Dielectric and Magnetic Properties of Materials

Index

Dielectric Properties:

- Dielectric material
- Dielectric constant
- Polarization of dielectric materials,
- Types of Polarization (Polarizability).
- Equation of internal fields in liquid and solid (One Dimensional)
- Claussius Mussoti-Equation,
- Frequency dependence of dielectric constant,
- Dielectric Losses,

Index

Magnetic Properties:

- Magnetization,
- Dia, para and ferro magnetism,
- Langevin's theory for diamagnetic material,
- Phenomena of hysteresis and its applications.

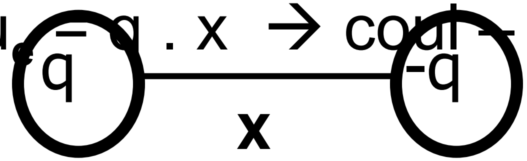
Dielectric material

Dielectrics are the materials having electric dipole moment permantly.

Dipole: A dipole is an entity in which equal positive and negative charges are separated by a small distance..

DIPOLE moment (μ_{ele}): The product of magnitude of either of the charges and separation distance b/w them is called Dipole moment.

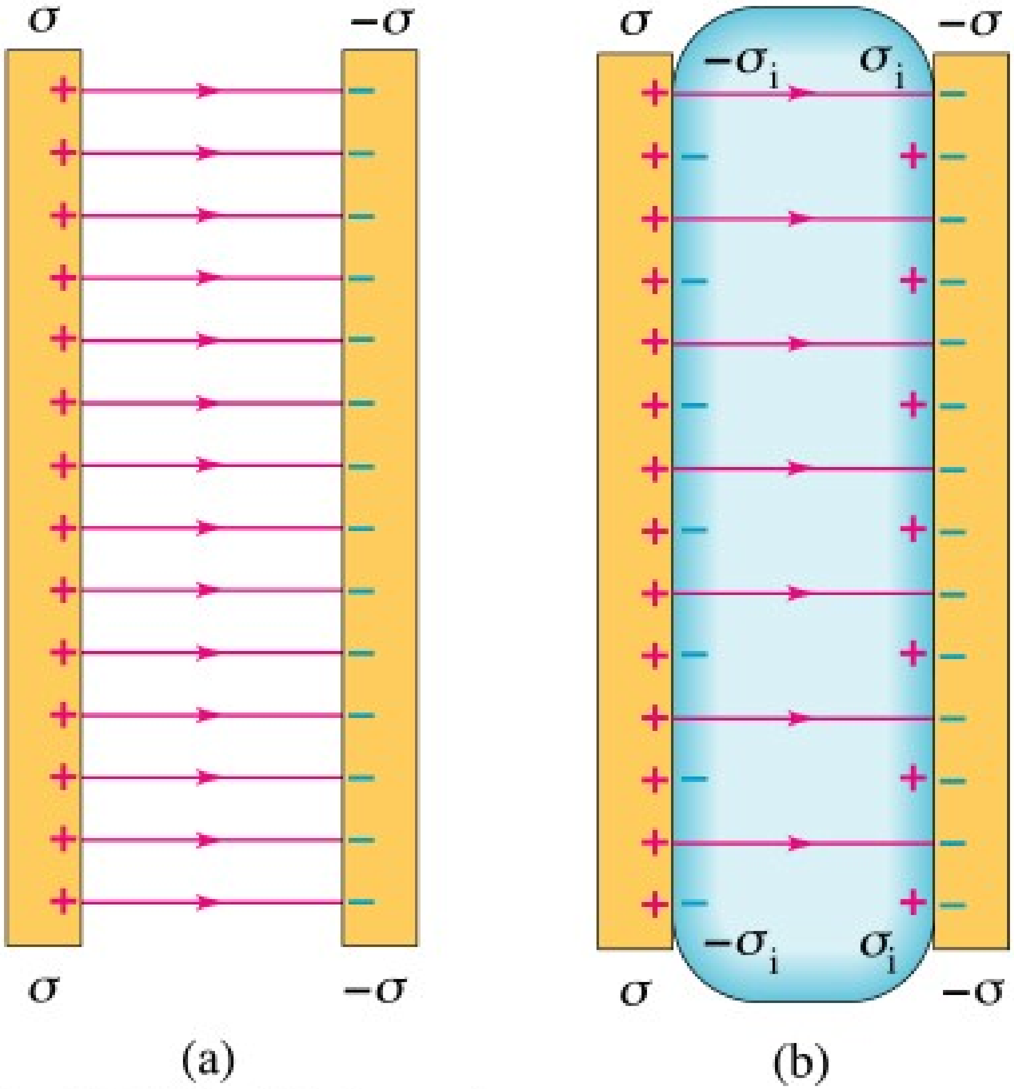
$$\mu_e = q \cdot x \rightarrow coul - m$$



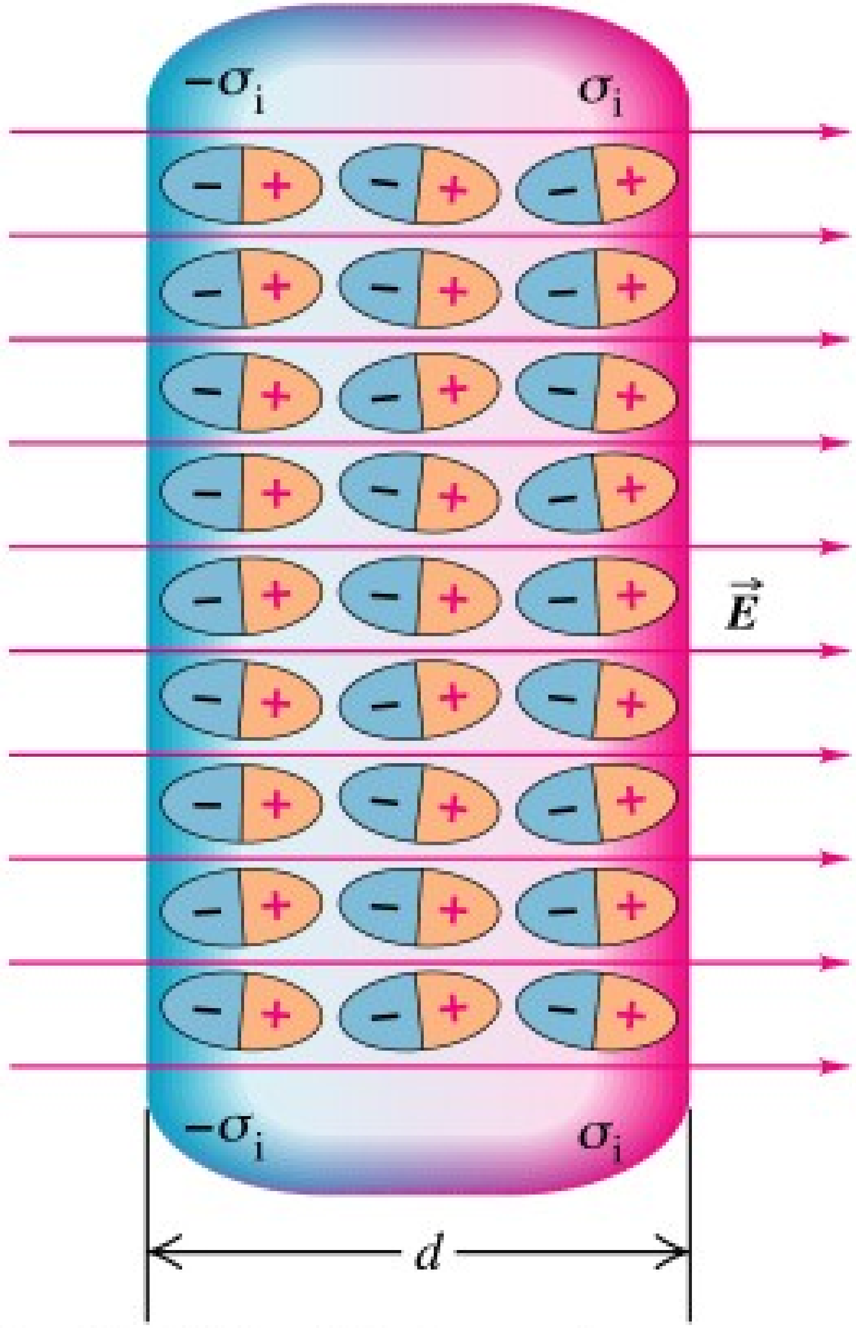
All dielectrics are electrical insulators and they are mainly used to store electrical energy.

