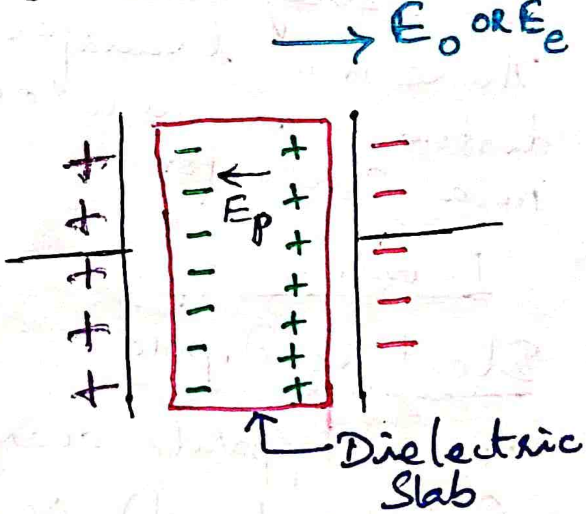
Dielectric properties

Dielectrics are Very bad Conductors of electricity.
Dielectrics are insulators.
In dielectrics there will be no free electrons for electrical conduction.
All the electrons are tightly bound to their respective nucleus of the Atoms.
Both Valence Band and Conduction Band are seperated by a large forbidden energy gap of the order of 5eV-10eV or even higher.
But the material as a whole contains both +Ve and -Ve
charges and the material is neutral.
Whenever a dielectric is applied with an external field, both +Ve and -Ve charges are seperated in the entire Volume of the material.
This process is called polarization this is shown in figure ① below.



The polarization of charges are produced at the faces of the dielectric are shown in the figure ①.

fig ① polarization of Dielectric in the electric field.

Inside the medium there is no excess charge.
The medium as a whole remains neutral.
The positive charge on right side is equal to the negative charge on the left side.

The seperated charges produce their own field E_p, called polarising field. (or) field due to polarization. The direction of this field is shown in the figure ①. The field due to polarization E_p opposes external field. The resultant field is given by

$$E = E_R = E_0 \sim E_p$$

Also $E < E_0$.

Thus the polarization of the medium reduces the electric field in the interior of the medium. Here charges are displaced from their equillibrium positions by distances that are considerably less than an atomic diameter.

Dielectrics are extensively used in electronic and electrical industry. They are used as an insulating media.

There is no transfer of charge over macroscopic distances as such occurs a current is set up in a conductor.

Terminology:

Electric dipole.

Two opposite charges of equal magnitude (+q and −q) seperated by a constant distance r, constitutes an electric dipole.

The dipolemoment of pair of charges is defined by

$$\mu = q \times r$$

A dipole is shown in figure ②

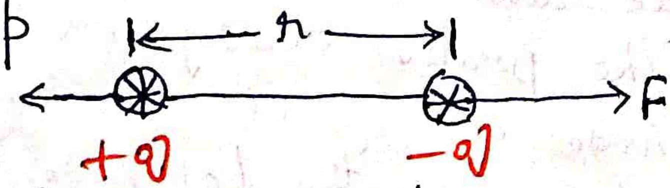


Fig ② A Dipole.

If each of the particles (Atoms) of a solid posses a dipolemomentum, the total dipolemoment of the sample will be, $p = q_1 r_1 + q_2 r_2 + q_3 r_3 + \dots + q_i r_i + \dots + q_n r_n$

$$p = \sum_{i=1}^{n} q_i r_i \quad \text{——— (1)}$$

Non-polar Dielectric

Usually monoatomic materials are made up of atoms. Here the center of negative charge and center of positive charge of an atom coincide with each other. Though there are two equal and opposite charges, they are not seperated.

Now dipolemoment p or $\mu = q \times 0 \quad (\because r = 0)$

$$p \text{ or } \mu = 0$$

Such dielectrics are called non-polar dielectrics.

Example: Diamond, Silicon, Germanium etc.

polar Dielectric

Usually polyatomic molecules also contain molecules. The center of negative charge distribution maynot coincide with centre of the positive charge distribution. If there is an effective seperation between the centers of negative and positive charge distributions, the molecule has a dipolemoment p or μ.

Such dielectrics are called polar dielectrics.

Examples: Water, NitroBenzene, NO_2, CH_3Cl, HBr, HI.

polarization can occur both in polar and non polar dielectrics.

When a non-polar molecule or Atom is subjected to an external electric field E, the center of the negative charge and positive charge distribution get seperated.

Hence the atoms or molecule acquires a net dipole moment.

The polarization is shown in the figure ③, in the case of non polar molecules.

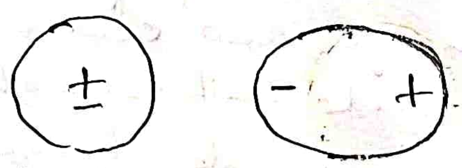


Fig ③ polarization in the case of non polar dielectrics

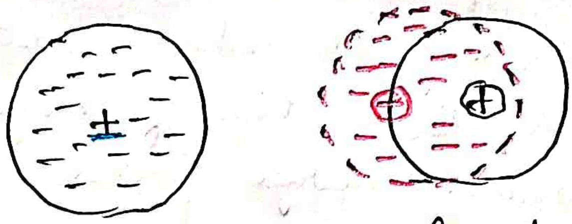


Fig ③a polarization in the non polar dielectrics.

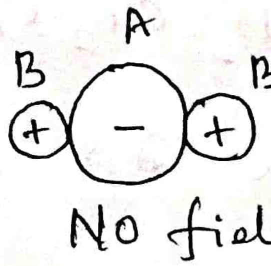
Usually in polar dielectrics, molecules are having random orientation. As a result in any volume containing a large number of molecules, the net dipolemoment is zero

When a polar molecule is subjected to an external electric field, each of the molecular dipoles experiences a torque.

Due to this they tend to orient themselves in the direction of the field.

As a result a net dipolemoment is induced in the molecule

This is shown in the figure ④, for AB_2 molecule.



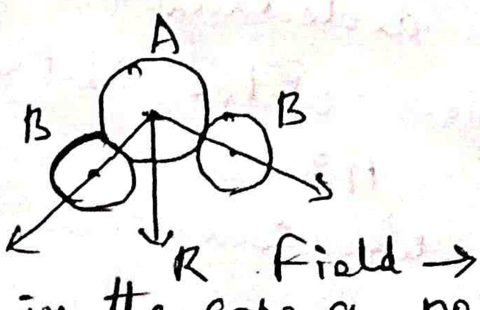


Figure ④ polarization in the case of polar molecule.

polarization

polarization is the process of inducing dipolemoment in a medium by an applied electric field.

The polarization P or the polarization vector in a solid is defined as the dipolemoment per unit volume.

$$P = \frac{p}{V} \text{ or } \frac{\mu}{V} \quad \text{ie } P = \frac{\text{Dipolemoment}}{\text{Volume.}}$$

Let us consider a rectangular slab of length l and area of cross section A.

This slab is placed in an electric field.

Let σ_p be the induced charge density due to polarization.

$$\text{Now polarization } P = \frac{\text{dipolemoment}}{\text{Volume}}$$

$$P = \frac{\sum_{i=1}^{n} q_i r_i}{A \times l}$$

$$P = \frac{\sum_{i=1}^{n} q_i \sum_{i=1}^{n} r_i}{Al}$$

$$P = \frac{\sum_{i=1}^{n} q_i}{A} \quad \frac{\sum_{i=1}^{n} r_i}{l}$$

$$P = \frac{Q}{A} \quad \frac{l}{l} \qquad \left[\because \sum_{i=1}^{n} q_i = Q \text{ and } \sum_{i=1}^{n} r_i = l \right]$$

$$P = \frac{Q}{A} = \frac{\text{charge}}{\text{Area}}$$

$$P = \sigma_p$$

i.e The induced charge density is equal to the magnitude of the polarization

Surface charge density :

charge per unit area of the specimen is called surface charge density.

$$\frac{Q}{A} = \sigma$$

Note: polarization has got the same units as that of surface charge density
- A polarized object will have induced surface charge at two ends.

Gauss Law

Gauss Law is a Law and can be applied any closed surface that permits to calculate the field of an enclosed charge by mapping the field on a surface outside the charge distribution.
It simplifies the calculation of the electric field with the symmetric geometrical shape of the surface.
Its typical case will be the charged particle with spherical symmetry.

