used to levitate above its rail
3. Superconductors are used as storage devices in computers
4. Superconducting electric generators are small in size. They produce more power when compared to conventional electric generators.

Josephson effect

In 1962, Brian Josephson predicted that this effect is due to tunneling of Cooper pairs according to Josephson effect. The tunneling of Cooper pairs takes place between two superconductors separated by an insulator, even in the absence of applied voltage between the superconductors. The current flowing through the device has both ac and dc components.

D.C. Josephson effect

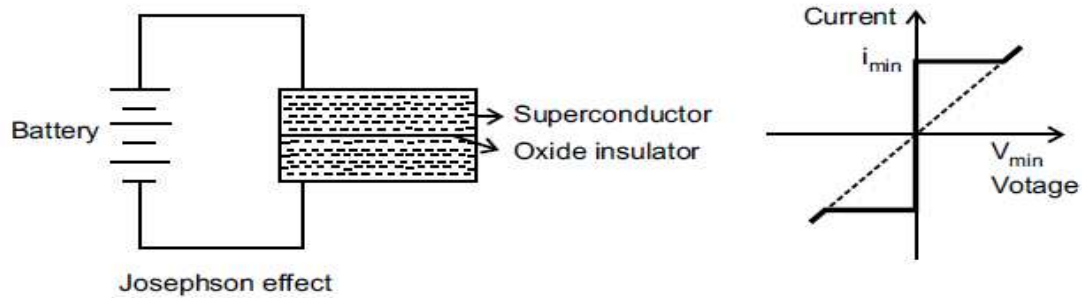
A d.c. current flows across the junction of two superconductors separated by a thin insulating layer in the absence of any electric or magnetic field is called D.C. Josephson effect.

A.C. Josephson effect

When d.c. voltage is applied across the junction of two superconductors separated by a thin insulating layer, it reduces r.f. current oscillations across the junction with frequency of $\omega = q/h V$. Moreover, if a r.f. voltage is applied along with the d.c. voltage, there is a flow of l.c. current across the junction.

Let V_{ap} be the applied voltage and V_{min} be the minimum value of d.c. voltage required to produce a.c. Josephson effect.

From the figure,



1. If $V_{ap} = 0$, there is a constant flow of d.c. current equal to i_{min} through the junction. This current is called superconducting current. This effect is the d.c. Josephson effect.
2. If $V_{ap} < V_{min}$, there will be a constant flow of d.c current equal to i_{min} only.
3. When $V_{ap} < V_{min}$, the junction has a finite resistance and the current oscillates with a frequency $\omega = \frac{qV_{ap}}{h}$ where $q = 2e =$ charge of opposite pair. This represents a.c. Josephson effect.
4. If the applied voltage is the sum of d.c. voltage a.c. voltage such that a.c. voltage is lesser than d.c. voltage then a d.c. current flows through the junction.

5.4 Nano materials

Nano materials form a branch of materials science that deals with the study of materials and their morphological characteristics on the nanoscale (i.e., 10^{-9}m). Nano materials are classified into the following categories:

1. Nano particles,
2. Nano thin films,
3. Nano dots,
4. Nano rods,
5. Nano tubes
6. Nano composites.

The size of the nanomaterials is in the range of 0.1-100nm. Nanotechnology is the field deals with the manufacture, design and properties of materials on the nanoscale.

5.4.1 Definition and introduction

Nanophase materials are the nano structures materials having a characteristic *length*, less than *100nm*. Their *grain size* is the order of *1nm to 100nm*. They exhibit greatly altered physical chemical and mechanical properties when compared to their normal, large grained (macro size) counter parts with the same chemical composition.

Nano phase material is identified as one of the major field in modern material science by the research work done by Gleiter and coworkers in 1990. A cluster (group) of nano particle contains less than 10^4 molecules or atoms corresponding to a diameter of a few nanometers. Hence one can conclude the size of a nano particle is

about 1nm. Since the size of nanoparticles lie between *molecular and bulk material they have hybrid properties*. They have *non linear optical and magnetic properties*.

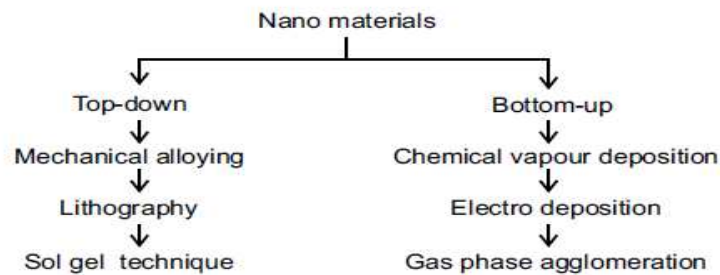
5.4.2 Preparation of nanomaterials

Depending upon the needs and requirements, nanomaterials can be produced in one, two or three dimensions. Based on the grain size the classification of nanomaterials is given below.

