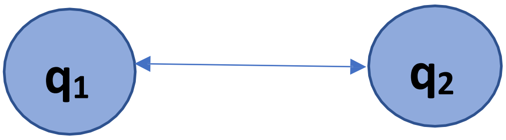
Dielectric Materials

1. Dielectrics are **insulating or non-conducting ceramic materials** with enhanced applications, dielectrics are useful in capacitors, memories, sensors etc.,
2. Dielectrics are insulating materials that **exhibit the property of electrical polarization**
3. **Faraday** was carried out the first numerical measurements on the properties of insulating materials when placed between the two parallel plates, and named it as dielectrics
4. The difference between dielectric material and insulator depends on its application.

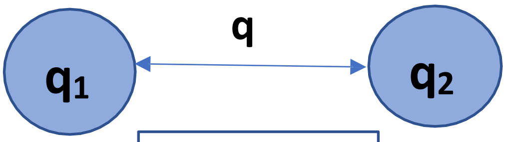
Electric Dipole:

Two opposite charges of equal magnitude separated by a finite distance constitutes an electric dipole.



Dipole moment(μ):

Electric dipole moment is equal to the product of one of the charge of any one of the dipole and the distance of separation between them.



$$\mu = q \times r$$

Units: c-m or Debye, 1 Debye =3.3 × 10^{-30} c-m

Permittivity (ε): Permittivity represents the easily polarisable nature of the dielectric or medium.

ε_0= permittivity of free space=8.854×10^{-12} F/m

Electric field intensity or electric field strength (E)

The force experienced by a unit test charge is known as electric field strength E

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

where ε is the permittivity or dielectric constant of the medium in which electric charge is placed. For vacuum $\varepsilon = \varepsilon_o = 8.854 \times 10^{-12} Fm^{-1}$

Electric flux density or electric displacement vector (D)

The electric flux density or electric displacement vector is the number of flux lines crossing normal to a unit surface area. The electric flux density at a distance from the point charge Q is

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

$$D = \varepsilon E$$

Dielectric constant (ε_r)

The dielectric constant of a material is defined as the ratio of the permittivity of the medium (ε) to the permittivity of free space (ε_o). It can also defined as the ratio of the capacitance with dielectric (C_d) and with air (C_A) between the plates.

$$\varepsilon_r = \frac{\varepsilon}{\varepsilon_o}$$

Polarization

When an electric field is applied to a dielectric material , the positive charges are displaced opposite to the direction of the field and negative charges displaced in the direction of the field. The displacement of these two charges create a local dipole, creation of dipole by applying electric field is called as polarization.

Polarization is defined as induced dipole moment per unit volume.

$$P = \frac{\mu}{Volume}$$

Polarisability

The polarization P is directly proportional to the electric field strength E

$$P \propto E$$

$$P = \alpha E$$

Where α proportionality is constant called as polarisability.

The polarisability is defined as polarization per unit applied electric field. If the material contains **N** number of dipoles per unit volume then

$$P = N\alpha E$$

Types of polarization

Dielectric polarization is the displacement of charge particles with the applied electric field. The displacement of electric charges results in formation of electric dipole moment in atoms, ions or molecules of the material. There are four different types of polarization, they are listed below.

1. Electronic polarization,
2. Ionic polarization,
3. Orientation polarization

Electronic polarization

The displacement of the positively charged nucleus and the negatively charged electrons of an atom in opposite directions, on application of an electric field, result in electronic polarization.

On applying a field, the electron cloud around the nucleus shifts towards the positive end of the field. As the nucleus and electron cloud are separated by a distance, dipole moment is created within each atom. The extent of this shift is proportional to the field strength

Induced dipole moment

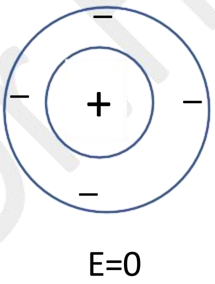
$$\mu_e \propto E$$

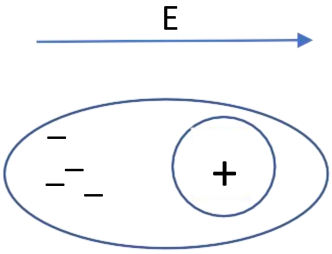
$$\mu_e = \alpha_e E$$

α_e = Electronic Polarisability

The dipole moment per unit volume is called electronic polarization.