Ex: Mica, glass, plastic, water & polar molecules…

The charges induced on the surface of the dielectric (insulator) reduce the electric field.



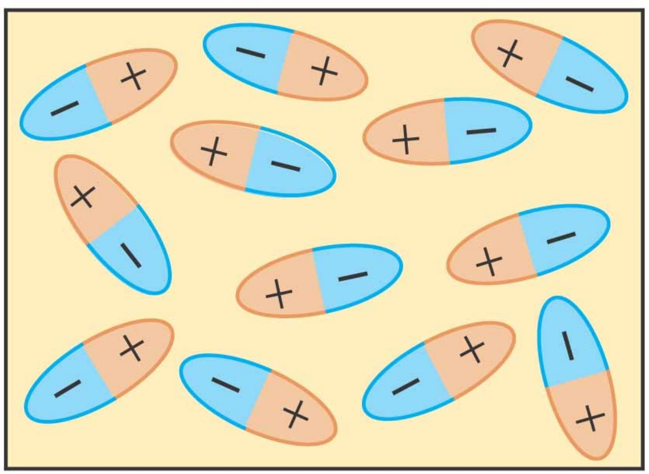
"Polarization" of a dielectric in an electric field E gives rise to thin layers of bound charges on the dielectric's surfaces, creating surface charge densities $+\sigma_i$ and $-\sigma_i$.



Atomic View of Dielectrics: The molecules of the dielectric are modeled as dipoles

No External E-Field

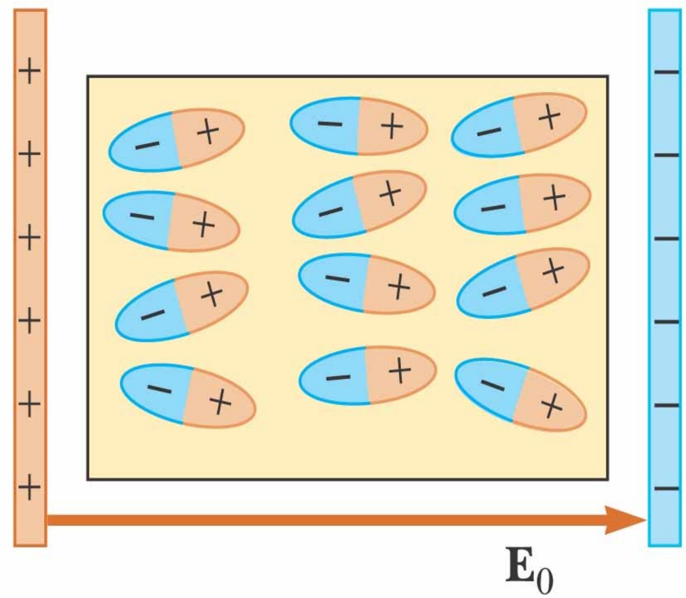
Random orientation of molecules



(a)

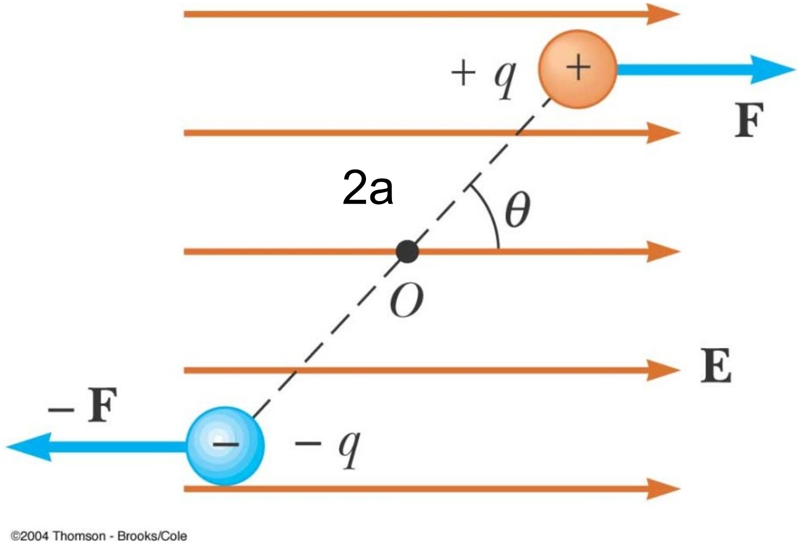
External E-Field

Partial Alignment of Molecules



(b)

