

leadframe, which in turn is bonded to a printed circuit board. Enlarged photographs of microprocessor chips at different magnifications are presented in Figures 18.27a and 18.27b; these micrographs reveal the intricacy of integrated circuits. At this time, microprocessor chips approaching one billion transistors are being produced, and this number doubles about every 18 months.

Microelectronic circuits consist of many layers that lie within or are stacked on top of the silicon wafer in a precisely detailed pattern. Using photolithographic techniques, for each layer, very small elements are masked in accordance with a microscopic pattern. Circuit elements are constructed by the selective introduction of specific materials (by diffusion or ion implantation) into unmasked regions to create localized *n*-type, *p*-type, high-resistivity, or conductive areas. This procedure is repeated layer by layer until the total integrated circuit has been fabricated, as illustrated in the MOSFET schematic (Figure 18.26). Elements of integrated circuits are shown in Figure 18.27 and in the chapter-opening photographs for this chapter.

Case Study:
“Materials for Integrated Circuit Packages,” Chapter 22, which may be found at www.wiley.com/college/callister (Student Companion Site).

Electrical Conduction in Ionic Ceramics and in Polymers

Most polymers and ionic ceramics are insulating materials at room temperature and, therefore, have electron energy band structures similar to that represented in Figure 18.4c; a filled valence band is separated from an empty conduction band by a relatively large band gap, usually greater than 2 eV. Thus, at normal temperatures only very few electrons may be excited across the band gap by the available thermal energy, which accounts for the very small values of conductivity; Table 18.4

Table 18.4 Typical Room-Temperature Electrical Conductivities for 13 Nonmetallic Materials

Material	Electrical Conductivity [(Ω·m) ^{−1}]
Graphite	3 × 10 ⁴ –2 × 10 ⁵
<i>Ceramics</i>	
Concrete (dry)	10 ^{−9}
Soda–lime glass	10 ^{−10} –10 ^{−11}
Porcelain	10 ^{−10} –10 ^{−12}
Borosilicate glass	~ 10 ^{−13}
Aluminum oxide	<10 ^{−13}
Fused silica	<10 ^{−18}
<i>Polymers</i>	
Phenol-formaldehyde	10 ^{−9} –10 ^{−10}
Poly(methyl methacrylate)	<10 ^{−12}
Nylon 6,6	10 ^{−12} –10 ^{−13}
Polystyrene	<10 ^{−14}
Polyethylene	10 ^{−15} –10 ^{−17}
Polytetrafluoroethylene	<10 ^{−17}

gives the room-temperature electrical conductivities of several of these materials. (The electrical resistivities of a large number of ceramic and polymeric materials are provided in Table B.9, Appendix B.) Of course, many materials are utilized on the basis of their ability to insulate, and thus a high electrical resistivity is desirable. With rising temperature, insulating materials experience an increase in electrical conductivity, which may ultimately be greater than that for semiconductors.

18.16 CONDUCTION IN IONIC MATERIALS

Both cations and anions in ionic materials possess an electric charge and, as a consequence, are capable of migration or diffusion when an electric field is present. Thus an electric current will result from the net movement of these charged ions, which will be present in addition to current due to any electron motion. Of course, anion and cation migrations will be in opposite directions. The total conductivity of an ionic material σ_{total} is thus equal to the sum of both electronic and ionic contributions, as follows:

$$\sigma_{\text{total}} = \sigma_{\text{electronic}} + \sigma_{\text{ionic}} \tag{18.22}$$

Either contribution may predominate depending on the material, its purity, and, of course, temperature.

A mobility μ_I may be associated with each of the ionic species as follows:

$$\mu_I = \frac{n_I e D_I}{kT} \tag{18.23}$$

where n_I and D_I represent, respectively, the valence and diffusion coefficient of a particular ion; e , k , and T denote the same parameters as explained earlier in the chapter. Thus, the ionic contribution to the total conductivity increases with increasing temperature, as does the electronic component. However, in spite of the two conductivity contributions, most ionic materials remain insulative, even at elevated temperatures.

