

**MATERIALS**

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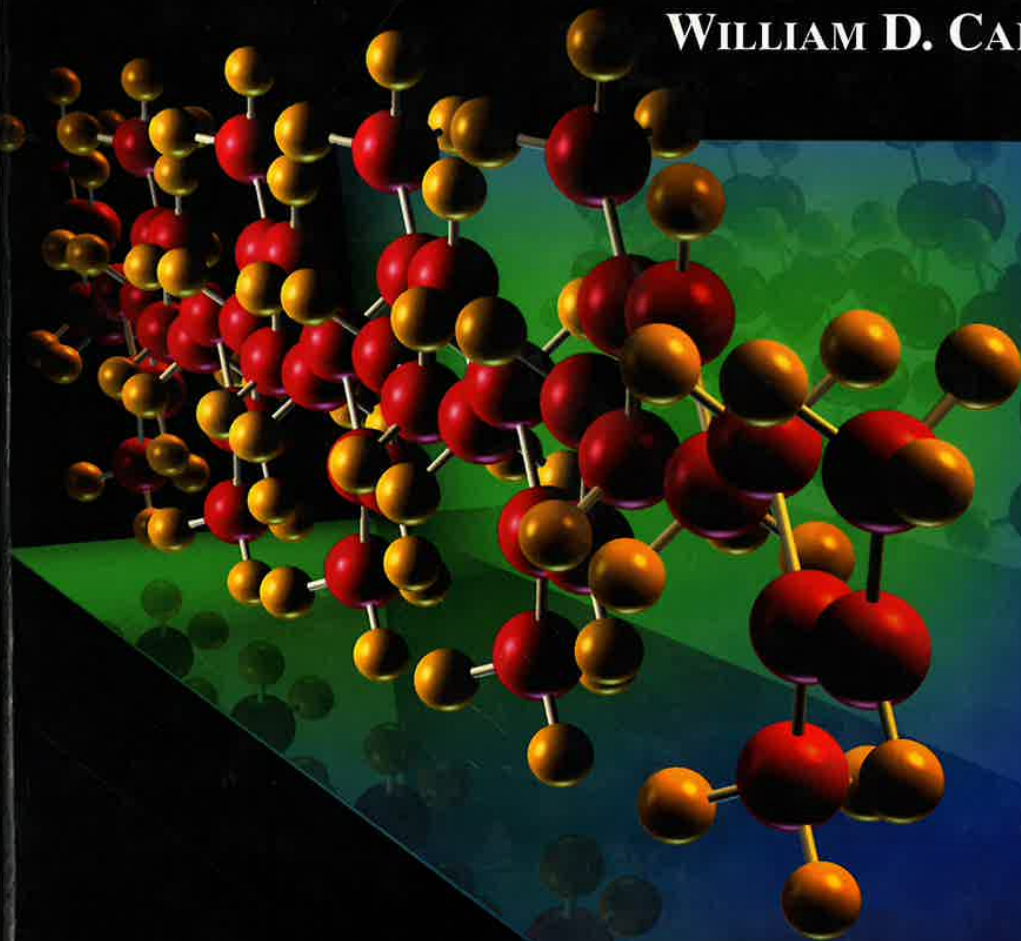
**AND**

**ENGINEERING**

**AN INTRODUCTION**

**FIFTH EDITION**

**WILLIAM D. CALLISTER, JR.**



FIFTH EDITION

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# Materials Science and Engineering

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An Introduction

**William D. Callister, Jr.**

*Department of Metallurgical Engineering  
The University of Utah*



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**Back Cover:** Depiction of a molecular segment of *trans* polyisoprene (or gutta percha). Again, the red and yellow spheres represent carbon and hydrogen atoms.

