Chapter

Electronic Materials

Have You Ever Wondered?

- Is diamond a good conductor of electricity?
- How many devices are there in a single microchip?
- How are thin films less than 1 micron thick deposited on a substrate?
- How does a microwave oven heat food?

ilicon-based microelectronics are a ubiquitous part of modern life. With microchips in items from laundry machines and microwaves to cell phones, in MP3 players and from personal computers to the world's fastest super computers, silicon was the defining material of the later 20th century and will dominate computer-based and information-related technologies for the foreseeable future.

While silicon is the substrate or base material of choice for most devices, microelectronics include materials of nearly every class, including metals such as copper and gold, other semiconductors such as gallium arsenide, and insulators such as silicon dioxide. Even semiconducting polymers are finding applications in such devices as light-emitting diodes.

In this chapter, we will discuss the principles of electrical conductivity in metals, semiconductors, insulators, and ionic materials. We will see that a defining difference between metals and semiconductors is that as temperature increases, the resistivity of a metal increases, while the resistivity of a semiconductor decreases. This critical difference arises from the **band structure** of these materials. The band structure consists of the array of energy levels that are available to or forbidden for electrons to occupy and determines the electronic behavior of a solid, such as whether it is a conductor, semiconductor, or insulator. The conductivity of a semiconductor that does not contain impurities generally increases exponentially with temperature. From a reliability standpoint, an exponential dependence of conductivity on temperature is undesirable for electronic devices that generate heat as they operate. Thus, semiconductors are doped (i.e., impurities are intentionally added) in order to control the conductivity of semiconductors with extreme precision. We will learn how **dopants** change the band structure of a semiconductor so that the electrical conductivity can be tailored for particular applications.

Metals, semiconductors, and insulators are all critical components of integrated circuits. Some features of integrated circuits are now approaching atomic-scale dimensions, and the fabrication of integrated circuits is arguably the most sophisticated manufacturing process in existence. It involves simultaneously fabricating hundreds of millions, and even billions, of devices on a single microchip and represents a fundamentally different manufacturing paradigm from that of any other process. We will learn about some of the steps involved in fabricating integrated circuits, including the process of depositing thin films (films on the order of 10 Å to 1 μ m in thickness).

We will examine some of the properties of insulating materials. Insulators are used in microelectronic devices to electrically isolate active regions from one another. Insulators are also used in capacitors due to their dielectric properties. Finally, we will consider piezoelectric materials, which change their shape in response to an applied voltage or vice versa. Such materials are used as actuators in a variety of applications.

Superconductors comprise a special class of electronic materials. Superconductors are materials that exhibit zero electrical resistance under certain conditions (which usually includes a very low temperature on the order of 135 K or less) and that completely expel a magnetic field. A discussion of superconductivity is beyond the scope of this text.

19-1 Ohm's Law and Electrical Conductivity

Most of us are familiar with the common form of Ohm's law,

$$V = IR \tag{19-1}$$

where V is the voltage (volts, V), I is the current (amperes or amps, A), and R is the resistance (ohms, Ω) to the current flow. This law is applicable to most but not all materials. The resistance (R) of a resistor is a characteristic of the size, shape, and properties of the material according to

$$R = \rho \frac{l}{A} = \frac{l}{\sigma A} \tag{19-2}$$

where *l* is the length (cm) of the resistor, *A* is the cross-sectional area (cm²) of the resistor, ρ is the electrical resistivity (ohm \cdot cm or $\Omega \cdot$ cm), and σ , which is the reciprocal of ρ , is the electrical conductivity (ohm⁻¹ \cdot cm⁻¹). The magnitude of the resistance depends upon the dimensions of the resistor. The resistivity or conductivity does not depend on the dimensions of the material. Thus, resistivity or conductivity allows us to compare different materials. For example, silver is a better conductor than copper. Resistivity is a **microstructure-sensitive property**, similar to yield strength. The resistivity of pure copper is much less than that of commercially pure copper, because impurities in commercially

pure copper scatter electrons and contribute to increased resistivity. Similarly, the resistivity of annealed, pure copper is slightly lower than that of cold-worked, pure copper because of the scattering effect associated with dislocations.

In components designed to conduct electrical energy, minimizing power losses is important, not only to conserve energy, but also to minimize heating. The electrical power P (in watts, W) lost when a current flows through a resistance is given by

$$P = VI = I^2 R \tag{19-3}$$

A high resistance R results in larger power losses. These electrical losses are known as Joule heating losses.

A second form of Ohm's law is obtained if we combine Equations 19-1 and 19-2 to give

$$\frac{I}{A} = \sigma \frac{V}{l}$$

If we define I/A as the current density $J(A/cm^2)$ and V/l as the electric field E(V/cm), then $J = \sigma E$ (19-4)

The current density J is also given by

$$J = nq\overline{v}$$

where *n* is the number of charge carriers (carriers/cm³), *q* is the charge on each carrier $(1.6 \times 10^{-19} \text{ C})$, and \bar{v} is the average **drift velocity** (cm/s) at which the charge carriers move [Figure 19-1(a)]. Thus,

$$\sigma E = nq\overline{v}$$
 or $\sigma = nq\frac{\overline{v}}{E}$

Diffusion occurs as a result of temperature and concentration gradients, and drift occurs as a result of an applied electric or magnetic field. Conduction may occur as a result of diffusion, drift, or both, but drift is the dominant mechanism in electrical conduction.

The term \bar{v}/E is called the **mobility** $\mu\left(\frac{\text{cm}^2}{\text{V}\cdot\text{s}}\right)$ of the carriers (which in the case of metals is the mobility of electrons):

$$\mu = \frac{\overline{v}}{E}$$

Finally,

$$\sigma = nq\mu \tag{19-5a}$$

The charge q is a constant; from inspection of Equation 19-5a, we find that we can control the electrical conductivity of materials by (1) controlling the number of charge carriers in the material or (2) controlling the mobility—or ease of movement—of the charge carriers. The mobility is particularly important in metals, whereas the number of carriers is more important in semiconductors and insulators.

Electrons are the charge carriers in metals [Figure 19-1(b)]. Electrons are, of course, negatively charged. In semiconductors, electrons conduct charge as do positively charged carriers known as holes [Figure 19-1(c)]. We will learn more about holes in Section 19-4. In semiconductors, electrons and holes flow in opposite directions in response to an applied electric field, but in so doing, they both contribute to the net current. Thus, Equation 19-5a can be modified as follows for expressing the conductivity of semiconductors:

$$\sigma = nq\mu_n + pq\mu_p \tag{19-5b}$$

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Figure 19-1

(a) Charge carriers, such as electrons, are deflected by atoms or defects and take an irregular path through a conductor. The average rate at which the carriers move is the drift velocity \bar{v} . (b) Valence electrons in metals move easily. (c) Covalent bonds must be broken in semiconductors and insulators that do not contain impurities for an electron to be able to move. (d) Entire ions may diffuse via a vacancy mechanism to carry charge in many ionically bonded materials.

In this equation, μ_n and μ_p are the mobilities of electrons and holes, respectively. The terms n and p represent the concentrations of free electrons and holes in the semiconductor.

In ceramics, when conduction does occur, it can be the result of electrons that "hop" from one defect to another or the movement of ions [Figure 19-1(d)]. The mobility depends on atomic bonding, imperfections, microstructure, and, in ionic compounds, diffusion rates.

Because of these effects, the electrical conductivity of materials varies tremendously, as illustrated in Table 19-1. These values are approximate and are for high-purity materials at 300 K (unless noted otherwise). Note that the values of conductivity for metals and semiconductors depend very strongly on temperature. Table 19-2 includes some useful units and relationships.

Electronic materials can be classified as (a) superconductors, (b) conductors, (c) semiconductors, and (d) dielectrics or insulators, depending upon the magnitude of their electrical conductivity. Materials with conductivity less than $10^{-12} \Omega^{-1} \cdot \text{cm}^{-1}$, or resistivity greater than $10^{12} \Omega \cdot \text{cm}$, are considered insulating or dielectric. Materials with conductivity less than $10^3 \Omega^{-1} \cdot \text{cm}^{-1}$ but greater than $10^{-12} \Omega^{-1} \cdot \text{cm}^{-1}$ are considered semiconductors. Materials with conductivity greater than $10^3 \Omega^{-1} \cdot \text{cm}^{-1}$, or resistivity less than $10^3 \Omega^{-1} \cdot \text{cm}^{-1}$, are considered conductors. (These are approximate ranges of values.)

Material	Conductivity (ohm ^{-1} · cm ^{-1})	Material	Conductivity (ohm ⁻¹ · cm ⁻¹)
Superconductors Hg, Nb ₃ Sn YBa ₂ Cu ₃ O _{7-x} MgB ₂ Metals Alkali metals Na	Infinite (under certain conditions such as low temperatures) 2.13×10^5	Semiconductors Group 4B elements Si Ge Compound semiconductors GaAs AlAs	4×10^{-6} 0.02 2.5×10^{-9} 0.1
K Alkali earth metals Mg Ca	1.64×10^{5} 2.25×10^{5} 3.16×10^{5}	SiC Ionic Conductors Indium tin oxide (ITO) Yttria-stabilized zirconia (YSZ)	10 ⁻¹⁰
Al Ga Transition metals Fe Ni Group 1B metals Cu Ag Au	$\begin{array}{l} 3.77 \times 10^5 \\ 0.66 \times 10^5 \\ 1.00 \times 10^5 \\ 1.46 \times 10^5 \\ 5.98 \times 10^5 \\ 6.80 \times 10^5 \\ 4.26 \times 10^5 \end{array}$	Insulators, Linear, and Nonlinear Dielectrics Polymers Polyethylene Polytetrafluoroethylene Polystyrene Epoxy Ceramics Alumina (Al ₂ O ₃) Silicate glasses Boron nitride (BN) Barium titanate (BaTiO ₃) C (diamond)	$10^{-15} \\ 10^{-18} \\ 10^{-17} \text{ to } 10^{-19} \\ 10^{-12} \text{ to } 10^{-17} \\ 10^{-14} \\ 10^{-13} \\ 10^{-14} \\ < 10^{-18} \\ 10^{-1$

TABLE 19-1	Electrical	conductivit	v of	selected	materials	at T=	300 K*
	Licouroar	conductivity	, .,	30100100	materials	ati	000 A

* Unless specified otherwise, assumes high-purity material.

TABLE 19-2 Some useful relationships, constants, and units
Electron volt = 1 eV = 1.6×10^{-19} Joule = 1.6×10^{-12} erg
1 amp = 1 coulomb/second
$1 \text{ volt} = 1 \text{ amp} \cdot \text{ohm}$
$k_B T$ at room temperature (300 K) = 0.0259 eV
$c =$ speed of light 2.998 $\times 10^8$ m/s
ε_0 = permittivity of free space = 8.85×10^{-12} F/m
$q =$ charge on electron = 1.6×10^{-19} C
Avogadro constant N _A = 6.022×10^{23}
$k_B = Boltzmann constant = 8.63 \times 10^{-5} \text{ eV/K} = 1.38 \times 10^{-23} \text{ J/K}$
h = Planck's constant 6.63×10^{-34} J·s = 4.14×10^{-15} eV·s

We use the term "dielectric" for materials that are used in applications where the dielectric constant is important. The **dielectric constant** (\mathbf{k}) of a material is a microstructuresensitive property related to the material's ability to store an electrical charge. We use the term "insulator" to describe the ability of a material to stop the flow of DC or AC current, as opposed to its ability to store a charge. A measure of the effectiveness of an insulator is the maximum electric field it can support without an electrical breakdown.

Example 19-1 Design of a Transmission Line

Design an electrical transmission line 1500 m long that will carry a current of 50 A with no more than 5×10^5 W loss in power. The electrical conductivity of several materials is included in Table 19-1.

SOLUTION

Electrical power is given by the product of the voltage and current or

$$P = VI = I^2 R = (50)^2 R = 5 \times 10^5 W$$

 $R = 200 \text{ ohms}$

From Equation 19-2,

$$A = \frac{l}{R \cdot \sigma} = \frac{(1500 \text{ m})(100 \text{ cm/m})}{(200 \text{ ohms})\sigma} = \frac{750}{\sigma}$$

Let's consider three metals—aluminum, copper, and silver—that have excellent electrical conductivity. The table below includes appropriate data and some characteristics of the transmission line for each metal.

	σ (ohm ⁻¹ \cdot cm ⁻¹)	A (cm ²)	Diameter (cm)
Aluminum	3.77×10^{5}	0.00199	0.050
Copper	5.98×10^{5}	0.00125	0.040
Silver	6.80×10^{5}	0.00110	0.037

Any of the three metals will work, but cost is a factor as well. Aluminum will likely be the most economical choice (Chapter 14), even though the wire has the largest diameter. Other factors, such as whether the wire can support itself between transmission poles, also contribute to the final choice.

Example 19-2 Drift Velocity of Electrons in Copper

Assuming that all of the valence electrons contribute to current flow, (a) calculate the mobility of an electron in copper and (b) calculate the average drift velocity for electrons in a 100 cm copper wire when 10 V are applied.

