Chapter 8: Dielectrical Behavior

A dielectric material is one that is electrically **insulating** (nonmetallic) and exhibits or may be made to exhibit an "**electric dipole structure**".

•**Dipol:** A separation of positive and negative electrically charged entities on a molecular or atomic level.

•As a result of dipole interactions with electric fields, dielectric materials are utilized in **capacitors**.

Figure: Examples of various types of capacitors.

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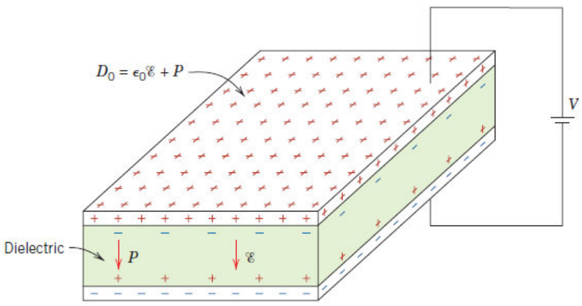
Capacitance:

•When a voltage is applied across a capacitor, one plate becomes positively charged, the other negatively charged, with the corresponding electric field directed from the positive to the negative.



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•The capacitance **C** is related to the quantity of charge stored on either plate.

Capacitance

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

Quantitiy of charge stored on either plate

(Coulombs/Volt or Farads (F))

Voltage applied across the capacitor

A parallel-plate capacitor with **a vacuum in the region** between the plates

Permittivity (8.85x10^{-12} F/m)

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

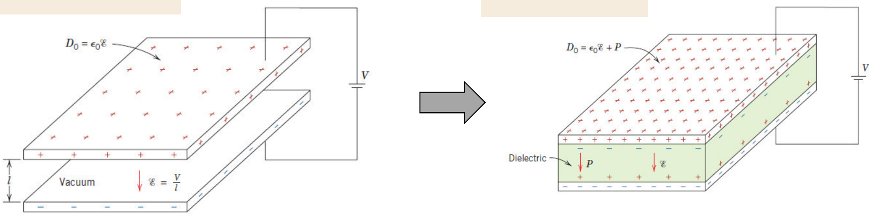
Area

Distance

A parallel-plate capacitor with **a dielectric material** inserted between the plates

Permittivity of dielectric medium

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



Relative permittivity = Dielectric constant = $\epsilon_r = \frac{\epsilon}{\epsilon_0}$

•**Dielectric constant** represents the increase in charge storing capacity by insertion of the dielectric medium between the plates.
•The dielectric constant is one material property that is of prime consideration for capacitor design.

•The ε_r values of a number of dielectric materials:

Material	*Dielectric Constant* 60 Hz	*Dielectric Constant* 1 MHz
	Ceramics	
Titanate ceramics	—	15–10,000
Mica	—	5.4–8.7
Steatite ($MgO-SiO_2$)	—	5.5–7.5
Soda–lime glass	6.9	6.9
Porcelain	6.0	6.0
Fused silica	4.0	3.8
	Polymers	
Phenol-formaldehyde	5.3	4.8
Nylon 6,6	4.0	3.6
Polystyrene	2.6	2.6
Polyethylene	2.3	2.3
Polytetrafluoroethylene	2.1	2.1

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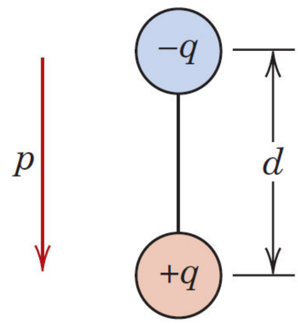
Polarization:

•For every electric dipole there is a separation between a positive and a negative electric charge.