18.17 ELECTRICAL PROPERTIES OF POLYMERS

Most polymeric materials are poor conductors of electricity (Table 18.4) because of the unavailability of large numbers of free electrons to participate in the conduction process. The mechanism of electrical conduction in these materials is not well understood, but it is felt that conduction in polymers of high purity is electronic.

Conducting Polymers

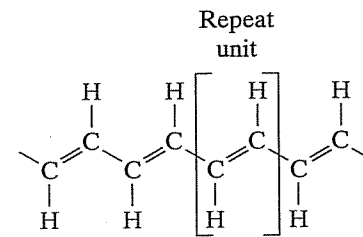
Within the past several years, polymeric materials have been synthesized that have electrical conductivities on par with metallic conductors; they are appropriately termed *conducting polymers*. Conductivities as high as 1.5 × 10⁷ (Ω·m)^{−1} have been achieved in these materials; on a volume basis, this value corresponds to one-fourth of the conductivity of copper, or twice its conductivity on the basis of weight.

This phenomenon is observed in a dozen or so polymers, including polyacetylene, polyparaphenylene, polypyrrole, and polyaniline. Each of these polymers contains a system of alternating single and double bonds and/or aromatic

For ionic materials, conductivity is equal to the sum of electronic and ionic contributions

Computation of mobility for an ionic species

units in the polymer chain. For example, the chain structure of polyacetylene is as follows:



The valence electrons associated with the alternating single and double chain-bonds are delocalized, which means they are shared amongst the backbone atoms in the polymer chain—similar to the way that electrons in a partially filled band for a metal are shared by the ion cores. In addition, the band structure of a conductive polymer is characteristic of that for an electrical insulator (Figure 18.4c)—viz. at 0 K, a filled valence band separated from an empty conduction band by a forbidden energy band gap. These polymers become conductive when doped with appropriate impurities such as AsF₅, SbF₅, or iodine. As with semiconductors, conducting polymers may be made either *n*-type (i.e., free-electron dominant) or *p*-type (i.e., hole dominant) depending on the dopant. However, unlike semiconductors, the dopant atoms or molecules do not substitute for or replace any of the polymer atoms.

The mechanism by which large numbers of free electrons and holes are generated in these conducting polymers is complex and not well understood. In very simple terms, it appears that the dopant atoms lead to the formation of new energy bands that overlap the valence and conduction bands of the intrinsic polymer, giving rise to a partially filled band, and the production at room temperature of a high concentration of free electrons or holes. Orienting the polymer chains, either mechanically (Section 15.7) or magnetically, during synthesis results in a highly anisotropic material having a maximum conductivity along the direction of orientation.

These conducting polymers have the potential to be used in a host of applications inasmuch as they have low densities, are highly flexible, and are easy to produce. Rechargeable batteries and fuel cells are currently being manufactured that employ polymer electrodes. In many respects these batteries are superior to their metallic counterparts. Other possible applications include wiring in aircraft and aerospace components, antistatic coatings for clothing, electromagnetic screening materials, and electronic devices (e.g., transistors and diodes).

Dielectric Behavior

dielectric
electric dipole

A **dielectric** material is one that is electrically insulating (nonmetallic) and exhibits or may be made to exhibit an **electric dipole** structure; that is, there is a separation of positive and negative electrically charged entities on a molecular or atomic level. This concept of an electric dipole was introduced in Section 2.7. As a result of dipole interactions with electric fields, dielectric materials are utilized in capacitors.