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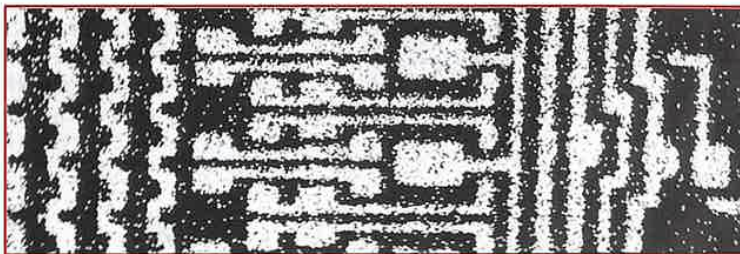
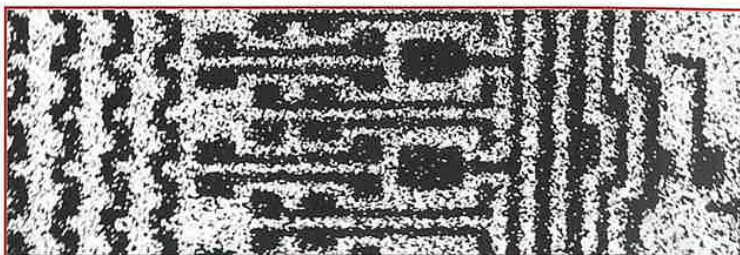
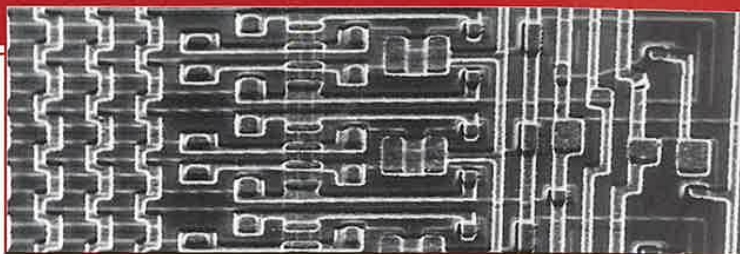
## Chapter 19 / Electrical Properties

**I**t was noted in Section 4.9 that an image is generated on a scanning electron micrograph as a beam of electrons scans the surface of the specimen being examined. The electrons in this beam cause some of the specimen surface atoms to emit x-rays; the energy of an x-ray photon depends on the particular atom from which it radiates. It is possible to selectively filter out all but the x-rays emitted from one kind of atom. When projected on a cathode ray tube, small white dots are produced indicating the locations of the particular atom type; thus, a "dot map" of the image is generated.

Top: Scanning electron micrograph of an integrated circuit.

Center: A silicon dot map for the integrated circuit above, showing regions where silicon atoms are concentrated. Doped silicon is the semiconducting material from which integrated circuit elements are made.

Bottom: An aluminum dot map. Metallic aluminum is an electrical conductor and, as such, wires the circuit elements together. Approximately 200 $\times$ .



### Why Study the *Electrical Properties* of Materials?

Consideration of the electrical properties of materials is often important when materials selection and processing decisions are being made during the design of a component or structure. For example, we discuss in Sections 23.12 through 23.17 materials that are used in the several components of one type

of integrated circuit package. The electrical behaviors of the various materials are diverse. Some need to be highly electrically conductive (e.g., connecting wires), whereas electrical insulativity is required of others (e.g., the protective package encapsulation).

## Learning Objectives

After careful study of this chapter you should be able to do the following:

1. Describe the four possible electron band structures for solid materials.
2. Briefly describe electron excitation events that produce free electrons/holes in (a) metals, (b) semiconductors (intrinsic and extrinsic), and (c) insulators.
3. Calculate the electrical conductivities of metals, semiconductors (intrinsic and extrinsic), and insulators given their charge carrier density(s) and mobility(s).
4. Distinguish between *intrinsic* and *extrinsic* semiconducting materials.
5. Note the manner in which electrical conductivity changes with increasing temperature for (a) metals, (b) semiconductors, and (c) insulating materials.
6. For a *p-n* junction, explain the rectification process in terms of electron and hole motions.
7. Calculate the capacitance of a parallel-plate capacitor.
8. Define dielectric constant in terms of permittivities.
9. Briefly explain how the charge storing capacity of a capacitor may be increased by the insertion and polarization of a dielectric material between its plates.
10. Name and describe the three types of polarization.

## 19.1 INTRODUCTION

The prime objective of this chapter is to explore the electrical properties of materials, that is, their responses to an applied electric field. We begin with the phenomenon of electrical conduction: the parameters by which it is expressed, the mechanism of conduction by electrons, and how the electron energy band structure of a material influences its ability to conduct. These principles are extended to metals, semiconductors, and insulators. Particular attention is given to the characteristics of semiconductors, and then to semiconducting devices. Also treated are the dielectric characteristics of insulating materials. The final sections are devoted to the peculiar phenomena of ferroelectricity and piezoelectricity.

