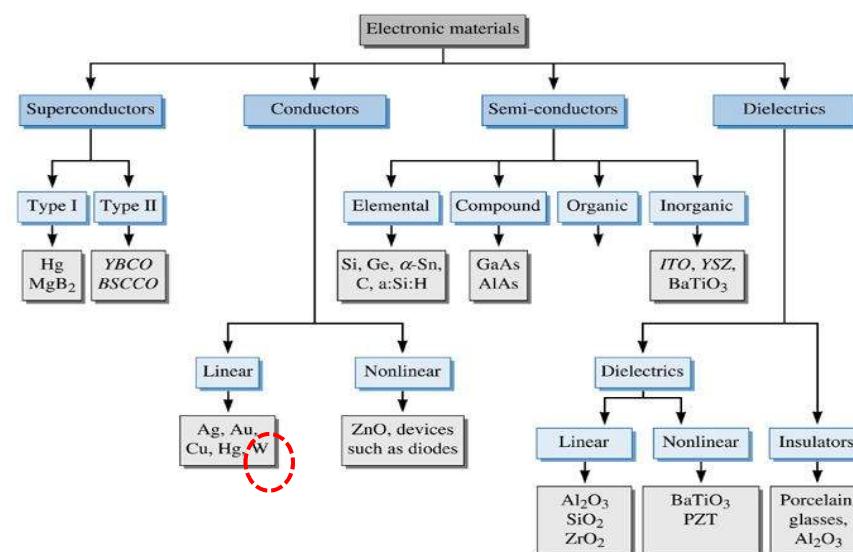
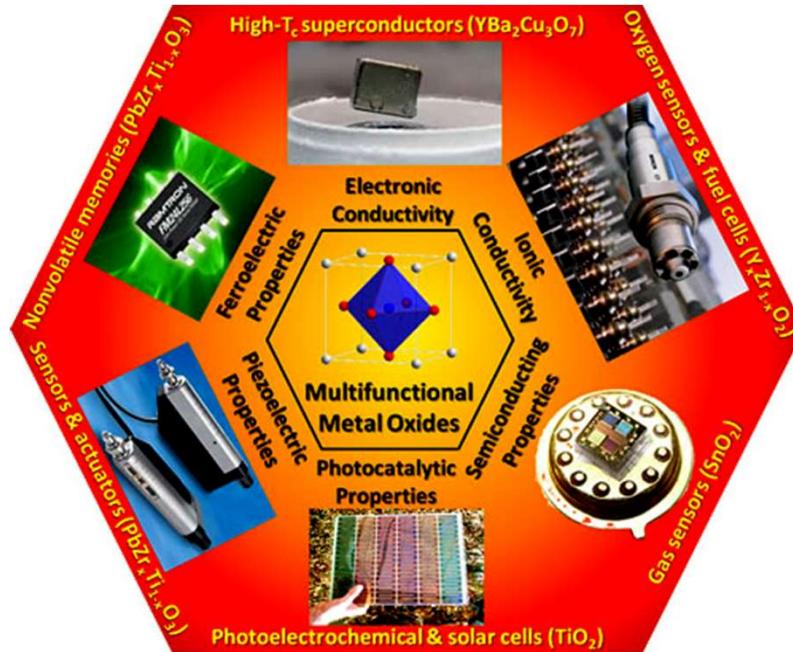


Dielectric Materials

1



2



3

Electroceramics

- Ceramics conductor
Heating element
Varistor
Thermistor
Ionic conductor
Humidity Sensor
Gas Sensor
Superconductor

- Dielectrics and Insulators
Multilayer Ceramic
Capacitor
Electrical Insulator

Electroceramics
: Ceramic materials and devices using electronic properties.

- Piezoelectric ceramics
Ultrasonic transducer
Water level sensor
Proximity sensor
PZT

- Pyroelectric ceramics
PZT
Temperature sensor

- Electro-optic ceramics
- PLZT

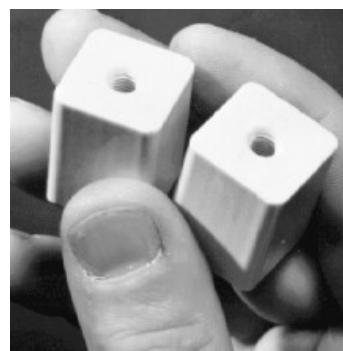
- Magnetic ceramics
ferrite

4

Common Applications for Electroceramics

- Insulator
- Resistor
- High dielectric constant capacitors
- Piezoelectric sonar transducers
- Ultrasonic transducers
- Radio & communication filters
- Medical diagnostic transducers
- Ultrasonic motors
- Electro-optic light valves
- Thin-film capacitors
- Ferroelectric thin-film memories

5



Ceramic insulators



6



**Bulk Ceramic Varistors
(VDR-voltage dependent
resistors)**



Bulk Ceramic Thermistors

7



Bulk ceramic resistors

8

Cellular Telephone

- Portable communication devices such as cordless, portable, and car telephone have become popular worldwide.
- Do you know what kind of **dielectric and ferroelectric components** are used in a cellular phone?



9

Cellular Telephone

- Chip Monolithic ceramic capacitors
- Microwave Oscillators
- Microwave Filters
- Ceramic Resonators
- High Frequency Surface Acoustic Wave (SAW) Filter
- Ceramic Filters
- Piezoelectric Receivers
- Piezoelectric Speakers

10

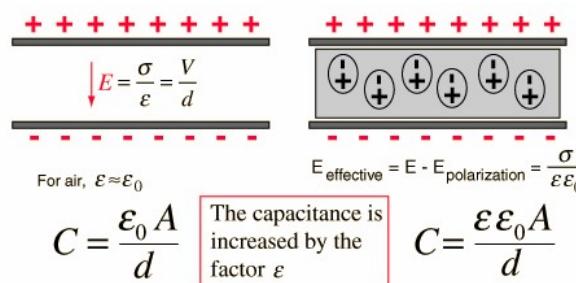


Johanson Dielectrics Capacitor Products:

Ceramic SMT and
Leaded High Voltage
and High
Temperature, Dual
and Multi Capacitor
Arrays, Low
Inductance, X2Y,
Switchmode.