18.18 CAPACITANCE

capacitance

Capacitance in terms of stored charge and applied voltage

$$C = \frac{Q}{V} \quad (18.24)$$

Capacitance (for parallel-plate capacitor, in a vacuum)—dependence on permittivity of a vacuum, and plate area and separation distance

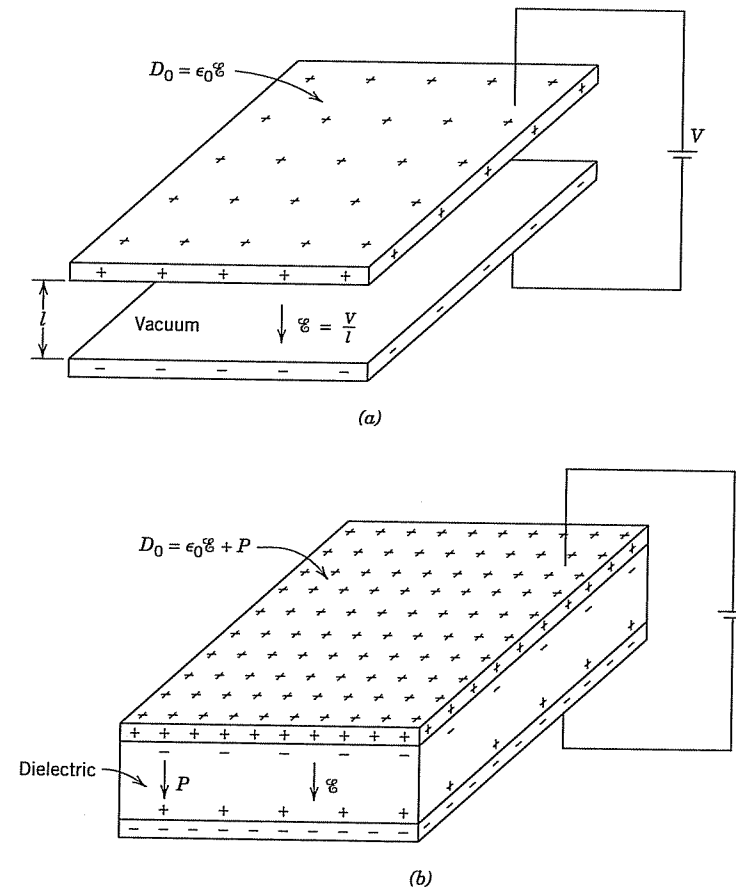
When a voltage is applied across a capacitor, one plate becomes positively charged, the other negatively charged, with the corresponding electric field directed from the positive to the negative. The **capacitance** *C* is related to the quantity of charge stored on either plate *Q* by⁹

where *V* is the voltage applied across the capacitor. The units of capacitance are coulombs per volt, or farads (F).

Now, consider a parallel-plate capacitor with a vacuum in the region between the plates (Figure 18.28a). The capacitance may be computed from the relationship

$$C = \epsilon_0 \frac{A}{l} \quad (18.25)$$

Figure 18.28 A parallel-plate capacitor (a) when a vacuum is present and (b) when a dielectric material is present. (From K. M. Ralls, T. H. Courtney, and J. Wulff, *Introduction to Materials Science and Engineering*. Copyright © 1976 by John Wiley & Sons, Inc. Reprinted by permission of John Wiley & Sons, Inc.)



⁹ By convention, the uppercase “C” is used to represent both capacitance and the unit of charge, coulomb. To minimize confusion in this discussion, the capacitance designation will be italicized, as *C*.

Table 18.5 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
Steatite (MgO–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.

where A represents the area of the plates and l is the distance between them. The parameter ϵ_0 , called the **permittivity** of a vacuum, is a universal constant having the value of 8.85×10^{-12} F/m.

If a dielectric material is inserted into the region within the plates (Figure 18.28b), then

$$C = \epsilon \frac{A}{l} \tag{18.26}$$

where ϵ is the permittivity of this dielectric medium, which will be greater in magnitude than ϵ_0 . The relative permittivity ϵ_r , often called the **dielectric constant**, is equal to the ratio

$$\epsilon_r = \frac{\epsilon}{\epsilon_0} \tag{18.27}$$

which is greater than unity and 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 are contained in Table 18.5.