1.	Zero dimension	Clusters or powders (Quantum dots)
2.	One dimension	Multilayers (Quantum wires)
3.	Two dimension	Buried layers (Quantum carbon tubes)
4.	Three dimension	Nanometer sized grains

Nanomaterials can be synthesized in two broad ways

1. Top down approach
2. Bottom-up approach



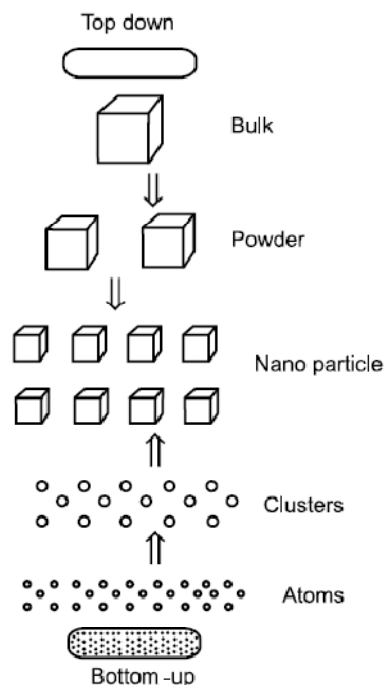
In Top-down approach, the bulk solids are dissociated into fine pieces until particles of order of nanometer size is obtained. On other hand in Bottom-up approach, the nanostructured materials are produced by atoms or molecules together to form nanomaterials.

5.4.3 Production of Nano Structured Materials

It is possible to produce nano structured materials by using a variety synthetic methods. Depending upon the desired properties or applications, each method will have some advantages and disadvantages.

a) Vapour Condensation

Method of synthesis:



In this method clusters of atoms are synthesized through vapour condensation. This method involves the process of *evaporation* of a solid metal followed by *rapid(fast) condensation* in order to form nanosize clusters. Thus the resulting powder can be *used as filter* for composites materials or consolidated in to bulk material.

Application:

This method is used to produce ceramic or metal nano structured powders.

b) **Chemical Synthesis**

Method of synthesis

By using a *variety of chemical approaches* such as *sol-gel* or *thermal decomposition*, nanostructured materials are synthesized. These methods provide large quantities of nano sized materials at low cost.

Application

This method is used to produce both metals and ceramics of nano material size.

c) **Mechanical deformation**

Method of synthesis

This method involves *milling or shock deformation*. It is a common method used to produce nanostructured powders which in turn produces nano structured materials. By mechanical milling, it is possible to produce nano structured powders of different systems.(other wise it become immisible)

Application

This method is applied to produce nano structured powders of a bulk material (or) different systems.

d) **Thermal crystallization**

Method:

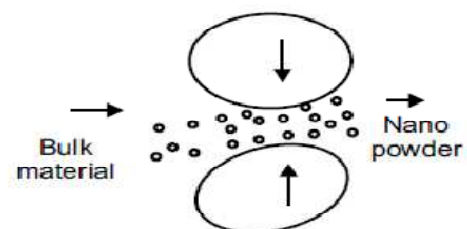
By controlling the nucleation and growth rate during annealing (slow cooling) of an amorphous materials, we can produce bulk materials with an average grain size of 20nm without using condensation and sintering steps.

Application

This method is used to produce three dimensional nano materials (crystalline materials).

e) **Ball milling**

This method uses the principle of mechanical crushing and is an examples of top-down method of synthesising nanomaterials. It is very simple, popular and inexpensive method to produce all kinds of nanomaterials especially oxides-based nanoparticles (e.g. CeO_2 , TiO_2).



In this method, small balls inside a drum() cavity are rotated at high speeds and by gravity action they settle on a solid layer where they are crushed into nanocrystals. Depending upon the material to be synthesised one can use either steel balls or refractory balls or plastic balls. When balls rotate of a particular rpm, the energy is transferred to the powder which reduces the grain sized powder to ultrafine nanoparticles. The size of the nanoparticles produced depends on size of the ball, rotational speed of the balls, number of balls, milling time, milling atmosphere & the ratio of ball of powder mass. To increase the brittleness of the powders, cryogenic liquids can be used.