11

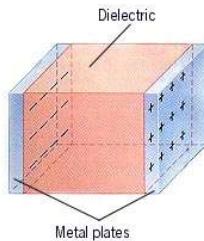
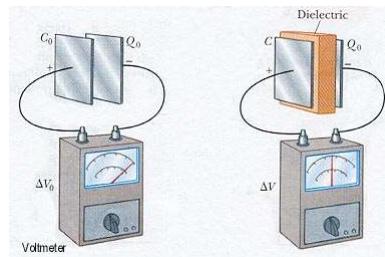
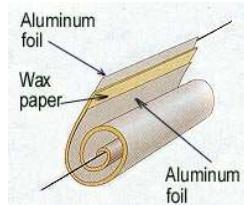
Capacitors



$$E_{\text{stored}} = \frac{1}{2} C V^2 = \frac{1}{2} \frac{Q^2}{C} = \frac{1}{2} V Q$$

12

Capacitors



13

Capacitors

$$C = \text{"capacitance"} \\ = q / \Delta V$$

Units: Coulomb/Volt
= Farad (F)

The capacitance of a capacitor is constant; if q increases, ΔV increases proportionately.



Michael Faraday
(1791-1867)

14

Charge

ϵ

V

$$C = \epsilon_r \epsilon_0 \frac{A}{d}$$

$$Q = \epsilon_r \epsilon_0 \frac{AV}{d}$$

$$Q = CV$$

Most common properties of dielectric materials are:

- (i) dielectric constant
- (ii) dielectric strength
- (iii) insulation resistance
- (iv) surface resistivity
- (v) loss factor
- (vi) tangent of loss factor in terms of a capacitor or phase difference
- (vii) polar and non-polar materials.

Q: charge (Coulomb)

C: capacitance (Farad)

V: potential difference (Volt)

d: separation/thickness (meter)

ϵ_0 : permittivity of vacuum = $8.854 \times 10^{-12} \text{ C}^2/\text{m}^2$ or F/m

ϵ_r : dielectric constant

15



Supercapacitor

(Also known as an ultracapacitor or a double-layer capacitor)

❑ somewhere in between electrolytic capacitors and rechargeable batteries. With features like:

1. Charge much faster than batteries
2. Can store much more energy than electrolytic capacitors
3. Have a lifespan (measured in charge/discharge cycles) somewhere between the two (more than rechargeable batteries and less than electrolytic capacitors)

The benefits of supercapacitors include:

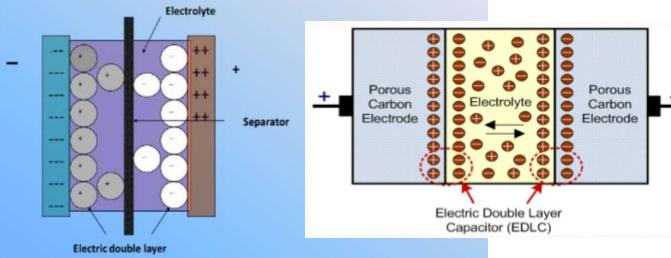
1. **Balancing energy storage with charge and discharge times.** While they can't store as much energy as a comparably sized lithium-ion battery (they store roughly 1/4 the energy by weight), supercapacitors can compensate for that with the speed of charge. In some cases, they're nearly 1,000x faster than the charge time for a similar-capacity battery.
2. **Wide-ranging Operating Temperatures.** Supercapacitors have a much broader effective operating temperature (from roughly -40°C to +65°C).

Disadvantages:

1. **Self-discharge rate.** Not well-suited for long-term energy storage. The discharge rate is significantly higher than Li-ion batteries; can lose up to 10-20% of their charge per day due to self-discharge.
2. **Gradual voltage loss.** While batteries provide a near-constant voltage output until spent, the voltage output of capacitors declines linearly with their charge.
3. Cannot be used in AC & high frequency circuits

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Applying a voltage to an electrochemical capacitor causes both electrodes in the capacitor to generate electrical double-layers.



The two layers are separated by a monolayer of solvent molecules.

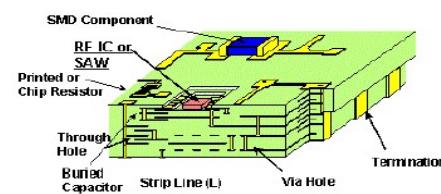
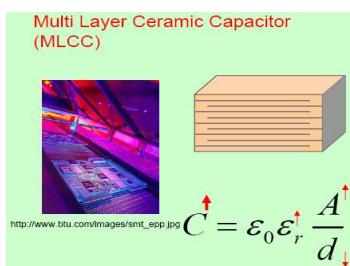
Applications in: Smartphone, UPS, RAM, Light rail

Double-layer capacitors have much higher capacitance values than conventional capacitors, arising from the extremely large surface area of activated carbon electrodes and extremely thin double-layer distance on the order of a few angstroms (0.3-0.8 nm).

1. [Where do batteries end and supercapacitors begin?](#), Y Gogotsi, B Dunn - *Science*, Vol 343, Issue 6176, 2014
2. Highly confined ions store charge more efficiently in supercapacitors, *Nature Communications* volume 4, Article number: 2701 (2013)
3. Nanoporous metal/oxide hybrid electrodes for electrochemical supercapacitors, *Nature Nanotechnology* volume 6, pages232–236(2011)
4. Ultrahigh-power micrometre-sized supercapacitors based on onion-like carbon, *Nature Nanotechnology* volume 5, pages651–654(2010)

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Dielectric Materials and Devices