18.19 FIELD VECTORS AND POLARIZATION

Perhaps the best approach to an explanation of the phenomenon of capacitance is with the aid of field vectors. To begin, for every electric dipole there is a separation between a positive and a negative electric charge as demonstrated in Figure 18.29. An electric dipole moment p is associated with each dipole as follows:

$$p = qd \tag{18.28}$$

where q is the magnitude of each dipole charge and d is the distance of separation between them. In reality, a dipole moment is a vector that is directed from

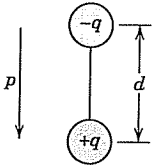


Figure 18.29 Schematic representation of an electric dipole generated by two electric charges (of magnitude q) separated by the distance d ; the associated polarization vector p is also shown.

the negative to the positive charge, as indicated in Figure 18.29. In the presence of an electric field \mathcal{E} , 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; this phenomenon is illustrated in Figure 18.30. The process of dipole alignment is termed **polarization**.

Again, returning to the capacitor, the surface charge density D , or quantity of charge per unit area of capacitor plate (C/m^2), is proportional to the electric field. When a vacuum is present, then

$$D_0 = \epsilon_0 \mathcal{E} \tag{18.29}$$

the constant of proportionality being ϵ_0 . Furthermore, an analogous expression exists for the dielectric case; that is,

$$D = \epsilon \mathcal{E} \tag{18.30}$$

Sometimes, D is also called the **dielectric displacement**.

The increase in capacitance, or dielectric constant, can be explained using a simplified model of polarization within a dielectric material. Consider the capacitor in Figure 18.31a, the vacuum situation, wherein a charge of $+Q_0$ is stored on the top plate and $-Q_0$ on the bottom one. When a dielectric is introduced and an electric field is applied, the entire solid within the plates becomes polarized (Figure 18.31c). As a result of this polarization, there is a net accumulation of negative charge of magnitude $-Q'$ at the dielectric surface near the positively charged plate and, in a similar manner, a surplus of $+Q'$ charge at the surface adjacent to the negative plate. For the region of dielectric removed from these surfaces, polarization effects are not important. Thus, if each plate and its adjacent dielectric surface are considered to be a single entity, the induced charge from the dielectric ($+Q'$ or $-Q'$) may be thought of as nullifying some of the charge that originally existed on the plate for a vacuum ($-Q_0$ or $+Q_0$). The voltage imposed across the plates is maintained at the vacuum value by increasing the charge at the negative (or bottom) plate by an amount $-Q'$, and the top plate by $+Q'$. Electrons are caused to flow from the positive to the negative plate by the external voltage source such that the proper voltage is reestablished. And so the charge on each plate is now $Q_0 + Q'$, having been increased by an amount Q' .

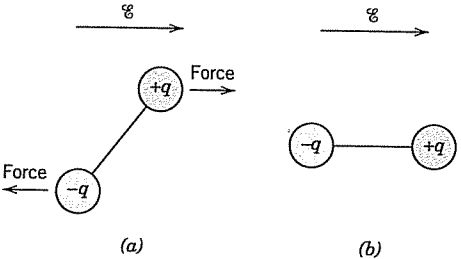


Figure 18.30 (a) Imposed forces (and torque) acting on a dipole by an electric field. (b) Final dipole alignment with the field.

permittivity
 Capacitance (for parallel-plate capacitor, with dielectric material)—dependence on permittivity of the material, and plate area and separation distance
 dielectric constant
 Definition of dielectric constant

polarization
 Dielectric displacement (surface charge density) in a vacuum
 Dielectric displacement when a dielectric medium is present
 dielectric displacement