SOLUTION

(a) The valence of copper is one; therefore, the number of valence electrons equals the number of copper atoms in the material. The lattice parameter of copper is 3.6151×10^{-8} cm and, since copper is FCC, there are four atoms/unit cell. From Table 19-1, the conductivity $\sigma = 5.98 \times 10^5 \Omega^{-1} \cdot \text{cm}^{-1}$

$$n = \frac{(4 \text{ atoms/cell})(1 \text{ electron/atom})}{(3.6151 \times 10^{-8} \text{ cm})^3} = 8.466 \times 10^{22} \text{ electrons/cm}^3$$

$$q = 1.6 \times 10^{-19} \text{ C}$$

$$\mu = \frac{\sigma}{nq} = \frac{5.98 \times 10^5}{(8.466 \times 10^{22})(1.6 \times 10^{-19})}$$
$$= 44.1 \frac{\text{cm}^2}{\Omega \cdot \text{C}} = 44.1 \frac{\text{cm}^2}{\text{V} \cdot \text{s}}$$

(b) The electric field is

$$E = \frac{V}{l} = \frac{10}{100} = 0.1 \,\mathrm{V/cm}$$

The mobility is 44.1 cm²/(V \cdot s); therefore,

$$\bar{v} = \mu E = (44.1)(0.1) = 4.41 \,\mathrm{cm/s}$$

19-2 Band Structure of Solids

As we saw in Chapter 2, the electrons of atoms in isolation occupy fixed and discrete energy levels. The Pauli exclusion principle is satisfied for each atom because only two electrons, at most, occupy each energy level, or orbital. When *N* atoms come together to form a solid, the Pauli exclusion principle still requires that no more than two electrons in the solid have the same energy. As two atoms approach each other in order to form a bond, the Pauli exclusion principle would be violated if the energy levels of the electrons did not change. Thus, the energy levels of the electrons "split" in order to form new energy levels.

Figure 19-2 schematically illustrates this concept. Consider two atoms approaching each other to form a bond. The orbitals that contain the valence electrons are located (on average) farther from the nucleus than the orbitals that contain the "core" or innermost electrons. The orbitals that contain the valence electrons of one atom thus interact with the orbitals that contain the valence electrons of the other atom first. Since the orbitals of these electrons have the same energy when the atoms are in isolation, the orbitals shift in energy or "split" so that the Pauli exclusion principle is satisfied. As shown in Figure 19-2, when considering two atoms, each with one orbital of interest, one of the orbitals shifts to a higher energy level while the other orbital shifts to a lower energy level. The electrons of the atoms will occupy these new orbitals by first filling the lowest energy levels. As the number of atoms increases, so does the number of energy levels. A new orbital with its own energy is formed for each orbital of each atom, and as the number of atoms in the solid increases, the separation in energy between orbitals becomes finer, ultimately forming what is called an energy band. For example, when N atoms come together to form a solid, the 2s energy band contains N discrete energy levels, one for each atom in the solid since each atom contributes one orbital.

In order for charge carriers to conduct, the carriers must be able to accelerate and increase in energy. The energy of the carriers can increase only if there are available energy states to which the carriers can be promoted. Thus, the particular distribution of energy states in the band structure of a solid has critical implications for its electrical and optical properties.

Depending on the type of material involved (metal, semiconductor, insulator), there may or may not be a sizable energy gap between the energy levels of the orbitals that shifted to a lower energy state and the energy levels of the orbitals that shifted to a



Figure 19-2 The energy levels broaden into bands as the number of electrons grouped together increases. (*Courtesy of John Bravman.*)

higher energy state. This energy gap, if it exists, is known as the bandgap. We will discuss the bandgap in more detail later.

Band Structure of Sodium Sodium is a metal and has the electronic structure $1s^22s^22p^63s^1$. Figure 19-3 shows a schematic diagram of the band structure of sodium as a function of the interatomic separation. (Note that Figure 19-2 shows a



Figure 19-3

The simplified band structure for sodium. The energy levels broaden into bands. The 3s band, which is only half filled with electrons, is responsible for conduction in sodium. Note that the energy levels of the orbitals in the 1s, 2s, and 2p levels do not split at the equilibrium spacing for sodium. general band diagram for a fixed interatomic separation.) The energies within the bands depend on the spacing between the atoms; the vertical line represents the equilibrium interatomic spacing of the atoms in solid sodium.

Sodium and other alkali metals in column 1A of the periodic table have only one electron in the outermost *s* level. The 3*s* valence band in sodium is half filled and, at absolute zero, only the lowest energy levels are occupied. The **Fermi energy** (E_f) is the energy level at which half of the possible energy levels in the band are occupied by electrons. It is the energy level where the probability of finding an electron is 1/2. When electrons gain energy, they are excited into the empty higher energy levels. The promotion of carriers to higher energy levels enables electrical conduction.

Band Structure of Magnesium and Other Metals

Magnesium and other metals in column 2A of the periodic table have two electrons in their outermost s band. These metals have a high conductivity because the p band overlaps the s band at the equilibrium interatomic spacing. This overlap permits electrons to be excited into the large number of unoccupied energy levels in the combined 3s and 3p band. Overlapping 3s and 3p bands in aluminum and other metals in column 3B provide a similar effect.

In the transition metals, including scandium through nickel, an unfilled 3d band overlaps the 4s band. This overlap provides energy levels into which electrons can be excited; however, complex interactions between the bands prevent the conductivity from being as high as in some of the better conductors. In copper, the inner 3d band is full, and the atom core tightly holds these electrons. Consequently, there is little interaction between the electrons in the 4s and 3d bands, and copper has a high conductivity. A similar situation is found for silver and gold.

Band Structure of Semiconductors and Insulators

The elements in Group 4—carbon (diamond), silicon, germanium, and tin—contain two electrons in their outer p shell and have a valence of four. Based on our discussion in the previous section, we might expect these elements to have a high conductivity due to the unfilled p band, but this behavior is not observed!

These elements are covalently bonded; consequently, the electrons in the outer s and p bands are rigidly bound to the atoms. The covalent bonding produces a complex change in the band structure. The 2s and 2p levels of the carbon atoms in diamond can contain up to eight electrons, but there are only four valence electrons available. When carbon atoms are brought together to form solid diamond, the 2s and 2p levels interact and produce two bands (Figure 19-4). Each hybrid band can contain 4N electrons. Since there are only 4N electrons available, the lower (or **valence**) band is completely full, whereas the upper (or **conduction**) band is empty.

A large **energy gap** or **bandgap** (E_g) separates the valence band from the conduction band in diamond $(E_g \sim 5.5 \text{ eV})$. Few electrons possess sufficient energy to jump the forbidden zone to the conduction band. Consequently, diamond has an electrical conductivity of less than 10^{-18} ohm⁻¹ \cdot cm⁻¹. Other covalently and ionically bonded materials have a similar band structure and, like diamond, are poor conductors of electricity. Increasing the temperature supplies the energy required for electrons to overcome the energy gap. For example, the electrical conductivity of boron nitride increases from about 10^{-13} at room temperature to 10^{-4} ohm⁻¹ \cdot cm⁻¹ at 800°C.

Figure 19-5 shows a schematic of the band structure of typical metals, semiconductors, and insulators. Thus, an important distinction between metals and semiconductors is that the conductivity of semiconductors *increases* with temperature, as more and



Figure 19-4

The band structure of carbon in the diamond form. The 2s and 2p levels combine to form two hybrid bands separated by an energy gap, E_{g} .

more electrons are promoted to the conduction band from the valence band. In other words, an increasing number of electrons from the covalent bonds in a semiconductor is freed and becomes available for conduction. The conductivity of most metals, on the other hand, *decreases* with increasing temperature. This is because the number of electrons that are already available begin to scatter more (i.e., increasing temperature reduces mobility).

Although germanium (Ge), silicon (Si), and α -Sn have the same crystal structure and band structure as diamond, their energy gaps are smaller. In fact, the energy gap (E_g) in α -Sn is so small ($E_g = 0.1 \text{ eV}$) that α -Sn behaves as a metal. The energy gap is somewhat larger in silicon ($E_g = 1.1 \text{ eV}$) and germanium ($E_g = 0.67 \text{ eV}$)—these elements behave as semiconductors. Typically, we consider materials with a bandgap greater than 4.0 eV as insulators, dielectrics, or nonconductors; materials with a bandgap less than 4.0 eV are considered semiconductors.



Figure 19-5 Schematic of band structures for (a) metals, (b) semiconductors, and (c) dielectrics or insulators. (Temperature is assumed to be 0 K.)

19-3 Conductivity of Metals and Alloys

The conductivity of a pure, defect-free metal is determined by the electronic structure of the atoms, but we can change the conductivity by influencing the mobility, μ , of the carriers. Recall that the mobility is proportional to the average drift velocity, $\bar{\nu}$. The average drift velocity is the velocity with which charge carriers move in the direction dictated by the applied field. The paths of electrons are influenced by internal fields due to atoms in the solid and imperfections in the lattice. When these internal fields influence the path of an electron, the drift velocity (and thus the mobility of the charge carriers) decreases. The **mean free path** (λ_e) of electrons is defined as

$$\lambda_e = \tau \overline{v} \tag{19-6}$$

The average time between collisions is τ . The mean free path defines the average distance between collisions; a longer mean free path permits higher mobilities and higher conductivities.

Temperature Effect When the temperature of a metal increases, thermal energy causes the amplitudes of vibration of the atoms to increase (Figure 19-6). This increases the *scattering cross section* of atoms or defects in the lattice. Essentially, the atoms and defects act as larger targets for interactions with electrons, and interactions occur more frequently. Thus, the mean free path decreases, the mobility of electrons is reduced, and the resistivity increases. The change in resistivity of a pure metal as a function of temperature can be estimated according to

$$\rho = \rho_{RT} (1 + \alpha_R \Delta T) \tag{19-7}$$

where ρ is the resistivity at any temperature T, ρ_{RT} is the resistivity at room temperature (i.e., 25°C), $\Delta T = (T - T_{RT})$ is the difference between the temperature of interest and room temperature, and α_R is the *temperature resistivity coefficient*. The relationship between resistivity and temperature is linear over a wide temperature range (Figure 19-7). Examples of the temperature resistivity coefficient are given in Table 19-3.



Figure 19-6 Movement of an electron through (a) a perfect crystal, (b) a crystal heated to a high temperature, and (c) a crystal containing atomic level defects. Scattering of the electrons reduces the mobility and conductivity.



Figure 19-7

The effect of temperature on the electrical resistivity of a metal with a perfect crystal structure.

Metal	Room Temperature Resistivity (ohm • cm)	Temperature Resistivity Coefficient (α_R) [ohm/(ohm \cdot °C)]
Ве	4.0×10 ⁻⁶	0.0250
Mg	4.45×10^{-6}	0.0037
Са	3.91×10^{-6}	0.0042
AI	2.65×10^{-6}	0.0043
Cr	12.90×10 ⁻⁶ (0°C)	0.0030
Fe	9.71×10 ⁻⁶	0.0065
Со	6.24×10^{-6}	0.0053
Ni	6.84×10^{-6}	0.0069
Cu	1.67×10^{-6}	0.0043
Ag	1.59×10^{-6}	0.0041
Au	2.35×10^{-6}	0.0035
Pd	10.8×10^{-6}	0.0037
W	5.3×10 ⁻⁶ (27°C)	0.0045
Pt	9.85×10^{-6}	0.0039

TABLE 19-3 The temperature resistivity coefficient α_R for selected metals

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The following example illustrates how the resistivity of pure copper can be calculated.

Example 19-3 *Resistivity of Pure Copper*

Calculate the electrical conductivity of pure copper at (a) 400°C and (b) –100°C.

SOLUTION

The resistivity of copper at room temperature is 1.67×10^{-6} ohm \cdot cm, and the temperature resistivity coefficient is 0.0043 ohm/(ohm \cdot °C). (See Table 19-3.)

(a) At 400°C:

$$\rho = \rho_{RT} (1 + \alpha_R \Delta T) = (1.67 \times 10^{-6})[1 + 0.0043(400 - 25)]$$

$$\rho = 4.363 \times 10^{-6} \text{ ohm} \cdot \text{cm}$$

$$\sigma = 1/\rho = 2.29 \times 10^5 \text{ ohm}^{-1} \cdot \text{cm}^{-1}$$

(b) At -100°C:

$$\rho = (1.67 \times 10^{-6})[1 + 0.0043(-100 - 25)] = 7.724 \times 10^{-7} \text{ ohm} \cdot \text{cm}$$

 $\sigma = 12.9 \times 10^{5} \text{ ohm}^{-1} \cdot \text{cm}^{-1}$

Effect of Atomic Level Defects Imperfections in crystal structures scatter electrons, reducing the mobility and conductivity of the metal [Figure 19-6(c)]. For example, the increase in the resistivity due to solid solution atoms for dilute solutions is

$$\rho_d = b(1 - x)x \tag{19-8}$$

where ρ_d is the increase in resistivity due to the defects, x is the atomic fraction of the impurity or solid solution atoms present, and b is the defect resistivity coefficient. In a similar manner, vacancies, dislocations, and grain boundaries reduce the conductivity of the metal. Each defect contributes to an increase in the resistivity of the metal. Thus, the overall resistivity is

$$\rho = \rho_T + \rho_d \tag{19-9}$$

where ρ_d equals the contributions from all of the defects. Equation 19-9 is known as **Matthiessen's rule**. The effect of the defects is *independent* of temperature (Figure 19-8)

Effect of Processing and Strengthening Strengthening mechanisms and metal processing techniques affect the electrical properties of a metal in different ways (Table 19-4). Solid-solution strengthening is *not* a good way to obtain high strength in metals intended to have high conductivities. The mean free paths are short due to the random distribution of the interstitial or substitutional atoms. Figure 19-9 shows the effect of zinc and other alloying elements on the conductivity of copper; as the amount of alloying element increases, the conductivity decreases substantially.

