Dielectric Loss

- ε_r is static dielectric constant (result of polarization under dc conditions). Under ac conditions, the dielectric constant is different from the above as energy losses have to be taken into account.

- Thermal agitation tries to randomize the dipole orientations. Hence dipole moments cannot react instantaneously to changes in the applied field → losses.

- The absorption of electrical energy by a dielectric material that is subjected to an alternating electric field is termed dielectric loss.

- In general, the dielectric constant ε_r is a complex number given by

$$\varepsilon_r = \varepsilon_r' - j\varepsilon_r''$$

where, ε_r' is the real part and ε_r'' is the imaginary part.

Dielectric Loss

- Consider parallel plate capacitor with lossy dielectric

$$C = \frac{\varepsilon_o \varepsilon_r A}{d}$$

- Impedance of the circuit

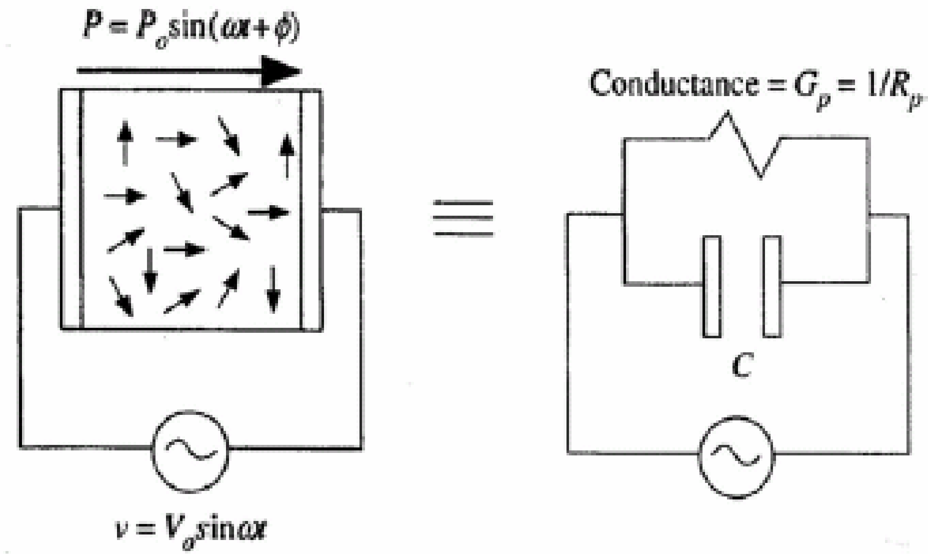
$$Z = \frac{1}{j\omega C} = \frac{d}{j\omega \varepsilon_o \varepsilon_r A}$$

- Thus, admittance (Y=1/Z) given by

$$Y = \frac{1}{Z} = \frac{j\omega \varepsilon_o \varepsilon_r A}{d}$$

$$= \frac{j\omega \varepsilon_o \left(\varepsilon_r' - j\varepsilon_r''\right) A}{d}$$

$$= \frac{j\omega \varepsilon_o \varepsilon_r' A}{d} + \frac{\omega \varepsilon_o \varepsilon_r'' A}{d}$$



Dielectric Loss

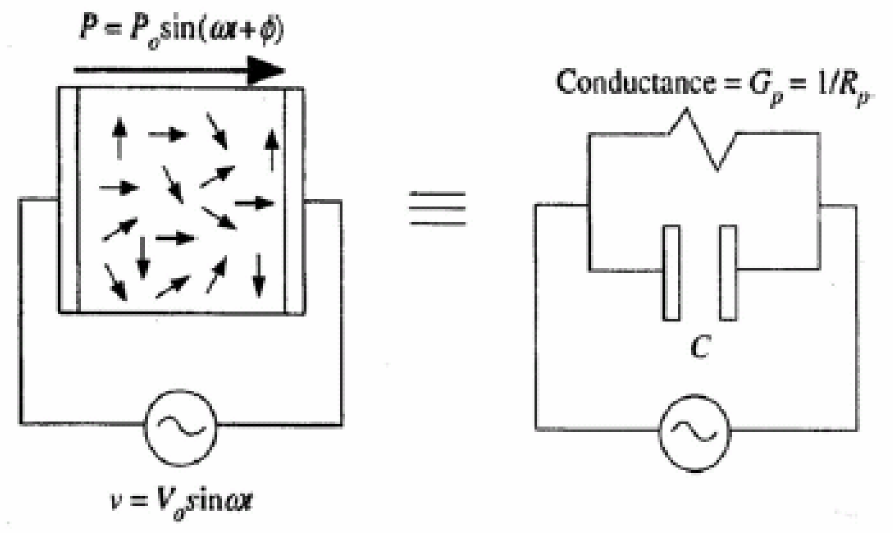
- The admittance can be written in the form