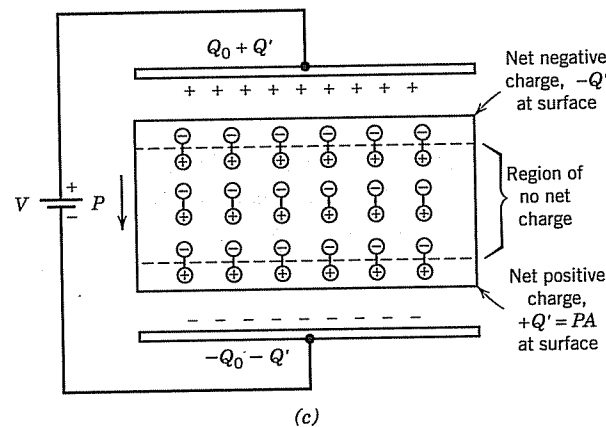
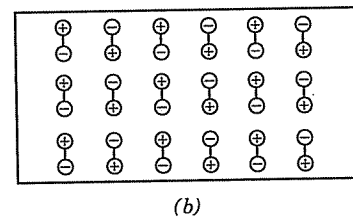
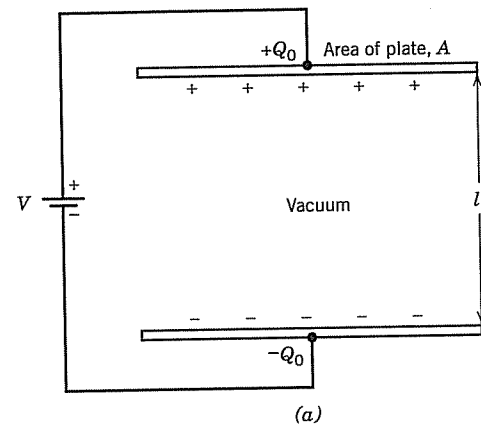


Figure 18.31 Schematic representations of (a) the charge stored on capacitor plates for a vacuum, (b) the dipole arrangement in an unpolarized dielectric, and (c) the increased charge storing capacity resulting from the polarization of a dielectric material. (Adapted from A. G. Guy, *Essentials of Materials Science*, McGraw-Hill Book Company, New York, 1976.)

In the presence of a dielectric, the surface charge density on the plates of a capacitor may also be represented by

$$D = \epsilon_0 \mathcal{E} + P \tag{18.31}$$

where P is the *polarization*, or the increase in charge density above that for a vacuum because of the presence of the dielectric; or, from Figure 18.31c, $P = Q'/A$, where A is the area of each plate. The units of P are the same as for D (C/m^2).

The polarization P may also be thought of as the total dipole moment per unit volume of the dielectric material, or as a polarization electric field within the dielectric that results from the mutual alignment of the many atomic or molecular

Polarization of a dielectric medium—dependence on dielectric constant and electric field intensity

Table 18.6 Primary and Derived Units for Various Electrical Parameters and Field Vectors

Quantity	Symbol	SI Units	
		Derived	Primary
Electric potential	V	volt	$kg\cdot m^2/s^2\cdot C$
Electric current	I	ampere	C/s
Electric field strength	\mathcal{E}	volt/meter	$kg\cdot m/s^2\cdot C$
Resistance	R	ohm	$kg\cdot m^2/s^2\cdot C^2$
Resistivity	ρ	ohm-meter	$kg\cdot m^3/s^2\cdot C^2$
Conductivity	σ	(ohm-meter) $^{-1}$	$s\cdot C^2/kg\cdot m^3$
Electric charge	Q	coulomb	C
Capacitance	C	farad	$s^2\cdot C^2/kg\cdot m^2$
Permittivity	ϵ	farad/meter	$s^2\cdot C^2/kg\cdot m^3$
Dielectric constant	ϵ_r	ratio	ratio
Dielectric displacement	D	farad-volt/ m^2	C/m^2
Electric polarization	P	farad-volt/ m^2	C/m^2

dipoles with the externally applied field \mathcal{E} . For many dielectric materials, P is proportional to \mathcal{E} through the relationship

$$P = \epsilon_0(\epsilon_r - 1)\mathcal{E} \tag{18.32}$$

in which case ϵ_r is independent of the magnitude of the electric field. Table 18.6 lists the several dielectric parameters along with their units.