Age hardening and dispersion strengthening reduce the conductivity to an extent that is less than solid-solution strengthening, since there is a longer mean free path between precipitates, as compared with the path between point defects. Strain hardening and grainsize control have even less effect on conductivity (Figure 19-9 and Table 19-4). Since dislocations and grain boundaries are further apart than solid-solution atoms, there are large volumes of metal that have a long mean free path. Consequently, cold working is an effective way to increase the strength of a metallic conductor without seriously impairing the electrical properties of the material. In addition, the effects of cold working on conductivity can be eliminated by the low-temperature recovery heat treatment in which good conductivity is restored while the strength is retained.



Figure 19-8

The electrical resistivity of a metal is due to a constant defect contribution ρ_d and a variable temperature contribution ρ_T .

TABLE 19-4 The effect of alloying, strengthening, and processing on the electrical conductivity of copper and its alloys

Alloy	$rac{\sigma_{ m alloy}}{\sigma_{ m Cu}} imes 100$	Remarks
Pure annealed copper	100	Few defects to scatter electrons; the mean free path is long.
Pure copper deformed 80%	98	Many dislocations, but because of the tangled nature of the dislocation networks, the mean free path is still long.
Dispersion-strengthened Cu-0.7% Al ₂ O ₃	85	The dispersed phase is not as closely spaced as solid-solution atoms, nor is it coherent, as in age hardening. Thus, the effect on conductivity is small.
Solution-treated Cu-2% Be	18	The alloy is single phase; however, the small amount of solid-solution strengthening from the supersaturated beryllium greatly decreases conductivity.
Aged Cu-2% Be	23	During aging, the beryllium leaves the copper lattice to produce a coherent precipitate. The precipitate does not interfere with conductivity as much as the solid-solution atoms.
Cu-35% Zn	28	This alloy is solid-solution strengthened by zinc, which has an atomic radius near that of copper. The conductivity is low, but not as low as when beryllium is present.



Figure 19-9 (a) The effect of solid-solution strengthening and cold work on the electrical conductivity of copper, and (b) the effect of the addition of selected elements on the electrical conductivity of copper.

Conductivity of Alloys Alloys typically have higher resistivities than pure metals because of the scattering of electrons due to the alloying additions. For example, the resistivity of pure Cu at room temperature is $\sim 1.67 \times 10^{-6} \Omega \cdot \text{cm}$ and that of pure gold is $\sim 2.35 \times 10^{-6} \Omega \cdot \text{cm}$. The resistivity of a 35% Au-65% Cu alloy at room temperature is much higher, $\sim 12 \times 10^{-6} \Omega \cdot \text{cm}$. Ordering of atoms in alloys by heat treatment can decrease their resistivity. Compared to pure metals, the resistivity of alloys tends to be stable in regards to temperature variation. Relatively high-resistance alloys such as nichrome ($\sim 80\%$ Ni-20% Cr) can be used as heating elements. Certain alloys of Bi-Sn-Pb-Cd are used to make electrical fuses due to their low melting temperatures.

19-4 Semiconductors

Elemental semiconductors are found in Group 4B of the periodic table and include germanium and silicon. Compound semiconductors are formed from elements in Groups 2B and 6B of the periodic table (e.g., CdS, CdSe, CdTe, HgCdTe, etc.) and are known as II–VI (two–six) semiconductors. They also can be formed by combining elements from Groups 3B and 5B of the periodic table (e.g., GaN, GaAs, AlAs, AlP, InP, etc.). These are known as III–V (three–five) semiconductors.

An **intrinsic semiconductor** is one with properties that are not controlled by impurities. An **extrinsic semiconductor** (*n*- or *p*-type) is preferred for devices, since its properties are stable with temperature and can be controlled using ion implantation or diffusion of impurities known as dopants. Semiconductor materials, including silicon and germanium, provide the building blocks for many electronic devices. These materials have an easily controlled electrical conductivity and, when properly combined, can act as switches, amplifiers, or information storage devices. The properties of some of the commonly encountered semiconductors are included in Table 19-5.

As we learned in Section 19-2, as the atoms of a semiconductor come together to form a solid, two energy bands are formed [Figure 19-5(b)]. At 0 K, the energy levels of the valence band are completely full, as these are the lowest energy states for the electrons. The valence band is separated from the conduction band by a bandgap. At 0 K, the conduction band is empty.

The energy gap E_g between the valence and conduction bands in semiconductors is relatively small (Figure 19-5). As a result, as temperature increases, some electrons possess enough thermal energy to be promoted from the valence band to the conduction band. The excited electrons leave behind unoccupied energy levels, or holes, in the valence band. When an electron moves to fill a hole, another hole is created; consequently, the holes appear to act as positively charged electrons and carry an electrical charge. When a voltage is applied to the material, the electrons in the conduction band accelerate toward the positive terminal, while holes in the valence band move toward the negative terminal (Figure 19-10). Current is, therefore, conducted by the movement of both electrons and holes.

Semiconductor	Bandgap (eV)	$\begin{array}{c} \textbf{Mobility of} \\ \textbf{Electrons (} \boldsymbol{\mu_n}\textbf{)} \\ & \left(\frac{\mathtt{cm}^2}{\mathtt{V}\cdot\mathtt{s}}\right) \end{array}$	$\begin{array}{c} \text{Mobility of} \\ \text{Holes } (\mu_p) \\ \left(\frac{\text{cm}^2}{\text{V}\cdot\text{s}}\right) \end{array}$	Dielectric Constant (k)	Resistivity ($\Omega \cdot cm$)	$\frac{\text{Density}}{\left(\frac{\text{g}}{\text{cm}^2}\right)}$	Melting Temperature (°C)
Silicon (Si)	1.11	1350	480	11.8	2.5×10^{5}	2.33	1415
Amorphous Silicon (a:Si:H)	1.70	1	10-2	~11.8	10 ¹⁰	~2.30	
Germanium (Ge)	0.67	3900	1900	16.0	43	5.32	936
SiC (α)	2.86	500		10.2	10 ¹⁰	3.21	2830
Gallium Arsenide (GaAs)	1.43	8500	400	13.2	4×10^{8}	5.31	1238
Diamond	~5.50	1800	1500	5.7	$> 10^{18}$	3.52	~3550

TABLE 19-5 Properties of commonly encountered semiconductors at room temperature



Figure 19-10 When a voltage is applied to a semiconductor, the electrons move through the conduction band, while the holes move through the valence band in the opposite direction.

The conductivity is determined by the number of electrons and holes according to

$$\sigma = nq\mu_n + pq\mu_p \tag{19-10}$$

where *n* is the concentration of electrons in the conduction band, *p* is the concentration of holes in the valence band, and μ_n and μ_p are the mobilities of electrons and holes, respectively (Table 19-5). This equation is the same as Equation 19-5b.

In intrinsic semiconductors, for every electron promoted to the conduction band, there is a hole left in the valence band, such that

$$n_i = p_i$$

where n_i and p_i are the concentrations of electrons and holes, respectively, in an intrinsic semiconductor. Therefore, the conductivity of an intrinsic semiconductor is

$$\sigma = qn_i(\mu_n + \mu_p) \tag{19-11}$$

In intrinsic semiconductors, we control the number of charge carriers and, hence, the electrical conductivity by controlling the temperature. At absolute zero temperature, all of the electrons are in the valence band, whereas all of the levels in the conduction band are unoccupied [Figure 19-11(a)]. As the temperature increases, there is a greater probability that an energy level in the conduction band is occupied (and an equal probability that a level in the valence band is unoccupied, or that a hole is present) [Figure 19-11(b)]. The number of electrons in the conduction band, which is equal to the number of holes in the valence band, is given by

$$n = n_i = p_i = n_0 \exp\left(\frac{-E_g}{2k_BT}\right)$$
(19-12a)



where n_0 is given by

$$n_0 = 2\left(\frac{2\pi k_B T}{h^2}\right)^{3/2} (m_n^* m_p^*)^{3/4}$$
(19-12b)

In these equations, k and h are the Boltzmann and Planck's constants and m_n^* and m_p^* are the effective masses of electrons and holes in the semiconductor, respectively. The effective masses account for the effects of the internal forces that alter the acceleration of electrons in a solid relative to electrons in a vacuum. For Ge, Si, and GaAs, the room temperature values of n_i are 2.5×10^{13} , 1.5×10^{10} , and 2×10^6 electrons/cm³, respectively. The $n_i p_i$ product remains constant at any given temperature for a given semiconductor. This allows us to calculate n_i or p_i values at different temperatures.

Higher temperatures permit more electrons to cross the forbidden zone and, hence, the conductivity increases:

$$\sigma = n_0 q(\mu_n + \mu_p) \exp\left(\frac{-E_g}{2k_B T}\right)$$
(19-13)

Note that both n_i and σ are related to temperature by an Arrhenius equation, rate = $A \exp\left(\frac{-Q}{RT}\right)$. As the temperature increases, the conductivity of a semiconductor also increases because more charge carriers are available for conduction. Note that as for metals, the mobilities of the carriers decrease at high temperatures, but this is a much weaker dependence than the exponential increase in the number of charge carriers. The increase in conductivity with temperature in semiconductors sharply contrasts with the decrease in conductivity of metals with increasing temperature (Figure 19-12). Even at high temperatures, however, the conductivity of a metal is orders of magnitudes higher than the conductivity of a semiconductor. The example that follows shows the calculation for carrier concentration in an intrinsic semiconductor.



Figure 19-12

The electrical conductivity versus temperature for intrinsic semiconductors compared with metals. Note the break in the vertical axis scale.

Example 19-4 Carrier Concentrations in Intrinsic Ge

For germanium at 25°C, estimate (a) the number of charge carriers, (b) the fraction of the total electrons in the valence band that are excited into the conduction band, and (c) the constant n_0 in Equation 19-12a.

SOLUTION

From Table 19-5, $\rho = 43 \ \Omega \cdot \text{cm}$, $\therefore \sigma = 0.0233 \ \Omega^{-1} \cdot \text{cm}^{-1}$ Also from Table 19-5,

$$E_g = 0.67 \,\mathrm{eV}, \,\mu_n = 3900 \,\frac{\mathrm{cm}^2}{\mathrm{V} \cdot \mathrm{s}}, \,\mu_p = 1900 \,\frac{\mathrm{cm}^2}{\mathrm{V} \cdot \mathrm{s}}$$

$$2k_BT = (2)(8.63 \times 10^{-5} \text{ eV/K})(273 + 25) = 0.05143 \text{ eV}$$
 at $T = 25^{\circ}\text{C}$

(a) From Equation 19-10,

$$n = \frac{\sigma}{q(\mu_n + \mu_p)} = \frac{0.0233}{(1.6 \times 10^{-19})(3900 + 1900)} = 2.51 \times 10^{13} \frac{\text{electrons}}{\text{cm}^3}$$

There are 2.51×10^{13} electrons/cm³ and 2.51×10^{13} holes/cm³ conducting charge in germanium at room temperature.

(b) The lattice parameter of diamond cubic germanium is 5.6575×10^{-8} cm. The total number of electrons in the valence band of germanium at 0 K is

Total electrons =
$$\frac{(8 \text{ atoms/cell})(4 \text{ electrons/atom})}{(5.6575 \times 10^{-8} \text{ cm})^3}$$

= 1.77×10^{23}
Fraction excited = $\frac{2.51 \times 10^{13}}{1.77 \times 10^{23}} = 1.42 \times 10^{-10}$

(c) From Equation 19-12a,

$$n_0 = \frac{n}{\exp(-E_g/2k_BT)} = \frac{2.51 \times 10^{13}}{\exp(-0.67/0.05143)}$$
$$= 1.14 \times 10^{19} \text{ carriers/cm}^3$$

Extrinsic Semiconductors The temperature dependence of conductivity in intrinsic semiconductors is nearly exponential, but this is not useful for practical applications. We cannot accurately control the behavior of an intrinsic semiconductor because slight variations in temperature can significantly change the conductivity. By intentionally adding a small number of impurity atoms to the material (called doping), we can produce an extrinsic semiconductor. The conductivity of the extrinsic semiconductor depends primarily on the number of impurity, or dopant, atoms and in a certain temperature range is independent of temperature. This ability to have a tunable yet temperature independent conductivity is the reason why we almost always use extrinsic semiconductor tors to make devices.