Force Acting by a Uniform External Field on the Dipole



- **Note: E** is not the field produced by the dipole
- The force acting on each charge is
  F = Eq
- The net force on the dipole is **zero**
- The forces produce a net torque on the dipole

$$\tau = 2Fa \sin \theta = pE \sin \theta$$

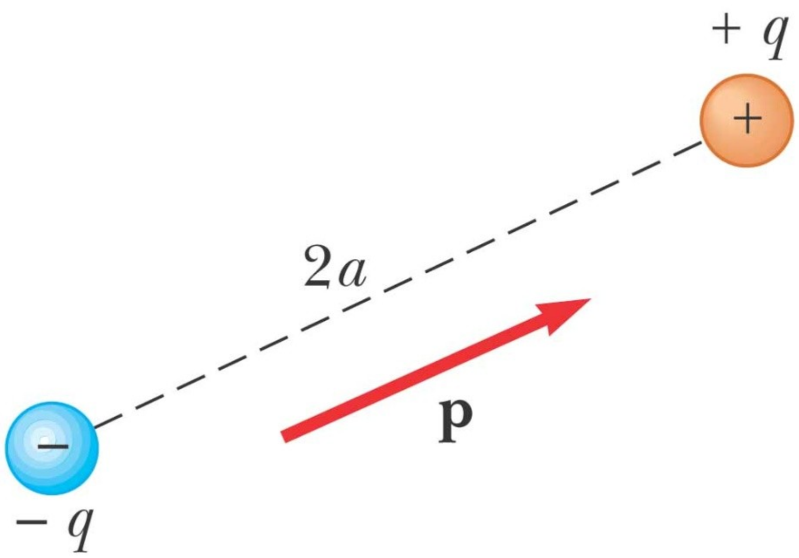
$$p = 2aq$$

$$\tau = p \times E$$

Electric Dipole Moment, (p)

- The **electric dipole moment** (**p**) is a vector directed along the line joining the charges from –*q* to +*q* ,
- A dipole has two equal but opposite sign charges
- Assume the distance between the charges is 2*a*

$$p=2aq$$



Dielectric constant

Dielectric Constant

Dielectric Constant is the ratio between the permittivity of the medium to the permittivity of free space.

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

The characteristics of a dielectric material are determined by the dielectric constant and it has no units.

Electric Polarization

The process of producing electric dipoles by an electric field is called polarization in dielectrics.

Polarizability:

The induced dipole moment per unit electric field is called Polarizability.

The induced dipole moment is proportional to the intensity of the electric field.

$$\mu \propto E$$

$$\mu = \alpha E$$

$$\alpha \rightarrow \text{polarizability constant}$$

Is a Polarizability constant

Electric susceptibility:

The polarization vector P is proportional to the total electric flux density and direction of electric field.

Therefore the polarization vector can be written

$$\overline{P} = \varepsilon_0 \chi_e E$$

$$\chi_e = \frac{\overline{P}}{\varepsilon_0 E}$$

$$= \frac{\varepsilon_0(\varepsilon_r - 1)E}{\varepsilon_0 E}$$

$$\chi_e = \varepsilon_r - 1$$

Various polarization processes:

When the specimen is placed inside a d.c. electric field, polarization is due to four types of processes….

1. Electronic polarization
2. Ionic polarization
3. Orientation polarization
4. Space charge polarization

Electronic Polarization

When an EF is applied to an atom, +vely charged nucleus displaces in the direction of field and ẽ could in opposite direction. This kind of displacement will produce an electric dipole with in the atom.

i.e, dipole moment is proportional to the magnitude of field strength and is given by

$$\mu_e \propto E$$

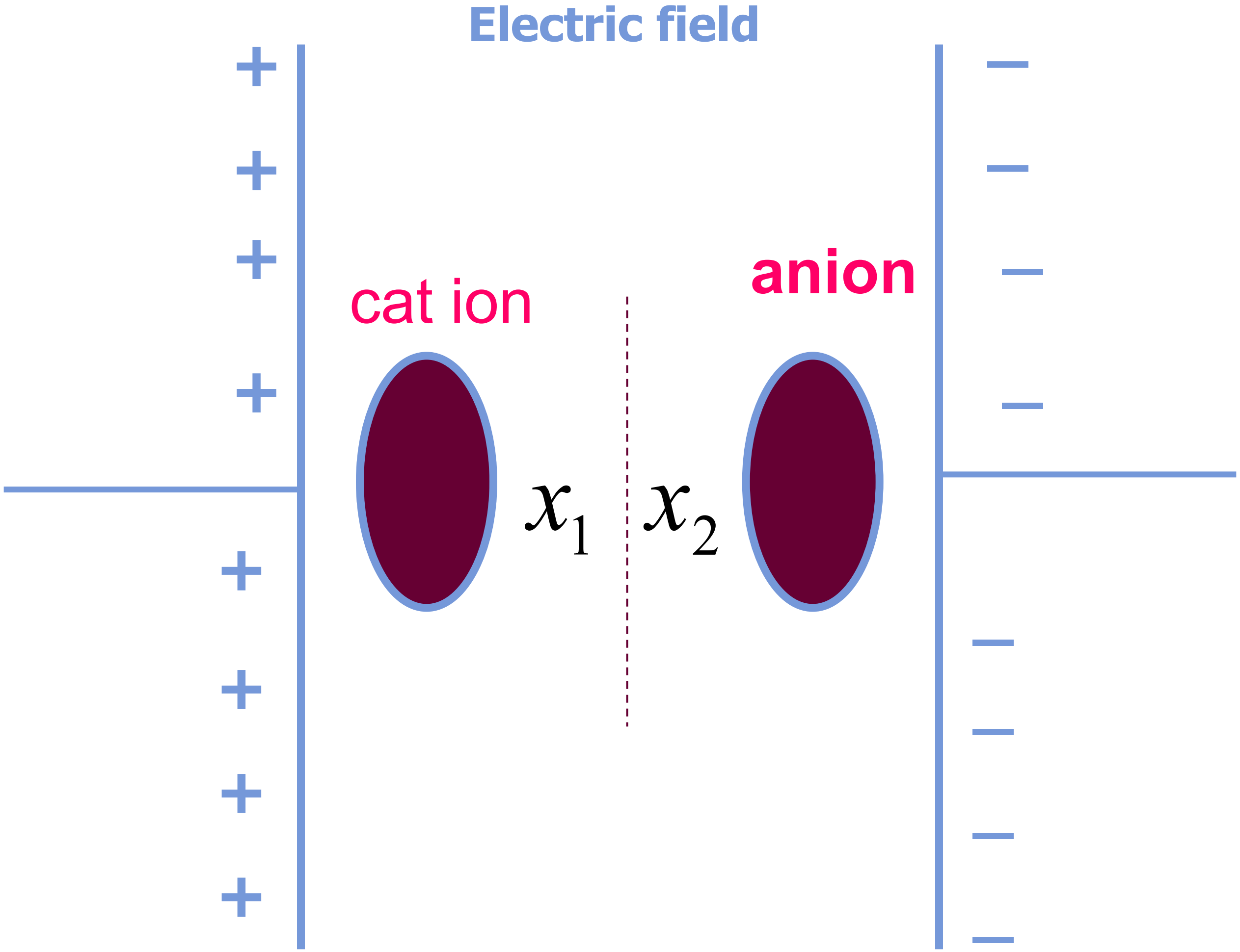
or

$$\mu_e = \alpha_{\mathrm{e}} E$$

where 'α_e' is called electronic Polarizability constant

Ionic polarization

- The ionic polarization occurs, when atoms form molecules and it is mainly due to a relative displacement of the atomic components of the molecule in the presence of an electric field.
- When a EF is applied to the molecule, the positive ions displaced by X_1 to the negative side electric field and negative ions displaced by X_2 to the positive side of field.
- The resultant dipole moment $\mu = q (X_1 + X_2)$..