Statement:
Gauss Law states that the electric flux through a closed surface is equal to the ratio of total charge enclosed by that surface to the permittivity of free space.

i.e The total charge enclosed in any closed surface is proportional to the total flux enclosed by the surface.

i.e $Q \propto \phi$

$$Q = \epsilon_0 \phi$$

$$\Rightarrow \phi = \frac{Q}{\epsilon_0} \quad \text{———} \quad (1)$$

where ϕ = Electric flux
Q = Electric charge
ϵ_0 = permittivity of free space.

Let us suppose that, there is a spherical surface.
Surface Area $A = 4\pi r^2$, r = Radius of the sphere.
Now electric flux ϕ is given by

$$d\phi = E \cdot dA \quad \text{———} \quad (2)$$

$$d\phi = E \cdot dA \cos\theta \quad (E \text{ \& } dA \text{ are parallel}, \theta = 0^\circ)$$

$$\phi = \int_S E \, dA(1) = \int_S E \, dA$$

$$\phi = E \, 4\pi r^2 \quad \text{——— (3)}$$

Now from gauss Law $\phi = \frac{Q}{\epsilon_0}$

Now $E \, 4\pi r^2 = \frac{Q}{\epsilon_0}$

$$\therefore E_1 = \frac{Q}{4\pi r^2 \epsilon_0}$$

$$E = \frac{Q}{4\pi r^2} \cdot \frac{1}{\epsilon_0}$$

$$E = \frac{\sigma}{\epsilon_0} \quad \text{——— (4)}$$

where $\frac{Q}{4\pi r^2} = \frac{\text{charge}}{\text{Area}}$ = Surface charge density

$$\frac{Q}{4\pi r^2} = \sigma$$

Electric Displacement (D)

Electric displacement is denoted by D.

It is defined as the charge per unit area that would be displaced across a layer of conductor placed across an electric field.

Electric displacement is used in the dielectric material to find the response of the materials on the application of an electric field. E.

S.I. unit : Coulomb-m^{-2}

Displacement $D \propto E$

$D = \epsilon E$

$D = \epsilon_0 \epsilon_R E$ ——— (5)

ϵ = Absolute permittivity.

Relation Between polarization P, Susceptibility χ and Dielectric Constant ϵ_r:

Consider a parallel plate capacitor. Between the parallel plates an electric field E_0 exists as shown in figure ⑤.

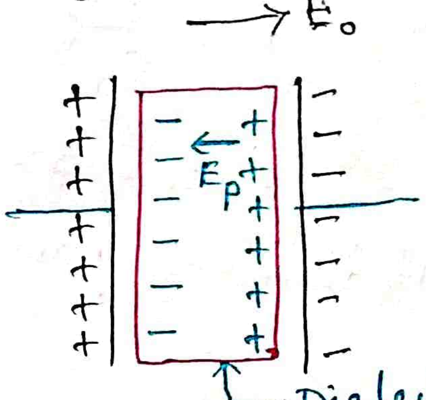


Fig ⑤ Fields in between charged plates and Dielectric Slab.

If σ is the charge per unit area on the plates, then from Gauss law we have

$$E_0 = \frac{\sigma}{\epsilon_0} \quad \text{——— ①}$$

Now the given dielectric slab is placed between the two plates.

Now polarization occurs with in the dielectric medium.

Due to polarization, opposite charges appear on the two faces of the slab.

This establishes an electric field within the dielectric medium.

This electric field is called field due to polarization.

This is denoted by E_p.

The direction of E_p is opposite to E_0. [shown in fig ①]

Now the resultant field can be written as

$$E = E_R = E_0 - E_p \quad \text{——— ②}$$

If $\sigma_p = \frac{\text{charge}}{\text{Area}}$, ie charge per unit area on the slab surfaces, then by using Gauss law, we have

$$E = E_p = \frac{\sigma_p}{\epsilon_0} \quad \text{——— ③}$$

∴ From Equations (1), (2) and (3), we got

$$E = \frac{\sigma}{\epsilon_0} - \frac{\sigma_p}{\epsilon_0}$$

$$E = \frac{1}{\epsilon_0}(\sigma - \sigma_p)$$

$$\epsilon_0 E = \sigma - \sigma_p \quad \text{——— (4)}$$

Also, we have polarization $P = \frac{\text{charge}}{\text{unit Area}}$

$$P = \sigma_p$$

Also from Gauss law, we have
Electric displacement (OR) Electric flux density,

$$D = \sigma$$

Now equation (4), can be written as

$$\epsilon_0 E = D - P$$

$$\therefore P = D - \epsilon_0 E \quad \text{——— (5)}$$

Also electric displacement D is given by

$$D = \epsilon E$$

$$D = \epsilon_0 \epsilon_R E \quad \text{——— (6)}$$

Now from equations (5) and (6), we get

$$P = \epsilon_0 \epsilon_R E - \epsilon_0 E$$

$$P = \epsilon_0 E(\epsilon_R - 1) \quad \text{——— (7)}$$

$$P = \epsilon_0 E \chi \quad \text{——— (8)}$$

where $\chi = \epsilon_R - 1$

χ = Dielectric Susceptibility

Dielectric Constant (K) (or) ϵ_r

Dielectric constant K or ϵ_r is given by

$$K = \frac{\text{Absolute permittivity of a medium}}{\text{permittivity of free space}}$$

$$\epsilon_r = K = \frac{\epsilon}{\epsilon_0}$$

Dielectric constant is also known as Relative permittivity of the material.

permittivity(ϵ) is a measure of the ability of a material to be polarized by an electric field.

$$\text{Also } K = \frac{C}{C_0} = \frac{\text{Capacity of capacitor with dielectric}}{\text{Capacity of capacitor with air as medium}}$$

Dielectric constant has no units.

It expresses the extent to which a material can hold electric flux in it.

Dielectric Susceptibility (χ_e) or χ

Dielectric Susceptibility indicates degree of polarization in response to applied electric field.

It is only a number and has no units.

Now Dielectric constant 'K' is defined as

$$K = \frac{\text{Applied Electric field}}{\text{Net Electric field inside Dielectric}}$$

$$K = \frac{E_0}{E} \quad \text{——— (1)}$$

when a dielectric is placed in an electric field, it gets polarized.

Now polarization $P = \frac{\text{Total Dipolemoment}}{\text{Volume}}$

Also $P = \sigma_p$ or σ_i ——— (2)

i.e $P =$ Induced Surface charge density due to polarization.

Also $P \propto E$

$P = \chi_e \epsilon_0 E$, where E = Resultant electric field.

But $E = E_0 - E_p$

$$E = E_0 - \frac{\sigma_p}{\epsilon_0}$$

$$E = E_0 - \frac{P}{\epsilon_0}$$

$$E = E_0 - \frac{\chi_e \cancel{\epsilon_0} E}{\cancel{\epsilon_0}}$$

$$E = E_0 - \chi_e E.$$

deviding the above equation with E,

$$\frac{E}{E} = \frac{E_0}{E} - \chi_e \frac{E}{E}$$

$$1 = \frac{E_0}{E} - \chi_e, \quad \text{But } \frac{E_0}{E} = K$$

$$\therefore \quad 1 = K - \chi_e$$

$$\Rightarrow \boxed{\chi_e = K-1} \quad (\text{OR}) \quad \boxed{K = \chi_e + 1}$$

polarizability (α)

Any bulk material consists of individual atoms (or) molecules (or) Ions.

Now let the dielectric material is subjected to an electric field E.

Now μ be the induced dipole moment in the presence of electric field.

Also it is found that μ varies directly as E.

$$\therefore \quad \mu \propto E$$

Dipolemoment of an Atom, $\mu = \alpha E$.

Where α is a constant of proportionality.

This 'α' is called polarizability of the Atom.

units: $F\text{-}m^2$

polarizability is not a bulk property of the material. But it is the property of an individual atom or molecule.

This is an important microscopic electrical parameter of a dielectric material.

Types of polarization (Sources of polarizability)

When an electric field acts on a molecule, its positive charges are displaced along the field while the negative charges in a direction opposite to that of the field. Here the opposite charges are pulled apart and the molecule is polarized.

Three mechanisms are responsible for polarization of dielectric materials.

Dipolar polarization or orientation polarization:

This type of polarization occurs in polar dielectrics only. Let us consider a molecule has a permanent dipolemoment. There exists dipolemoment even in the absence of an electric field.

Now we will consider a dipolar molecule and hence a dipolar substance.

For example water molecule is a dipolar molecule. It is shown below.

Figure (6)
Water molecule.