Figure 19-13 When a dopant atom with a valence greater than four is added to silicon, an extra electron is introduced and a donor energy state is created. Now electrons are more easily excited into the conduction band.

n-Type Semiconductors Suppose we add an impurity atom such as antimony (which has a valence of five) to silicon or germanium. Four of the electrons from the antimony atom participate in the covalent-bonding process, while the extra electron enters an energy level just below the conduction band (Figure 19-13). Since the extra electron is not tightly bound to the atoms, only a small increase in energy, E_d , is required for the electron to enter the conduction band. This energy level just below the conduction band is called a donor state. An *n*-type dopant "donates" a free electron for cach impurity added. The energy gap controlling conductivity is now E_d rather than E_g (Table 19-6). No corresponding holes are created when the donor electrons enter the conduction band. It is still the case that electron-hole pairs are created when thermal energy causes electrons to be promoted to the conduction band from the valence band; however, the number of electron-hole pairs is significant only at high temperatures.

p-Type Semiconductors When we add an impurity such as gallium or boron, which has a valence of three, to Si or Ge, there are not enough electrons to complete the covalent bonding process. A hole is created in the valence band that can be filled by electrons from other locations in the band (Figure 19-14). The holes act as "acceptors" of electrons. These hole sites have a somewhat higher than normal energy and create an acceptor level of possible electron energies just above the valence band (Table 19-6). An electron must gain an energy of only E_a in order to create a hole in the valence band. The hole then carries charge. This is known as a *p*-type semiconductor.

Charge Neutrality In an extrinsic semiconductor, there has to be overall electrical neutrality. Thus, the sum of the number of donor atoms (N_d) and holes per unit volume (p_{ext}) (both are positively charged) is equal to the number of acceptor atoms (N_a) and electrons per unit volume (n_{ext}) (both are negatively charged):

$$p_{\text{ext}} + N_d = n_{\text{ext}} + N_a$$



Figure 19-14 When a dopant atom with a valence of less than four is substituted into the silicon structure, a hole is introduced in the structure and an acceptor energy level is created just above the valence band.

	Silio	con	Germanium			
Dopant	E _d	Ea	E _d	Ea		
P	0.045		0.0120			
As	0.049		0.0127			
Sb	0.039		0.0096			
В		0.045		0.0104		
AI		0.057		0.0102		
Ga		0.065		0.0108		
In		0.160		0.0112		

TABLE 19-6	The donor a	nd acceptor	energy	levels	(in e	electron	volts)	when
silicon and gei	rmanium sen	niconductors	s are do	ped				

In this equation, n_{ext} and p_{ext} are the concentrations of electrons and holes in an extrinsic semiconductor.

If the extrinsic semiconductor is heavily *n*-type doped (i.e., $N_d \gg n_i$), then $n_{\text{ext}} \sim N_d$. Similarly, if there is a heavily acceptor-doped (*p*-type) semiconductor, then $N_a \gg p_i$ and hence $p_{\text{ext}} \sim N_a$. This is important, since this says that by adding a considerable amount of dopant, we can dominate the conductivity of a semiconductor by controlling the dopant concentration. This is why extrinsic semiconductors are most useful for making controllable devices such as transistors.

The changes in carrier concentration with temperature are shown in Figure 19-15. From this, the approximate conductivity changes in an extrinsic semiconductor are easy to follow. When the temperature is too low, the donor or acceptor atoms are not ionized and hence the conductivity is very small. As temperature begins to increase, electrons (or holes) contributed by the donors (or acceptors) become available for conduction. At sufficiently high temperatures, the conductivity is nearly independent of temperature



Figure 19-15 The effect of temperature on the carrier concentration of an *n*-type semiconductor. At low temperatures, the donor or acceptor atoms are not ionized. As temperature increases, the ionization process is complete, and the carrier concentration increases to a level that is dictated by the level of doping. The conductivity then essentially remains unchanged until the temperature becomes too high and the thermally generated carriers begin to dominate. The effect of dopants is lost at very high temperatures, and the semiconductor essentially shows "intrinsic" behavior.

(region labeled as extrinsic). The value of conductivity at which the plateau occurs depends on the level of doping. When temperatures become too high, the behavior approaches that of an intrinsic semiconductor since the effect of dopants essentially is lost. In this analysis, we have not accounted for the effects of dopants concentration on the mobility of electrons and holes and the temperature dependence of the bandgap. At very high temperatures (not shown in Figure 19-15), the conductivity *decreases* again as scattering of carriers dominates.

Example 19-5 *Design of a Semiconductor*

Design a *p*-type semiconductor based on silicon, which provides a constant conductivity of 100 $\text{ohm}^{-1} \cdot \text{cm}^{-1}$ over a range of temperatures. Compare the required concentration of acceptor atoms in Si with the concentration of Si atoms.

SOLUTION

In order to obtain the desired conductivity, we must dope the silicon with atoms having a valence of +3, adding enough dopant to provide the required number of charge carriers. If we assume that the number of intrinsic carriers is small compared to the dopant concentration, then

where $\sigma = 100 \text{ ohm}^{-1} \cdot \text{cm}^{-1}$ and $\mu_p = 480 \text{ cm}^2/(\text{V} \cdot \text{s})$. Note that electron and hole mobilities are properties of the host material (i.e., silicon in this case) and not the dopant species. If we remember that coulomb can be expressed as ampere-seconds and voltage can be expressed as ampere \cdot ohm, the number of charge carriers required is

$$N_a = \frac{\sigma}{q\mu_p} = \frac{100}{(1.6 \times 10^{-19})(480)} = 1.30 \times 10^{18} \operatorname{acceptor atoms/cm}^3$$

Assume that the lattice constant of Si remains unchanged as a result of doping:

$$N_a = \frac{(1 \text{ hole/dopant atom})(x \text{ dopant atom/Si atom})(8 \text{ Si atoms/unit cell})}{(5.4307 \times 10^{-8} \text{ cm})^3/\text{unit cell}}$$
$$x = (1.30 \times 10^{18})(5.4307 \times 10^{-8})^3/8 = 26 \times 10^{-6} \text{ dopant atom/Si atom}$$
or 26 dopant atoms/10⁶ Si atoms

Possible dopants include boron, aluminum, gallium, and indium. High-purity chemicals and clean room conditions are essential for processing since we need 26 dopant atoms in a million silicon atoms.

Many other materials that are normally insulating (because the bandgap is too large) can be made semiconducting by doping. Examples of this include $BaTiO_3$, ZnO, TiO₂, and many other oxides. Thus, the concept of *n*- and *p*-type dopants is not limited to Si, Ge, GaAs, etc. We can dope $BaTiO_3$, for example, and make *n*- or *p*-type $BaTiO_3$. Such materials are useful for many sensor applications such as **thermistors**.

Direct and Indirect Bandgap Semiconductors In a

direct bandgap semiconductor, an electron can be promoted from the conduction band to the valence band without changing the momentum of the electron. An example of a direct bandgap semiconductor is GaAs. When the excited electron falls back into the valence band, electrons and holes combine to produce light. This is known as **radiative recombination**. Thus, direct bandgap materials such as GaAs and solid solutions of these (e.g., GaAs-AlAs, etc.) are used to make light-emitting diodes (LEDs) of different colors. The bandgap of semiconductors can be tuned using solid solutions. The change in bandgap produces a change in the wavelength (i.e., the frequency of the color (v) is related to the bandgap E_g as $E_g = hv$, where h is Planck's constant). Since an optical effect is obtained using an electronic material, often the direct bandgap materials are known as optoelectronic materials (Chapter 21). Many lasers and LEDs have been developed using these materials. LEDs that emit light in the infrared range are used in optical-fiber communication systems to convert light waves into electrical pulses. Different colored lasers, such as the blue laser using GaN, have been developed using direct bandgap materials.

In an indirect bandgap semiconductor (e.g., Si, Ge, and GaP), the electrons cannot be promoted to the valence band without a change in momentum. As a result, in materials that have an indirect bandgap (e.g., silicon), we cannot get light emission. Instead, electrons and holes combine to produce heat that is dissipated within the material. This is known as **nonradiative recombination**. Note that both direct and indirect bandgap materials can be doped to form n- or p-type semiconductors.

19-5 Applications of Semiconductors

We fabricate diodes, transistors, lasers, and LEDs using semiconductors. The *p-n* junction is used in many of these devices, such as transistors. Creating an *n*-type region in a *p*-type semiconductor (or vice versa) forms a *p-n* junction [Figure 19-16(a)]. The *n*-type region contains a relatively large number of free electrons, whereas the *p*-type region contains a relatively large number of free holes. This concentration gradient causes diffusion of electrons from the *n*-type material to the *p*-type material and diffusion of holes from the *p*-type material to the *n*-type material. At the junction where the *p*- and *n*-regions meet, free electrons in the *n*type material recombine with holes in the *p*-type material. This creates a *depleted region* at the junction where the number of available charge carriers is low, and thus, the resistivity is high. Consequently, an electric field develops due to the distribution of exposed positive ions on the *n*-side of the junction and the exposed negative ions on the *p*- side of the junction. The electric field counteracts further diffusion.

Electrically, the *p*-*n* junction is conducting when the *p*-side is connected to a positive voltage. This **forward bias** condition is shown in Figure 19-16(a). The applied voltage directly counteracts the electric field at the depleted region, making it possible for electrons from the *n*-side to diffuse across the depleted region to the *p*-side and holes from the *p*-side to diffuse across the depleted region to the *n*-side. When a negative bias is applied to the *p*-side of a *p*-*n* junction (**reverse bias**), the *p*-*n* junction does not permit much current to flow. The depleted region simply becomes larger because it is further depleted of carriers. When no bias is applied, there is no current flowing through the *p*-*n* junction. The forward current can be as large as a few milli-amperes, while the reverse-bias current is a few nano-amperes.

The current–voltage (I-V) characteristics of a *p-n* junction are shown in Figure 19-16(b). Because the *p-n* junction permits current to flow in only one direction, it passes only half of an alternating current, therefore converting the alternating current to direct current [Figure 19-6(c)]. These junctions are called **rectifier diodes**.



Figure 19-16 (a) A *p*-*n* junction under forward bias. (b) The current–voltage characteristic for a *p*-*n* junction. Note the different scales in the first and third quadrants. At sufficiently high reverse bias voltages, "breakdown" occurs, and large currents can flow. Typically this destroys the devices. (c) If an alternating signal is applied, rectification occurs, and only half of the input signal passes the rectifier. (*From Floyd,* Thomas L., ELECTRONIC DEVICES (CONVENTIONAL FLOW VERSION), *6th, © 2002. Electronically reproduced by permission of Pearson Education, Inc., Upper Saddle River, New Jersey.*)

Bipolar Junction Transistors There are two types of transistors based on *p*-*n* junctions. The term transistor is derived from two words, "transfer" and "resistor." A transistor can be used as a switch or an amplifier. One type of transistor is the *bipolar junction transistor* (BJT). In the era of mainframe computers, bipolar junction transistor is a sandwich of either *n*-*p*-*n* or *p*-*n*-*p* semiconductor materials, as shown in Figure 19-17(a). There are three zones in the transistor: the emitter, the base, and the collector. As in the *p*-*n* junction, electrons are initially concentrated in the *n*-type material, and holes are concentrated in the *p*-type material.

Figure 19-17(b) shows a schematic diagram of an *n-p-n* transistor and its electrical circuit. The electrical signal to be amplified is connected between the base and the emitter, with a small voltage between these two zones. The output from the transistor, or the amplified signal, is connected between the emitter and the collector and operates at a higher voltage. The circuit is connected so that a forward bias is produced between the emitter and the base (the positive voltage is at the *p*-type base), while a reverse bias is produced between the base and the collector (with the positive voltage at the *n*-type collector). The forward bias causes electrons to leave the emitter and enter the base.



(c)

Figure 19-17 (a) Sketch of the cross-section of the transistor. (b) A circuit for an *n*-*p*-*n* bipolar junction transistor. The input creates a forward and reverse bias that causes electrons to move from the emitter, through the base, and into the collector, creating an amplified output. (c) Sketch of the cross-section of a metal oxide semiconductor field effect transistor.

Electrons and holes attempt to recombine in the base; however, if the base is exceptionally thin and lightly doped, or if the recombination time τ is long, almost all of the electrons pass through the base and enter the collector. The reverse bias between the base and collector accelerates the electrons through the collector, the circuit is completed, and an output signal is produced. The current through the collector (I_c) is given by

$$I_c = I_0 \, \exp\left(\frac{V_E}{B}\right) \tag{19-14}$$

where I_0 and B are constants and V_E is the voltage between the emitter and the base. If the input voltage V_E is increased, a very large current I_c is produced.

Field Effect Transistors A second type of transistor, which is almost universally used today for data storage and processing, is the field effect transistor (FET). A metal oxide semiconductor (MOS) field effect transistor (or MOSFET) consists of two highly doped *n*-type regions (n+) in a *p*-type substrate or two highly doped *p*-type regions in an *n*-type substrate. (The manufacturing processes by which a device such as this is formed will be discussed in Section 19-6.) Consider a MOSFET that consists of two highly doped *n*-type regions in a *p*-type substrate. One of the *n*-type regions is called the source; the second is called the drain. A potential is applied between the source and the drain with the drain region being positive, but in the absence of a third component of the transistor (a conductor called the gate), electrons cannot flow from the source to the drain under the action of the electric field through the low conductivity *p*-type region. The gate is separated from the semiconductor by a thin insulating layer of oxide and spans the distance between the two *n*-type regions. In advanced device structures, the insulator is only several atomic layers thick and comprises materials other than pure silica.