EXAMPLE PROBLEM 18.5

Computations of Capacitor Properties

Consider a parallel-plate capacitor having an area of $6.45 \times 10^{-4} \text{ m}^2$ (1 in.²) and a plate separation of $2 \times 10^{-3} \text{ m}$ (0.08 in.) across which a potential of 10 V is applied. If a material having a dielectric constant of 6.0 is positioned within the region between the plates, compute

- (a) The capacitance.
- (b) The magnitude of the charge stored on each plate.
- (c) The dielectric displacement D .
- (d) The polarization.

Solution

(a) Capacitance is calculated using Equation 18.26; however, the permittivity ϵ of the dielectric medium must first be determined from Equation 18.27 as follows:

$$\begin{aligned} \epsilon &= \epsilon_r \epsilon_0 = (6.0)(8.85 \times 10^{-12} \text{ F/m}) \\ &= 5.31 \times 10^{-11} \text{ F/m} \end{aligned}$$

Thus, the capacitance is

$$\begin{aligned} C &= \epsilon \frac{A}{l} = (5.31 \times 10^{-11} \text{ F/m}) \left(\frac{6.45 \times 10^{-4} \text{ m}^2}{2 \times 10^{-3} \text{ m}} \right) \\ &= 1.71 \times 10^{-11} \text{ F} \end{aligned}$$

Dielectric displacement—dependence on electric field intensity and polarization (of dielectric medium)

(b) Since the capacitance has been determined, the charge stored may be computed using Equation 18.24, according to

$$Q = CV = (1.71 \times 10^{-11} \text{ F})(10 \text{ V}) = 1.71 \times 10^{-10} \text{ C}$$

(c) The dielectric displacement is calculated from Equation 18.30, which yields

$$D = \epsilon \mathcal{E} = \epsilon \frac{V}{l} = \frac{(5.31 \times 10^{-11} \text{ F/m})(10 \text{ V})}{2 \times 10^{-3} \text{ m}} \\ = 2.66 \times 10^{-7} \text{ C/m}^2$$

(d) Using Equation 18.31, the polarization may be determined as follows:

$$P = D - \epsilon_0 \mathcal{E} = D - \epsilon_0 \frac{V}{l} \\ = 2.66 \times 10^{-7} \text{ C/m}^2 - \frac{(8.85 \times 10^{-12} \text{ F/m})(10 \text{ V})}{2 \times 10^{-3} \text{ m}} \\ = 2.22 \times 10^{-7} \text{ C/m}^2$$

18.20 TYPES OF POLARIZATION

Again, polarization is the alignment of permanent or induced atomic or molecular dipole moments with an externally applied electric field. There are three types or sources of polarization: electronic, ionic, and orientation. Dielectric materials ordinarily exhibit at least one of these polarization types depending on the material and also the manner of the external field application.

Electronic Polarization

electronic
polarization

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 (Figure 18.32a). This polarization type is found in all dielectric materials and, of course, exists only while an electric field is present.

Ionic Polarization

ionic polarization

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. This phenomenon is illustrated in Figure 18.32b. 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, or

$$p_i = qd_i \quad (18.33)$$

Orientation Polarization

orientation
polarization

The third type, **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, as represented in Figure 18.32c. This alignment tendency is counteracted by the thermal vibrations of the atoms, such that polarization decreases with increasing temperature.