$$Y = j\omega C' + G_p$$

$$C' = \frac{\varepsilon_o \varepsilon_r' A}{d}$$

$$G_p = \frac{\omega \varepsilon_o \varepsilon_r'' A}{d}$$

- Note: compared to parallel resistance formula.



The admittance of the dielectric medium is equivalent to a parallel combination of an ideal lossless capacitor C' with a relative permittivity εr' and a resistance of 1/Gp or conductance Gp.

Dielectric Loss

- Input power:

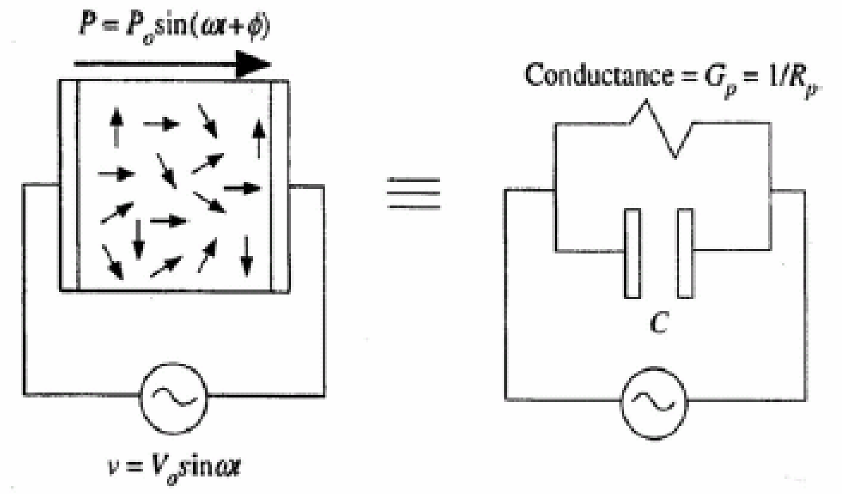
$$YV^2 = j\omega C'V^2 + \frac{V^2}{R_p}$$

- Real part ε_r' represents the *relative permittivity* (static dielectric contribution) in capacitance calculation; imaginary part ε_r'' represents the *energy loss* in dielectric medium.

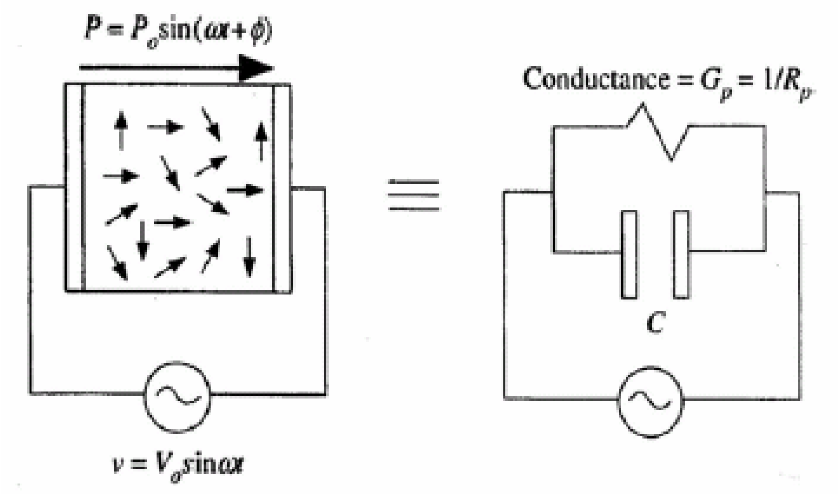
- Loss tangent: defined as

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

represents how lossy the material is for ac signals.