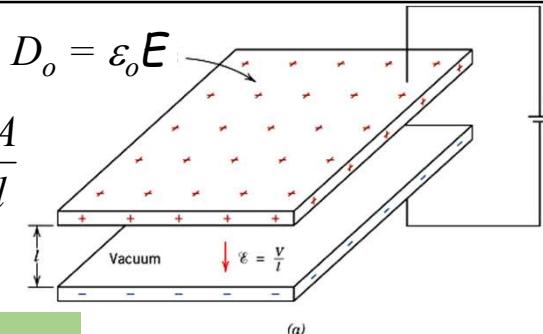
18

Dielectric material
Electric dipole structure
Charge separation

$$C = \frac{Q}{V}$$

$$C = \epsilon_0 \frac{A}{l}$$

ϵ_0 = permittivity of vacuum
 $= 8.85 \times 10^{-12} \text{ F/m}$

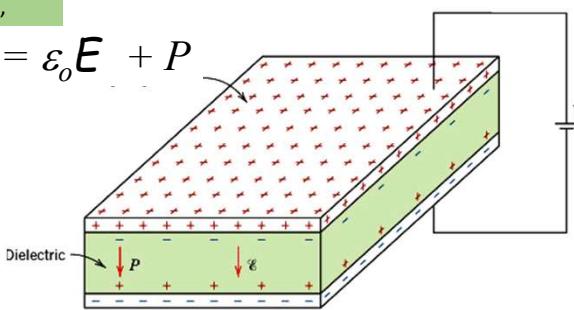


dielectric displacement D as the surface charge on the metal plates,

$$D_o = \epsilon_0 E + P$$

$$C = \epsilon \frac{A}{l}$$

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



Dielectric Behavior

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Table 12.5 Dielectric Constants and Strengths for Some Dielectric Materials

Material	Dielectric Constant		Dielectric Strength (V/mil) ^a
	60 Hz	1 MHz	
Ceramics			
Titanate ceramics	—	15–10,000	50–300
Mica	—	5.4–8.7	1000–2000
Stearite ($\text{MgO}-\text{SiO}_2$)	—	5.5–7.5	200–350
Soda-lime glass	6.9	6.9	250
Porcelain	6.0	6.0	40–400
Fused silica	4.0	3.8	250
Polymers			
Phenol-formaldehyde	5.3	4.8	300–400
Nylon 6,6	4.0	3.6	400
Polystyrene	2.6	2.6	500–700
Polyethylene	2.3	2.3	450–500
Polytetrafluoroethylene	2.1	2.1	400–500

^a One mil = 0.001 in. These values of dielectric strength are average ones, the magnitude being dependent on specimen thickness and geometry, as well as the rate of application and duration of the applied electric field.

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Field vectors and polarization

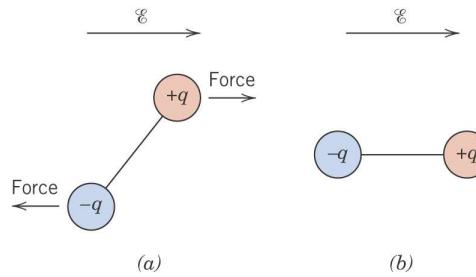
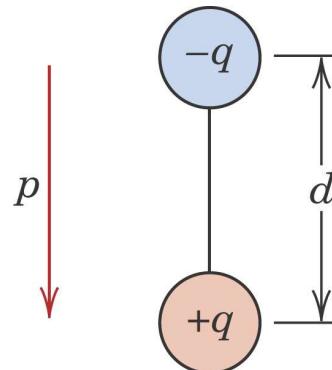
$$p = qd$$

Surface charge density or dielectric displacement (C/m^2)

$$D_o = \epsilon_0 E$$

For the dielectric case

$$D = \epsilon E$$



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Microscopic approach. A **dipole moment** μ (Fig. 14.3) is defined as²⁴⁶

$$\mu = q\delta$$

where δ is the distance separating the centers of the +ve and -ve charges $q = \pm ze$. μ is a vector with its positive sense directed from the negative to the positive charge.

If there are N such dipoles per unit volume, it can be shown that P is simply

$$P = N\mu = Nq\delta \quad (14.12)$$

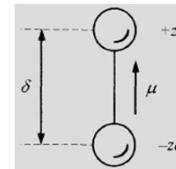


Figure 14.3 Definition of an electric dipole moment.

²⁴⁶ The dipole moment of a charge $q = ze$ relative to a fixed point is defined as the vector $ze\zeta_i$, where ζ_i is the radius vector from the fixed point to the position of the charge. The total dipole moment of a system is the vector sum of all the individual dipoles

$$\mu = \sum z_i e \zeta_i$$

This quantity is *independent* of the position of the fixed point. In the absence of a field, $\sum z_i e \zeta_{i0} = 0$. The application of an electric field results in the displacement of the charges by an amount δ_i from their equilibrium position, that is, $\zeta = \zeta_0 + \delta_i$. It follows that $\mu = \sum z_i e \zeta_i = \sum z_i e \delta_i$. Practically, it follows that to calculate the dipole moment of any ion, we need only know its position relative to its equilibrium position.

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Polarization of a dielectric material

Electrical dipole

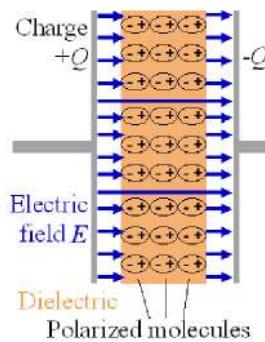


Electrical dipole moment:

$$\mu = q \cdot r \quad (C \cdot m)$$

If N dipoles per unit volume, the polarization:

$$P = N \cdot \mu \quad (C/m^2)$$



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$$D_o = \epsilon_0 \mathbf{E} + \mathbf{P} \quad \text{where } P \text{ is the polarization } (C/m^2)$$

or total dipole moment per unit volume of the dielectric

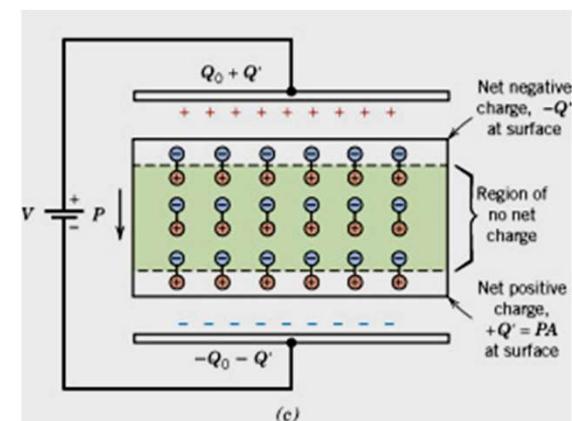
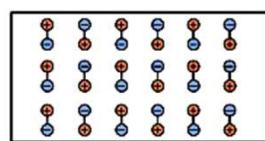
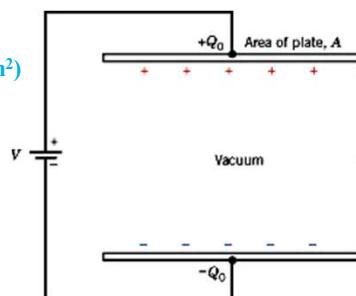
Surface charge density or dielectric displacement (C/m^2)