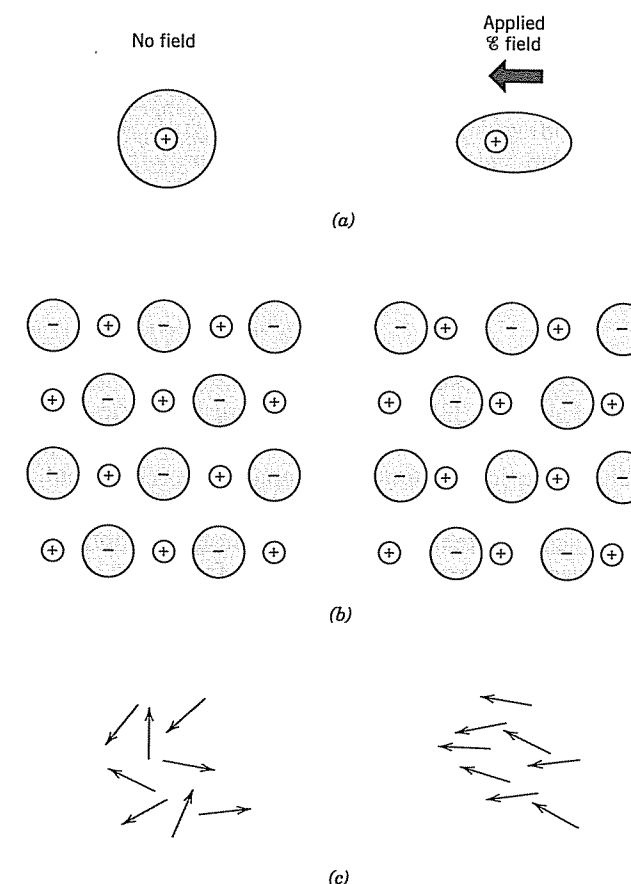


Figure 18.32 (a) Electronic polarization that results from the distortion of an atomic electron cloud by an electric field. (b) Ionic polarization that results from the relative displacements of electrically charged ions in response to an electric field. (c) Response of permanent electric dipoles (arrows) to an applied electric field, producing orientation polarization. (From O. H. Wyatt and D. Dew-Hughes, *Metals, Ceramics and Polymers*, Cambridge University Press, 1974.)

The total polarization P of a substance is equal to the sum of the electronic, ionic, and orientation polarizations (P_e , P_i , and P_o , respectively), or

$$P = P_e + P_i + P_o \quad (18.34)$$

Total polarization of a substance equals the sum of electronic, ionic, and orientation polarizations

It is possible for one or more of these contributions to the total polarization to be either absent or negligible in magnitude relative to the others. For example, ionic polarization will not exist in covalently bonded materials in which no ions are present.

✓ Concept Check 18.9

For solid lead titanate (PbTiO_3) what kind(s) of polarization is (are) possible? Why? *Note:* lead titanate has the same crystal structure as barium titanate (Figure 18.35).

[The answer may be found at www.wiley.com/college/callister (Student Companion Site).]

18.21 FREQUENCY DEPENDENCE OF THE DIELECTRIC CONSTANT

In many practical situations the current is alternating (ac); that is, an applied voltage or electric field changes direction with time, as indicated in Figure 18.23a. Now consider a dielectric material that is subject to polarization by an ac electric field.

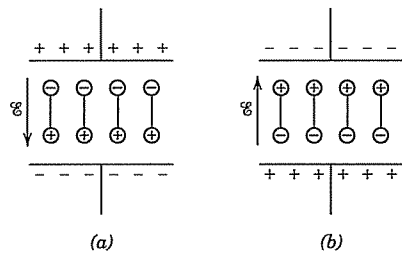


Figure 18.33 Dipole orientations for (a) one polarity of an alternating electric field and (b) for the reversed polarity. (From Richard A. Flinn and Paul K. Trojan, *Engineering Materials and Their Applications*, 4th edition. Copyright © 1990 by John Wiley & Sons, Inc. Adapted by permission of John Wiley & Sons, Inc.)

With each direction reversal, the dipoles attempt to reorient with the field, as illustrated in Figure 18.33, in a process requiring some finite time. 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.

relaxation frequency

A dipole cannot keep shifting orientation direction when the frequency of the applied electric field exceeds its relaxation frequency and, therefore, will not make a contribution to the dielectric constant. The dependence of ϵ_r on the field frequency is represented schematically in Figure 18.34 for a dielectric medium that exhibits all three types of polarization; note that the frequency axis is scaled logarithmically. As indicated in Figure 18.34, when a polarization mechanism ceases to function, there is an abrupt drop in the dielectric constant; otherwise, ϵ_r is virtually frequency independent. Table 18.5 gave values of the dielectric constant at 60 Hz and 1 MHz; these provide an indication of this frequency dependence at the low end of the frequency spectrum.