A potential is applied between the gate and the source with the gate being positive. The potential draws electrons to the vicinity of the gate (and repels holes), but the electrons cannot enter the gate because of the silica. The concentration of electrons beneath the gate makes this region (known as the channel) more conductive, so that a large potential between the source and drain permits electrons to flow from the source to the drain, producing an amplified signal ("on" state). By changing the input voltage between the gate and the source, the number of electrons in the conductive path changes, thus also changing the output signal. When no voltage is applied to the gate, no electrons are attracted to the region between the source and the drain, and there is no current flow from the source to the drain ("off" state).

19-6

General Overview of Integrated Circuit Processing

Integrated circuits (ICs, also known as microchips) comprise large numbers of electronic components that have been fabricated on the surface of a substrate material in the form of a thin, circular wafer less than 1 mm thick and as large as 300 mm in diameter. Two particularly important components found on ICs are transistors, which can serve as electrical switches, as discussed in Section 19-5, and **capacitors**, which can store data in a digital format. Each wafer may contain several hundred chips. Intel's well-known Xeon[™] microprocessor is an example of an individual chip.

When first developed in the early 1960s, an integrated circuit comprised just a few electrical components, whereas modern ICs may include several billion components, all in the area of a postage stamp. The smallest dimensions of IC components (or "devices") now approach the atomic scale. This increase in complexity and sophistication, achieved simultaneously with a dramatic decrease in the cost per component, has enabled the entire information technology era in which we live. Without these achievements, mobile phones, the Internet, desktop computers, medical imaging devices, and portable music systems—to name just a few icons of contemporary life—could not exist. It has been estimated that humans now produce more transistors per year than grains of rice.

Since the inception of modern integrated circuit manufacturing, a reduction in size of the individual components that comprise ICs has been a goal of researchers and technologists working in this field. A common expression of this trend is known as "Moore's Law," named after Gordon Moore, author of a seminal paper published in 1965. In that paper, Moore, who would go on to co-found Intel Corporation, predicted that the rapid growth in the number of components fabricated on a chip represented a trend that would continue far into the future. He was correct, and the general trends he predicted are still in evidence four decades later.

As a result, for instance, we see that the number of transistors on a microprocessor has grown from a few thousand to several hundred million, while dynamic random access memory (DRAM) chips have passed the billion-transistor milestone. This has led to enormous advances in the capability of electronic systems, especially on a per-dollar cost basis. During this time, various dimensions of every component on a chip have shrunk, often by orders of magnitude, with some dimensions now best measured in nanometers. This scaling, as it is called, drove and continues to drive Moore's Law and plays out in almost every aspect of IC design and fabrication. Maintaining this progress has required the commitment of enormous resources, both financial and human, as IC processing tools (and the physical environments in which they reside) have been serially developed to meet the challenges of reliably producing ever-smaller features.

Fabrication of integrated circuits involves several hundred individual processing steps and may require several weeks to effect. In many instances, the same types of processing step are repeated again and again, with some variations and perhaps with other processing steps interposed, to create the integrated circuit. These so-called "unit processes" include methods to deposit thin layers of materials onto a substrate, means to define and create intricate patterns within a layer of material, and methods to introduce precise quantities of dopants into layers or the surface of the wafer. The length scales involved with some of these processes are approaching atomic dimensions.

The equipment used for these unit processes includes some of the most sophisticated and expensive instruments ever devised, many of which must be maintained in "clean rooms" that are characterized by levels of dust and contamination orders of magnitude lower than that found in a surgical suite. A modern IC fabrication facility may require several billion dollars of capital expenditure to construct and a thousand or more people to operate.

Silicon wafers most often are grown using the Czochralski growth technique [Figure 19-18(a)]. A small seed crystal is used to grow very large silicon single crystals. The seed crystal is slowly rotated, inserted into, and then pulled from a bath of molten silicon. Silicon atoms attach to the seed crystal in the desired orientation as the seed crystal is retracted. Float zone and liquid encapsulated Czochralski techniques also are used. Single crystals are preferred, because the electrical properties of uniformly doped and essentially dislocation-free single crystals are better defined than those of polycrystalline silicon.

Following the production of silicon wafers, which itself requires considerable expense and expertise, there are four major classes of IC fabrication procedures. The first,



(b)

Figure 19-18 (a) Czochralski growth technique for growing single crystals of silicon. (*From* Microchip Fabrication, Third Edition, *by P. VanZant, Fig. 3-7. Copyright © 1997 The McGraw-Hill Companies. Reprinted by permission The McGraw-Hill Companies.*) (b) Overall steps encountered in the processing of semiconductors. Production of a FET semiconductor device: (i) A *p*-type silicon substrate is oxidized. (ii) In a process known as photolithography, ultraviolet radiation passes through a photomask (which is much like a stencil), thereby exposing a photosensitive material known as photoresist that was previously deposited on the surface. (iii) The exposed photoresist is dissolved. (iv) The exposed silica is removed by etching. (v) An *n*-type dopant is introduced to produce the source and drain. (vi) The silicon is again oxidized. (vii) Photolithography is repeated to introduce other components, including electrical connections, for the device. (*From* Fundamentals of Modern Manufacturing, *by M.P. Groover, p. 849, Fig. 34-3. © John Wiley & Sons, Inc. Reproduced with permission of John Wiley & Sons, Inc.*)

known as "front end" processing, comprises the steps in which the electrical components (e.g., transistors) are created in the uppermost surface regions of a semiconductor wafer. It is important to note that most of the thickness of the wafer exists merely as a mechanical support; the electrically active components are formed on the surface and typically extend only a few thousandths of a millimeter into the wafer. Front-end processing may include a hundred or more steps. A schematic diagram of some exemplar front-end processing steps to produce a field-effect transistor are shown in Figure 19-18(b).

"Back end" processing entails the formation of a network of "interconnections" on and just above the surface of the wafer. Interconnections are formed in thin films of material deposited on top of the wafer that are patterned into precise networks; these serve as three-dimensional conductive pathways that allow electrical signals to pass between the individual electronic components, as required for the IC to operate and perform mathematical and logical operations or to store and retrieve data. Back-end processing culminates with protective layers of materials applied to the wafers that prevent mechanical and environmental damage. One feature of IC fabrication is that large numbers of wafers—each comprising several hundred to several thousand ICs, which in turn may each include several million to several billion individual components—are often fabricated at the same time.

Once back-end processing has been completed, wafers are subjected to a number of testing procedures to evaluate both the wafer as a whole and the individual chips. As the number of components per chip has increased and the size of the components has diminished, testing procedures have themselves become ever more complex and specialized. Wafers with too small a fraction of properly functioning chips are discarded.

The last steps in producing functioning ICs are collectively known as "packaging," during which the wafers are cut apart to produce individual, physically distinct chips. To protect the chips from damage, corrosion, and the like, and to allow electrical signals to pass into and out of the chips, they are placed in special, hermitically sealed containers, often only slightly larger than the chip itself. A computer powered by a single microprocessor contains many other chips for many other functions.

19-7 Deposition of Thin Films

As noted in Section 19-6, integrated circuit fabrication depends in part on the deposition of **thin films** of materials onto a substrate. This is similarly true for many technologies that employ films, coatings, or other thin layers of materials, such as wear-resistant coatings on cutting tools, anti-reflective coatings on optical components, and magnetic layers deposited onto aluminum discs for data storage. Thin films may display very different microstructures and physical properties than their bulk counterparts, features that may be exploited in a number of ways. Creating, studying, and using thin films represents a tremendously broad area of materials science and engineering that has enormous impact on modern technology.

Thin films are, as the name implies, very small in one dimension—especially in comparison to their extent in the other two dimensions. There is no well-defined upper bound on what constitutes "thin," but many modern technologies routinely employ thicknesses of several microns down to just a few atomic dimensions. There are myriad ways by which thin films can be deposited, but in general, any technique involves both a *source* of the material to be deposited and a means to *transport* the material from the source to the workpiece surface upon which it is to be deposited. Many deposition techniques require that the source and workpiece be maintained in a vacuum system, while others place the workpiece in a liquid environment.

Physical vapor deposition (PVD) is one very important category of thin-film growth techniques. PVD takes places in a vacuum chamber, and by one means or another creates a low-pressure vapor of the material to be deposited. Some of this vapor will condense on the workpiece and thereby start to deposit as a thin film. Simply melting a material in vacuum, depending on its vapor pressure, may sometimes produce a useful deposit of material.

Sputtering is an example of physical vapor deposition and is the most important PVD method for integrated circuit manufacturing. The interconnections that carry electrical signals from one electronic device to another on an IC chip typically have been made from aluminum alloys that have been sputter deposited. Sputtering can be used to deposit both conducting and insulating materials.

As shown in Figure 19-19, in a sputtering chamber, argon or other atoms in a gas are first ionized and then accelerated by an electric field towards a source of material to be deposited, sometimes called a "target." These ions dislodge and eject atoms from the surface of the source material, some of which drift across a gap towards the workpiece; those that condense on its surface are said to be deposited. Depending on the how long the process continues, it is possible to sputter deposit films that are many microns thick.

Chemical vapor deposition (CVD) represents another set of techniques that is widely employed in the IC industry. In CVD, the source of the material to be deposited exists in gaseous form. The source gas and other gases are introduced into a heated vacuum chamber where they undergo a chemical reaction that creates the desired material as a product. This product condenses on the workpiece (as in PVD processes) creating, over time, a layer of the material. In some CVD processes, the chemical reaction may take place preferentially on the workpiece itself. Thin films of polycrystalline silicon, tungsten, and



Figure 19-19 Schematic illustration of sputtering. The workpiece and sputter target are placed in a vacuum chamber. (1) An inlet allows a gas such as argon to enter at low pressure. In the presence of the electric field across the target and workpiece, some of the argon atoms are ionized (2) and then accelerated towards the target. By momentum transfer, atoms of the target are ejected (3), drift across the gap towards the workpiece (4), and condense on the workpiece (5), thereby depositing target atoms and eventually forming a film. (*Courtesy of John Bravman.*)

titanium nitride are commonly deposited by CVD as part of IC manufacturing. Nanowire growth, which was discussed in Chapter 11, also often proceeds via a CVD process.

Electrodeposition is a third method for creating thin films on a workpiece. Although this is a very old technology, it has recently been adopted for use in IC manufacturing, especially for depositing the copper films that are replacing aluminum films in most advanced integrated circuits. In electrodeposition, the source and workpiece are both immersed in a liquid electrolyte and also are connected by an external electrical circuit. When a voltage is applied between the source and workpiece, ions of the source material dissolve in the electrolyte, drift under the influence of the field towards the workpiece, and chemically bond on its surface. Over time, a thin film is thus deposited. In some circumstances, an external electric field may not be required; this is called electroless deposition. Electrodeposition and electroless deposition are sometimes referred to as "plating," and the deposited film is sometimes said to be "plated out" on the workpiece.

19-8 Conductivity in Other Materials

Electrical conductivity in most ceramics and polymers is low; however, special materials provide limited or even good conduction. In Chapter 4, we saw how the Kröger-Vink notation can be used to explain defect chemistry in ceramic materials. Using dopants, it is possible to convert many ceramics (e.g., $BaTiO_3$, TiO_2 , ZrO_2) that are normally insulating into conductive oxides. The conduction in these materials can occur as a result of movement of ions or electrons and holes.

Conduction in lonic Materials Conduction in ionic materials often occurs by movement of entire ions, since the energy gap is too large for electrons to enter the conduction band. Therefore, most ionic materials behave as insulators.

In ionic materials, the mobility of the charge carriers, or ions, is

$$\mu = \frac{ZqD}{k_{\rm B}T} \tag{19-15}$$

where *D* is the diffusion coefficient, k_B is the Boltzmann constant, *T* is the absolute temperature, *q* is the electronic charge, and *Z* is the charge on the ion. The mobility is many orders of magnitude lower than the mobility of electrons; hence, the conductivity is very small:

$$\sigma = nZq\mu \tag{19-16}$$

For ionic materials, n is the concentration of ions contributing to conduction. Impurities and vacancies increase conductivity. Vacancies are necessary for diffusion in substitutional types of crystal structures, and impurities can diffuse and help carry the current. High temperatures increase conductivity because the rate of diffusion increases. The following example illustrates the estimation of mobility and conductivity in MgO.

Example 19-6 Ionic Conduction in MgO

Suppose that the electrical conductivity of MgO is determined primarily by the diffusion of the Mg²⁺ ions. Estimate the mobility of the Mg²⁺ ions and calculate the electrical conductivity of MgO at 1800°C. The diffusion coefficient of Mg²⁺ ions in MgO at 1800°C is 10^{-10} cm²/s.