Electric field
cat ion
anion
x_1
x_2

Orientational Polarization

It is also called dipolar or molecular polarization. The molecules such as H_2 , N_2,O_2,Cl_2 ,CH_4,CCl_4 etc., does not carry any dipole because centre of positive charge and centre of negative charge coincides. On the other hand molecules like CH_3Cl, H_2O,HCl, ethyl acetate (polar molecules) carries dipoles even in the absence of electric field.

How ever the net dipole moment is negligibly small since all the molecular dipoles are oriented randomly when there is no EF. In the presence of the electric field these all dipoles orient them selves in the direction of field as a result the net dipole moment becomes enormous.

Equation of internal fields in liquid and solid

(One Dimensional)

$$E_i = E + \frac{1.2\mu_i}{\pi a^3 \varepsilon_0}$$

Classius – Mosotti relation:

Consider a dielectric material having cubic structure , and assume ionic Polarizability & Orientational polarizability are zero..

$$\alpha_i = \alpha_0 = 0$$

$$polarization..P = N\mu$$

$$P = N\alpha_e E_i ......where., \mu = \alpha_e E_i$$

$$where., E_i = E + \frac{P}{3\varepsilon_0}$$

$$P = N\alpha_e E_i$$

$$P = N\alpha_e\left(E + \frac{P}{3\varepsilon_0}\right)$$

$$P = N\alpha_e E + N\alpha_e \frac{P}{3\varepsilon_0}$$

$$or, P - N\alpha_e \frac{P}{3\varepsilon_0} = N\alpha_e E$$

$$or, P\left(1 - \frac{N\alpha_e}{3\varepsilon_0}\right) = N\alpha_e E$$

$$or, P = \frac{N\alpha_e E}{\left(1 - \frac{N\alpha_e}{3\varepsilon_0}\right)} \ldots\ldots\ldots\ldots\ldots\ldots\ldots (1)$$

We known that the polarization vector

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

from eq$^n s$(1) & (2)

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

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

$$1 = \frac{N\alpha_e}{3\varepsilon_0} + \frac{N\alpha_e E}{\varepsilon_0 E(\varepsilon_r - 1)}$$

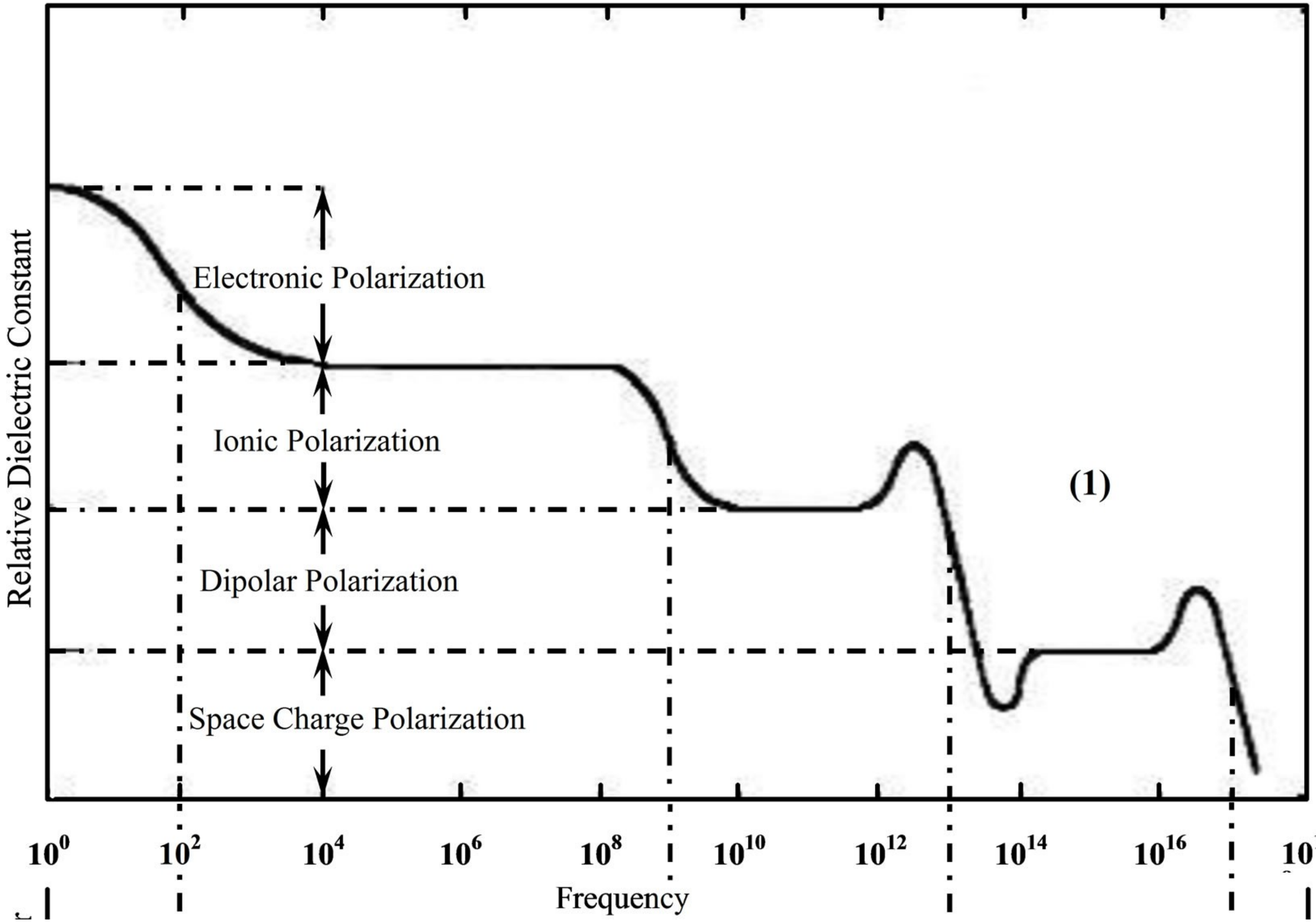
$$1 = \frac{N\alpha_e}{3\varepsilon_0} + \frac{N\alpha_e}{\varepsilon_0 (\varepsilon_r - 1)}$$

$$1 = \frac{N\alpha_e}{3\varepsilon_0}(1 + \frac{3}{\varepsilon_r - 1})$$

$$\frac{N\alpha_e}{3\varepsilon_0} = \frac{1}{(1 + \frac{3}{\varepsilon_r - 1})}$$

$$\frac{N\alpha_e}{3\varepsilon_0} = \frac{\varepsilon_r - 1}{\varepsilon_r + 2} ...... \rightarrow \text{Classius Mosottirelation}$$