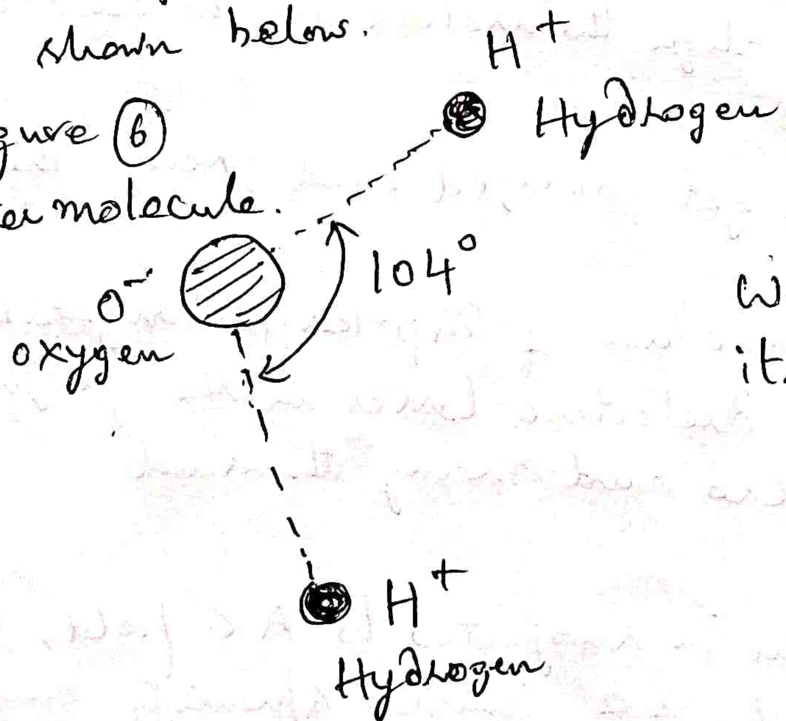
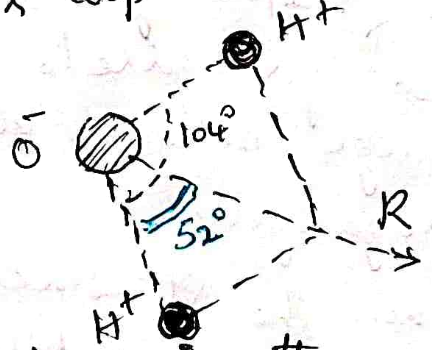


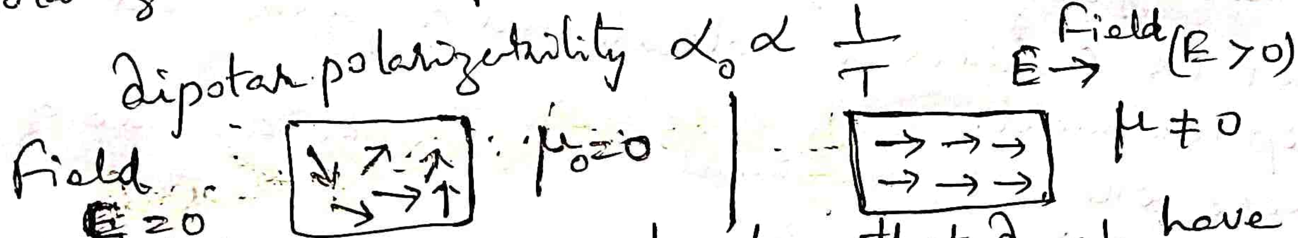
Figure (6) a
Water molecule and its dipolemoment-Resultant



The dipolemoment of the water molecule is the resultant of the dipolemoments of the two OH bonds.

When these molecules condense into solid state,
they retain their dipolemoments.
In the absence of an electric field, the dipoles are randomly oriented.
This results in a zero net dipolemoment and resulting in complete cancellation of the polarization.
But when an electric field is applied, these dipoles tend to orient and align with the field.
This gives rise to an effective polarization.
this leads to dipolar or oriental polarization. This polarization is temperature dependent

dipolar polarizability $\alpha_o \propto \frac{1}{T}$



Even in the case of molecules that donot have permanent dipoles, can be rotated in the presence of an external field.
This is because each molecule experiences a torque.
Here the molecules align themselves in the direction of the field.
Here the molecules get polarized and hence the material.
The frequency dependence of dipolar polarizability also gives rise to dielectric losses in the frequency range between zero and many thousand megacycles.
When the specimen is subjected to A.C field, the dipolar polarizability is a complex quantity and is given by $\alpha_d^* = \alpha_d' - j\alpha_d''$

where $\alpha_d^* =$ Complex polarizability

$\alpha_d' =$ Real part

$\alpha_d'' =$ Imaginary part.

Similarly in the case of dipolar polarization, in A.C fields. it is a Complex quantity. This is given by

$$P_d^* = P_d' - j P_d''$$

where $P_d^* =$ Complex polarization

$P_d' =$ Real part

$P_d'' =$ Imaginary part

The general expression for orientation polarizability is given by $\alpha_o = \dfrac{\mu^2}{3 K_B T}$

where $\mu =$ permanent dipolemoment

$K_B =$ Boltzmann Constant

$T =$ Temperature in °k.

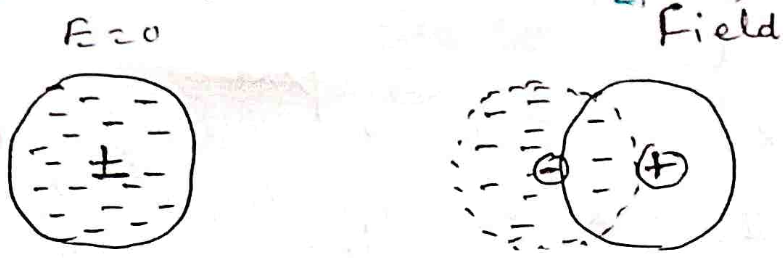
Electronic polarization

Electronic polarization occurs on account of the fact that the individual atoms in a molecule are themselves polarized in a field.

It is a rapid process

This type of polarization occurs in non-polar dielectrics.

The following figure illustrates how an atom is polarized. Figure (7)



Unpolarized Atom

polarized Atom.

Figure (7) polarization in an Atom

When there is no field, the atom is unpolarized. This is due to the fact that center of positive charge distribution and the center of negative charge distribution will be coinciding each other.

In the presence of the field, the electrons present in various shells are displaced relative to the nucleus. This produces an electric dipole moment. This is called electronic polarization and hence electronic polarizability.

Thus every atom in the crystal should have an electronic polarizability and electronic polarization. Electronic polarization and polarizability are independent of temperature.

Due to the application of electric field, there is a displacement between electron cloud and nucleus of the atom. That is the nucleus and electron cloud are pulled apart. As they pulled apart, a Coulombic force develops between them, which tends to counter at the displacement.

For a field of $30 \, kV m^{-1}$ the displacement is of the order of $10^{-17} m$.

Here the induced dipolemoment is proportional to the applied electric field.

i.e $\mu_e \propto E \Rightarrow \mu_e = \alpha_e E$

α_e = Electronic polarizability

μ_e = Induced electronic dipolemoment

E = Applied electric field.

For an Atom having Atomic radius R, placed in an electric field, electronic polarizability is given by

$$\alpha_e = 4\pi\epsilon_0 R^3$$

where ϵ_0 = permittivity of free space

The dipolemoment per unit volume is called electronic polarization.

$$\frac{\mu_e}{V} = P_e$$

If there are N number of atoms per m^3, then electronic polarization is given by

$$P_e = N\alpha_e E$$

Also we have $P = \epsilon_0(\epsilon_r - 1)E$

$$\text{Now } P_e = \epsilon_0 \cancel{E}(\epsilon_r - 1) = N\alpha_e \cancel{E}$$

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

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

In A.C. fields, the Complex polarizability α_e^* for electronic polarizability is given by

$\alpha_e^* = \alpha_e' - j\alpha_e''$ $\quad$ α_e' = Real part

α_e'' = Imaginary part.

In A.C. fields, the complex polarization P_e^* is given by $P_e^* = P_e' - j P_e''$, for electronic polarization.

P_e' = Real part and P_e'' = Imaginary part.

The natural frequencies for electronic vibration lie about 10^{16} rad s^{-1}! These frequencies lie in ultraviolet part of the electromagnetic spectrum.

Ionic polarization:

If the molecule or material contains ions, then the field tends to displace the positive and negative ions in opposite directions.

This causes a change in the length of the ionic Bond.

This also changes the dipolemoment.

But if we consider the crystal as a whole, net dipolemoment is equal to zero.