SOLUTION

For MgO, Z = 2/ion, $q = 1.6 \times 10^{-19}$ C, $k_B = 1.38 \times 10^{-23}$ J/K, and T = 2073 K:

$$\mu = \frac{ZqD}{k_BT} = \frac{(2)(1.6 \times 10^{-19})(10^{-10})}{(1.38 \times 10^{-23})(2073)} = 1.12 \times 10^{-9} \,\mathrm{C} \cdot \mathrm{cm}^2 / (\mathrm{J} \cdot \mathrm{s})$$

Since one coulomb is equivalent to one ampere \cdot second, and one Joule is equivalent to one ampere \cdot second \cdot volt:

$$\mu = 1.12 \times 10^{-9} \,\mathrm{cm}^2/(\mathrm{V} \cdot \mathrm{s})$$

MgO has the NaCl structure with four magnesium ions per unit cell. The lattice parameter is 3.96×10^{-8} cm, so the number of Mg²⁺ ions per cubic centimeter is

$$n = \frac{4 \text{ Mg}^{2+} \text{ ions/cell}}{(3.96 \times 10^{-8} \text{ cm})^3} = 6.4 \times 10^{22} \text{ ions/cm}^3$$

$$\sigma = nZq\mu = (6.4 \times 10^{22})(2)(1.6 \times 10^{-9})(1.12 \times 10^{-9})$$

$$= 23 \times 10^{-6} \text{ C} \cdot \text{cm}^2/(\text{cm}^3 \cdot \text{V} \cdot \text{s})$$

Since one coulomb is equivalent to one ampere \cdot second (A \cdot s) and one volt is equivalent to one ampere \cdot ohm (A \cdot Ω),

$$\sigma = 2.3 \times 10^{-5} \,\mathrm{ohm}^{-1} \cdot \mathrm{cm}^{-1}$$

Applications of lonically Conductive Oxides The most widely used conductive and transparent oxide is indium tin oxide (ITO), used as a transparent conductive coating on plate glass. Other applications of (ITO) include touch screen displays for computers and devices such as automated teller machines. Other conductive oxides include ytrria-stabilized zirconia (YSZ), which is used as a solid electrolyte in solid oxide fuel cells. Lithium cobalt oxide is used as a solid electrolyte in lithium ion batteries. It is important to remember that, although most ceramic materials behave as electrical insulators, by properly engineering the point defects in ceramics, it is possible to convert many of them into semiconductors.

Conduction in Polymers Because their valence electrons are involved in covalent bonding, polymers have a band structure with a large energy gap, leading to low-electrical conductivity. Polymers are frequently used in applications that require electrical insulation to prevent short circuits, arcing, and safety hazards. Table 19-1 includes the conductivity of four common polymers. In some cases, however, the low conductivity is a hindrance. For example, if lightning strikes the polymer-matrix composite wing of an airplane, severe damage can occur. We can solve these problems by two approaches: (1) introducing an additive to the polymer to improve the conductivity, and (2) creating polymers that inherently have good conductivity.

The introduction of electrically conductive additives can improve conductivity. For example, polymer-matrix composites containing carbon or nickel-plated carbon fibers combine high stiffness with improved conductivity; hybrid composites containing metal fibers, along with normal carbon, glass, or aramid fibers, also produce lightning-safe aircraft skins. Figure 19-20 shows that when enough carbon fibers are introduced to nylon



Figure 19-20

Effect of carbon fibers on the electrical resistivity of nylon.

in order to ensure fiber-to-fiber contact, the resistivity is reduced by nearly 13 orders of magnitude. Conductive fillers and fibers are also used to produce polymers that shield against electromagnetic radiation.

Some polymers inherently have good conductivity as a result of doping or processing techniques. When acetal polymers are doped with agents such as arsenic penta-fluoride, electrons or holes are able to jump freely from one atom to another along the backbone of the chain, increasing the conductivity to near that of metals. Some polymers, such as polyphthalocyanine, can be cross-linked by special curing processes to raise the conductivity to as high as 10^2 ohm⁻¹ · cm⁻¹, a process that permits the polymer to behave as a semiconductor. Because of the cross-linking, electrons can move more easily from one chain to another. Organic light-emitting diodes are fabricated from semiconducting polymers including polyanilines.

19-9 Insulators and Dielectric Properties

Materials used to insulate an electric field from its surroundings are required in a large number of electrical and electronic applications. Electrical insulators obviously must have a very low conductivity, or high resistivity, to prevent the flow of current. Insulators must also be able to withstand intense electric fields. Insulators are produced from ceramic and polymeric materials in which there is a large energy gap between the valence and conduction bands; however, the high-electrical resistivity of these materials is not always sufficient. At high voltages, a catastrophic breakdown of the insulator may occur, and current may flow. For example, the electrons may have kinetic energies sufficient to ionize the atoms of the insulator, thereby creating free electrons and generating a current at high voltages. In order to select an insulating material properly, we must understand how the material stores, as well as conducts, electrical charge. Porcelain, alumina, cordierite, mica, and some glasses and plastics are used as insulators. The resistivity of most of these is $> 10^{14} \Omega \cdot cm$, and the breakdown electric fields are ~ 5 to 15 kV/mm.

19-10 Polarization in Dielectrics

When we apply stress to a material, some level of strain develops. Similarly, when we subject materials to an electric field, the atoms, molecules, or ions respond to the applied electric field (*E*). Thus, the material is said to be polarized. A dipole is a pair of opposite charges separated by a certain distance. If one charge of +q is separated from another charge of -q (*q* is the electronic charge) and *d* is the distance between these charges, the dipole moment is $q \times d$. The magnitude of polarization is given by P = zqd, where *z* is the number of charge centers that are displaced per cubic meter.

Any separation of charges (e.g., between the nucleus and electron cloud) or any mechanism that leads to a change in the separation of charges that are already present (e.g., movement or vibration of ions in an ionic material) causes **polarization**. There are four primary mechanisms causing polarization: (1) electronic polarization, (2) ionic polarization, (3) molecular polarization, and (4) space charge (Figure 19-21). Their occurrence depends upon the electrical frequency of the applied field, just like the mechanical behavior of materials depends on the strain rate (Chapters 6 and 8). If we apply a very rapid rate of strain, certain mechanisms of plastic deformation are not activated. Similarly, if we apply a rapidly alternating electric field, some polarization mechanisms may be unable to induce polarization in the material.

Polarization mechanisms play two important roles. First, if we make a **capacitor** from a material, the polarization mechanisms allow charge to be stored, since the dipoles created in the material (as a result of polarization) can bind a certain portion of the charge on the electrodes of the capacitor. Thus, the higher the dielectric polarization, the higher the dielectric constant (k) of the material. The dielectric constant is defined as the ratio of capacitance between a capacitor filled with dielectric material and one with vacuum between its electrodes. This charge storage, in some ways, is similar to the elastic strain in a material subjected to stress. The second important role played by polarization mechanisms is that when polarization sets in, charges move (ions or electron clouds are displaced). If the electric field oscillates, the charges move back and forth. These displacements are extremely small (typically < 1 Å); however, they cause **dielectric losses**. This energy is lost as heat. The dielectric loss is similar to the viscous deformation of a material. If we want to store a charge, as in a capacitor, dielectric loss is not good; however, if we want to use microwaves to heat up our food, dielectric losses that occur in water contained in the food are great! The dielectric losses are often measured by a parameter known as *tan* δ . When we are interested in extremely low loss materials, such as those used in microwave communications, we refer to a parameter known as the dielectric quality factor $(Q_d \sim 1/\tan \delta)$. The dielectric constant and dielectric losses depend strongly on electrical frequency and temperature.

Electronic polarization is omnipresent since all materials contain atoms. The electron cloud gets displaced from the nucleus in response to the field seen by the atoms. The separation of charges creates a dipole moment [Figure 19-21(a)]. This mechanism can survive at the highest electrical frequencies ($\sim 10^{15}$ Hz) since an electron cloud can be displaced rapidly, back and forth, as the electrical field switches. Larger atoms and ions have higher electronic polarizability (tendency to undergo polarization), since the electron cloud is farther away from the nucleus and held less tightly. This polarization mechanism is also linked closely to the refractive index of materials, since light is an electromagnetic wave for which the electric field oscillates at a very high frequency ($\sim 10^{14} - 10^{16}$ Hz). The higher the electronic polarizability, the higher the refractive index. We use this mechanism in making "lead crystal," which is really an amorphous glass that contains up to 30% PbO.



Figure 19-21 Polarization mechanisms in materials: (a) electronic, (b) atomic or ionic, (c) high-frequency dipolar or orientation (present in ferroelectrics), (d) low-frequency dipolar (present in linear dielectrics and glasses), (e) interfacial-space charge at electrodes, and (f) interfacial-space charge at heterogeneities such as grain boundaries. (*From* Principles of Electronic Ceramics, *L.L. Hench and J.K. West, p. 188, Fig. 5-2. Copyright © 1990 Wiley Interscience. Reprinted by permission. This material is used by permission of John Wiley & Sons, Inc.)*

The large lead ions (Pb^{+2}) are highly polarizable due to the electronic polarization mechanisms and provide a high-refractive index when high enough concentrations of lead oxide are present in the glass.

Example 19-7 *Electronic Polarization in Copper*

Suppose that the average displacement of the electrons relative to the nucleus in a copper atom is 10^{-8} Å when an electric field is imposed on a copper plate. Calculate the electronic polarization.

SOLUTION

The atomic number of copper is 29, so there are 29 electrons in each copper atom. The lattice parameter of copper is 3.6151 Å. Thus,

$$z = \frac{(4 \text{ atoms/cell})(29 \text{ electrons/atom})}{(3.6151 \times 10^{-10} \text{ m})^3} = 2.455 \times 10^{30} \text{ electrons/m}^3$$
$$P = zqd = \left(2.455 \times 10^{30} \frac{\text{electrons}}{\text{m}^3}\right) \left(1.6 \times 10^{-19} \frac{\text{C}}{\text{electron}}\right) (10^{-8} L)(10^{-10} \text{ m/Å})$$
$$= 3.93 \times 10^{-7} \text{ C/m}^2$$

Frequency and Temperature Dependence of the Dielectric Constant and Dielectric Losses A capacitor is

a device that is capable of storing electrical charge. It typically consists of two electrodes with a dielectric material situated between them. The dielectric may or may not be a solid; even an air gap or vacuum can serve as a dielectric. Two parallel, flat-plate electrodes represent the simplest configuration for a capacitor.

Capacitance C is the ability to store charge and is defined as

$$C = \frac{Q}{V} \tag{19-17}$$

where Q is the charge on the electrode plates of a capacitor and V is the applied voltage [Figure 19-22(a)]. Note that a voltage must be applied to create the charge on the electrodes, but that the charge is "stored" in the absence of the voltage until an external circuit allows it to dissipate. In microelectronic devices, this is the basis for digital data



Figure 19-22 (a) A charge can be stored on the conductor plates in a vacuum. (b) When a dielectric is placed between the plates, the dielectric polarizes, and additional charge is stored.

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storage. If the space between two parallel plates (with surface area A and separated by a distance t) is filled with a material, then the dielectric constant k, also known as the relative permittivity ε_r , is determined according to

$$C = \frac{k \varepsilon_0 A}{t} \tag{19-18}$$

The constant ε_0 is the **permittivity** of a vacuum and is 8.85×10^{-12} F/m. As the material undergoes polarization, it can bind a certain amount of charge on the electrodes, as shown in Figure 19-22(b). The greater the polarization, the higher the dielectric constant, and therefore, the greater the bound charge on the electrodes.

The dielectric constant is the measure of how susceptible the material is to the applied electric field. The dielectric constant depends on the composition, microstructure, electrical frequency, and temperature. The capacitance depends on the dielectric constant, area of the electrodes, and the separation between the electrodes. Capacitors in parallel provide added capacitance (just like resistances add in series). This is the reason why multi-layer capacitors consist of 100 or more layers connected in parallel. These are typically based on BaTiO₃ formulations and are prepared using a tape-casting process. Silver-palladium or nickel is used as electrode layers.

For electrical insulation, the **dielectric strength** (i.e., the electric field value that can be supported prior to electrical breakdown) is important. The dielectric properties of some materials are shown in Table 19-7

Linear and Nonlinear Dielectrics The dielectric constant, as expected, is related to the polarization that can be achieved in the material. We can show that the dielectric polarization induced in a material depends upon the applied electric field and the dielectric constant according to

$$P = (k - 1)\varepsilon_0 E \text{ (for linear dielectrics)}$$
(19-19)

TABLE 19-7 Properties of selected dielectric materials

	Dielectri	c Constant	Dielectric		
Material	(at 60 Hz)	(at 10 ⁶ Hz)	Strength (10 ⁶ V/m)	tan δ (at 10 ⁶ Hz)	Resistivity (ohm · cm)
Polyethylene	2.3	2.3	20	0.00010	$> 10^{16}$
Teflon	2.1	2.1	20	0.00007	10 ¹⁸
Polystyrene	2.5	2.5	20	0.00020	10 ¹⁸
PVC	3.5	3.2	40	0.05000	10 ¹²
Nylon	4.0	3.6	20	0.04000	10 ¹⁵
Rubber	4.0	3.2	24		
Phenolic	7.0	4.9	12	0.05000	10 ¹²
Ероху	4.0	3.6	18		10 ¹⁵
Paraffin wax		2.3	10		$10^{13} - 10^{19}$
Fused silica	3.8	3.8	10	0.00004	$10^{11} - 10^{12}$
Soda-lime glass	7.0	7.0	10	0.00900	10 ¹⁵
Al ₂ O ₃	9.0	6.5	6	0.00100	$10^{11} - 10^{13}$
TiO ₂		14–110	8	0.00020	$10^{13} - 10^{18}$
Mica		7.0	40		10 ¹³
BaTiO ₃		2000-5000	12	~0.0001	$10^{8} - 10^{15}$
Water		78.3			10 ¹⁴

where *E* is the strength of the electric field (V/m). For materials that polarize easily, both the dielectric constant and the capacitance are large and, in turn, a large quantity of charge can be stored. In addition, Equation 19-19 suggests that polarization increases, at least until all of the dipoles are aligned, as the voltage (expressed by the strength of the electric field) increases. The quantity (k–1) is known as dielectric susceptibility (χ_e). The dielectric constant of vacuum is one, or the dielectric susceptibility is zero. This makes sense since a vacuum does not contain any atoms or molecules.