## ELECTRICAL CONDUCTION

### 19.2 OHM'S LAW

One of the most important electrical characteristics of a solid material is the ease with which it transmits an electric current. **Ohm's law** relates the current  $I$ —or time rate of charge passage—to the applied voltage  $V$  as follows:

$$V = IR \quad (19.1)$$

where  $R$  is the resistance of the material through which the current is passing. The units for  $V$ ,  $I$ , and  $R$  are, respectively, volts (J/C), amperes (C/s), and ohms (V/A). The value of  $R$  is influenced by specimen configuration, and for many materials is independent of current. The **resistivity**  $\rho$  is independent of specimen geometry but related to  $R$  through the expression

$$\rho = \frac{RA}{l} \quad (19.2)$$

where  $l$  is the distance between the two points at which the voltage is measured, and  $A$  is the cross-sectional area perpendicular to the direction of the current.

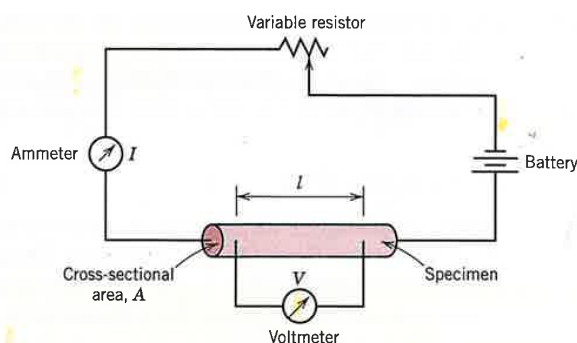


**FIGURE 19.1** Schematic representation of the apparatus used to measure electrical resistivity.

The units for  $\rho$  are ohm-meters ( $\Omega\cdot\text{m}$ ). From the expression for Ohm's law and Equation 19.2,

$$\rho = \frac{VA}{Il} \quad (19.3)$$

Figure 19.1 is a schematic diagram of an experimental arrangement for measuring electrical resistivity.

## 19.3 ELECTRICAL CONDUCTIVITY

Sometimes, **electrical conductivity**  $\sigma$  is used to specify the electrical character of a material. It is simply the reciprocal of the resistivity, or

$$\sigma = \frac{1}{\rho} \quad (19.4)$$

and is indicative of the ease with which a material is capable of conducting an electric current. The units for  $\sigma$  are reciprocal ohm-meters [ $(\Omega\cdot\text{m})^{-1}$ , or mho/m]. The following discussions on electrical properties use both resistivity and conductivity.

In addition to Equation 19.1, Ohm's law may be expressed as

$$J = \sigma \mathcal{E} \quad (19.5)$$

in which  $J$  is the current density, the current per unit of specimen area  $I/A$ , and  $\mathcal{E}$  is the electric field intensity, or the voltage difference between two points divided by the distance separating them, that is,

$$\mathcal{E} = \frac{V}{l} \quad (19.6)$$

The demonstration of the equivalence of the two Ohm's law expressions (Equations 19.1 and 19.5) is left as a homework exercise.

Solid materials exhibit an amazing range of electrical conductivities, extending over 27 orders of magnitude; probably no other physical property experiences this breadth of variation. In fact, one way of classifying solid materials is according to the ease with which they conduct an electric current; within this classification scheme there are three groupings: *conductors*, *semiconductors*, and *insulators*. **Metals** are

good conductors, typically having conductivities on the order of  $10^7 (\Omega\text{-m})^{-1}$ . At the other extreme are materials with very low conductivities, ranging between  $10^{-10}$  and  $10^{-20} (\Omega\text{-m})^{-1}$ ; these are electrical **insulators**. Materials with intermediate conductivities, generally from  $10^{-6}$  to  $10^4 (\Omega\text{-m})^{-1}$ , are termed **semiconductors**.