- It increases with increase of volume of the atom.
- This kind of polarization is mostly exhibited in monoatomic gases.(e.g. He, Ne, Ar, Kr, Xe etc..)
- It is independent of temperature.
- It occurs only at optical frequencies (10^{15}Hz)
- Vast fast process: 10^{-15}~10^{-16} s



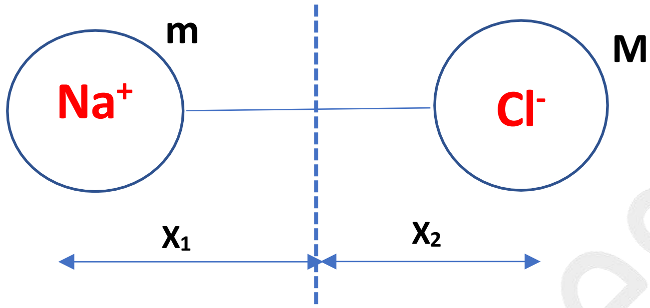


$$\boxed{\mu_e = 4\pi R^3 E}$$

μ_e = Electronic Polarisability
R- Radius of the atom
E- Applied Electrical Field

Ionic Polarization

Ionic polarization occurs in ionic solids such as NaCl, KBr, and LiBr. When an electric field is applied to an ionic solid the positive and negative ions displace to their respective polarities creating an electric dipole this is called as ionic polarization.
In the absence of an electric field there is no displacement of ions. When an electric field is applied an induced dipole moment μ_i is produced.
Let x_1 and x_2 be the displacement of positive and negative ion respectively.



Then the induced dipole moment is given by

$$\mu_i = e(x_1+x_2)$$

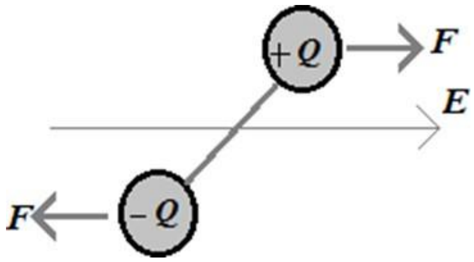
$$\alpha_i = \frac{e^2}{\omega_0^2}\left[\frac{1}{M}+\frac{1}{m}\right]$$ called ionic polarizability

- This polarization occurs at frequency 10^{13} Hz (IR).
- It is a slower process compared to electronic polarization.
- It is independent of temperature.

Orientation Polarization

Orientation polarization occurs only in polar molecules (the molecules which have permanent dipole moment eg H_2O, Phenol, etc.). When an electric field is applied to a polar molecule, the dipoles experience a torque and try to align parallel to the applied field.

Consider a polar molecule subjected to an electric field *E*. The alignment of electric dipole with the electric field is similar to the alignment of magnetic dipole with the applied magnetic field in paramagnetic material.



The expression for polarization can be obtained from the theory of paramagnetism.
The orientation polarization is given as

$$P_o = \frac{N\mu_o^2 E}{3KT} = \alpha_o E$$

$$\mu_o = \frac{\mu_o^2}{3KT}$$ is called as orientation polarizability

- It occurs at a frequency 10^6 Hz to 10^{10}Hz.
- It is slow process compare to ionic polarization.
- It greatly depends on temperature.

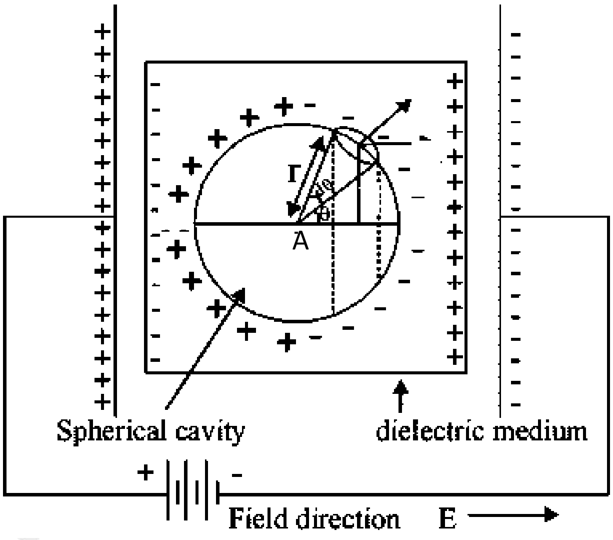
Internal Field

Definition:

The resultant electric field acting on an atom in a dielectric material is called Local field or internal field denoted as “E_i”