In linear dielectrics, P is linearly related to E and k is constant. This is similar to how stress and strain are linearly related by Hooke's law. In linear dielectrics, k (or χ_e) remains constant with changing E. In materials such as BaTiO₃, the dielectric constant changes with E, and hence, Equation 19-19 cannot be used. These materials in which P and E are not related by a straight line are known as **nonlinear dielectrics** or ferroelectrics. These materials are similar to elastomers for which stress and strain are not linearly related and a unique value of the Young's modulus cannot be assigned.

19-11 Electrostriction, Piezoelectricity, and Ferroelectricity

When any material undergoes polarization, its ions and electron clouds are displaced, causing the development of a mechanical strain in the material. This effect is seen in all materials subjected to an electric field and is known as **electrostriction**.

Of the total 32 crystal classes, eleven have a center of symmetry. This means that if we apply a mechanical stress, there is no dipole moment generated since ionic movements are symmetric. Of the 21 that remain, 20 point groups, which lack a center of symmetry, exhibit the development of dielectric polarization when subjected to stress. These materials are known as **piezoelectric**. (The word *piezo* means pressure.) When these materials are stressed, they develop a voltage. This development of a voltage upon the application of stress is known as the *direct* or *motor piezoelectric effect* (Figure 19-23). This effect helps us make devices such as spark igniters, which are often made using lead zirconium titanate (PZT). This effect is also used, for example, in detecting submarines and other objects under water.



Figure 19-23 The (a) direct and (b) converse piezoelectric effect. In the direct piezoelectric effect, applied stress causes a voltage to appear. In the converse effect (b), an applied voltage leads to the development of strain.

Conversely, when an electrical voltage is applied, a piezoelectric material shows the development of strain. This is known as the *converse* or *generator piezoelectric effect*. This effect is used in making actuators. For example, this movement can be used to generate ultrasonic waves that are used in medical imaging, as well as such applications as ultrasonic cleaners or toothbrushes. Sonic energy can also be created using piezoelectrics to make the high-fidelity "tweeter" found in most speakers. In addition to Pb(Zr_xTi_{1-x})O₃ (PZT), other piezoelectrics include SiO₂ (for making quartz crystal oscillators), ZnO, and polyvinylidene fluoride (PVDF). Many naturally occurring materials such as bone and silk are also piezoelectric.

The "d" constant for a piezoelectric is defined as the ratio of strain (ε) to electric field:

$$\varepsilon = d \cdot E \tag{19-20}$$

The "g" constant for a piezoelectric is defined as the ratio of the electric field generated to the stress applied (X):

$$E = g \cdot X \tag{19-21}$$

The *d* and *g* piezoelectric coefficients are related by the dielectric constant as:

$$g = \frac{d}{\mathbf{k}\varepsilon_0} \tag{19-22}$$

We define **ferroelectrics** as materials that show the development of a spontaneous and reversible dielectric polarization (P_s). Examples include the tetragonal polymorph of barium titanate. Lead zirconium titanate is both ferroelectric and piezoelectric. Ferroelectric materials show a **hysteresis loop** (i.e., the induced polarization is not linearly related to the applied electric field) as seen in Figure 19-24.



Figure 19-24

The ferroelectric hysteresis loop for a single-domain single crystal of BaTiO₃. (*From* Electroceramics: Material, Properties, Applications, by A.J. Moulson and J.M. Herbert, p. 76, Fig. 2-46. Copyright © 1990 Chapman and Hall. Reprinted with kind permission of Kluwer Academic Publishers and the author.)



Figure 19-25

Ferroelectric domains can be seen in the microstructure of polycrystalline BaTiO₃. (*Courtesy of Dr. Rodney Roseman, University of Cincinnati.*)

Ferroelectric materials exhibit ferroelectric domains in which the region (or domain) has uniform polarization (Figure 19-25.) Certain ferroelectrics, such as PZT, exhibit a strong piezoelectric effect, but in order to maximize the piezoelectric effect (e.g., the development of strain or voltage), piezoelectric materials are deliberately "poled" using an electric field to align all domains in one direction. The electric field is applied at high temperature and maintained while the material is cooled.

The dielectric constant of ferroelectrics reaches a maximum near a temperature known as the **Curie temperature**. At this temperature, the crystal structure acquires a center of symmetry and thus is no longer piezoelectric. Even at these high temperatures, however, the dielectric constant of ferroelectrics remains high. BaTiO₃ exhibits this behavior, and this is the reason why BaTiO₃ is used to make single and multi-layer capacitors. In this state, vibrations and shocks do not generate spurious voltages due to the piezoelectric effect. Since the Curie transition occurs at a high temperature, use of additives in BaTiO₃ helps to shift the Curie transition. Materials such as Pb(Mg_{1/3}Nb_{2/3})O₃ or PMN are known as *relaxor ferroelectrics*. These materials show very high dielectric constants (up to 20,000) and good piezoelectric behavior, so they are used to make capacitors and piezoelectric devices.

Example 19-8 *Design of a Multi-Layer Capacitor*

A multi-layer capacitor is to be designed using a BaTiO₃ formulation containing SrTiO₃. The dielectric constant of the material is 3000. (a) Calculate the capacitance of a multi-layer capacitor consisting of 100 layers connected in parallel using nicklel electrodes. The area of each layer is 10 mm \times 5 mm, and the thickness of each layer is 10 μ m.

SOLUTION

(a) The capacitance of a parallel plate capacitor is given by

$$C = \frac{k\varepsilon_0 A}{t}$$

Thus, the capacitance per layer will be

$$C_{\text{layer}} = \frac{(3000)(8.85 \times 10^{-12} \,\text{F/m})(10 \times 10^{-3} \,\text{m})(5 \times 10^{-3} \,\text{m})}{10 \times 10^{-6} \,\text{m}}$$
$$C_{\text{layer}} = 13.28 \times 10^{-8}$$

We have 100 layers connected in parallel. Capacitances add in this arrangement. All layers have the same geometric dimensions in this case.

 $C_{\text{total}} = (\text{number of layers}) \cdot (\text{capacitance per layer})$ $C_{\text{total}} = (100)(13.28 \times 10^{-8} \text{ F}) = 13.28 \,\mu\text{F}$

Summary

- Electronic materials include insulators, dielectrics, conductors, semiconductors, and superconductors. These materials can be classified according to their band structures. Electronic materials have enabled many technologies ranging from high-voltage line insulators to solar cells, computer chips, and many sensors and actuators.
- Important properties of conductors include the conductivity and the temperature dependence of conductivity. In pure metals, the resistivity increases with temperature. Resistivity is sensitive to impurities and microstructural defects such as grain boundaries. Resistivity of alloys is typically higher than that of pure metals.
- Semiconductors have conductivities between insulators and conductors and are much poorer conductors than metals. The conductivities of semiconductors can be altered by orders of magnitude by minute quantities of certain dopants. Semiconductors can be classified as elemental (Si, Ge) or compound (SiC, GaAs). Both of these can be intrinsic or extrinsic (*n* or *p*-type). Some semiconductors have direct bandgaps (e.g., GaAs), while others have indirect bandgaps (e.g., Si).
- Creating an *n*-type region in a *p*-type semiconductor (or vice versa) forms a *p*-*n* junction. The *p*-*n* junction is used to make diodes and transistors.
- Microelectronics fabrication involves hundreds of precision processes that can produce hundreds of millions and even a billion transistors on a single microchip.
- Thin films are integral components of microelectronic devices and also are used for wear-resistant and anti-reflective coatings. Thin films can be deposited using a variety of techniques, including physical vapor deposition, chemical vapor deposition, and electrodeposition.

- · Ionic materials conduct electricity via the movement of ions or electrons and holes.
- Dielectrics have large bandgaps and do not conduct electricity. With insulators, the focus is on breakdown voltage or field. With dielectrics, the emphasis is on the dielectric constant, frequency, and temperature dependence. Polarization mechanisms in materials dictate this dependence.
- In piezoelectrics, the application of stress results in the development of a voltage; the application of a voltage causes strain.
- Ferroelectrics are materials that show a reversible and spontaneous polarization. BaTiO₃, PZT, and PVDF are examples of ferroelectrics. Ferroelectrics exhibit a large dielectric constant and are often used to make capacitors.

Glossary

Bandgap (E_g) The energy between the top of the valence band and the bottom of the conduction band.

Band structure The band structure consists of the array of energy levels that are available to or forbidden for electrons to occupy and determines the electronic behavior of a solid, such as whether it is a conductor, semiconductor, or insulator.

Capacitor A device that is capable of storing electrical charge. It typically consists of two electrodes with a dielectric material situated between them, but even an air gap can serve as a dielectric. A capacitor can be a single layer or multi-layer device.

Chemical Vapor Deposition (CVD) A thin-film growth process in which gases undergo a reaction in a heated vacuum chamber to create the desired product on a substrate.

Conduction band The unfilled energy levels into which electrons are excited in order to conduct.

Curie temperature The temperature above which a ferroelectric is no longer piezoelectric.

Current density Current per unit cross-sectional area.

Dielectric constant (*k***)** The ratio of the permittivity of a material to the permittivity of vacuum, thus describing the relative ability of a material to polarize and store a charge; the same as relative permittivity.

Dielectric loss A measure of how much electrical energy is lost due to motion of charge entities that respond to an electric field via different polarization mechanisms. This energy appears as heat.

Dielectric strength The maximum electric field that can be maintained between two conductor plates without causing a breakdown.

Doping Deliberate addition of controlled amounts of other elements to increase the number of charge carriers in a semiconductor.

Drift velocity The average rate at which electrons or other charge carriers move through a material under the influence of an electric or magnetic field.

Electric field The voltage gradient or volts per unit length.

Electrodeposition A method for depositing materials in which a source and workpiece are connected electrically and immersed in an electrolyte. A voltage is applied between the source and workpiece, and ions from the source dissolve in the electrolyte, drift to the workpiece, and gradually deposit a thin film on its surface.

Electrostriction The dimensional change that occurs in any material when an electric field acts on it.

Energy gap (E_g) (Bandgap) The energy between the top of the valence band and the bottom of the conduction band.

Extrinsic semiconductor A semiconductor prepared by adding dopants, which determine the number and type of charge carriers. Extrinsic behavior can also be seen due to impurities.

Fermi energy The energy level at which the probability of finding an electron is 1/2.

Ferroelectric A material that shows spontaneous and reversible dielectric polarization.

Forward bias Connecting a *p*-*n* junction device so that the *p*-side is connected to a positive terminal, thereby enabling current to flow.

Holes Unfilled energy levels in the valence band. Because electrons move to fill these holes, the holes produce a current.

Hysteresis loop The loop traced out by the nonlinear polarization in a ferroelectric material as the electric field is cycled. A similar loop occurs in certain magnetic materials.

Integrated circuit An electronic package that comprises large numbers of electronic devices fabricated on a single chip.

Intrinsic semiconductor A semiconductor in which properties are controlled by the element or compound that is the semiconductor and not by dopants or impurities.

Linear dielectrics Materials in which the dielectric polarization is linearly related to the electric field; the dielectric constant is not dependent on the electric field.

Matthiessen's rule The resistivity of a metallic material is given by the addition of a base resistivity that accounts for the effect of temperature (ρ_T) and a temperature independent term that reflects the effect of atomic level defects, including solutes forming solid solutions (ρ_d).

Mean free path (λ_{e}) The average distance that electrons move without being scattered by other atoms or lattice defects.

Microstructure-sensitive property Properties that depend on the microstructure of a material (e.g., conductivity, dielectric constant, or yield strength).

Mobility The ease with which a charge carrier moves through a material.

Nonlinear dielectrics Materials in which dielectric polarization is not linearly related to the electric field (e.g., ferroelectric). These have a field-dependent dielectric constant.

Nonradiative recombination The generation of heat when an electron loses energy and falls from the conduction band to the valence band to occupy a hole; this occurs mainly in indirect bandgap materials such as Si.

p-n junction A device made by creating an *n*-type region in a *p*-type material (or vice versa). A *p*-*n* junction behaves as a diode and multiple *p*-*n* junctions function as transistors. It is also the basis of LEDs and solar cells.