Frequency dependence of dielectric constant



Dielectric Loss

- For a lossy (imperfect) dielectric the dielectric constant can be represented by a complex relative dielectric constant:

$$\varepsilon = \varepsilon' - i\varepsilon''$$

- The imaginary part of this complex dielectric constant, ε at a frequency, ω is equivalent to a frequency-dependent conductivity, σ(ω), given by:

$$\sigma(\omega) = \omega\varepsilon_0\varepsilon''$$

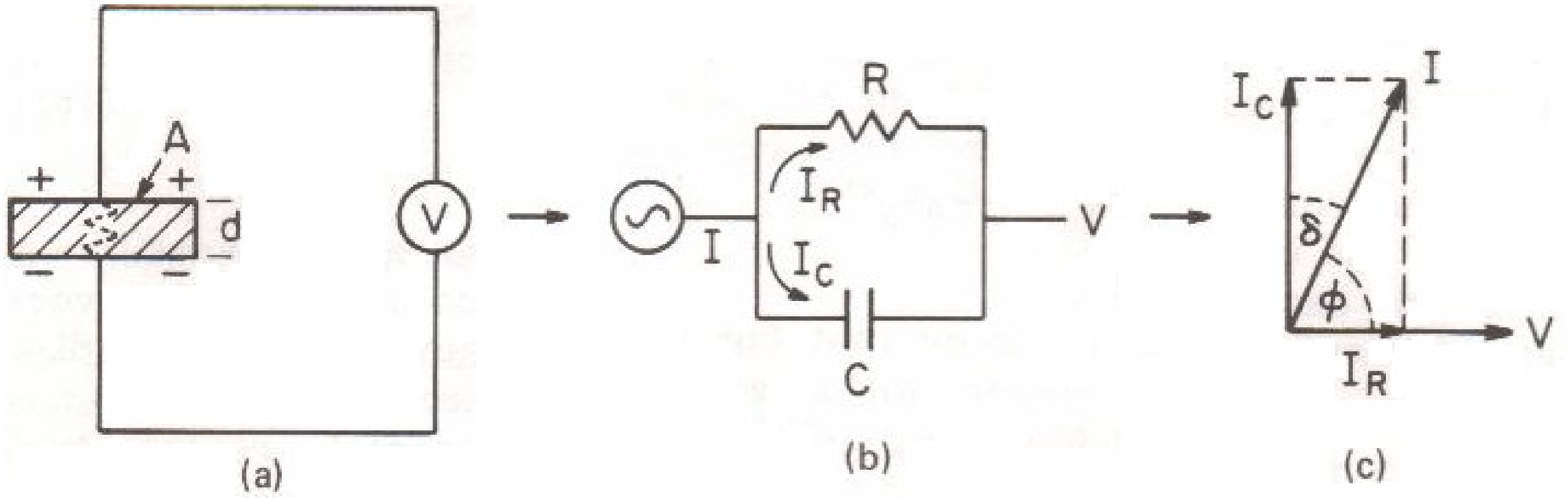
Dielectric Loss

- ε'' is also known as the loss factor.
- The small difference in phase from ideal behaviour is defined by an angle δ, defined through the equation

$$\frac{\varepsilon''}{\varepsilon'} = \tan\delta$$

- tan δ is known as the loss tangent or dissipation factor.
- A quality factor, Q, for the dielectric is given by the reciprocal of tan δ.

Dielectric Loss



Equivalent circuit diagrams: (a) capacitive cell, (b) charging and loss current, (c) loss tangent for a typical dielectric

DIELECTRIC LOSS

- From $Q = \varepsilon \, \varepsilon_o A V/d = CV$
- If V being sinusoidal, total charge Q may be written as

$$Q = C V_o e^{i\omega t}$$

- Current flow on discharge of the capacitive cell in time, t:

$$I = \frac{dQ}{dt} = i\omega CV$$

- For a real dielectric the current I has vector components I_C and I_R:

$$I = I_C + I_R$$

Dielectric Loss

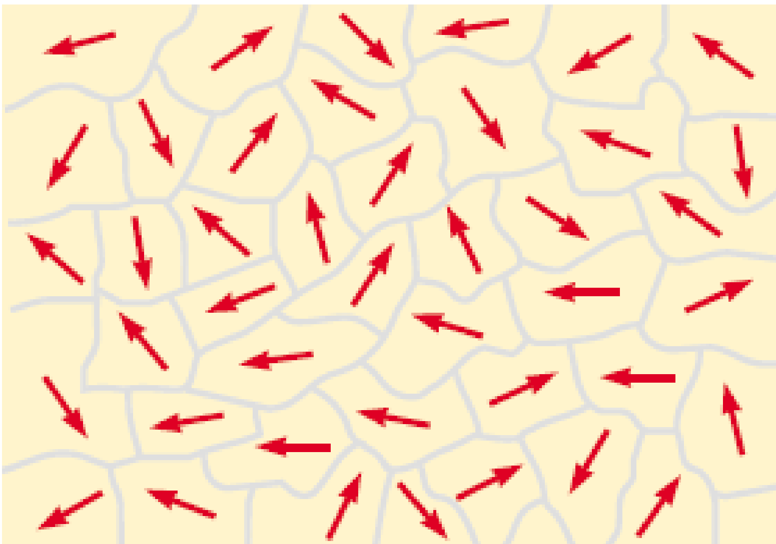
- From magnitude of these currents, also we can define a dissipation factor, tan δ, as

$$\tan\delta = \left|\frac{I_R}{I_C}\right|$$

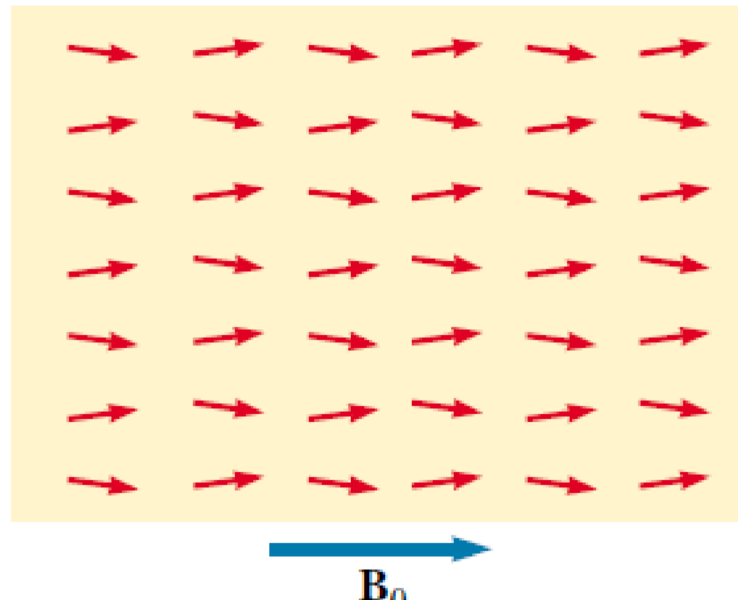
- Quality factor Q is:

$$Q = \frac{1}{\tan\delta} = \frac{\text{average energy stored}}{\text{energy dissipated per cycle}}$$