$$D_o = \epsilon_0 \mathbf{E}$$

For the dielectric case

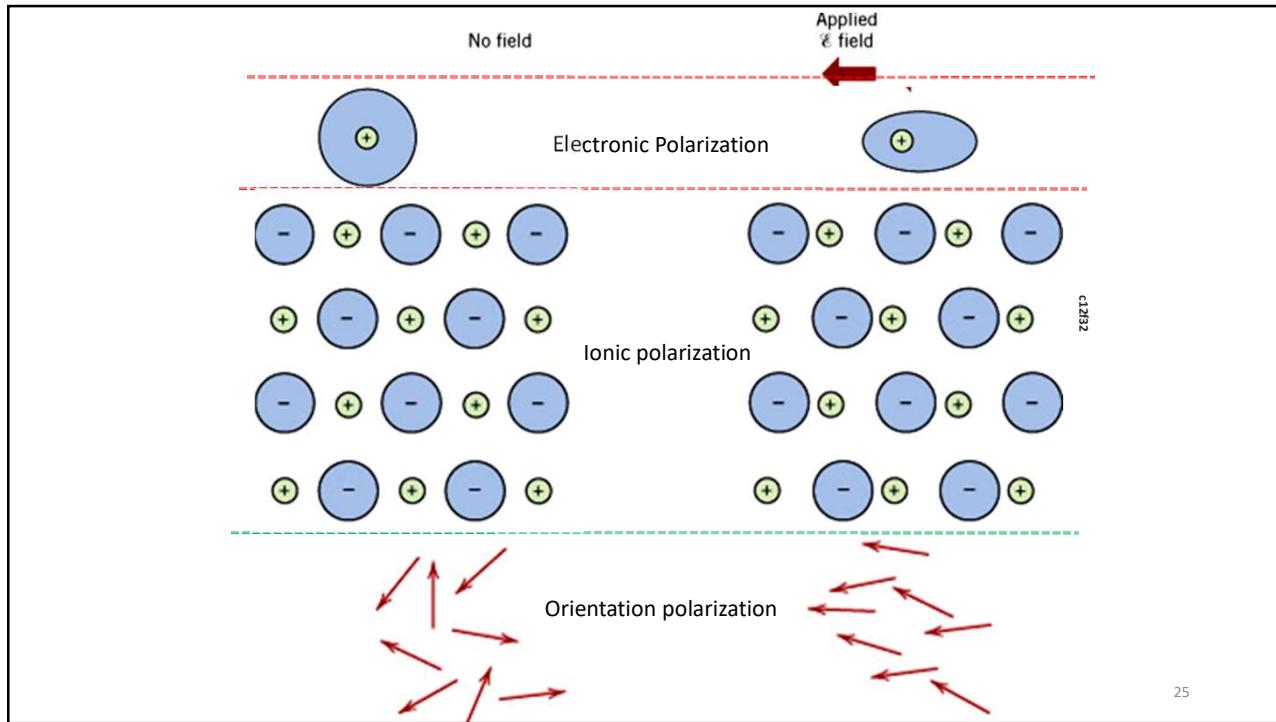
$$D = \epsilon \mathbf{E}$$

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



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

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Relation between $P, \epsilon_0, \epsilon_r$ and E

The polarization 'P' is related to the electric flux density D as,

$$D = \epsilon_0 E + P$$

Since $D = \epsilon_0 \epsilon_r E$, the above relation becomes,

$$\begin{aligned} \epsilon_0 \epsilon_r E &= \epsilon_0 E + P \\ (\text{or}) \quad P &= \epsilon_0 \epsilon_r E - \epsilon_0 E \\ \text{i.e.} \quad P &= \epsilon_0 (\epsilon_r - 1) E \end{aligned}$$

Electric susceptibility

The polarization P is proportional to the applied electric field intensity E and it is in the same direction of 'E'. It can be written as,

$$P \propto E \quad (\text{or}) \quad P = \epsilon_0 \chi_e E$$

Various Polarization mechanisms in Dielectrics

Dielectric polarization is the displacement of charged particles under the action of the external electric field. Several microscopic mechanisms are responsible for dielectric polarization.

➤Four types of microscopic polarization mechanisms.

- Electronic polarization
- Ionic polarization
- Orientation polarization and
- Space-charge polarization.

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➤i. Electronic Polarization

➤ Electronic Polarization occurs due to the displacement of positively charged nucleus and negatively charged electrons in opposite directions, when an external electric field is applied, and thereby a dipole moment is created in the dielectric.

- ∴ The induced dipole moment $\mu = \alpha e E$
- where αe = electronic polarizability.

➤ Monoatomic gases exhibit this kind of polarization, Electronic polarizability is proportional to the volume of the atoms and is **independent of temperature**.

➤ The electronic polarizability = $\alpha e = 4\pi e_0 R^3$ (Farad.m²) where R is the radius of the atom.