Inside the dielectrics, the atoms or molecules not only experience the external field, but also the internal electric fields created due to the creation of the dipoles inside the material

Calculation of the internal field by Lorentz method



In order to calculate the internal field, let us consider a small spherical region inside the dielectric material, an atom is “A” is situated at the center, the resultant field acting on the atom is given by

$$E_{internal} = E_1+E_2+E_3+E_4$$

The electrical field due to the charges on the capacitor plates (E_1)

The electrical field due to the induced charges on the dielectric slab (E_2)

The electrical field due to the induced dipoles present within the spherical region (E_3)

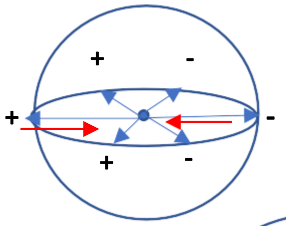
The electrical field due to the induced dipoles present on the surface of the spherical region (E_4)

$$E = E_1 + E_2 \text{ (Macroscopic field)}$$

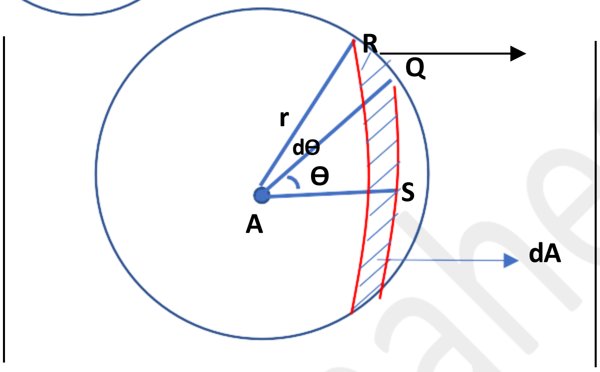
$$\text{Therefore, } E_{internal} = E + E_4$$

Calculation of E_3:

By Symmetry = E_3 =0



Calculation of E_4 :



$$dA = 2\pi(\underbrace{SQ}_{\text{circumference}})\,(\underbrace{RQ}_{\text{width}}) \qquad \text{circumference} \times \text{width}$$

$$= 2\pi(r \sin\theta)(r\, d\theta)$$

$$= 2\pi r^2 \sin\theta\, d\theta$$

In triangle ASQ

$$\sin\theta = \frac{SQ}{AQ} = \frac{SQ}{r}$$

$$SQ = r \sin\theta$$

In triangle AQR

$$\sin d\theta = \frac{RQ}{AR} = \frac{RQ}{r}$$

$$RQ = r \sin d\theta$$

Since dϴ is very small

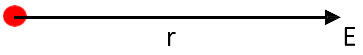
$$\sin d\theta \approx d\theta$$

Therefore $RQ = r\, d\theta$

$$dQ = (P\cos\theta)(dA)$$

$$= P\cos\theta \;\; 2\pi r^2 \sin\theta\, d\theta$$

If “dQ” is the amount of charges existing on the small surface “dA”. Then



$$\boxed{E = \frac{q}{4\pi\epsilon r^2}}$$

The electric field created due to the charges “ dQ” is

$$dE_4 = \frac{dQ}{4\pi\epsilon_0 r^2}\cos\theta = \frac{P 2\pi r^2 \cos\theta^2 \sin\theta\, d\theta}{4\pi\epsilon_0 r^2} = \frac{P\cos\theta^2 \sin\theta\, d\theta}{2\epsilon_0}$$

therefore the charge due to the charges on the entire surface of the sphere is

$$E_4 = \int_0^{\pi} \frac{P\cos\theta^2 \sin\theta \, d\theta}{2\epsilon_0} = \frac{P}{2\epsilon_0}\int_0^{\pi} \underbrace{\cos\theta^2}\, \underbrace{\sin\theta \, d\theta}$$

X = cosΘ

dx = - sinΘ dΘ

$$= -\frac{P}{2\epsilon_0}\int_0^{\pi} x^2 \, dx$$

$$= -\frac{P}{2\epsilon_0}\left[\frac{x^3}{3}\right] = -\frac{P}{2\epsilon_0}\left[\frac{\cos\theta^3}{3}\right]_{\theta=0}^{\theta=\pi} = -\frac{P}{2\epsilon_0}\left[\underbrace{\cos\pi^3} - \underbrace{\cos 0^3}\right]$$

$$= -\frac{P}{2\times 3\times \epsilon_0}[-1 - 1]$$

$$= -\frac{P}{\cancel{2}\times 3\epsilon_0}\cancel{(-2)}$$

$$E_4 = \frac{P}{3\epsilon_0}$$

There fore

$$E_{internal} = E + \frac{P}{3\epsilon_0}$$

Clausius - Mosotti equation

Clausius - Mosotti explains the relation between the microscopic quantity (polarizability α) and the macroscopic quantity (ε).