Magnetism

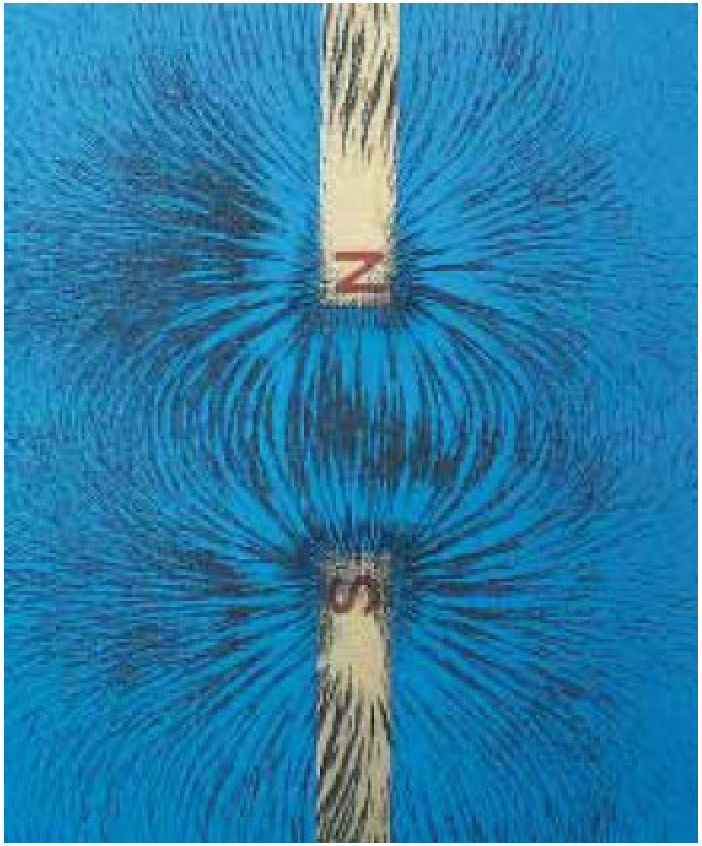


(a)



(b)

Magnetization



Magnetization, Permeability, and the Magnetic Field

- Magnetic permeability - The ratio between inductance or magnetization and magnetic field. It is a measure of the ease with which magnetic flux lines can “flow” through a material.
- Magnetization - The total magnetic moment per unit volume.
- Magnetic susceptibility - The ratio between magnetization and the applied field.

Dia, para and ferro magnetism,

- Ferromagnetism - Alignment of the magnetic moments of atoms in the same direction so that a net magnetization remains after the magnetic field is removed.
- Ferrimagnetism - Magnetic behavior obtained when ions in a material have their magnetic moments aligned in an antiparallel arrangement such that the moments do not completely cancel out and a net magnetization remains.
- Diamagnetism - The effect caused by the magnetic moment due to the orbiting electrons, which produces a slight opposition to the imposed magnetic field.

- Antiferromagnetism - Arrangement of magnetic moments such that the magnetic moments of atoms or ions cancel out causing zero net magnetization.
- Hard magnet - Ferromagnetic or ferrimagnetic material that has a coercivity > 10^4 A . m^{-1}.