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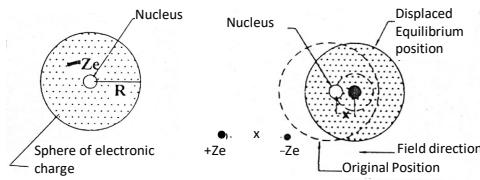


Fig. (a) Position of +ve and –ve charges in an atom without field (b) Position of +ve and –ve charges in an atom with field

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ii. Ionic Polarization

Ionic polarization arises due to the displacement of -ve ions and +ve ions in opposite directions and it occurs in ionic solids, in the presence of electric field. The displacement is independent of temperature. Example : NaCl crystal

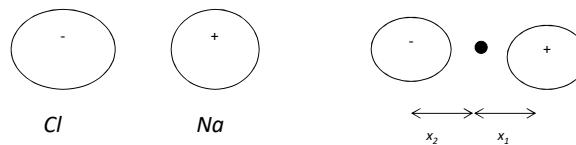


Fig. (a) Without field (b) With field

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14.4.3 Dipolar Polarization

In contrast to electronic polarization and ionic polarization, which occur at high frequencies ($\omega > 10^{10}$ Hz), dipolar polarization occurs at lower frequencies and is thus important because it can greatly affect the capacitive and insulative properties of glasses and ceramics in low-frequency applications.

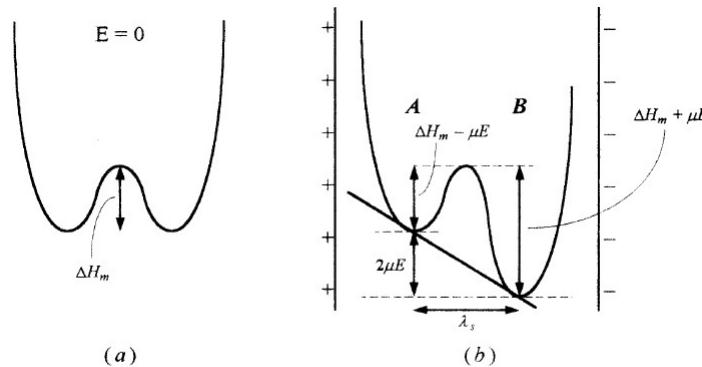


Figure 14.10 Dipolar polarization; (a) energy versus distance diagram in the absence of applied field; the two sites are equally populated. (b) The application of an electric field will bias one site relative to the other.

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iii. Orientation Polarization

The orientation polarization arises due to the presence of polar molecule in the dielectric medium.

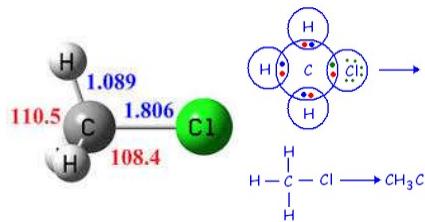


Fig. (a) Without field (b) With field

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➤Explanation:

- In the case of a CH_3Cl molecule, the positive and negative charges do not coincide. The Cl^- has more electro negativity than hydrogen. Therefore, the chlorine atoms pull the bonded electrons towards them more strongly than hydrogen atoms. Therefore, even in the absence of field, there exists a net dipole moment.
- Now, when the field is applied, positive portion align along the direction of field and negative portion align in the opposite direction of the field. This kind of polarization is called as orientation polarization.
- This depends on temperature; when temperature is increased, the thermal energy tends to randomize the alignment



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Space-Charge Polarization

The space-charge polarization occurs due to the diffusion of ions, along the field direction, thereby giving rise to redistribution of charges in the dielectrics

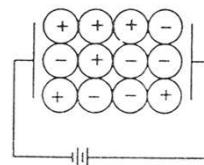
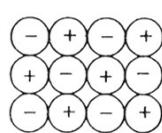


Fig. (a) Without field (b) With field

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➤ *Explanation*

- Without the application of external field, the ions are orderly arranged as shown in the Fig.
- Now, when the field is applied, the ions diffuse with respect to the direction of applied field. Thus the polarization occurs, known as space charge polarization.
- Normally, this type of polarization occurs in ferrites and semiconductors and will be very small.

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Table 7.1 Typical examples of polarization mechanisms.

Example	Polarization	Static ϵ_r	Comment
Ar gas	Electronic	1.0005	Small N in gases: $\epsilon_r \approx 1$
Ar liquid ($T < 87.3\text{K}$)	Electronic	1.53	van der Waals bonding
Si crystal	Electronic polarization due to valence electrons	11.9	Covalent solid; Electronic bond polarization
NaCl crystal	Ionic	5.90	Ionic crystalline solid
CsCl crystal	Ionic	7.20	Ionic crystalline solid
Water	Orientational	80	Dipolar liquid
Nitromethane (27°C)	Orientational	34	Dipolar liquid
PVC (Polyvinyl chloride)	Orientational	7	Dipole orientations partly hindered in the solid

From *Principles of Electronic Materials and Devices, Second Edition*, S.O. Kasap (© McGraw-Hill, 2002)
<http://Materials.Uask.Ca>

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Dielectric Spectrum

From the foregoing discussion, it is clear that the dielectric response is a complex function of frequency, temperature, and type of solid. Under dc conditions, all mechanisms are operative, and the dielectric constant is at its maximum and is given by the sum of all mechanisms. As the frequency increases, various mechanisms will be unable to follow the field and will drop off, as shown in Fig. 14.13. At very high frequencies, none of the mechanisms is capable of following the field, and the relative dielectric constant approaches 1.0.

Temperature will influence only the polarization mechanisms that depend on long-range ionic displacement such as dipolar polarization. Ionic polarization is not strongly affected by temperature since long-range mobility of the ions is not required for it to be operative.²⁵⁹