Let us consider elemental solid dielectric which exhibits only electronic polarization.

$$P = N\alpha_e E_i$$

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

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

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

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

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

We known that the polarizati on vector

$$P = \varepsilon_0 E(\varepsilon_r - 1)\ldots\ldots\ldots\ldots(2)$$

From equations (1) and (2)

$$\varepsilon_0 E(\varepsilon_r - 1) = \frac{N\alpha E}{1 - \frac{N\alpha}{3\epsilon_0}}$$

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

$$1 = \frac{N\alpha \cancel{E}}{\epsilon_0 \cancel{E}(\epsilon_r - 1)} + \frac{N\alpha}{3\epsilon_0}$$

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

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

$$\boxed{\frac{N\alpha}{3\epsilon_0} = \frac{\epsilon_r - 1}{\epsilon_r + 2}}$$

The above equation represents Clausius – Mosotti equation

Frequency dependence of polarizability:

On application of an electric field, polarization process occurs as a function of time. The polarization P(t) as a function of time. The polarization P(t) as a function of time t is given by

$P(t) = P[\ 1 - \exp(-t/\tau_r)]$

Where P – max. Polarization attained on prolonged application of static field.

τ_r - relaxation time for particular polarization process

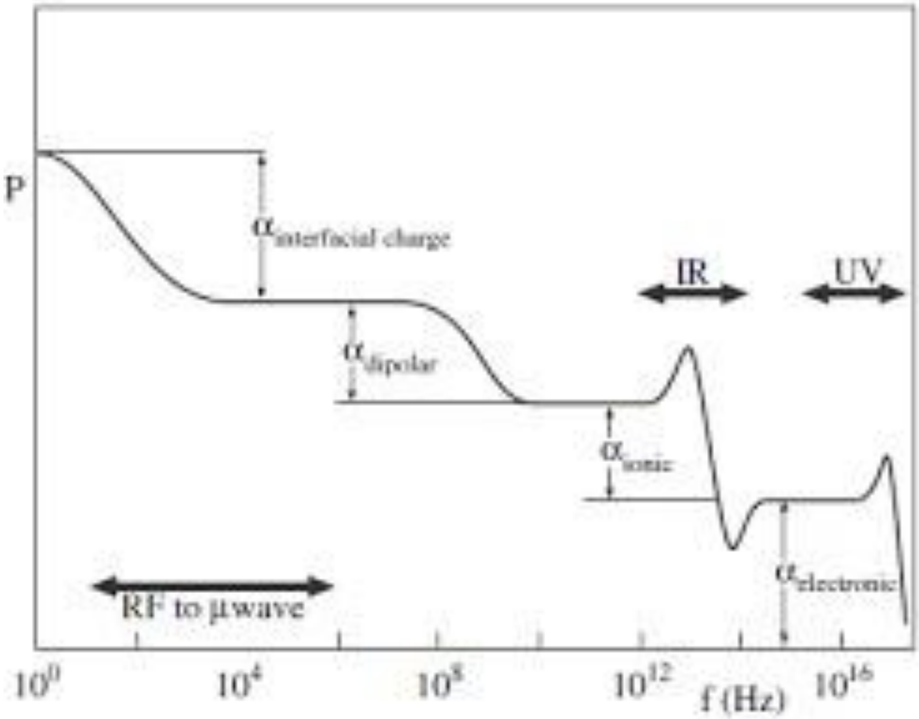
The relaxation time τ_r is a measure of the time scale of polarization process. It is the time

taken for a polarization process to reach 0.63 of the max. value.

Electronic polarization is extremely rapid. Even when the frequency of the applied voltage is very high in the optical range ($\approx 10^{15}$ Hz), electronic polarization occurs during every cycle of the applied voltage.

Ionic polarization is due to displacement of ions over a small distance due to the applied field. Since ions are heavier than electron cloud, the time taken for displacement is larger. The frequency with which ions are displaced is of the same order as the lattice vibration frequency ($\approx 10^{13}$Hz). Hence, at optical frequencies, there is no ionic polarization. If the frequency of the applied voltage is less than 10^{13} Hz, the ions respond.