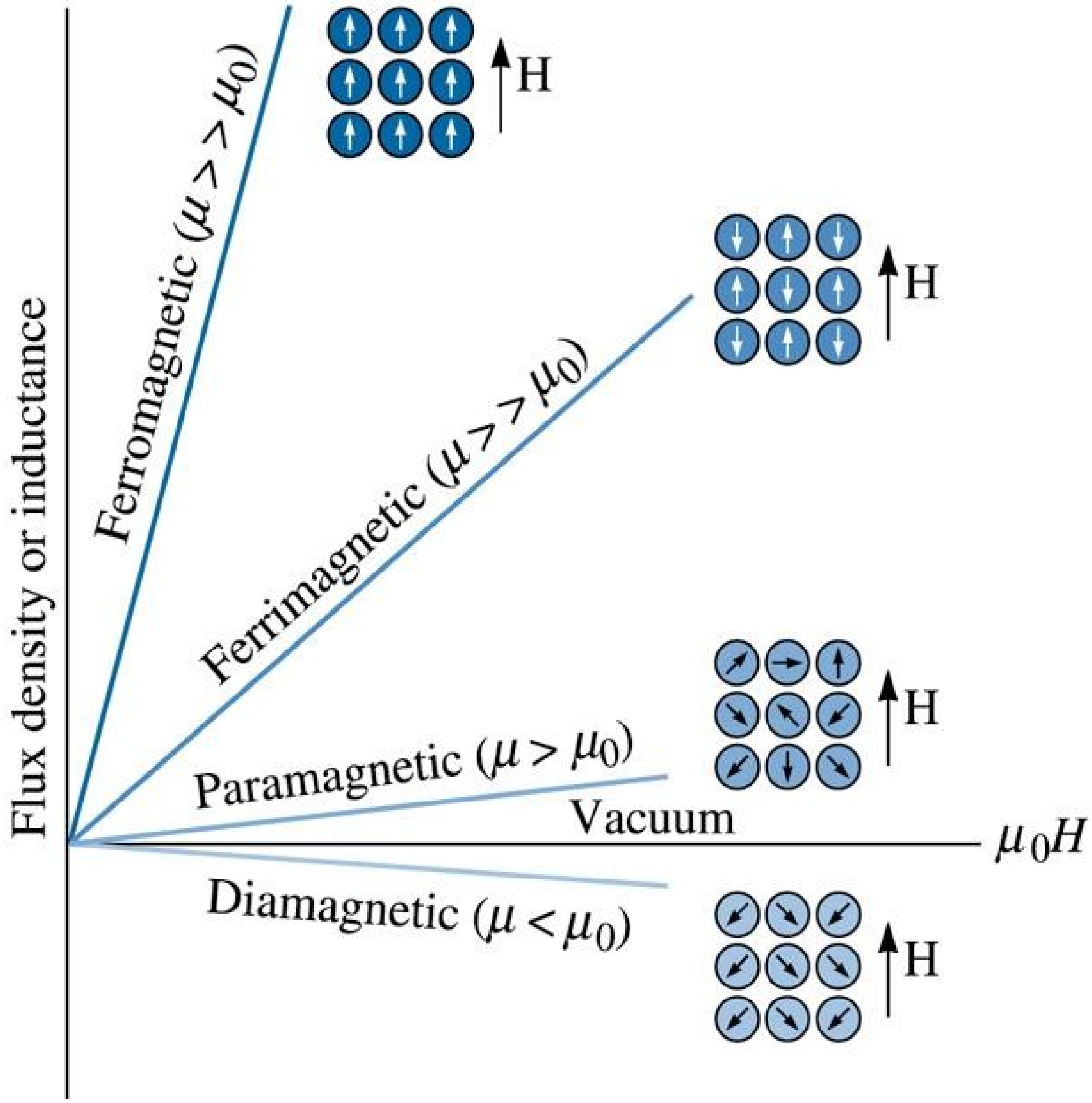


Figure 19.3 The effect of the core material on the flux density. The magnetic moment opposes the field in diamagnetic materials. Progressively stronger moments are present in paramagnetic, ferrimagnetic, and ferromagnetic materials for the same applied field.

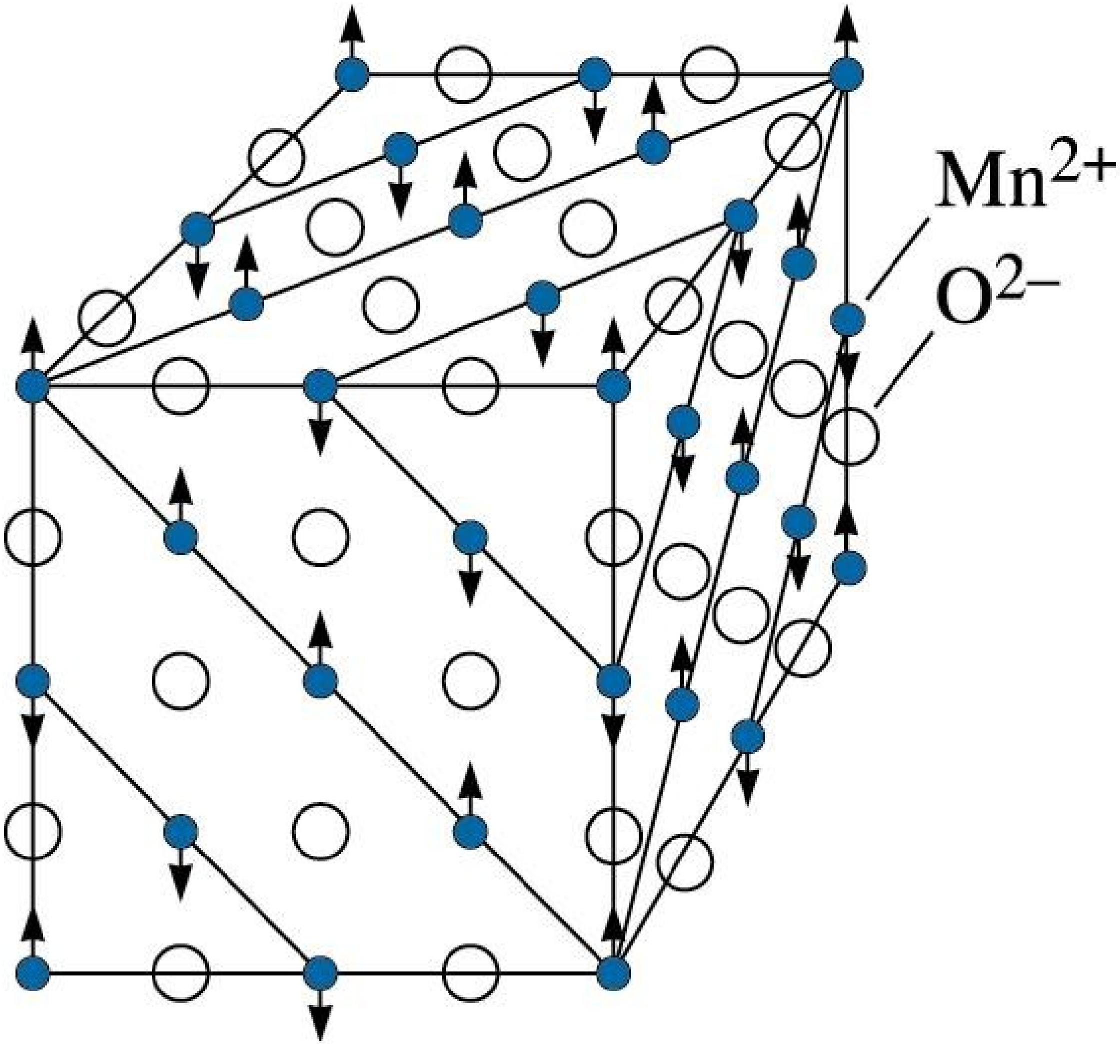


Figure 19.4 The crystal structure of Mn0 consists of alternating layers of {111} type planes of oxygen and manganese ions. The magnetic moments of the manganese ions in every other (111) plane are oppositely aligned. Consequently, Mn0 is antiferromagnetic.

Domain Structure and Hysteresis Loop

- Domains - Small regions within a single or polycrystalline material in which all of the magnetization directions are aligned.
- Bloch walls - The boundaries between magnetic domains.
- Saturation magnetization - When all of the dipoles have been aligned by the field, producing the maximum magnetization.
- Remanance - The polarization or magnetization that remains in a material after it has been removed from the field.
- Hysteresis loop - The loop traced out by magnetization in a ferromagnetic or ferrimagnetic material as the magnetic field is cycled.