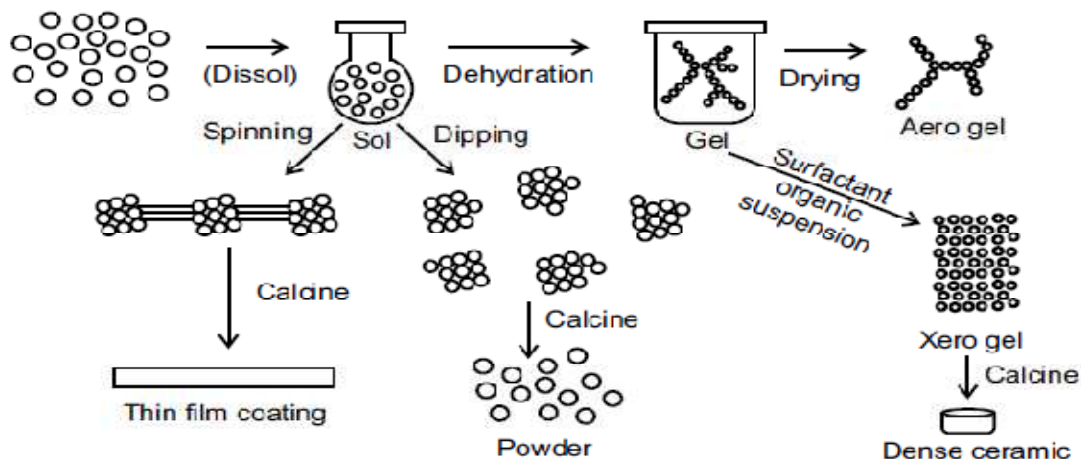
various types of ball mills are,

- (a) Attrition ball mill,
- (b) Planetary ball mill,
- (c) Low energy ball mill,
- (d) High energy ball mill and
- (e) Vibrating ball mill.

f) Solgel techniques

The solgel technique is a wet-chemical technique, i.e., chemical deposition technique for the production of high purity and homogeneous nanoparticles. This process used colloidal suspension (Sol) and gelatin to form a network in a continuous liquid phase (gel). The removal of the liquid phase from the sol yields the gel. The particle size and shape are controlled by the sol/gel transitions. the precursor for synthesizing these colloids consists of ions of metals alkoxides & aloxysilanes.

The initial material is processed with water or dilute acid in an alkaline solvent. The material undergoes hydrolysis and poly condensation reaction which leads to colloids formation. The sol is then introduced to form and inorganic network containing liquid phase (gel). The schematic diagram showing synthesis of nanoparticles using sol-gel technique is shown below.



The sol can further be processed to obtain the substrate in a film, either by dip coating or spin coating or cast into a container with desired shape or powder by calcinations. It is an interesting, cheap and low temperature technique used to produce a range of nanoparticled with controlled chemical compositions. The sol-gel have variety of applications like optics, electronics, energy, space, bio sensors and drug delivery.

5.4.4 Properties of nanostructured particles, physical properties

(a) Variation of physical properties with size

In this section let us discuss how the geometrical arrangement of atoms and hence their stability changes with size.

Discussion

When the bulk material is reduced to nanoparticle size, it creates more surface sizes (area). This will in turn changes, the surface pressure and leads to a change in the inter particle spacing. This effect is shown in the graph drawn between size of particle and inter atomic distance for Cu_n . (36)

Applications

In nano phase materials, there are two types of applications

- a) Structural applications
- b) Functional applications.

a) Structural applications

These applications are mainly based on the mechanical properties of nano phase materials. They are used to produce *plastic ceramics* and *extremely hard materials*.

b) Functional applications

These applications are mainly based on the *transformation of external signals* like the filtering of incident light and the *change of electrical resistance* in different gas concentrations.

c) Other applications

1. They are used to produce *soft magnetic materials* and *tiny permanent magnets* with high energy product ($B_r \times H_C$). Hence they are used in *high density magnetic recording, information storage devices*.
2. They are used as magnetic nano-composite *refrigerants* and *magneto resistance spin valves applications*.

3. Quantum wells, quantum dots and quantum wires having quantum confinement are mainly produced from fermi conductor nano materials are used in *computer storage (memory) devices*.
4. Since these materials have large ratio between surface area and volume, they are used to improve the mechanical behaviour of materials in *potential structural applications*.