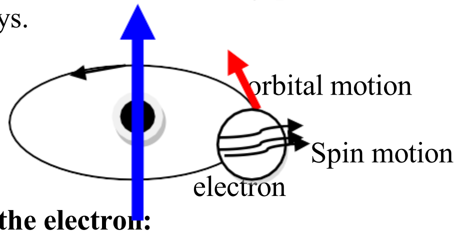
Orientation polarization is even slower than ionic polarization. The relaxation time for orientation polarization in a liquid is less than that in a solid. Orientation polarization occurs, when the frequency of applied voltage is in audio range (10^{10} Hz).


P
$\alpha_{\text{interfacial charge}}$
IR
UV
α_{dipolar}
α_{ionic}
$\alpha_{\text{electronic}}$
RF to µwave
10^0
10^4
10^8
10^{12}
f (Hz)
10^{16}

MAGNETIC MATERIALS

Origin of magnetic moment in magnetic materials:

Magnetic materials are the materials which are having **permanent magnetic moment**. The magnetic moment arises in two different ways.



1. **Due to orbital motion of the electron:**

When the electrons are revolving round the nucleus in the circular orbit, it is consider to be equivalent to a closed current loop capable of producing a magnetic field with a north pole and south pole known as magnetic dipole. The orbital magnetic moment is known as

$$\boxed{M_L = \frac{e\hbar}{2m} L}$$ L-orbital angular momentum

2. **Due to spin motion of the electron:**

In addition to the orbital motion of the electrons are capable of spinning on their own axix. This in tern equivalent to a current loop and produce a magnetic dipole. The magnetic moment is given by

$$\boxed{M_S = g \frac{e\hbar}{2m} S}$$

S-Spin angular momentum

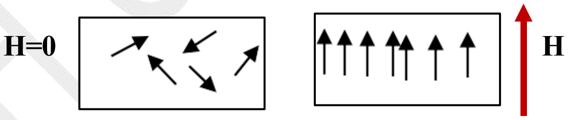
g-lande-g-factor

$\frac{e\hbar}{2m} = 9.27 \times 10^{-24}$ Amp-m^2

In general in atoms two electrons form pairs with opposite spins, thus if atom is having even number of electrons the spin magnetic moments will cancel with each other and the resultant magnetic moment will become zero. Therefore to get a resultant magnetic moment the atom should posses unpaired electron or odd number of electrons.

Magnetization:

In the magnetic materials like iron, nickel, cobalt, though the atoms are having unpaired electrons and magnetic dipoles, the dipoles will be orienting randomly and the resultant dipole moment will be zero. In order to align the dipoles along a particular direction the material should be subjected to an external magnetic field. Then the dipoles will be started orienting along the field direction. This process is Known as magnetization.



Permeability (μ):

The amount of magnetic lines of forces penetrating through a material

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

Relative permeability (μ_r):

It is the ratio between the permeability of material to the permeability of free space

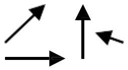
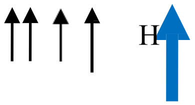
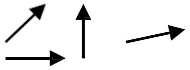
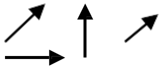
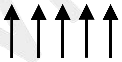
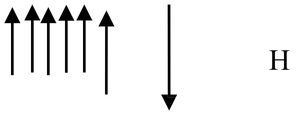
$$\boxed{\mu_r = \frac{\mu}{\mu_0}}$$

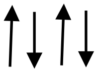
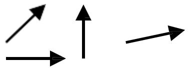
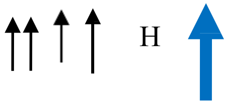
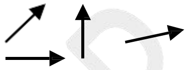
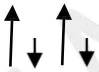
Magnetic susceptibility (χ):