This is because due to ~~random~~ orientation of the dipoles in the crystal.

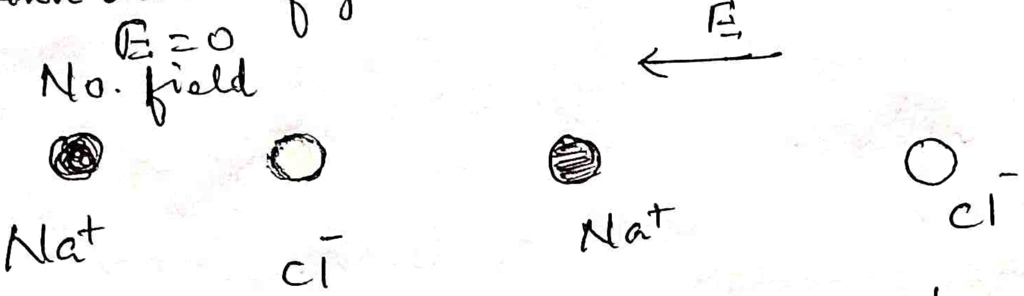
Since permanent dipolemoment $\mu_p = \sum_{i=1}^{n} e_i r_i = 0$.

Due to a change in the bond length of each molecule, a dipolemoment in the unit-cell will be developed.

Here the polarization results in relative displacement of ions, we call this as ionic displacement and hence it is called ionic displacement polarization.

$$\left[\mu_p = e_1 r_1 + e_2 r_2 + e_3 r_3 + \cdots + e_i r_i + \cdots + e_n r_n\right]$$

The displacement of ions for a Nacl molecule is shown in the figure below. figure (8)



Figure(8) polarization in Nacl molecule

The induced dipolemoment is proportional to the applied electric field.

$$\therefore \mu_i \propto E$$

$$\mu_i = \alpha_i E$$

where α_i = Ionic polarizability.

For most of the ionic materials, ionic polarization is less than electronic polarization.

Typically $\alpha_i = 0.1\,\alpha_e$.

Ionic polarization occurs in polar Dielectrics.

This is also independent of temperature.

When ionic materials subjected to A.C. field, it will give rise to Complex polarization and complex polarizability α_I^*.

α_I^* is given by $\alpha_I^* = \alpha_I' - j\,\alpha_I''$

α_I' = Real part and α_I'' = Imaginary part

Complex polarization is given by $P_I^* = P_I' - j\,P_I''$

P_I' = Real part and P_I'' = Imaginary part

The natural frequencies of the ionic vibrations lie in the infrared part of the electromagnetic spectrum.

Local Field (or) Internal Field (OR) Lorentz Field

In Solids usually an Atom experiences the experiences external field and also fields produced by the dipoles as well. Due to long range nature of coulombic forces, the fields produced by the dipoles cannot be neglected.

The resultant field which is responsible for polarizing individual molecules or Atoms of Solids is called the local field or internal field. This is denoted by E_{loc} (OR) E_i.

Now a dielectric medium is placed in an electric field. The external field is a uniform electric field. Now the dielectric get polarized uniformly in the electric field. For calculating the local field, a spherical region is selected in the dielectric as shown in the figure ①.

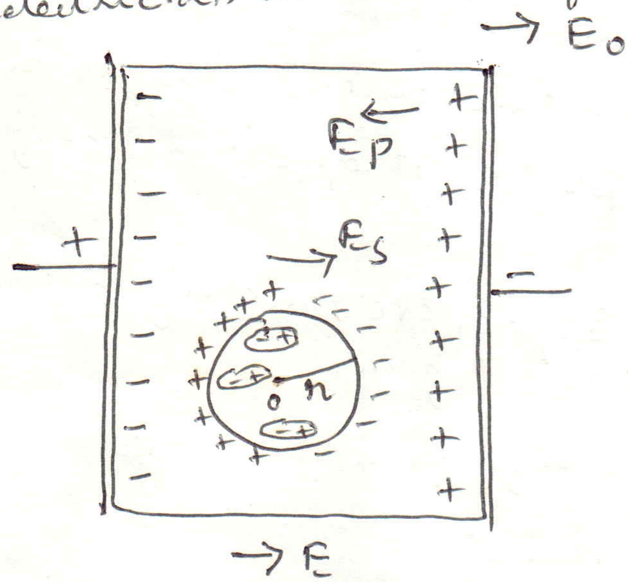


Fig (1) calculating internal field.

It is assumed that outside the spherical Region the dielectric is uniformly polarized. But inside the spherical region, it has the material. (Atoms are prevalent)

Now the dielectric is polarized uniformly, with a polarizing field E_p. The dielectric is induced with charges, as indicated in the diagram.

Now $E = E_0 + E_p$ is the resultant electric field.

Also the spherical Region is induced with surface charges as shown in the figure ①.

The local field at the centre of the sphere can be written as

$$E_{loc} = E_0 + E_p + E_s + E_m \quad \text{———} \quad (1)$$

But $E_0 + E_p = E$ ——— (2)

$$\therefore E_{loc} = E + E_s + E_m \quad \text{———} \quad (3)$$

For high symmetric crystals such as cubic crystals $E_m = 0$.

Also E_0 = External applied electric field.

E_p = Field due to polarization of the dielectric

E_s = Field due to the charges induced at the spherical surface.

E_m = Field due to all the dipoles of the atoms inside the spherical Region.

$E_m = 0$ for high symmetric and Isotropic dielectrics.

$E_m = 0$ is not true for anisotropic and nonsymmetric materials.

$E_m = 0$, because the dipoles are randomly distributed inside the spherical Region.

Now (3) $\Rightarrow$ $E_{loc} = E + E_s$ ——— (4)

$\boxed{\text{Calculation of } E_s}$

The spherical views of the chosen sphere is shown in the figure (2). For calculating the E_s, we will consider an elemental Area ds (or) dA. of the chosen sphere. Here we will calculate the charge on ds.

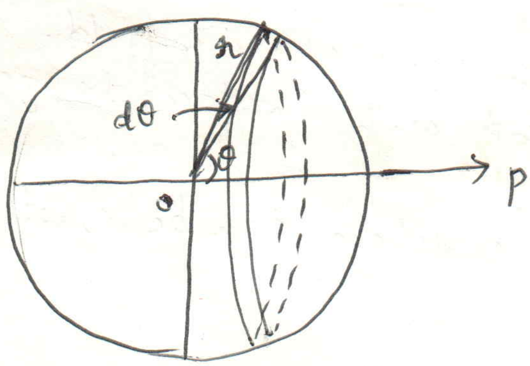


Fig (2) Calculation of E_s.

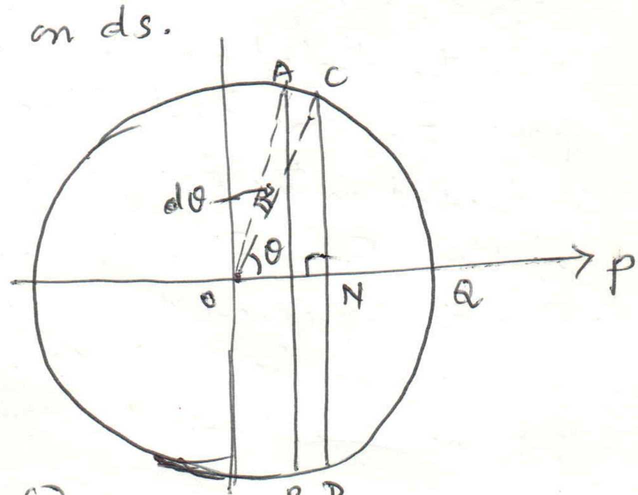


Fig (3) Elemental Ring of elemental Areas ds.

D.Ramanujan (2)

Now elemental charge dq' on ds is given by product of polarization along P and the Surface element ds.

$$dq' = (P\cos\theta) \times ds \quad \text{——— (5)}$$

$P\cos\theta$ = Component of polarization along P (Normal component of polarization)

Now ds = Area of the Ring ABCD.

ds = (perimetre) × width

ie ds = (Circumference) × width

From figure (3), $C\hat{O}Q = \theta$

$A\hat{O}C = d\theta$

Radius of the Ring ABCD = CN

width of the Ring ABCD = AC.

From figure (3), we have $OC = OA = OQ = r$, Radius of the Sphere.