Permittivity The ability of a material to polarize and store a charge within it.

Physical Vapor Deposition (PVD) A thin-film growth process in which a low-pressure vapor supplies the material to be deposited on a substrate. Sputtering is one example of PVD.

Piezoelectrics Materials that develop voltage upon the application of a stress and develop strain when an electric field is applied.

Polarization Movement of charged entities (i.e., electron cloud, ions, dipoles, and molecules) in response to an electric field.

Radiative recombination The emission of light when an electron loses energy and falls from the conduction band to the valence band to occupy a hole; this occurs in direct bandgap materials such as GaAs.

Rectifier A *p*-*n* junction device that permits current to flow in only one direction in a circuit.

Reverse bias Connecting a junction device so that the *p*-side is connected to a negative terminal; very little current flows through a *p*-*n* junction under reverse bias.

Sputtering A thin-film growth process by which gas atoms are ionized and then accelerated by an electric field towards the source, or "target," of material to be deposited. These ions eject atoms from the target surface, some of which are then deposited on a substrate. Sputtering is one type of a physical vapor deposition process.

Superconductor A material that exhibits zero electrical resistance under certain conditions.

Thermistor A semiconductor device that is particularly sensitive to changes in temperature, permitting it to serve as an accurate measure of temperature.

Thin film A coating or layer that is small or thin in one dimension. Typical thicknesses range from 10 Å to a few microns depending on the application.

Transistor A semiconductor device that amplifies or switches electrical signals.

Valence band The energy levels filled by electrons in their lowest energy states.

Problems

Section 19-1 Ohm's Law and Electrical Conductivity

Section 19-2 Band Structure of Solids

Section 19-3 Conductivity of Metals and Alloys

- **19-1** A current of 10 A is passed through a 1-mm diameter wire 1000 m long. Calculate the power loss if the wire is made from
 - (a) aluminum and
 - (b) silicon (see Table 19-1).
- **19-2** A 0.5-mm-diameter fiber, 1 cm in length, made of boron nitride is placed in a 120 V circuit. Using Table 19-1, calculate
 - (a) the current flowing in the circuit and
 - (b) the number of electrons passing through the boron nitride fiber per second.
 - (c) What would the current and number of electrons be if the fiber were made of magnesium instead of boron nitride?
- **19-3** The power lost in a 2-mm-diameter copper wire is to be less than 250 W when a 5 A current is flowing in the circuit. What is the maximum length of the wire?
- **19-4** A current density of 100,000 A/cm² is applied to a gold wire 50 m in length. The resistance of the wire is found to be 2 ohms.

Calculate the diameter of the wire and the voltage applied to the wire.

- **19-5** We would like to produce a 5000-ohm resistor from boron-carbide fiber having a diameter of 0.1 mm. What is the required length of the fiber?
- **19-6** Ag has an electrical conductivity of $6.80 \times 10^5 \Omega^{-1} \cdot \text{cm}^{-1}$. Au has an electrical conductivity of $4.26 \times 10^5 \Omega^{-1} \cdot \text{cm}^{-1}$. Calculate the number of charge carriers per unit volume and the electron mobility in each in order to account for this difference in electrical conductivity. Comment on your findings.
- **19-7** A current density of 5000 A/cm² is applied to a magnesium wire. If half of the valence electrons serve as charge carriers, calculate the average drift velocity of the electrons.
- **19-8** We apply 10 V to an aluminum wire 2 mm in diameter and 20 m long. If 10% of the valence electrons carry the electrical charge, calculate the average drift velocity of the electrons in km/h.
- **19-9** In a welding process, a current of 400 A flows through the arc when the voltage is 35 V. The length of the arc is about 0.25 cm, and the average diameter of the arc is about 0.45 cm. Calculate the current density in the arc, the electric field across the arc, and the electrical conductivity of the hot gases in the arc during welding.

- **19-10** Draw a schematic of the band structures of an insulator, a semiconductor, and a metallic material. Use this to explain why the conductivity of pure metals decreases with increasing temperature, while the opposite is true for semiconductors and insulators.
- **19-11** A typical thickness for a copper conductor (known as an interconnect) in an integrated circuit is 250 nm. The mean free path of electrons in pure, annealed copper is about 40 nm. As the thickness of copper interconnects approaches the mean free path, how do you expect conduction in the interconnect is affected? Explain.
- **19-12** Calculate the electrical conductivity of platinum at -200°C.
- **19-13** Calculate the electrical conductivity of nickel at -50°C and at +500°C.
- **19-14** The electrical resistivity of pure chromium is found to be 18×10^{-6} ohm \cdot cm. Estimate the temperature at which the resistivity measurement was made.
- **19-15** After finding the electrical conductivity of cobalt at 0°C, we decide we would like to double that conductivity. To what temperature must we cool the metal?
- **19-16** From Figure 19-9 (b), estimate the defect resistivity coefficient for tin in copper.



Figure 19-9 (Repeated for Problem 19-16.) (b) The effect of selected elements on the electrical conductivity of copper.

- **19-17** (a) Copper and nickel form a complete solid solution. Draw a schematic diagram illustrating the resistivity of a copper and nickel alloy as a function of the atomic percent nickel. Comment on why the curve has the shape that it does.
 - (b) Copper and gold do not form a complete solid solution. At the compositions of 25 and 50 atomic percent gold, the ordered phases Cu₃Au and CuAu form, respectively. Do you expect that a plot of the resistivity of a copper and gold alloy as a function of the atomic percent gold will have a shape similar to the plot in part (a)? Explain.
- **19-18** The electrical resistivity of a beryllium alloy containing 5 at% of an alloying element is found to be 50 × 10⁻⁶ ohm · cm at 400°C. Determine the contributions to resistivity due to temperature and due to impurities by finding the expected resistivity of pure beryllium at 400°C, the resistivity due to impurities, and the defect resistivity coefficient. What would be the electrical resistivity if the beryllium contained 10 at% of the alloying element at 200°C?

Section 19-4 Semiconductors

Section 19-5 Applications of Semiconductors

Section 19-6 General Overview of Integrated Circuit Processing

Section 19-7 Deposition of Thin Films

- **19-19** Explain the following terms: semiconductor, intrinsic semiconductor, extrinsic semiconductor, elemental semiconductor, compound semiconductor, direct bandgap semiconductor, and indirect bandgap semiconductor.
- **19-20** What is radiative and nonradiative recombination? What types of materials are used to make LEDs?
- **19-21** For germanium and silicon, compare, at 25°C, the number of charge carriers per cubic centimeter, the fraction of the total

electrons in the valence band that are excited into the conduction band, and the constant n_0 .

- **19-22** For germanium and silicon, compare the temperature required to double the electrical conductivity from the room temperature value.
- **19-23** Determine the electrical conductivity of silicon when 0.0001 at% antimony is added as a dopant and compare it to the electrical conductivity when 0.0001 at% indium is added.
- **19-24** We would like to produce an extrinsic germanium semiconductor having an electrical conductivity of 2000 ohm⁻¹ \cdot cm⁻¹. Determine the amount of phosphorous and the amount of gallium required to make *n* and *p*-type semiconductors, respectively.
- **19-25** Estimate the electrical conductivity of silicon doped with 0.0002 at% arsenic at 600°C, which is above the plateau in the conductivity-temperature curve.
- **19-26** Determine the amount of arsenic that must be combined with 1 kg of gallium to produce a *p*-type semiconductor with an electrical conductivity of 500 ohm⁻¹ \cdot cm⁻¹ at 25°C. The lattice parameter of GaAs is about 5.65 Å, and GaAs has the zinc blende structure.
- **19-27** Calculate the intrinsic carrier concentration for GaAs at room temperature. Given that the effective mass of electrons in GaAs is $0.067m_e$, where m_e is the mass of the electron, calculate the effective mass of the holes.
- **19-28** Calculate the electrical conductivity of silicon doped with 10¹⁸ cm⁻³ boron at room temperature. Compare the intrinsic carrier concentration to the dopant concentration.
- **19-29** At room temperature, will the conductivity of silicon doped with 10^{17} cm⁻³ of arsenic be greater than, about equal to, or less than the conductivity of silicon doped with 10^{17} cm⁻³ of phosphorus?
- **19-30** When a voltage of 5 mV is applied to the emitter of a transistor, a current of 2 mA is produced. When the voltage is increased to

8 mV, the current through the collector rises to 6 mA. By what percentage will the collector current increase when the emitter voltage is doubled from 9 mV to 18 mV?

- **19-31** Design a light-emitting diode that will emit at 1.12 micrometers. Is this wavelength in the visible range? What is a potential application for this type of LED?
- **19-32** How can we make LEDs that emit white light (i.e., light that looks like sunlight)?
- **19-33** Investigate the scaling relationship known as Moore's Law. Is it expected that this trend will continue to be followed in the future using established microelectronics fabrication techniques? If not, what are some of the alternatives currently being considered? Provide a list of the references or websites that you used.
- **19-34** Silicon is the material of choice for the substrate for integrated circuits. Explain why silicon is preferred over germanium, even though the electron and hole mobilities are much higher and the bandgap is much smaller for germanium than for silicon. Provide a list of the references or websites that you used.

Section 19-8 Conductivity in Other Materials

- **19-35** Calculate the electrical conductivity of a fiber-reinforced polyethylene part that is reinforced with 20 vol% of continuous, aligned nickel fibers.
- **19-36** What are ionic conductors? What are their applications?
- **19-37** How do the touch screen displays on some computers work?
- **19-38** Can polymers be semiconducting? What would be the advantages in using these instead of silicon?

Section 19-9 Insulators and Dielectric Properties

Section 19-10 Polarization in Dielectrics

19-39 With respect to mechanical behavior, we have seen that stress (a cause) produces strain (an effect). What is the electrical analog of this?

- **19-40** With respect to mechanical behavior, elastic modulus represents the elastic energy stored, and viscous dissipation represents the mechanical energy lost in deformation. What is the electrical analog for this?
- **19-41** Calculate the displacement of the electrons or ions for the following conditions:
 - (a) electronic polarization in nickel of $2 \times 10^{-7} \text{ C/m}^2$;
 - (b) electronic polarization in aluminum of $2 \times 10^{-8} \text{ C/m}^2$;
 - (c) ionic polarization in NaCl of $4.3 \times 10^{-8} \text{ C/m}^2$; and
 - (d) ionic polarization in ZnS of $5 \times 10^{-8} \text{ C/m}^2$.
- **19-42** A 2-mm-thick alumina dielectric is used in a 60 Hz circuit. Calculate the voltage required to produce a polarization of 5×10^{-7} C/m².
- **19-43** Suppose we are able to produce a polarization of 5×10^{-8} C/m² in a cube (5 mm side) of barium titanate. Assume a dielectric constant of 3000. What voltage is produced?
- **19-44** What polarization mechanism will be present in (a) alumina, (b) copper, (c) silicon, and (d) barium titanate?

Section 19-11 Electrostriction, Piezoelectricity, and Ferroelectricity

- **19-45** Define the following terms: electrostriction, piezoelectricity (define both its direct and converse effects), and ferroelectricity.
- **19-46** Calculate the capacitance of a parallelplate capacitor containing five layers of mica for which each mica sheet is $1 \text{ cm} \times 2 \text{ cm} \times 0.005 \text{ cm}$. The layers are connected in parallel.
- **19-47** A multi-layer capacitor is to be designed using a relaxor ferroelectric formulation

based on lead magnesium niobate (PMN). The apparent dielectric constant of the material is 20,000. Calculate the capacitance of a multi-layer capacitor consisting of ten layers connected in parallel using Ni electrodes. The area of the capacitor is $10 \text{ mm} \times 10 \text{ mm}$, and the thickness of each layer is $20 \mu \text{m}$.

19-48 A force of 90 N is applied to the face of a $0.5 \text{ cm} \times 0.5 \text{ cm} \times 0.1 \text{ cm}$ thickness of quartz crystal. Determine the voltage produced by the force. The modulus of elasticity of quartz is 72×10^3 MPa.

Design Problems

- **19-49** We would like to produce a 100-ohm resistor using a thin wire of a material. Design such a device.
- **19-50** Design a capacitor that is capable of storing 1 μ F when 100 V is applied.
- **19-51** Design an epoxy-matrix composite that has a modulus of elasticity of at least 240×10^3 MPa and an electrical conductivity of at least 1×10^5 ohm⁻¹ · cm⁻¹.

Computer Problems

19-52 *Design of Multi-layer Capacitors.* Write a computer program that can be used to calculate the capacitance of a multi-layer capacitor. The program, for example, should ask the user to provide values of the dielectric constant and the dimensions of the layer. The program should also be flexible in that if the user provides an intended value of capacitance and other dimensions, the program should provide the required dielectric constant.

U Knovel[®] **Problems**

- **K19-1** Calculate the resistivity of pure iridium at 673 K using its temperature resistivity coefficient.
- **K19-2** Electrical conductivity is sometimes given in the units of %IACS. What does IACS stand for? Define the unit using the information found.
- **K19-3** Can organic materials such as polymers and carbon nanotubes be semiconductors? If they are, what determines their semiconducting properties?