Dielectric Loss



The dielectric loss per unit volume:

$$W_{vol} = \frac{Power \quad loss}{volume}$$

$$= \frac{V^2 G_p}{Ad}$$

$$= \frac{V^2 \omega \varepsilon_o \varepsilon_r'' A}{Ad \cdot d}$$

$$= \frac{V^2}{d^2} \omega \varepsilon_o \varepsilon_r''$$

Since $E = V/d$

$$W_{vol} = \omega E^2 \varepsilon_o \varepsilon_r'' = \omega E^2 \varepsilon_o \varepsilon_r' \tan\delta$$

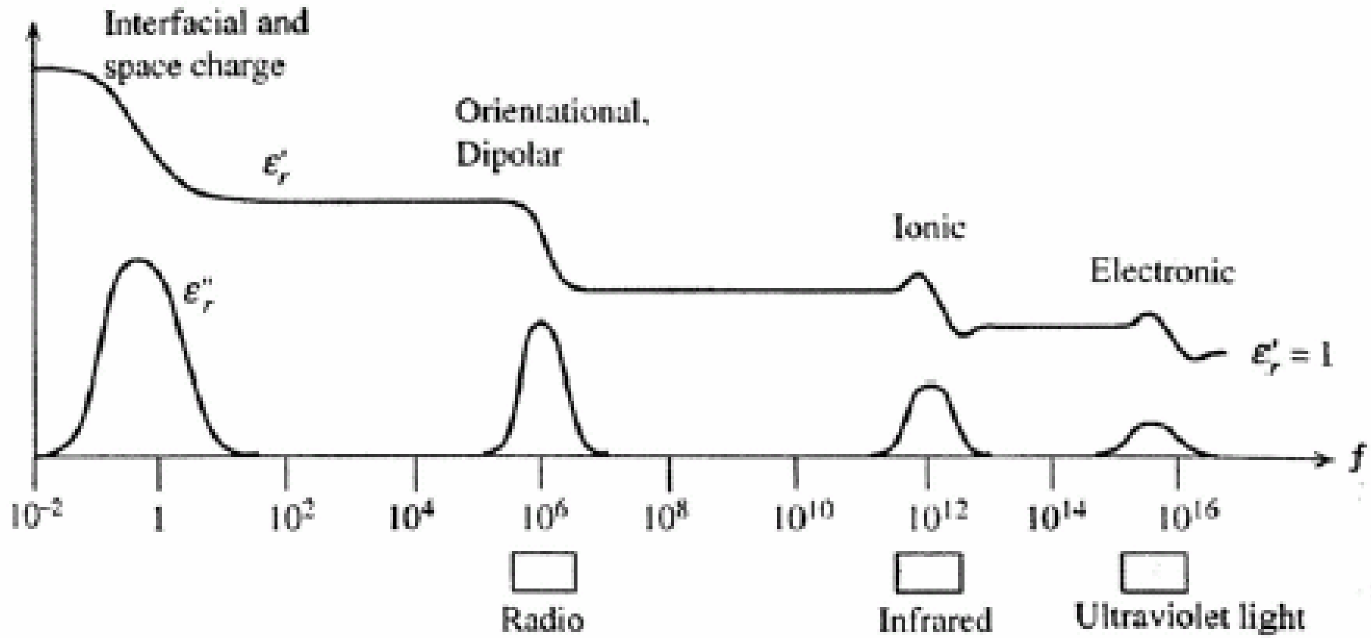
where E is the electric field, ω is the radian frequency.

Dielectric Loss

Material	tan δ
Ceramics	
Al_2O_3	0.0002–0.01
SiO_2	0.00038
$BaTiO_3$	0.0001–0.02
Mica	0.0016
Pyrex glass	0.006–0.025
Steatite ($2SiO_2 \cdot MgO$)	0.0002–0.004
Forsterite ($2MgO \cdot SiO_2$)	0.0004
Cordierite ($2MgO \cdot 2Al_2O_3 \cdot 5SiO_2$)	0.004–0.012
Polymers	
Phenol formaldehyde (Bakelite)	0.06–0.10
Silicone rubber	0.001–0.025
Epoxy	0.002–0.010
Nylon 6,6	0.01
Polycarbonate	0.0009
Polystyrene	0.0001–0.0006
High-density polyethylene	< 0.0001
Polytetrafluoroethylene	0.0002
Polyvinylchloride	0.007–0.020

- Note that the power loss is a function of ω, E and $\tan\delta$.
- We want a low loss tangent to ensure low power loss for a good electric material.
- The loss tangents of some comment dielectrics are listed here.