•A **dipole moment (p)** is a vector that is directed from the negative to the positive charge.

$$p = qd$$

Magnitude of each dipole charge



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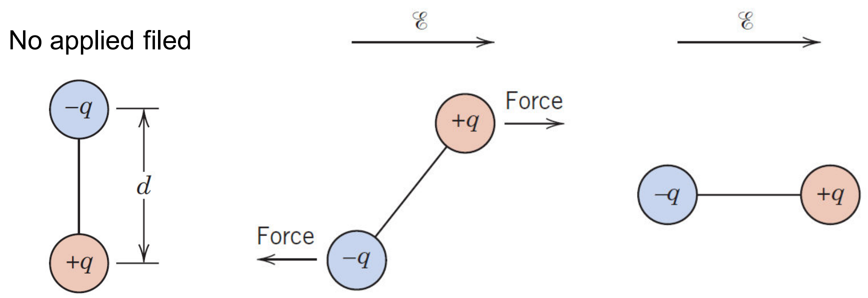
Polarization:

•In the presence of an electric field (ε) which is also a vector quantity, a force (or torque) will come to bear on an electric dipole to orient it with the applied field.

•The process of dipole alignment is termed **polarization.**



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•The **surface charge density** (dielectric displacement) D, or *quantity of charge per unit area of capacitor plate* (C/m²), is proportional to the electric field:

A parallel-plate capacitor with **a vacuum in the region** between the plates ⇒ $D_0 = \epsilon_0 \mathscr{E}$

A parallel-plate capacitor with **a dielectric material** between the plates ⇒ $D = \epsilon \mathscr{E}$

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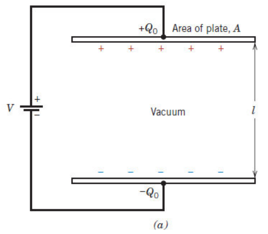
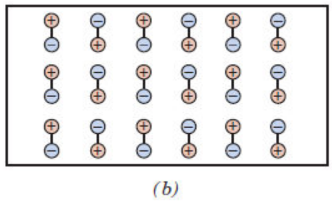
(**a**) The charge stored on capacitor plates for a vacuum

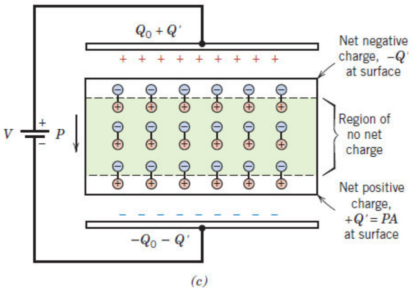


(**b**) Dipole arrangement in an **unpolarized** dielectric material (***rondom***)



(**c**) The increased charge storing capacity resulting from the polarization of a dielectric material.

$$D = \epsilon_0 \mathscr{E} + \boxed{P}$$



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Types of Polarization:

(P_i): Ionic Polarization

(P_e): Electronic Polarization

(P_o): Orientation Polarization

$$P = P_e + P_i + P_o$$

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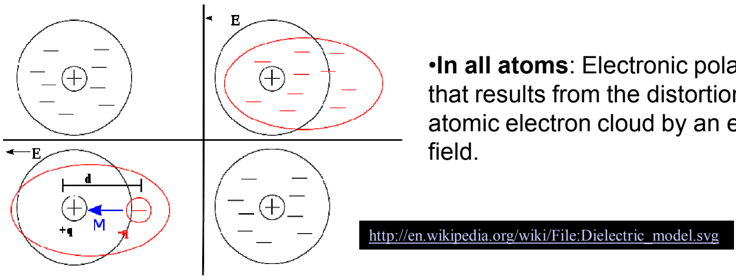
(P_e): Electronic Polarization



•**In all atoms**: Electronic polarization that results from the distortion of an atomic electron cloud by an electric field.

•Electronic polarization may be induced to one degree or another in all atoms.

•It results from a displacement of the center of the negatively charged electron cloud relative to the positive nucleus of an atom by the electric field.

•This polarization type is found in all dielectric materials and, of course, exists only while an electric field is present.