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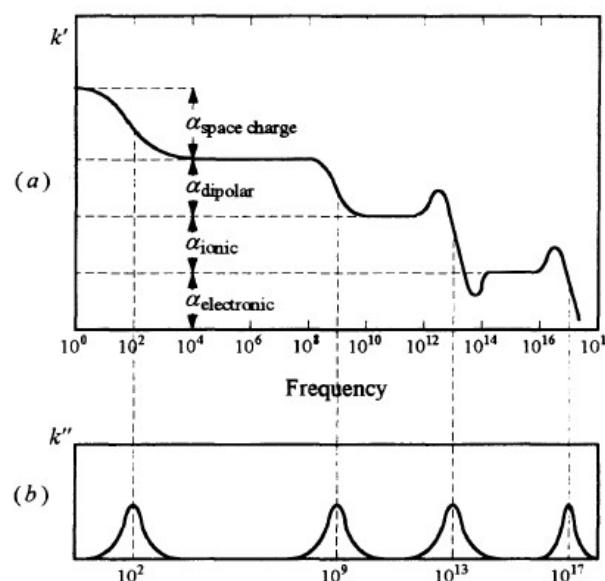
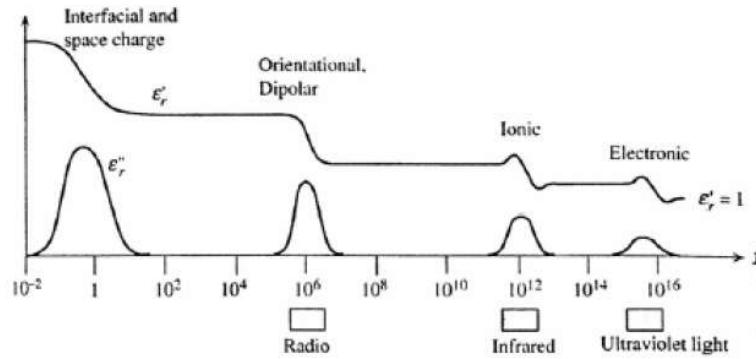


Figure 14.13 Variation of (a) relative dielectric constant and (b) dielectric loss with frequency.

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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.

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Dielectric Strength

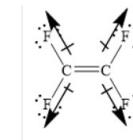
Substance	Dielectric Strength (MV/m)
Air	3
Quartz	8
Strontium titanate	8
Neoprene rubber	12
Nylon	14
Pyrex glass	14
Silicone oil	15
Paper	16
Bakelite	24
Polystyrene	24
Teflon	60

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Teflon (PTFE) →

Dielectric Strength: 60 (MV/m)

- Dipoles aligned so that net moment is 0.
- In the presence of E, the Orientation in the direction of the applied field is high.
- Depends on temperature. (Orientation polarization)

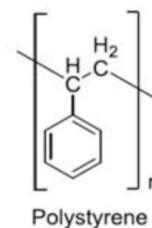


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Poly(Styrene) →

Dielectric Strength: 24 (MV/m)

- Due to the presence of bulky Aromatic ring, and the effect of the delocalized electrons.
- On the application of the applied field, the aromatic ring hinders the polymer alignment (orientation) and suppresses Polarization. (Electronic Polarization)



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Dielectric Constant

- The capacitance, C , of a capacitor formed by two parallel plates of area A spaced d apart with the area between the plates filled with dielectric material with a relative dielectric constant of ϵ is:

$$C = \frac{\epsilon \epsilon_0 A}{d}$$

Material	Dielectric Constant
Air	1
Alumina	10
Ta ₂ O ₅	27
Nb ₂ O ₅	42
Potassium niobate (KN)	700
Barium titanate (BT)	4000
Modified barium titanate	~ 10000
Lead magnesium niobate (PMN)	~ 20000

Another viewpoint for the **dielectric constant**: the extent to which a substance concentrates the electrostatic lines of flux.

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Dielectric Loss

- Dielectric materials: high electrical resistivities, but an efficient supporter of electrostatic fields.
- Dielectrics can store energy/charge.
- Able to support an electrostatic field while dissipating minimal energy in the form of heat.
- The lower the **dielectric loss** (proportion of energy lost as heat), the more effective is a dielectric material.

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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

$$\epsilon_r = \epsilon_r' - j\epsilon_r''$$

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

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Dielectric Loss

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

$$\epsilon = \epsilon' - i\epsilon''$$

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

$$\sigma(\omega) = \omega\epsilon_0\epsilon''$$

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Dielectric Loss

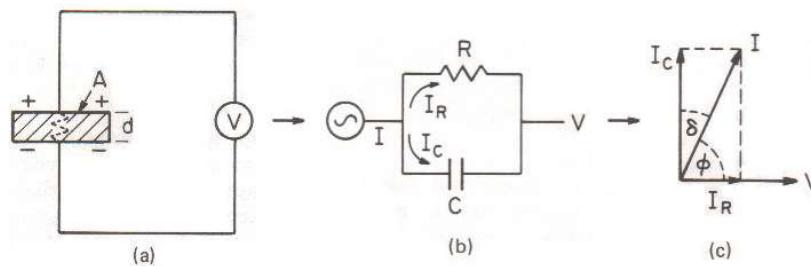
- ϵ'' is also known as the **loss factor**.
- The small difference in phase from ideal behaviour is defined by an angle δ , defined through the equation

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

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

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Dielectric Loss



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

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Dielectric Loss

- From $Q = \epsilon \epsilon_0 AV/d = CV$
- If V being sinusoidal, total charge Q may be written as

$$Q = CV_o e^{i\omega t}$$

- 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 :

$$I = I_C + I_R$$

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Dielectric Loss

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

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

- Quality factor Q is:

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

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Dielectric losses

Angular frequency $\omega = 2\pi f = 2\pi/T$

Ideal capacitor: 90° phase difference between I and U , no dissipation

Real capacitor: $<90^\circ$ phase difference between I and U .
 I_c : charging current (capacitive component)
 I_l : loss current, dissipative comp., power loss

Power dissipated per unit time $P_w = \frac{1}{2} U_0 I_c \tan \delta = \frac{1}{2} U_0^2 \omega C \tan \delta$

Dissipated power density $\frac{P_w}{V} = \frac{1}{2} E_0^2 \omega \epsilon_0 \epsilon_r \tan \delta$

tan δ: "dissipation factor" or "loss tangent"
ε_rtan δ: "loss factor"

$\frac{P_w}{V} = \frac{1}{2} E_0^2 \sigma_{ac}$ By analogy with dc current $\frac{P_w}{V} = \sigma E^2$

Dielectric or ac conductivity $\sigma_{ac} = \omega \epsilon_0 \epsilon_r \tan \delta$

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Complex permittivity

The behaviour of ac circuits can be conveniently analysed using complex quantities