It is the ration of the magnetization produced in the sample to the external field strength

$$\chi = \frac{M}{H}$$

CLASSIFICATION OF MAGNETIC MATERIALS

Magnetic materials	**Paramagnetic**	**Ferromagnetic**	**Diamagnetic**
Magnetic moment	The atoms in the materials posses **unpaired** electrons. Therefore a **resultant spin magnetic moment** **Since orbital magnetic moment is negligible**	The atoms in the materials posses **unpaired** electrons. Therefore, a **resultant spin magnetic moment**	The atoms in the materials posses **paired** electrons. Therefore a **resultant spin magnetic moment is zero** But in the presence of the external magnetic field orbital magnetic moment increases.
Magnetization	In the absence of the external magnetic field, the dipoles will be orienting randomly  **No field** After application of the external field they will be aligned along the field direction  If the external field is removed again the dipoles orient randomly  **H=0 M=0**	In the absence of the external magnetic field, the dipoles will be orienting randomly  **H=0** After application of the external field they will be aligned along the field direction.  Though the field is removed the alignment will be persisting  No field **H=0**	In the absence of the external magnetic field, the dipoles will be orienting randomly After application of the external field they will be aligned in the direction opposite to that of the external field direction. 
Relative Permeability	**$\mu_r > 1$** since it allows the magnetic lines of forces to pass through it	$\mu_r >> 1$ since it allows more magnetic lines of forces to pass through it	$\mu_r < 1$ since the alignment of the dipoles are in the opposite direction
Susceptibility	It is **positive** but **small**, it depends upon the temperature $\frac{C}{T} = \chi$, C= Curie const	It is positive but large ,it depends upon the temperature $\frac{C}{T-T_c} = \chi$, T_c= Curie Temp.	$\chi = -1$ independent of temperature
Example	**Al ,Pt** ,Mn, $CuCl_2$, etc.,	Fe,Ni,Co,Fe_2O_3,MnO, etc.,	Bi,Zn,H_2O,Au……

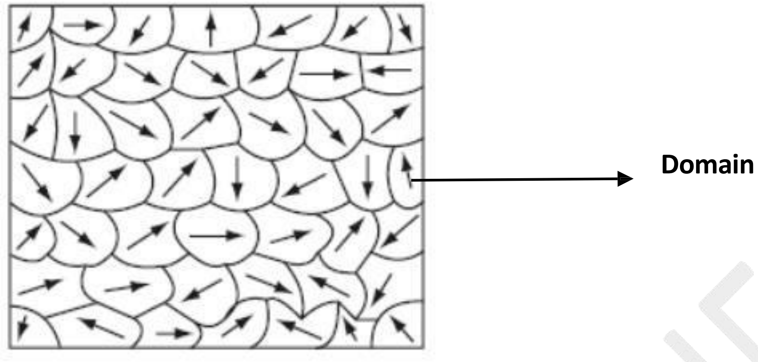
Magnetic materials	**Antiferro magnetic**	**Ferri magnetic**
Magnetic moment	The atoms in the materials posses **unpaired** electrons. Therefore a **resultant spin magnetic moment** **But the spin magnetic moments will be oriented anti parallely**	The atoms in the materials posses **unpaired** electrons. Therefore, a **resultant spin magnetic moment** **But the spin magnetic moments will be oriented anti parallelly , the magnetic moments have unequal magnitudes**
Magnetization	In the absence of the external magnetic field, the dipoles will be orienting antiparallel  **No field** As the temperature increases above Neel Temperature, the antiparallel alignment will be disturbed and they will become random  After applying the field, they will be aligned along the field direction  If the external field is removed again the dipoles orient randomly  **H=0 M=0**	In the absence of the external magnetic field, the dipoles will be orienting antiparallel  Since the magnetic moments have unequal magnitudes , there will be resultant spin magnetic moment.
Relative Permeability	$\mu_r > 1$ since it allows the magnetic lines of forces to pass through it	$\mu_r >> 1$ since it allows more magnetic lines of forces to pass through it

Susceptibility	It is **positive** but **small**, it depends upon the temperature $\chi = C/T \pm T_N$ T_N= Nell temprature	It is positive but large ,it depends upon the temperature $\chi = C/T \pm T_C$ T_c= Curie Temp.
Example	MnO, Mn_2O_3 and MnO_2	$MnFe_2O_4$, $BaFe_{12}O_{19}$, $Y_3Fe_5O_{12}$

Domain theory of ferromagnetism

In 1907, Weiss proposed domain theory to explain ferromagnetism.

According to this theory, a single crystal of ferromagnetic solid compresses a large number of small regions, and each region is spontaneously magnetized to saturation extent called a domain as shown in Fig..