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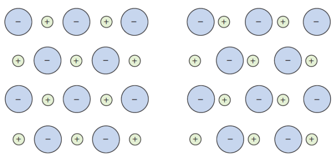
(P_i): Ionic Polarization



•**Materials that are ionic**: Ionic polarization that results from the relative displacements of electrically charged ions in response to an electric field

•Ionic polarization occurs only in materials that are ionic.

•An applied field acts to displace cations in one direction and anions in the opposite direction, which gives rise to a net dipole moment.

•The magnitude of the dipole moment for each ion pair (p_i) is equal to the product of the relative displacement (d_i) and the charge on each ion:

$$p_i = qd_i$$

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(P_o): Orientation Polarization:

•**Substances that have permanent dipole moments**: Response of permanent electric dipoles (arrows) to an applied electric field, producing orientation polarization.

•Orientation polarization, is found only in substances that possess permanent dipole moments.

•Polarization results from a rotation of the permanent moments into the direction of the applied field.

•This alignment tendency is neutralized by the thermal vibrations of the atoms, such that <u>polarization decreases with increasing temperature</u>.

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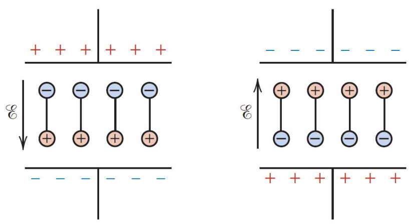
Frequency Dependence of Polarization:

•In many practical situations the current is alternating (AC); that is, an applied voltage or electric field changes direction with time.



(a) (b)

•With each direction reversal, the dipoles attempt to reorient with the field in a process <u>requiring some finite time</u>.

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Frequency Dependence of Polarization:

•For each polarization type, some minimum reorientation time exists, which depends on the ease with which the particular dipoles are capable of realignment.

•A **relaxation frequency** is taken as the reciprocal of this minimum reorientation time.

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Frequency Dependence of Polarization:

•A dipole **cannot** keep shifting orientation direction when the frequency of the applied electric field exceeds its relaxation frequency.

•Therefore, will not make a contribution to the dielectric constant.

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

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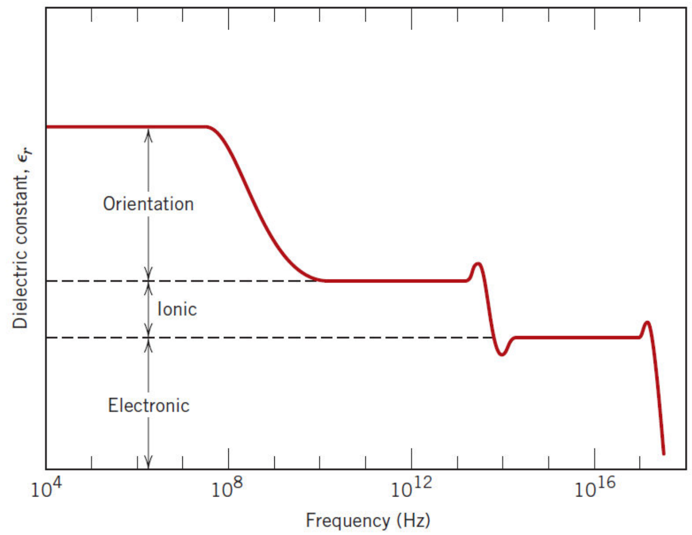
Frequency Dependence of Polarization:



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Dielectric Strength (Breakdown Strength):

•The **dielectric strength**, represents the magnitude of an electric field (E_{cr}) necessary to produce breakdown:

$$E_{applied} > E_{cr}$$

•When very high electric fields are applied across dielectric materials, large numbers of electrons may suddenly be excited to energies within the conduction band.
•The current through the dielectric material by the motion of these electrons increases dramatically:
•**Localized melting**, **burning**, or **vaporization** produces <u>irreversible degradation</u> or even <u>failure of the material</u>.