The absorption of electrical energy by a dielectric material that is subjected to an alternating electric field is termed *dielectric loss*. This loss may be important at electric field frequencies in the vicinity of the relaxation frequency for each of the operative dipole types for a specific material. A low dielectric loss is desired at the frequency of utilization.

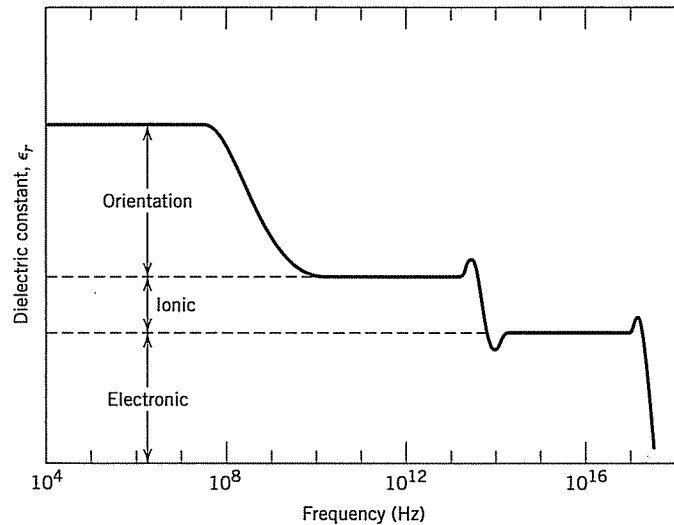


Figure 18.34 Variation of dielectric constant with frequency of an alternating electric field. Electronic, ionic, and orientation polarization contributions to the dielectric constant are indicated.

18.22 DIELECTRIC STRENGTH

dielectric strength

When very high electric fields are applied across dielectric materials, large numbers of electrons may suddenly be excited to energies within the conduction band. As a result, the current through the dielectric by the motion of these electrons increases dramatically; sometimes localized melting, burning, or vaporization produces irreversible degradation and perhaps even failure of the material. This phenomenon is known as dielectric breakdown. The **dielectric strength**, sometimes called the breakdown strength, represents the magnitude of an electric field necessary to produce breakdown. Table 18.5 presented dielectric strengths for several materials.

18.23 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 (Table 18.5). 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, which render them especially useful for some capacitor applications.

The magnitude of the dielectric constant for most polymers is less than for ceramics, since the latter may exhibit greater dipole moments: ϵ_r values for polymers generally 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.

Other Electrical Characteristics of Materials

Two other relatively important and novel electrical characteristics that are found in some materials deserve brief mention—namely, ferroelectricity and piezoelectricity.

18.24 FERROELECTRICITY

ferroelectric

The group of dielectric materials called **ferroelectrics** exhibit spontaneous polarization—that is, polarization in the absence of an electric field. They are the dielectric analogue of ferromagnetic materials, which may display permanent magnetic behavior. There must exist in ferroelectric materials permanent electric dipoles, the origin of which is explained for barium titanate, 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, as represented in Figure 18.35. The Ba^{2+} ions are located at the corners of the unit cell, which is of tetragonal symmetry (a cube that has been elongated slightly in one direction). The dipole moment results from the relative displacements of the O^{2-} and Ti^{4+} ions from their symmetrical positions as shown in the side view of the unit cell. The O^{2-} ions are located near, but slightly below, the centers of each of the six faces, whereas the Ti^{4+} ion is displaced upward from the unit cell center. Thus, a permanent ionic dipole moment is associated with each unit cell (Figure 18.35b). However, when barium titanate is heated above its *ferroelectric Curie temperature* [120°C (250°F)], the unit cell becomes cubic, and all ions assume symmetric positions within the cubic unit cell; the material now has a perovskite crystal structure (Section 12.2), and the ferroelectric behavior ceases.