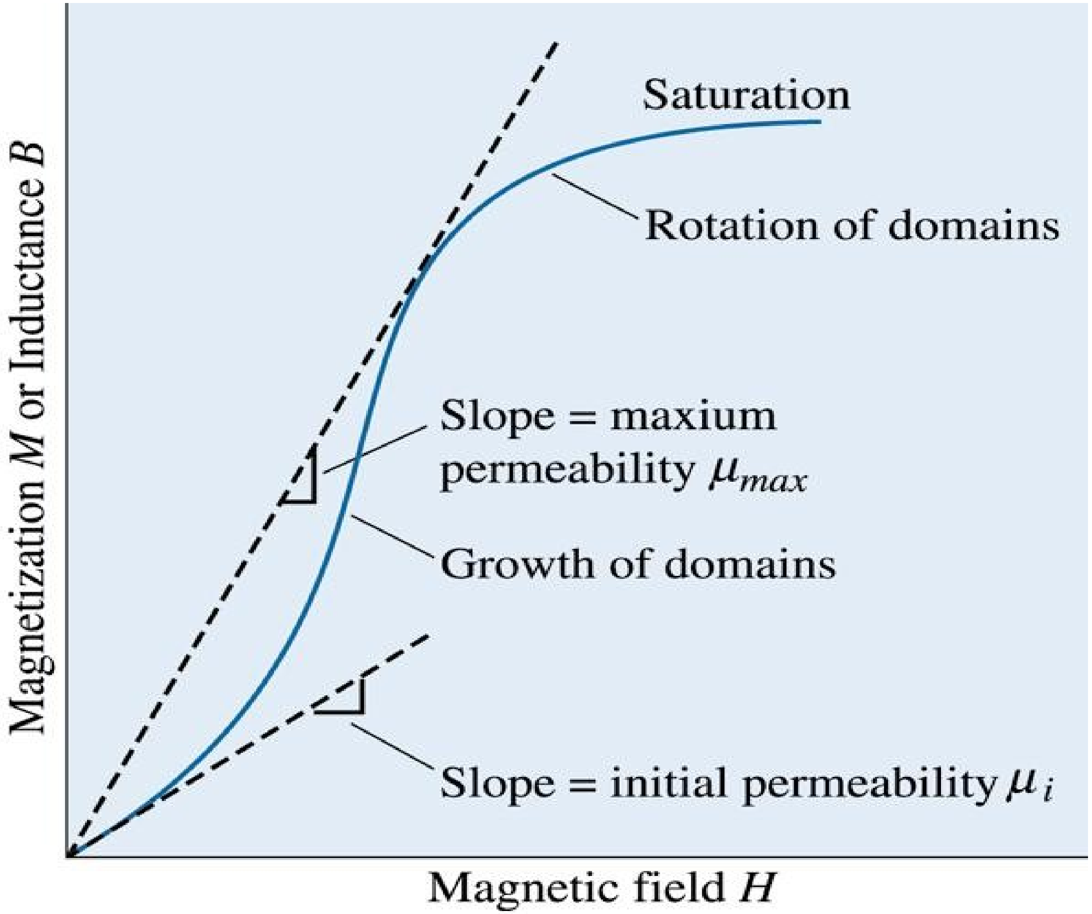


Figure 19.6 When a magnetic field is first applied to a magnetic material, magnetization initially increases slowly, then more rapidly as the domains begin to grow. Later, magnetization slows, as domains must eventually rotate to reach saturation. Notice the permeability values depend upon the magnitude of *H*.

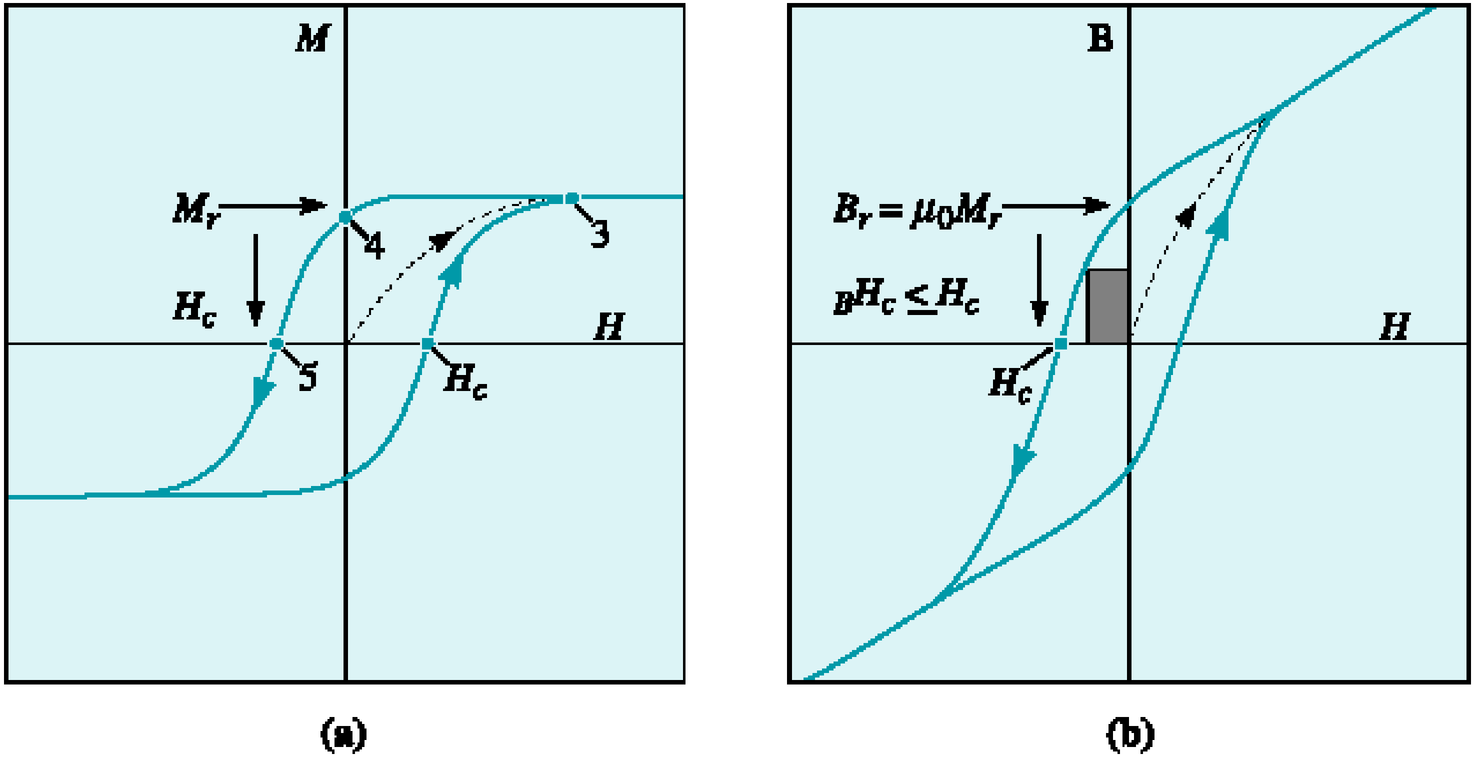


Figure 19.7 (a) The ferromagnetic hysteresis M-H loop showing the effect of the magnetic field on inductance or magnetization. The dipole alignment leads to saturation magnetization (point 3), a remanance (point 4), and a coercive field (point 5). (b) The corresponding B-H loop. Notice the end of the B-H loop, the B value does not saturate since B = $\mu_0 H + \mu_0 M$. (*Source: Adapted from* Permanent Magnetism, *by R. Skomski and J.M.D. Coey, p. 3, Fig. 1-1. Edited by J.M.D. Coey and D.R. Tilley. Copyright © 1999 Institute of Physics Publishing. Adapted by permission*.)

Phenomena of hysteresis and its applications