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Dielectric Materials:

•A number of ceramics and polymers are utilized as insulators and/or in capacitors.

•Many of the ceramics, including **glass**, **porcelain**, **steatite**, and **mica**, have dielectric constants within the range of 6 to 10. These materials also exhibit a high degree of dimensional stability and mechanical strength. Typical applications include powerline and electrical insulation, switch bases, and light receptacles.

•The **titania** (TiO_2) and **titanate ceramics**, such as barium titanate ($BaTiO_3$), can be made to have extremely high dielectric constants (especially useful for some capacitor applications).

•The magnitude of the dielectric constant for most **polymers** is less than for ceramics (lie between 2 and 5).These materials are commonly utilized for insulation of wires, cables, motors, generators, and so on, and, in addition, for some capacitors.

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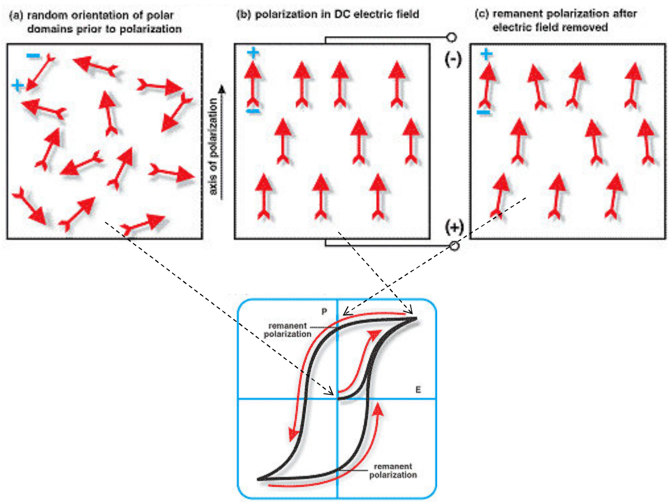
Ferroelectricity:

•Exhibit spontaneous polarization—that is, polarization in the absence of an electric field.



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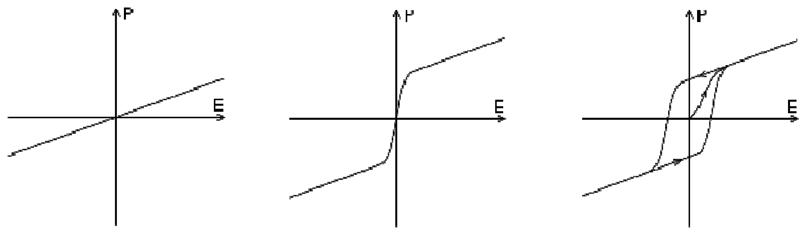
Ferroelectricity:



Dielectric polarization | Paraelectric polarization | Ferroelectric polarization

The distinguishing feature of "**ferroelectrics**" is that the direction of the spontaneous polarization can be reversed by an applied electric field, yielding a **hysteresis loop**.

http://en.wikipedia.org/wiki/Ferroelectricity

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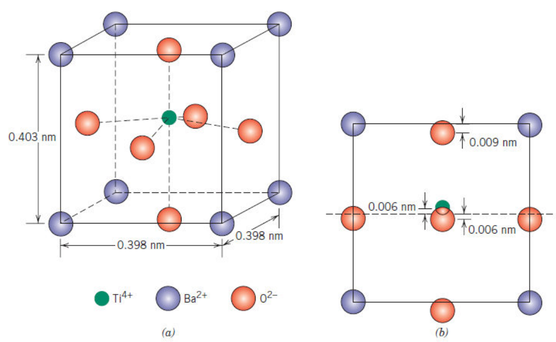
Ferroelectricity:

•Barium titanate ($BaTiO_3$), one of the most common ferroelectrics. The spontaneous polarization is a consequence of the positioning of the Ba^{2+}, Ti^{4+} and O^{2-} ions within the unit cell.