From figure (3),

AOC is a Sector,

$$\frac{\text{Arc}}{\text{Radius}} = \text{Angle}$$

$$\frac{AC}{OC} = d\theta$$

$$AC = OC\, d\theta$$

$$AC = r\, d\theta.$$

From the Right angled Δle OCN,

$$\sin\theta = \frac{CN}{OC}$$

$$CN = OC \sin\theta$$

$$CN = r\sin\theta$$

∴ Area of ABCD Ring = (Circumference) × width

$$ds = (2\pi\, CN) \times AC$$

$$ds = 2\pi r \sin\theta \times r\, d\theta$$

$$ds = 2\pi r^2 \sin\theta\, d\theta. \quad \text{——— (6)}$$

An elemental charge 'dq' on ds experiences a force due to a Test charge q at 'O'. According to Coulombs law, this is given by dF

$$dF = \frac{q\, P \cos\theta\, ds}{4\pi \epsilon_0 r^2} \quad \text{———} \quad (7)$$

Hence the field dE_s at 'O' due this charge element is given by

$$dE_s = \frac{dF}{q}$$

$$\therefore dE_s = \frac{\cancel{q}\, P \cos\theta\, ds}{4\pi \epsilon_0 r^2 \cancel{q}}$$

$$dE_s = \frac{P \cos\theta\, ds}{4\pi \epsilon_0 r^2} \quad \text{———} \quad (8)$$

The dE_s can be resolved into two components

(i) Component parallel to P, $dE_s \cos\theta$

(ii) Component perpendicular to P, $dE_s \sin\theta$.

The perpendicular component will be cancelled due to an equal contribution from another symmetrically situated surface element.

Thus only the component of dE_s parallel to the direction of P will contribute to equation (8) over the entire surface.

$$\therefore E_s = \int dE_s \cos\theta$$

$$E_s = \int \frac{P \cos\theta\, ds \cos\theta}{4\pi \epsilon_0 r^2}$$

$$E_s = \int \frac{P \cos^2\theta \, ds}{4\pi \epsilon_0 r^2} \qquad \text{——— (9)}$$

Now $ds = 2\pi r^2 \sin\theta \, d\theta$.

$$\therefore E_s = \int \frac{P \cos^2\theta \, \cancel{2}\cancel{\pi} \cancel{r^2} \sin\theta \, d\theta}{{}_2\cancel{4}\cancel{\pi} \epsilon_0 \cancel{r^2}}$$

The limits of integration with respect to θ are 0 to π

$$\therefore E_s = \int_0^{\pi} \frac{P}{2\epsilon_0} \cos^2\theta \sin\theta \, d\theta$$

$$E_s = \frac{P}{2\epsilon_0} \int_0^{\pi} \cos^2\theta \sin\theta \, d\theta$$

Let $\cos\theta = z$

$\Rightarrow dz = -\sin\theta \, d\theta$, $\quad \theta = 0 \Rightarrow z = +1$

$\theta = \pi \Rightarrow z = -1$

$$\therefore E_s = -\frac{P}{2\epsilon_0} \int_{+1}^{-1} z^2 \, dz$$

$$E_s = -\frac{P}{2\epsilon_0} (-1) \int_{-1}^{+1} z^2 \, dz$$

$$E_s = \frac{P}{2\epsilon_0} \left[\frac{z^3}{3}\right]_{-1}^{+1}$$

$$E_s = \frac{P}{6\epsilon_0}\left[(1)^3 - (-1)^3\right]$$

$$= \frac{P}{6\epsilon_0}\left[1+1\right]$$

$$= \frac{2P}{6\epsilon_0}$$

$$E_s = \frac{P}{3\epsilon_0} \quad \text{———} \quad (9)$$

From Equations (4) and (9), we have

$$E_{loc} = E + \frac{P}{3\epsilon_0} \quad \text{———} \quad (10).$$

The local field E_{loc} or E_i is different from E. The local field is greater than E, so that the molecules are effectively polarized.

Equation (10) is known as Lorentz Equation.

$\boxed{\text{Clausius- Mossotti Relation}}$

When a dielectric is placed in an Electric field, it will get polarized.

The dipolemoment of a single Atom, p is proportional to the local field.

$$p \propto E_{loc}$$

$$p = \alpha E_{loc}$$

α is a constant of proportionality called polarizability.

If there are different types of atoms, the polarizabilities are additive.

The Total polarization of the dielectric Containing 'n' types of atoms is

$$P = \left(\sum_{i=1}^{n} n_i \alpha_i\right) E_{loc} \qquad \text{——— (1)}$$

Here n_i is the number of i atoms per unit volume having polarizabilities α_i

E_{loc} is the local field acting on them.

Now $$E_{loc} = E + \frac{P}{3\epsilon_0} \qquad \text{——— (2)}$$

From equations (1) and (2),

$$P = \left(E + \frac{P}{3\epsilon_0}\right) \sum_{i=1}^{n} n_i \alpha_i$$

If the sample Contains all the i atoms as Same, then

$$\sum_{i=1}^{n} n_i \alpha_i = n\alpha$$

$$\therefore \quad P = \left(E + \frac{P}{3\epsilon_0}\right) n\alpha$$

$$P = E n\alpha + \frac{P}{3\epsilon_0} n\alpha$$

deviding the above equation by P,

$$1 = \frac{n\alpha E}{P} + \frac{\cancel{P}}{3\epsilon_0} \frac{n\alpha}{\cancel{P}}$$

$$\frac{E}{P} n\alpha = 1 - \frac{n\alpha}{3\epsilon_0}$$

$$\frac{E}{P} = \frac{\left(1 - \frac{n\alpha}{3\epsilon_0}\right)}{n\alpha}$$

$$\Rightarrow \frac{P}{E} = \frac{n\alpha}{\left(1 - \frac{n\alpha}{3\epsilon_0}\right)} \quad \text{——— (3)}$$

But $\frac{P}{E\epsilon_0} = \chi$

$$\frac{P}{E} = \chi\epsilon_0 \quad \text{——— (4)}$$

Also $\chi = \epsilon_r - 1$ ——— (5)

or $\chi = K - 1$

χ = dielectric Susceptibility

$\epsilon_r = K$ = dielectric constant.

ϵ_0 = permittivity of free Space.

From (3) and (4),

$$\chi\epsilon_0 = \frac{n\alpha}{\left(1 - \frac{n\alpha}{3\epsilon_0}\right)}$$

$$\chi = \frac{n\alpha}{\epsilon_0\left(1 - \frac{n\alpha}{3\epsilon_0}\right)} \quad \text{——— (6)}$$

But $\chi = \epsilon_r - 1$

$$\therefore (\epsilon_r - 1) = \frac{n\alpha}{\left(\epsilon_0 - \frac{n\alpha}{3}\right)}$$

$$\Rightarrow (\epsilon_r - 1)\epsilon_0 - (\epsilon_r - 1)\frac{n\alpha}{3} = n\alpha$$

$$\Rightarrow (\epsilon_r - 1)\epsilon_0 = n\alpha + \left[(\epsilon_r - 1)\frac{n\alpha}{3}\right]$$

$$\Rightarrow (\epsilon_r - 1)\epsilon_0 = n\alpha\left[1 + \frac{\epsilon_r - 1}{3}\right]$$

$$(\epsilon_r - 1)\,\epsilon_0 = \frac{n\alpha}{3}\left[3 + \epsilon_r - 1\right]$$

$$(\epsilon_r - 1)\,\epsilon_0 = \frac{n\alpha}{3}(\epsilon_r + 2)$$

$$\Rightarrow \left(\frac{\epsilon_r - 1}{\epsilon_r + 2}\right) = \frac{n\alpha}{3\epsilon_0} \quad \text{——— (7)}$$

This is clausius- Mossotti Ist Relation.

n = no. of Atoms per unit Volume of the Specimen

$$\therefore n = \frac{\rho N_a}{M} \quad \text{——— (8)}$$

ρ = Density of the material

N_a = Avogadro Number

M = Molecular Weight.

From equations (7) and (8), we get

$$\left(\frac{\epsilon_r - 1}{\epsilon_r + 2}\right) = \frac{\alpha}{3\epsilon_0}\,\frac{\rho N_a}{M}$$

$$\left(\frac{\epsilon_r - 1}{\epsilon_r + 2}\right)\frac{M}{\rho} = \frac{\alpha N_a}{3\epsilon_0} \quad \text{——— (9)}$$

This 2nd clausius Mossotti Relation.

MAGNETIC PROPERTIES

The magnetism of materials is due to the interaction of magnetic dipoles. Every magnetic material contains magnetic dipoles. These dipoles are due to the atoms or molecules present in the material.