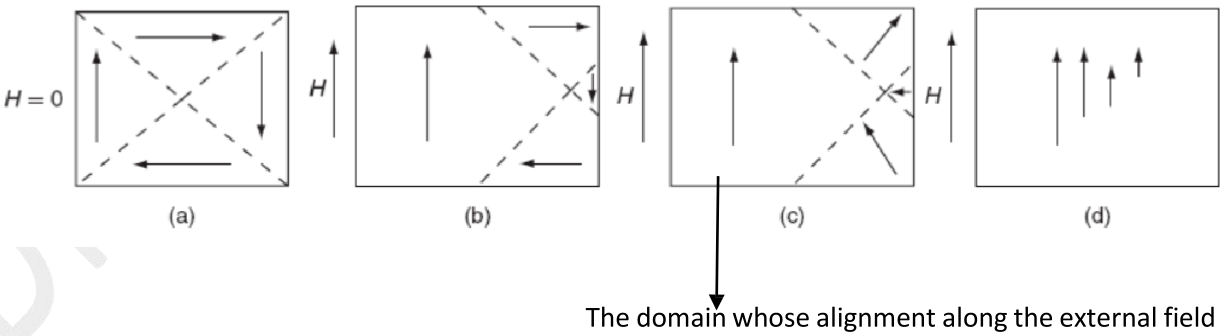


The domain size may vary from 10−6 m to the entire volume of the crystal. The spin magnetic moments of all the atoms in a domain are oriented in a particular direction. The magnetization directions of different domains of the specimen are random so that the resultant magnetization of the material is zero in the absence of an external magnetic field.

A ferromagnetic material magnetizes when an external magnetic field is applied. The individual domains contribute to the total magnetization, *M*, of the specimen.

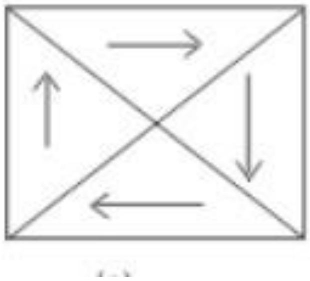
According to Becker two independent processes by which the magnetization of the ferromagnetic material takes place. They are:

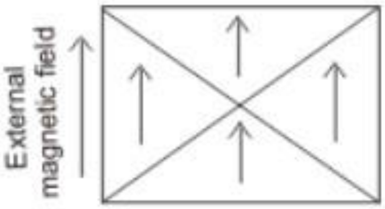
1.The domains that are parallel or nearly parallel to the direction of applied magnetic field will grow in size in comparison to other domains as shown below



The domain whose alignment along the external field direction increases in size

2, The magnetic moments of the domains can rotate in the direction of applied field. A symbolic representation of the response of the domains to the magnetic field is shown in Fig. . The highest magnetization of the material called saturated magnetization.





Effect of temperature

The Curie–Weiss law for magnetic susceptibility for ferromagnetic substance is

$$\chi = \frac{C}{T - T_C}$$

where C = Curie constant, T_c = Curie temperature and T is the temperature of the ferromagnetic material. Here, 'T_c' represents the tendency towards alignment of the dipole moments and on the other hand T represents the tendency of random orientation of dipoles due to thermal agitation.

For $T > T_c$, the thermal agitation is predominant; so, the substance is paramagnetic. For all temperatures, $T < T_c$, the material behaves as ferromagnetic.

Hard and soft magnetic materials:

Hard Magnetic Materials

Usually hard magnetic materials are characterized by

1. High Remnant magnetization
2. High coercivity
3. High saturation on the flux density
4. Low permeability and low susceptibility
5. High hysteresis loop
6. High hysteresis loss

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

a) Aloirico (alloy of Al, Ni, Co, Cn and Fo)
b) Tungsten steel Alloy
c) Platinum - Cobalt alloy
d) Invar steel

Hard magnetic materials are used to preparer **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.

Soft magnetic materials

The soft magnetic materials usually will have

i. Low permanent magnetization (Low retentivity)
ii. Low coercivity
iii. Low hysteresis losses Small hysteresis loop Area
iv. High magnetic permeability
v. 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 (Premallary)
5. Mumetal (Ni+ Cu+ Cr+Fe)

6. Amorphous ferrous alloys (Alloys of Fe, Si, B) **Applications**

Pure iron is generally used as the magnetic core for direct current applications.

Iron – silicon alloys containing upto 5% silicon, will have high electrical resistivity and high magnetic permeability under high flux densities. There materials are widely used as core materials for A.C. current machinery. Using iron – silicon alloys, minimization of eddy currents can be minimized. Iron – silicon alloys are used for low frequency and high power applications.