•The dipole moment results from the <u>relative displacements of the O^{2-} and Ti^{4+} ions</u> from their symmetrical positions.

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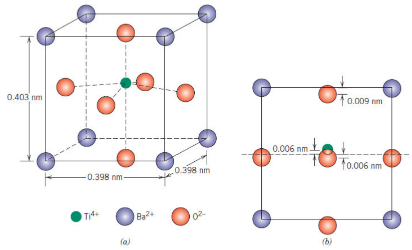
Ferroelectricity:

•When $BaTiO_3$ is heated above its ferroelectric *Curie* temperature [120ºC], the unit cell becomes cubic, and all ions assume symmetric positions within the cubic unit cell; and the ferroelectric behavior disappears.



•Rochelle salt ($NaKC_4H_4O_6.4H_2O$)
•Potassium dihydrogen phosphate (KH_2PO_4)
•Potassium niobate ($KNbO_3$)
•Lead zirconate–titanate ($PbZrO_3$, $PbTiO_3$)

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Ferroelectricity:

•Ferroelectrics have extremely high dielectric constants at relatively low applied field frequencies.

•At room temperature, dielectric constant for $BaTiO_3$ may be as high as **5000**.

• Consequently, capacitors made from these materials can be significantly smaller than capacitors made from other dielectric materials.

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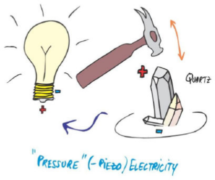
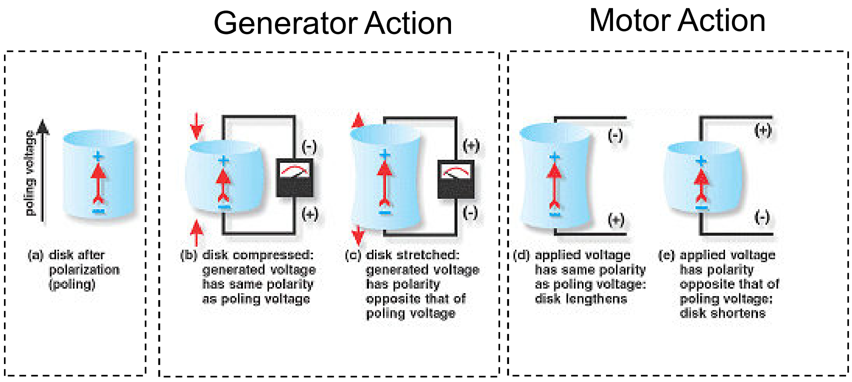
Piezoelectricity:

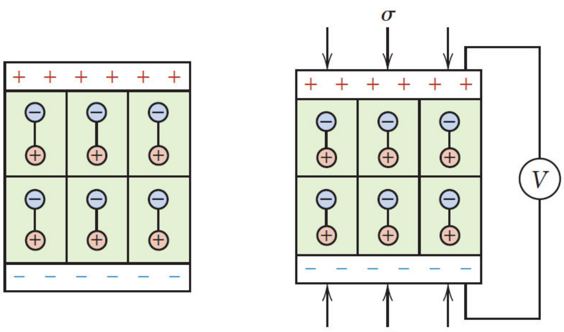


•An unusual property exhibited by a few ceramic materials is piezoelectricity, or, literally, *pressure electricity*.



Piezoelectricity:

•Polarization is induced and an electric field is established across a specimen by the application of external forces.
• Reversing the sign of an external force (i.e., from tension to compression) reverses the direction of the field.



(a) (b)

Piezoelectricity:

•Piezoelectric materials are utilized in transducers, which are devices that convert electrical energy into mechanical strains, or vice versa.

•Some other familiar applications:

- •Phonograph cartridges,
- •Microphones,
- •Speakers,
- •Audible alarms, and
- •Ultrasonic imaging.