Dielectric Loss



- The extent to which the material is polarized is also frequency dependent, ie. α is frequency dependent.
- Since α and ε are related, the dielectric constant (both real and imaginary parts) is also frequency dependent.

Dielectric Breakdown

- Insulating behavior is important as dielectrics are widely used as insulating material media between conductors at different voltages to prevent ionization of air and hence current flashovers between conductors.

- Breakdown occurs at "weak spots" if a substantial current flows when a certain high voltage is reached.

- In liquids and gases, breakdown does not generally damage the material permanently

- In solids, the breakdown process invariably leads to the formation of a permanent conducting channel and hence permanent damage.

- Define dielectric strength, E_{br}, as the maximum field that can be applied without causing dielectric breakdown.

Dielectric Breakdown

Dielectric Medium	Dielectric Strength	Comment
Atmosphere at 1 atm pressure	31.7 kV cm^{-1} at 60 Hz	1 cm gap. Breakdown by electron avalanche by impact ionization.
SF_6 gas	79.3 kV cm^{-1} at 60 Hz	Used in high voltage circuit breakers to avoid discharges.
Polybutene	>138 kV cm^{-1} at 60 Hz	Liquid dielectric used as oil filler and HV pipe cables.
Transformer oil	128 kV cm^{-1} at 60 Hz	—
Amorphous silicon dioxide (SiO_2) in MOS technology	10 MV cm^{-1} dc	Very thin oxide films without defects. Instrinsic breakdown limit.
Borosilicate glass	10 MV cm^{-1} duration of 10 μs 6 MV cm^{-1} duration of 30 s	Instrinsic breakdown. Thermal breakdown.
Polypropylene	295–314 kV cm^{-1}	Likely to be thermal breakdown or electrical treeing.

Dielectric strength (E_{br}) is dependent on factors such as molecular structure, impurities in materials, microstructural defects, sample geometry, nature of electrodes, temperature, ambient conditions, duration and frequency of applied field.

Dielectric Breakdown

Breakdown in gases:

One electron with sufficiently large kinetic energy hits neutral gas molecule (impact ionization) → more electrons impact ionize other gas molecules → electron avalanche effect.

Pressure of gas in a critical factor as this represents the mean free path of electron and hence how often the collisions occur. E_{br} increases with gas pressure. (explain)

Breakdown in liquids:

- Impurities coalesce to form conducting bridge between eletrodes; or
- Partial discharge in gas bubbles trapped in liquid. Local temperature raised and more liquid vaporized → size of bubble increased; or
- Oxidation of certain liquids (eg, oil) producing more acidic and higher conductivity regions that give rise to discharge

Dielectric Breakdown

Breakdown in Solids

- Intrinsic or electronics breakdown

  Free electron in solid accelerated by high field → collide and ionize host atom → break bond (electron from valence band excited into conduction band) → primary and secondary electron further ionize other host atoms → electron avalanche breakdown.

  This type of breakdown represents the upper limit that is achievable by 'perfect' dielectrics iwht no defects.

Dielectric Breakdown

Breakdown in Solids

- Thermal Breakdown

(i) Finite conductivity of dielectric → Joule heating in solids

(ii) At high frequencies, dielectric loss becomes significant. Conduction and dielectric losses generate heat in material. If heat is not removed rapidly by thermal conduction, then temperature of dielectric rises.

(iii) Thermal runaway → temperature and current increases until a discharge occurs through sectons of solid. Hot spots which suffer local melting and erosion formed.

Dielectric Breakdown

Breakdown in Solid

- Electrochemical Breakdown

  (i) Dielectric medium is situated between oppositely charged plates → experiences compressive forces as the two plates attract and pull towards each other

  (ii) Decrease in dielectric thickness leads to higher field and also more charges on electrode → deformation → electrofracture.

- Internal Discharge

  Partial discharges which occur in microstructural voids, cracks, pores within dielectric where gas atmosphere has lower dielectric strength, eg. In porous ceramics.