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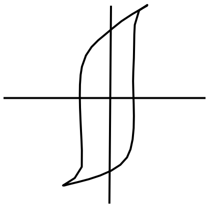
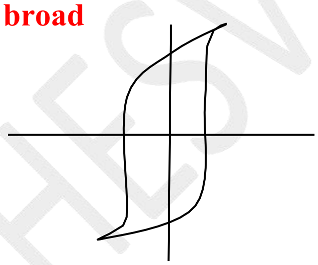
Difference between the soft and hard magnetic materials :

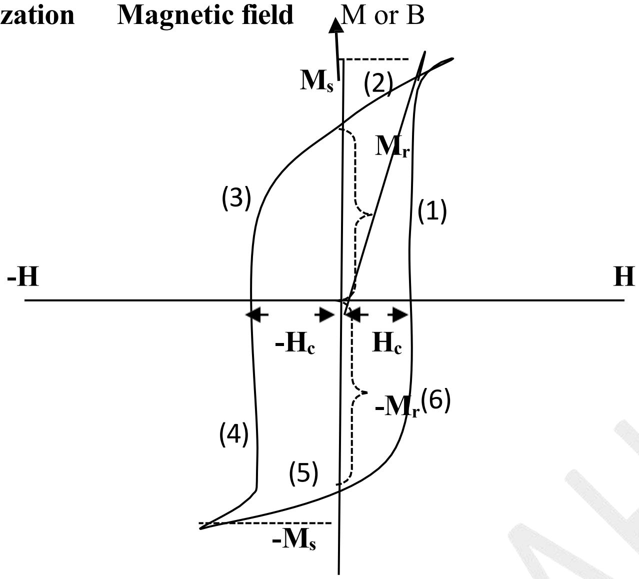
	SOFT MAGNETIC MATERIALS		**HARD** MAGNETIC MATERIALS
.	The material which are **easily magnetized and demagnetized** are called soft magnetic materials	.	The materials which are **very difficult to magnetized and demagnetized** are called hard magnetic materials.
.	These are prepared by heating with **pure material**	.	These are prepared by **heating with impurity**
.	The nature of hysteresis loop is **very steep** 	.	The nature of hysteresis **loop is very broad** 
.	The hysteresis area is very small hence the hysteresis loss is also small	.	The hysteresis area is very large hence the hysteresis loss is also large.
.	These materials have large values of **susceptibility and permeability**	.	These materials have **low value of susceptibility and permeability**
.	The **coercivity** and **retentivity** values are small	.	The **coercivity** and **retentivity** values are large
.	These materials are free from irregularities like strain or impurities	.	These materials have large amount of impurities and lattice defects.
.	**Example : Fe-Ni-Al alloys** **Cu-Ni-Fe alloys**	.	**Example: Ferrites and Garnets.**

↓

Hysteresis loop or B-H curve or M-H curve:

(“Lagging of effect behind the cause”)

Magnetization **Magnetic field**



The importance of the ferromagnetic materials is the relation between the magnetization and the applied magnetic field known as hysteresis. It is explained in the following steps.

Step-1:
When the applied external field intensity **H=0,** the dipoles will be orienting randomly, and hence magnetization **M=0**, as **“H”** increases **“M”** also be increasing and attains maximum value called **saturation magnetization “M_s”.**

Step-2:
If the applied external field reduces , magnetization also decreases, as **H =0 , “M”≠ 0,** some magnetization remains within the material , therefore the magnetization which is persisting even after the removal of the magnetic field is called remenant or **residual magnetization “M_r”.**

Step-3:
In order to make the residual magnetization equal to zero, the magnetic field should be applied in the opposite direction, the reverse field which is applied in order to make **M_r=0** is called **coercive field “H_c”**.

Step-4:
If the fielf is increases in the same reverse direction, magnetization also increases and attains maximum value called saturation magnetization **“-M_s”.**

Step-5:
If the applied external field reduces , magnetization also decreases, as **H =0 , “M”≠ 0,** some magnetization remains within the material , therefore the magnetization which is persisting even after the removal of the magnetic field is called remenant or **residual magnetization “-M_r”.**

Step-6:
In order to make the residual magnetization equal to zero, the magnetic field should be applied in the opposite direction, the reverse field which is applied in order to make **M_r=0** is called **coercive field “-H_c”.**

Step-7:
If the field is increases in the same reverse direction, magnetization also increases and attains maximum value called saturation magnetization **“M_s”.**