When such a magnetic material containing dipoles is subjected to an external magnetic field, they experience torque. Due to this torque, the dipoles tend to align their magnetic moment in the direction of the field. The degree of alignment is characterized by total magnetic moment.

Magnetism: The attracting property exhibited by the magnet is known as Magnetism.

Magnetic dipole: Two equal and opposite poles separated by certain distance Constitutes a magnetic dipole.

Magnetic dipole moment or Magnetic moment:

It is denoted by μ_m .If m is the pole strength and 2l is the length of the magnet or magnetic dipole then magnetic dipole moment or magnetic moment is given by the product m (2l).

When I amperes of electric current flows through a circular wire of cross sectional area A ,m^2, having one turn, then it will have a magnetic moment of $\mu_m = I A$.

Magnetic moment is a Vector quantity.

Units: A-m^2.

Magnetic field:

The space limit around a magnet in which its effect is felt is known as magnetic field.

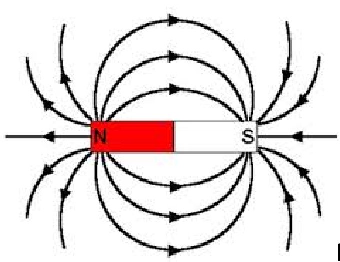


Figure (1) Magnetic field and Lines of force.

Magnetic Field strength (H): The magnetic field strength H is the force experienced by a unit North Pole placed at a point in the given magnetic field. It is expressed in A-m^{-1}.

Magnetization or Intensity of Magnetization (M):

Magnetic moment per unit volume is known as Magnetization.

$$Magnetizatin, M = \frac{magnetic\ moment}{Volume}$$

The magnetization is expressed in ampere- $(meter)^{-1}$.

Magnetic susceptibility (χ): The magnetic susceptibility is the ratio of Magnetization M and Magnetic Field strength H. $\chi = \frac{M}{H}$. χ has no units. It is only a number.

The ease with which a material can be magnetized is characterized by susceptibility.

Magnetic lines of force: Usually magnetic field is characterized by magnetic lines of force.

A line along which a unit north pole would tend to move is known as magnetic line of force.

Magnetic induction field strength (or) Magnetic Flux Density (B):

Magnetic flux density is denoted by B. It is defined as the number of magnetic lines of force passing through a unit area of cross section of the magnetic material.

If ϕ is the number of lines force passing through an area of cross section A, then $B = \frac{\phi}{A}$.

It is also defined as flux per unit area. It is expressed in weber-m^{-2}.

Magnetic permeability (μ):(Absolute permeability)

Permeability is the ability of a magnetic material to conduct lines of force through it in a field. Magnetic permeability is the ratio of magnetic flux density B in the material to the applied magnetic field strength H.

$$\mu = \frac{B}{H} or B = \mu H$$

Magnetic permeability of Free Space (μ_0):

The magnetic permeability of free space (μ_0) is the ability of air medium to allow the lines of force through it. It is denoted by μ_0.It is defined as the ratio between magnetic flux density B_0 of air or vacuum or free space and the applied magnetic field H.

$$\mu_0 = \frac{B_0}{H}$$

$B_0 = \mu_0 H$ Where $\mu_0 = 4\pi \times 10^{-7} Hm^{-1}$.

Relative Permeability (μ_r):

Relative permeability (μ_r) is the ratio between absolute permeability of a material (μ) and permeability of free space (μ_0)

$$i.e. \mu_r = \frac{\mu}{\mu_0}$$

$$\mu = \mu_0 \mu_r$$

<u>Relation between B, H and M</u>

We know that $B = \mu H$

But $\mu = \mu_0 \mu_r$

$$\therefore B = \mu_0 \mu_r H$$

$$B = \mu_0 \mu_r H + \mu_0 H - \mu_0 H$$

$$B = \mu_0 H + \mu_0 \mu_r H - \mu_0 H \qquad \text{--------------(1)}$$

$$B = \mu_0 H + \mu_0 H(\mu_r - 1)$$

$$But, B = H(\mu_r - 1) = M$$

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

$$\therefore B = \mu_0 (H + M) \qquad \text{.... (3)}$$

<u>Relation between χ and μ_r:</u>

The relation between B, H ,μ and M is given by

$$\mu = \frac{B}{H} \qquad \text{-------------.(1)}$$

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

$$\mu_r = \frac{\mu}{\mu_0} \qquad \text{-----------(3)}$$

From (1) , (2) and (3),

$$\mu_r = \frac{\frac{B}{H}}{\frac{B}{(H+M)}} = \frac{H+M}{H} \times \frac{B}{B}$$

$$\mu_r = 1 + \frac{M}{H}$$

$$\mu_r = 1 + \chi$$

$$\chi = \mu_r - 1$$

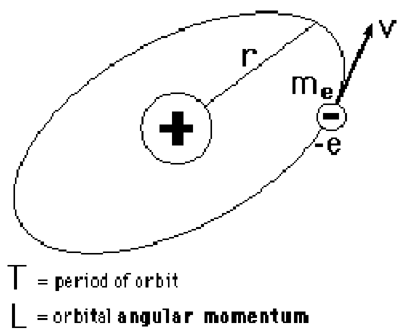
Magnetic moment (or) Origin of Magnetic moment:

Let us consider an electron revolving in an orbit round the nucleus.

Let r = Radius of the orbit.

Let v= linear velocity

And ω = angular velocity



Now $v = r\omega$

Also $\omega = 2\pi\upsilon$

$$\omega = \frac{2\pi}{T} \Rightarrow T = \frac{2\pi}{\omega}$$

ω= Angular frequency, and T= time period.

$$\upsilon = \frac{1}{T} = \frac{\omega}{2\pi}$$

The electron revolving round the nucleus is something similar to circulating current loop.

Now current $I = \frac{Charge}{time T}$

$$I = -\frac{e}{T}$$

$$I = -\frac{e\omega}{2\pi} \qquad \text{----------------------- (1)}$$

This circulating current loop is equivalent to a magnetic dipole.

Now the magnetic moment due to orbital motion of the electron is giving by μ_{el}

$$\mu_{el} = I \times A$$

Here A= Area of the circular loop.

A= πr^2

I = Current

Now $\mu_{el} = -\frac{e\omega}{2\cancel{\pi}}\cancel{\pi} r^2$

$\therefore \mu_{el} = -\frac{e\omega r^2}{2}$

$\mu_{el} = -\frac{er(r\omega)}{2}$

$\mu_{el} = -\frac{er(v)}{2}$ (Since v=rω)

..... (2)

$\mu_{el} = -\frac{em_e rv}{2m_e}$

$\mu_{el} = -\left(\frac{e}{2m_e}\right)m_e vr$

Now $m_e vr = L$, the angular momentum of the electron

$\therefore \mu_{el} = -\left(\frac{e}{2m_e}\right)L$ ... (3)

The negative sign signifies that μ_{el} and L are opposite to each other.

Bohr magneton:

The angular momentum associated with an election is given by. $mr^2\omega$

Now the magnetic dipole moment and angular momentum related as

$$\mu_{el} = -\left(\frac{e}{2m}\right)\times \text{ Angular momentum.}$$

The negative sign indicates that the dipole moment points in a direction opposite to the vector representing the angular momentum.

A substance therefore possesses permanent magnetic dipoles if the elections of its constituent atoms have a net non vanishing angular momentum.

The ratio of magnetic diopolemoment or magnetic moment of the electron due to its orbital motion and the angular momentum of the election due to orbital motion is called orbital gyro magnetic ratio. (or) orbital magneto mechanical ratio of an electron.

This is denoted by r

$\gamma = \frac{\text{Magnetic moment}}{\text{Angular Momentum}}$

$\gamma = \frac{\mu_{el}}{\mu_{el}\left(\frac{2m}{e}\right)}$

$\gamma = \frac{e}{2m}$ ..------------------ (1)

According to modern atomic theory the angular momentum of an electron in the orbit is determined by the orbital quantum number l, which is restricted to set of values.

i.e. l = 0,1,2,-----------,(n-1)

Where n= principal quantum Number

This principal quantum number determines the energy of the orbit.

n=1,2,3,4,------------only integer values.

The angular momentum of the electrons associated with a particular value of l is given by $l\left(\frac{h}{2\pi}\right)$

Now the strength of the permanent magnetic dipole is given by

$$\mu_{el} = -\left(\frac{e}{2m}\right)l\left(\frac{h}{2\pi}\right)$$

$$\mu_{el} = -\left(\frac{ehl}{4\pi m}\right)$$

$$\mu_{el} = -\mu_B l \qquad \ldots (2)$$

Here $\mu_B = \frac{eh}{4\pi m}$ is an atomic unit called Bohr magneton.