Dielectric Breakdown

Breakdown in Solids

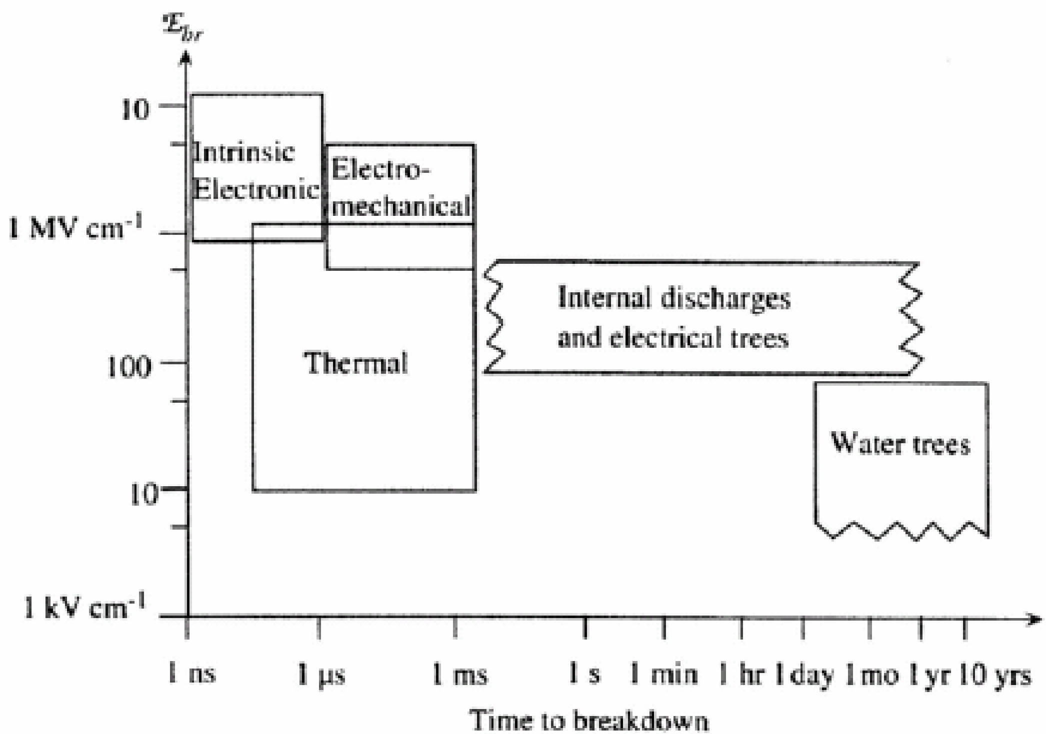
- Insulating Aging

  Deterioration with age of insulation or dielectric. Factors such as irradiation by ionizing radiation (eg, X-rays), temperature, mechanical stress etc give rise to insulation aging.

- External Discharges

  Surface contamination from external sources such as moisture, pollutants, dirt etc giving sufficient conductance to cause a discharge

Dielectric Breakdown



Typical values of breakdown field for different mechanisms versus time

Different fields correspond to different times to breakdown for different mechanisms. Difficult to isolate breakdown mechanism for given material.

Refractive Index

- Electric field interacts with the electron cloud surrounding each atom within its path resulting in electronic polarization. Two consequences of electronic polarization:

  (i) some the radiation energy may be absorbed.

  (ii) light waves are retarded in velocity as they pass through the medium → refraction

- Refraction is the phenomenon which occurs when light that is transmitted into the interior of a transparent material experiences a change in velocity and is bent at the interface.

- The refractive index of a material, n, is the ratio of the speed of light in vacuum, c, to the speed of light in medium, v,

$$n=c/v$$

Refractive Index

- The velocity of light in a medium is related to the dielectric permittivity and the magnetic permeability of the medium. So

$$c = \frac{1}{\sqrt{\varepsilon_o \mu_o}}$$

$$v = \frac{1}{\sqrt{\varepsilon \mu}}$$

- Hence refractive index given by

$$n = \frac{c}{v} = \frac{\sqrt{\varepsilon \mu}}{\sqrt{\varepsilon_o \mu_o}} = \sqrt{\varepsilon_r \mu_r}$$

- Since most optical materials and dielectrics are only slightly magnetic, we have μ_r=1, so,

$$n = \sqrt{\varepsilon_r}$$

Refractive Index

- Therefore, there is a relation between refractive index and dielectric constant,

- In general, the larger the atom or ion, the greater the electronic polarization → the slower the velocity, and the greater the refractive index

- For cubic crystal structures (eg. Glasses, crystalline ceramics), refractive index is independent of crystallographic direction (ie, it is isotropic).

- Non-cubic crystals have an anisotropic n → refractive index is greatest along the direction with the highest density of atoms.