$\exp(i\theta) = \cos \theta + i \sin \theta$

Real part Imaginary part

$i = \sqrt{-1}$

Complex sinusoidal voltage $U = U_0 \exp(i\omega t)$

Vacuum capacitor $I = \dot{Q} = \dot{U}C_0 = i\omega C_0 U$

90° in advance

Capacitor with a lossy dielectric

$\epsilon_r^* = \epsilon_r' - i\epsilon_r''$

$I = i\omega \epsilon_r' C_0 U + \omega \epsilon_r'' C_0 U$

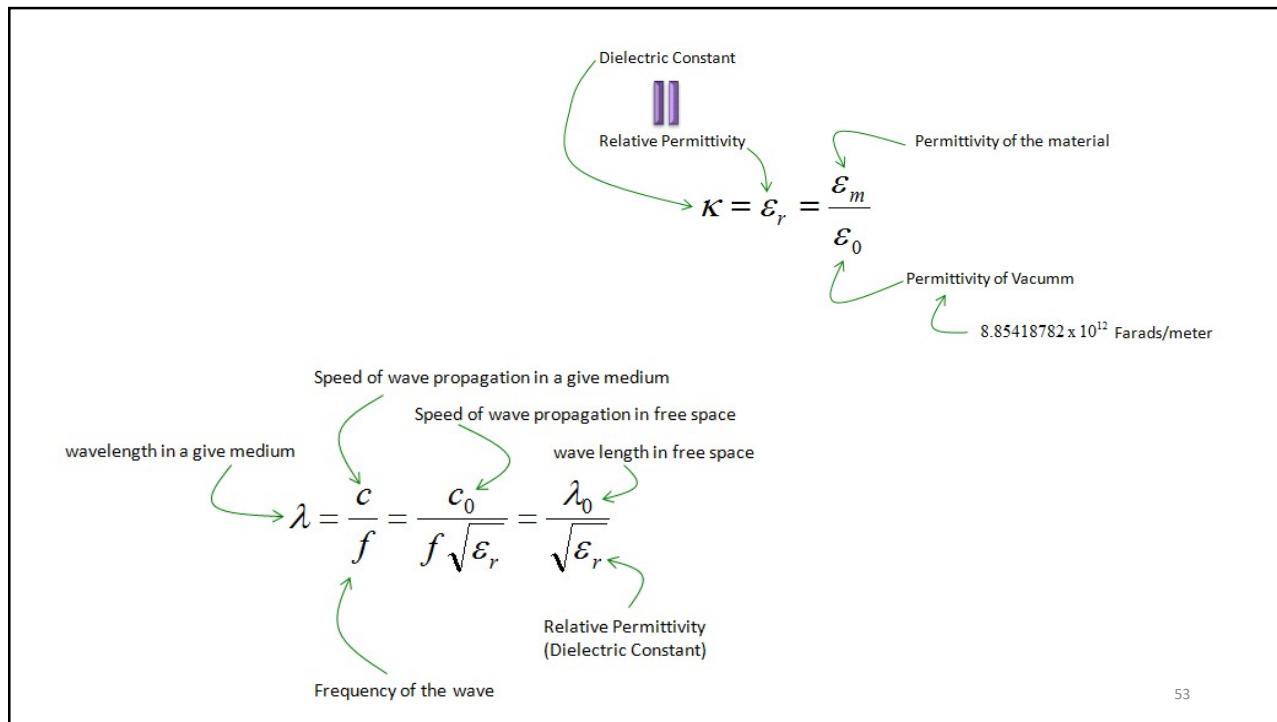
$I_C = i\omega \epsilon_0 \epsilon_r' E$ $I_l = \omega \epsilon_0 \epsilon_r'' E = \sigma_{ac} E$

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

By analogy with Ohm's law:
 $I = U/R$ or $J = \sigma E$

$\epsilon_r'' = \epsilon_r' \tan \delta$ "loss factor"

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Dielectric Loss

Material	$\tan \delta$
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 ($2\text{SiO}_2 \cdot \text{MgO}$)	0.0002–0.004
Forsterite ($2\text{MgO} \cdot \text{SiO}_2$)	0.0004
Cordierite ($2\text{MgO} \cdot 2\text{Al}_2\text{O}_3 \cdot 5\text{SiO}_2$)	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 dielectric material.
- The loss tangents of some common dielectrics are listed here.

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Dielectric Strength

- Dielectric materials are insulators (conduction cannot generally occur).
- However, under certain conditions, dielectric materials can break down and conduct a significant current.
- Generally, the lattice of a dielectric has sufficient strength to absorb the energy from impacting electrons that are accelerated by the applied electric field.
- However, under a sufficiently large electric field, some electrons present in the dielectric will have sufficient kinetic energy to ionize the lattice atoms causing an avalanching effect.
- As a result, the dielectric will begin to conduct a significant amount of current.

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Dielectric Strength

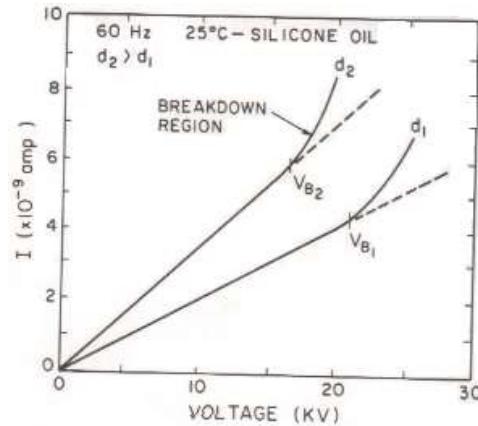
- This phenomenon is called dielectric breakdown and the corresponding field intensity is referred to as the dielectric breakdown strength.
- Dielectric strength may be defined as the maximum potential gradient to which a material can be subjected without insulating breakdown, that is

$$DS = \left(\frac{dV}{dx} \right)_{\max} = \frac{V_B}{d}$$

where DS is the dielectric strength in kV/mm,

V_B the breakdown voltage, and d the thickness.

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Current-voltage characteristic up to breakdown for a typical dielectric materials

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Dielectric Strength

- Dielectric strength depends on
 - material homogeneity,
 - specimen geometry,
 - electrode shape and disposition,
 - stress mode (ac, dc or pulsed) and
 - ambient condition.