1 Bohr magneton= 9.28x10^{-24} ampere-(metre)^2

Bohr magneton represents the magnetic moment of an elementary permanent magnetic dipole.

Electron spin-Magnetic moment

Usually the electron in atom revolves around the nucleus. In addition to this the electron revolves around a fixed axis. The magnetic moment associated with spinning of the electron is called spin magnetic moment μ_{es}.

The spinning of an electron is similar to spinning of earth about its own axis.

The spin magnetic moment s and spin Angular momentum s are related by

$$\mu_{es} = r\left(\frac{e}{2m}\right)S$$

Here r is called gyromagnetic ratio with respect to spin. experimental value of r for an electron is -2.0024. The negative sign indicates that μes is opposite to S.

Also $S = \frac{h}{4\pi}$

Now equation (1) gives, $\mu_{es} = 9.3\times10^{-24}$ ampere – (metre)^2

<u>Magnetic moment due to nuclear spin</u>

The atomic nucleus possesses intrinsic spin called nuclear spin.

Due to spin motion of nucleus, it will posses magnetic moment.

The nuclear magnetic moment is expressed in the unit of nuclear magnetron μ_n

$$\mu_n = \frac{eh}{4\pi M_p} \qquad \text{h= plank's constant}$$

$$\mu_n = 5.05\times10^{-27} A-m^2$$

$M_P =$ Mass of the proton , $M_p = 1.673\times10^{-27} kg$

Magnetic Hysteresis

The important property of the ferromagnetic material is relating the extent of magnetization with the strength of the magnetizing field.

"The lagging of Physical effect behind the cause of the effect" is called Hysteresis. The lagging of Magnetic flux density B behind Magnetizing field H, is called Magnetic hysteresis.

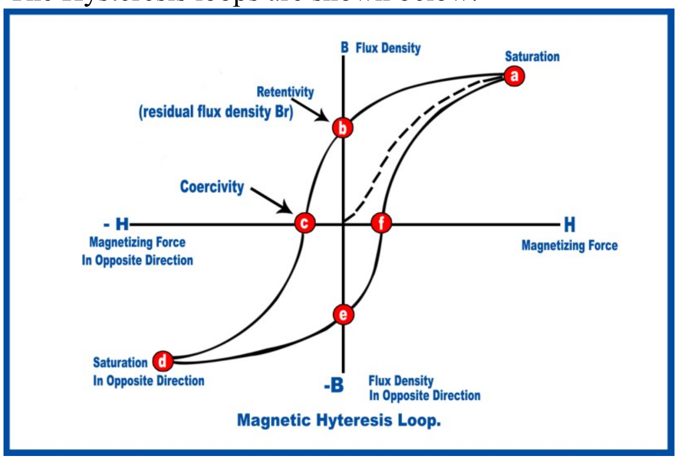
In our discussions the cause is the magnetizing field H. The effect is being the magnetization M. This Magnetization M has to be produced in the ferromagnetic material with the application of the field H.

A plot of M Versus H gives an interesting curve showing the phenomenon of M logging behind H.

This curve is called Hysteresis loop or Hysteresis curve. Hysteresis loop can be drawn relating magnetic induction B and the magnetizing field H.

This is because B can be measured directly.

The Hysteresis loops are shown below.



Salient features of the Hysteresis loop:

i) Let us start with a demagnetized specimen for which Magnetic flux density B=0.
With the increasing value of magnetizing field H, the magnetic flux density of the specimen increases from zero to higher values.
At the point **"a"** the maximum magnetization is attained. Beyond this point even if magnetizing field H is increased, Magnetization and magnetic flux density B remains constant. This value of magnetic flux density $B=B_s$ is known as saturated value of magnetic flux density.
Here all the molecular dipoles get aligned along the H direction. Hence the magnitude of magnetization M and magnetic flux density B stops increasing further.

ii) In the "ab" part of the loop, the magnetization does not decrease in phase with the decreasing value of magnetizing field H.
The lagging of M (or) B behind H is significant as H attains zero value.

Note that here the magnetization $B=B_r$ left behind instead of tending to zero along with H at H=0 is called the residual magnetization (or) Remenant magnetization or Residual magnetic flux density B_r. As we move along the part 'bc' the value of magnetizing filed H is negative. The magnetization M and magnetic flux density B comes back to its initial value of zero only at certain magnitude of the reversed field $\mathbf{H_c}$.

This H_c is called the coercive field.

Coercive field is the field applied in the reverse direction so as to make Retentivity (B_r) equal to zero.

iii) With the further increase in negative value of H, the saturation of magnetization (or) Magnetic flux density is attained in the opposite direction.

iv) When the magnetizing filed becomes zero, the residual magnetization will be negative (or) Magnetic flux density is negative. This is indicated by 'de' in the BH – loop.

v) If we further increase the magnetizing field H, the magnetization M and magnetic flux density B reaches the point 'a', indicating the completion of one cycle of operation.

Application of B-H loop

- Based on the magnetic hysteresis loop, different types of ferromagnetic materials are used to design electrical components.

A transformer contains iron cores, which are ferromagnetic.

In every cycle of the current flow, the core magnetization goes through one hysteresis loop. If the loop happens to have more Area the energy wasted will be naturally large.

(Area of B-H loop or M-H loop gives loss of energy) usually core material is chosen to have small retentivity and coercivity. In these cases a better efficiency can be achieved.

- Materials with large values of retentivity and coresivity are chosen for making permanent magnets.

Loss of energy

The loss of energy per unit cycle per unit volume due to hysteresis is equal to $\frac{1}{4\pi}$ times area of B-H loop.

ϕ H. dB= Area of B-H loop.

Also $\phi H.dI = \frac{1}{4\pi}[\text{Area of B-H loop}]$

Here I= Intensity of Magnetization.

During one cycle of operation, Magnetization and demagnetization is going to take place. i.e. Alignment and reversal of magnetic dipoles will takes place.

During the abcdefa path Reversal of magnetic dipoles and reversal of magnetization takes place. Here heat is dissipated in the material. This is wastage of power and wastage of energy.

Requirements of Magnetic Materials:

Whenever a magnetic material is magnetized, change in domain size – takes place. Usually some favorably oriented domains grow in size and unfavorably oriented domains shrink.

Basing on the domain size variation during magnetization, the area of the hysteresis loop and other properties, magnetic materials are classified into soft and hard magnetic materials.

Soft magnetic materials

The soft magnetic materials usually will have

i. Low permanent magnetization.
ii. Low retentivity.
iii. Low coercivity.
iv. Low hysteresis losses and Small hysteresis loop Area.
v. High magnetic permeability.
vi. High susceptibility.

Here these materials can be magnetized and demagnetized very easily.

The frequently used soft magnetic materials.

1. Pure iron.
2. Alloys of iron-silicon.
3. Iron –cobalt.
4. Iron – Nickel. (Perm alloy)
5. Mumetal. (Ni+ Cu+ Cr+Fe)
6. Amorphous ferrous alloys. (Alloys of Fe, Si, B)

Note: If the resistance to the movement of the magnetic domain walls is small, the materials are called soft magnetic materials.

Applications

- Pure iron is generally used as the magnetic core for direct current applications.
- Iron – silicon alloys containing up to 5% silicon, will have high electrical resistivity and high magnetic permeability under high flux densities. These materials are widely used as core materials for A.C. current machinery.

Using iron – silicon alloys, eddy currents can be minimized.

- Iron – silicon alloys are used for low frequency and high power applications.

High speed relays, wide Band transformers and Inductors

- Iron-Nickel alloys are used for audio frequency applications. In iron nickel alloys, nickel composition varies from 35 to 100 %.
- Higher the Nickel content, higher will be the permeability at low induction and lower the magnetic saturation of alloy. Maximum permeability is obtained for 79% of Nickel and the remaining is Iron.
- The alloy containing 79% Ni, 15% Fe, 5% Mo and 0.5%Cr. It is known as Supermalloy posses very high permeability.
- Iron – Cobalt alloys have very high magnetic saturation than either Iron or cobalt. Here maximum saturation is obtained for a composition of about 35 to 50% Cobalt.

- Soft magnetic materials are also used in magnetic amplifiers, magnetic switching circuits.

Hard Magnetic Materials

If the resistance to the movement of the magnetic domain walls in large, we have large coercivity. The material is called Hard Magnetic material.

This is because, due to the presence of impurities of non-magnetic materials or the lattice imperfections.