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Properties of ceramics with low permittivity and low losses

Typical properties of dielectric ceramics

Material	ϵ_r	$\tan \delta/10^{-4}$ at 1 MHz	α_L/MK^{-1} at 20–1000 °C	$\lambda/\text{Wm}^{-1}\text{K}^{-1}$ at 25 °C
'Low-loss' steatite	6.1	7	8.9	3
Cordierite	5.7	80	2.9	2
Forsterite	6.4	2	10.7	3
96Al ₂ O ₃	9.7	3	8.2	35
99.5BeO	6.8	2	8.8	250
AlN	8.8	5–10	4.5	100
Glass	4–15	2–22	0.8–9	[0.6–1.5]

Material	Applications
Steatite	Porcelain insulators
Cordierite	Has low thermal expansion . Applications requiring good thermal shock resistance . Supports for high-power wire-wound resistors.
Alumina	Best compromise of dielectric losses, high mechanical strength, high thermal conductivity. Reliable metal-ceramic joining technology (MolyMn) available.
Beryllia	Good properties, very high thermal conductivity , expensive and difficult processing. Insulating parts in high-power electromagnetic energy generation (klystrons and magnetotrons).
AlN	High thermal conductivity and TEC close to that of silicon . Substrate for power electronic circuits and chips.
Glass & glass-ceramics	Cheap material and easy processing. Low thermal conductivity

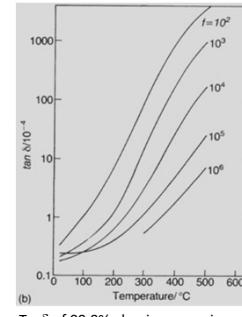
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Properties of ceramics with low permittivity and low losses

Typical properties of alumina ceramics

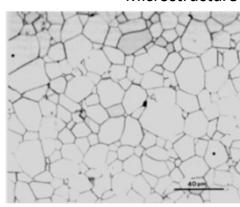
Alumina content/%	85	90	96 9.0–9.3	99.5	99.9 9.8–10.1
ϵ_r at 1 MHz	8.2	8.8	1–3	9.7	0.4–2
$\tan \delta/10^{-4}$ at 1 MHz	9	4	1–3	3	0.4–2
Resistivity/ Ωm at 300 °C	4.6×10^8	1.4×10^9	3.1×10^9	2.0×10^9	1.0×10^{13}
Thermal conductivity/ $\text{W m}^{-1}\text{K}^{-1}$ at 20 °C	14	16	24–35	35	40

Spark plugs

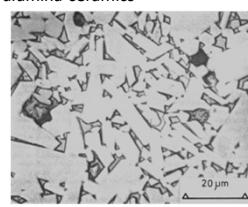


Tan δ of 99.9% alumina ceramics

Microstructure of alumina ceramics



99.9% Al₂O₃



96% Al₂O₃

Insulating parts in high-power electromagnetic generation. Windows for high-power microwave generators. Substrates for electronic circuits. Cheap packaging.

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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.

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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.

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Dielectric Breakdown

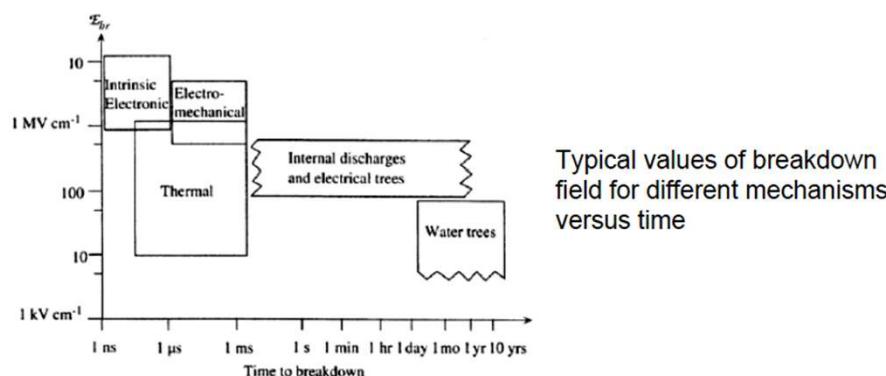
When a dielectric is subjected to an ever-increasing electric field, at some point a short circuit develops across it. **Dielectric breakdown** is defined as the voltage gradient or electric field sufficient to cause the short circuit. This phenomenon depends on many factors, such as sample thickness, temperature, electrode composition and shape, and porosity.

In ceramics, there are two basic types of breakdown: intrinsic and thermal.

- *Intrinsic*. In this mechanism, electrons in the conduction band are accelerated to such a point that they start to ionize lattice ions. As more ions are ionized and the number of free electrons increases, an avalanche effect is created. Clearly, the higher the electric field applied, the faster the electrons will be accelerated and the more likely this breakdown mechanism will be.
- *Thermal breakdown*. The criterion for thermal breakdown is that the rate of heat generation in the dielectric, as a result of losses, must be greater than the rate of heat removal from the sample. Whenever this condition occurs the dielectric will heat up, which in turn will increase its conductivity, which causes further heating, etc. This is termed *thermal breakdown* or *thermal runaway*.

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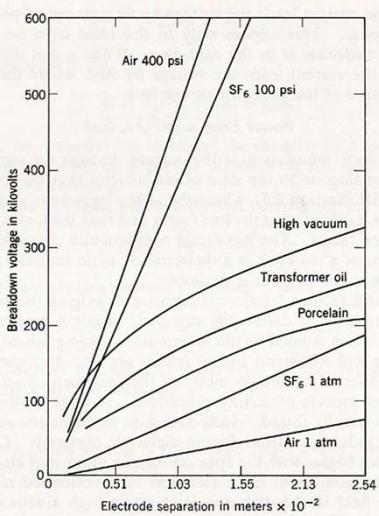
Dielectric Breakdown



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

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Dielectric Strength



Sulphur hexafluoride (SF₆) is the most common insulation gas in high voltage technology because of the electron attachment (electron affinity) SF₆ has a three times higher dielectric strength at 0.1 MPa compared to air.

Figure 12.2 D-c breakdown or dielectric strength of various solids, liquids, gases and vacuum, in uniform fields. Breakdown voltage versus dielectric thickness is plotted. (From J. Trump, in A. von Hippel, *Dielectric Materials and Application*: Wiley, New York, 1954.)

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