The presence of defects increases mechanical hardness to the material and increased in the electrical resistivity. This also reduced eddy current losses. Usually hard magnetic materials are characterized by

1. High Remnant magnetization.(or) High retentivity.
2. High coercivity.
3. High saturation of the flux density .
4. Low permeability and low susceptibility.
5. High hysteresis loop area.
6. High hysteresis loss.

Most widely used permanent magnetic materials are low alloy steels containing 0.6% - 1% carbon & other materials are:

a) Alnico (alloy of Al, Ni, Co, Cu and Fe)
b) Tungsten steel Alloy
c) Platinum - Cobalt alloy
d) Invar steel

Hard magnetic materials are used to prepare permanent magnets, here they are prepared from the alloys of steel with tungsten and chromium.

The permanent magnets are used in magnetic separators, magnetic detectors, in speakers used in audio systems and microphones.

Hard magnets made with carbon steel finds application in the making of magnets for toys and certain types of measuring meters.

Here the cost is very low.

We can as well produce magnets from powdered materials having a particle size of colloidal dimensions from 0.1-0.01 microns.

These iron based powdered permanent magnet alloys will have high coercivities.

The ceramic permanent magnetic materials such as $BaO6Fe_2O_3$, P_bO_6 Fe_2O_3 are considered to belong to the same class fine grained magnets.

Recently a new permanent magnet which exhibits very high coercive forces as well as high flux density has been developed from powdered manganese bismuthide (MnBi).

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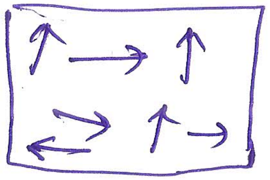
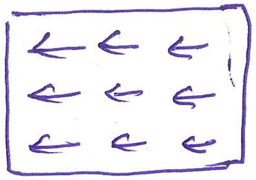
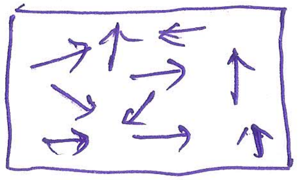
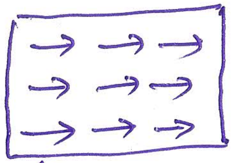
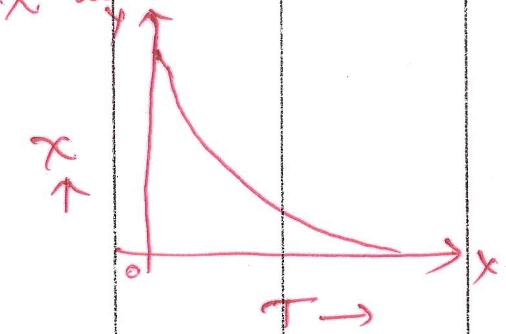
Type of Material	Interaction of dipoles and Alignment of dipoles	Magnetization M	μ	μ_r	Magnitude of Susceptibility χ	Temperature dependence	Examples.
Diamagnetic material It repels magnetic lines of force in the magnetic field. These materials move from stronger part of the field to weaker part of the field.	Random alignment of magnetic moments. These materials donot contain any permanent magnetic moment when $H=0$  Random magnetic moments. $H \rightarrow$  Magnetic moments aligned opposite to H Magnetic moment is induced in the direction opposite to the field.	M is Negative	$\mu < 1$	$\mu_r < 1$	Small and Negative	Independent	organic materials, Light elements
					Intermediate and Negative	Varies with magnetic field and Temperature	Alkali Earth Metals Bi, Zn, Gold etc
					Large & Negative	exists only below a Critical temperature	Super conducting materials.

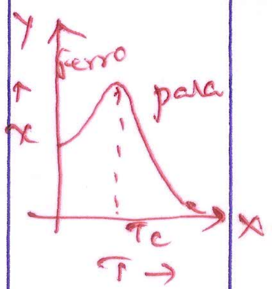
Type of Material	Interaction of dipoles and Alignment of dipoles	Magnetization M	μ	μ_r	Magnitude of Susceptibility	Temperature dependence	Examples.
paramagnetic material.	In the absence of the field H, the dipoles are having random alignment. $H=0$  Atoms with Random magnetic momenta In the field, the magnetic momenta aligned in the direction of field $H \rightarrow$  Magnetic moments aligned in the direction of field.	M is Small and +ve	$\mu > 1$	$\mu_r > 1$	χ is Small & +ve	Independent of Temperature	Alkali Metals, Transition Metals.
					χ is large and positive	Depends on Temperature $\chi = \frac{C}{T}$ Curie Law	Rare Earth Metals Aluminium, platinum, Mn, $CuCl_2$ etc

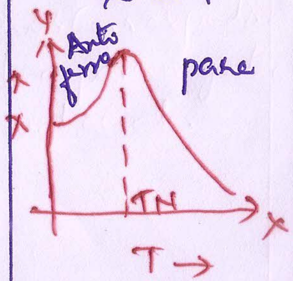
Graphical Representation of χ with T



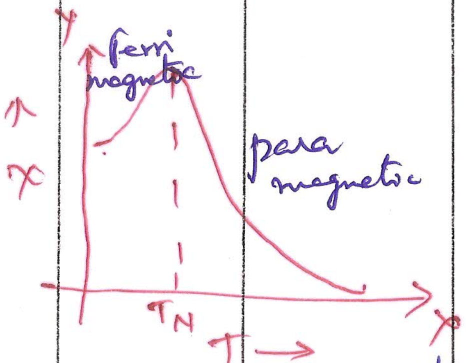
Type of Material	Interaction of dipoles and Alignment of dipoles	Magnetization M	μ	μ_r	Magnitude of Susceptibility	Temperature dependence	Examples
Ferromagnetic material	The dipoles are having parallel alignment. It is shown below $\uparrow\uparrow\uparrow\uparrow\uparrow\uparrow\uparrow\uparrow\uparrow\uparrow$ This is due to spin magnetic moments of electrons. Almost all the magnetic moments are having parallel alignment. When a magnetic field is applied (H), the magnetic moments align in the direction of the field. Even when $H=0$, it exhibits spontaneous magnetization. It also exhibits magnetic domains.	M is +ve and Very large	$\mu >> 1$	$\mu_r >> 1$	Very large and +ve	χ depends on temperature $\chi = \frac{C}{T \pm T_c}$ Curie Weiss Law Cond(i): $\chi = \frac{C}{T+T_c}$ When $T < T_c$ χ is high & +ve This corresponds to a ferro magnetic material. When $T > T_c$ χ is low & +ve This corresponds to a paramagnetic material. Cond(ii) $\chi = \frac{C}{T-T_c}$	Some Transition and Rare earth Metals Fe, Ni, Cobalt, Fe_2O_3, MnO

Graphical variation of χ with Temperature



Type of Material	Interaction of dipoles and Alignment of dipoles	Magnetization M	μ	μ_r	Magnitude of Susceptibility	Temperature Dependence	Examples.
						When $T < T_c$ χ is $-ve$ Corresponds to diamagnetic material. $T > T_c$. χ is $+ve$ Corresponds to either paramagnetism (or) Ferromagnetism.	
Antiferromagnetic material	These materials are having antiparallel magnetic moments ↑↓, ↑↓, ↑↓, ↑↓, ↑↓, this was first observed in MnO.	When field is applied it attains small value of Magnetization M is small & +ve	$\mu > 1$	$\mu_r > 1$	$\chi = \frac{C}{T+T_N}$ obeys Curie-Weiss law	$\chi = \frac{C}{T+T_N}$ Curie-Weiss Law for $T > T_N$. For $T < T_N$, $\chi \propto T$ 	Salts of Transition elements MnF_2, MnO, oxides of Nickel, Chromium.

Type of Material	Interaction of dipoles and Alignment of dipoles	Magnetization M	μ	μ_r	Magnitude of Susceptibility	Temperature dependance	Examples
Ferrimagnetic material.	This material contains antiparallel magnetic momenta with unequal magnitudes. This is shown below $\downarrow\uparrow\downarrow\uparrow\downarrow\uparrow\downarrow\uparrow\downarrow\uparrow$ Antiparallel Spin and having unequal magnitudes.	M is large and +ve	$\mu >> 1$	$\mu_r >> 1$	χ is large and +ve	$\chi = \frac{C}{T \pm T_N}$ when $T > T_N$ χ = Complex when $T < T_N$	XFe_2O_4 Ferrites X may be Cobalt, Nickel, Molibdinum, Zinc, Cd Mn etc.



Variation of χ with T