## 19.4 ELECTRONIC AND IONIC CONDUCTION

An electric current results from the motion of electrically charged particles in response to forces that act on them from an externally applied electric field. Positively charged particles are accelerated in the field direction, negatively charged particles in the direction opposite. Within most solid materials a current arises from the flow of electrons, which is termed *electronic conduction*. In addition, for ionic materials a net motion of charged ions is possible that produces a current; such is termed **ionic conduction**. The present discussion deals with electronic conduction; ionic conduction is treated briefly in Section 19.15.

## 19.5 ENERGY BAND STRUCTURES IN SOLIDS

In all conductors, semiconductors, and many insulating materials, only electronic conduction exists, and the magnitude of the electrical conductivity is strongly dependent on the number of electrons available to participate in the conduction process. However, not all electrons in every atom will accelerate in the presence of an electric field. The number of electrons available for electrical conduction in a particular material is related to the arrangement of electron states or levels with respect to energy, and then the manner in which these states are occupied by electrons. A thorough exploration of these topics is complicated and involves principles of quantum mechanics that are beyond the scope of this book; the ensuing development omits some concepts and simplifies others.

Concepts relating to electron energy states, their occupancy, and the resulting electron configuration for isolated atoms were discussed in Section 2.3. By way of review, for each individual atom there exist discrete energy levels that may be occupied by electrons, arranged into shells and subshells. Shells are designated by integers (1, 2, 3, etc.), and subshells by letters (*s*, *p*, *d*, and *f*). For each of *s*, *p*, *d*, and *f* subshells, there exist, respectively, one, three, five, and seven states. The electrons in most atoms fill just the states having the lowest energies, two electrons of opposite spin per state, in accordance with the Pauli exclusion principle. The electron configuration of an isolated atom represents the arrangement of the electrons within the allowed states.

Let us now make an extrapolation of some of these concepts to solid materials. A solid may be thought of as consisting of a large number, say,  $N$ , of atoms initially separated from one another, which are subsequently brought together and bonded to form the ordered atomic arrangement found in the crystalline material. At relatively large separation distances, each atom is independent of all the others and will have the atomic energy levels and electron configuration as if isolated. However, as the atoms come within close proximity of one another, electrons are acted upon, or perturbed, by the electrons and nuclei of adjacent atoms. This influence is such that each distinct atomic state may split into a series of closely spaced electron states in the solid, to form what is termed an **electron energy band**. The extent of splitting depends on interatomic separation (Figure 19.2) and begins with the outermost electron shells, since they are the first to be perturbed as the atoms coalesce. Within each band, the energy states are discrete, yet the difference between

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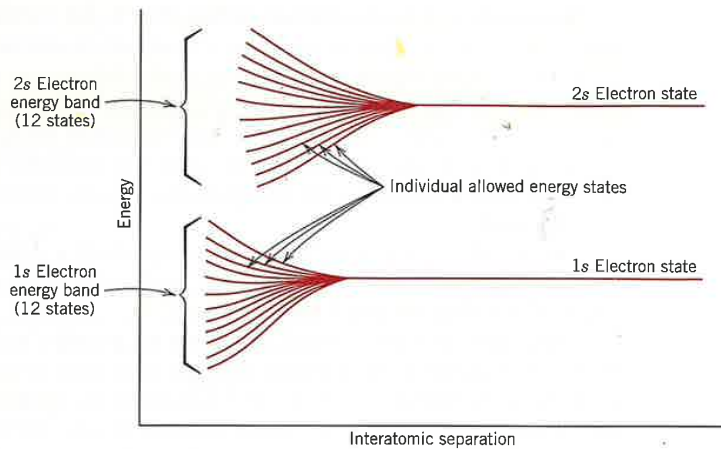
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**FIGURE 19.2**  
Schematic plot of  
electron energy versus  
interatomic separation  
for an aggregate of 12  
atoms ( $N = 12$ ). Upon  
close approach, each of  
the  $1s$  and  $2s$  atomic  
states splits to form an  
electron energy band  
consisting of 12 states.



adjacent states is exceedingly small. At the equilibrium spacing, band formation may not occur for the electron subshells nearest the nucleus, as illustrated in Figure 19.3b. Furthermore, gaps may exist between adjacent bands, as also indicated in the figure; normally, energies lying within these band gaps are not available for electron occupancy. The conventional way of representing electron band structures in solids is shown in Figure 19.3a.

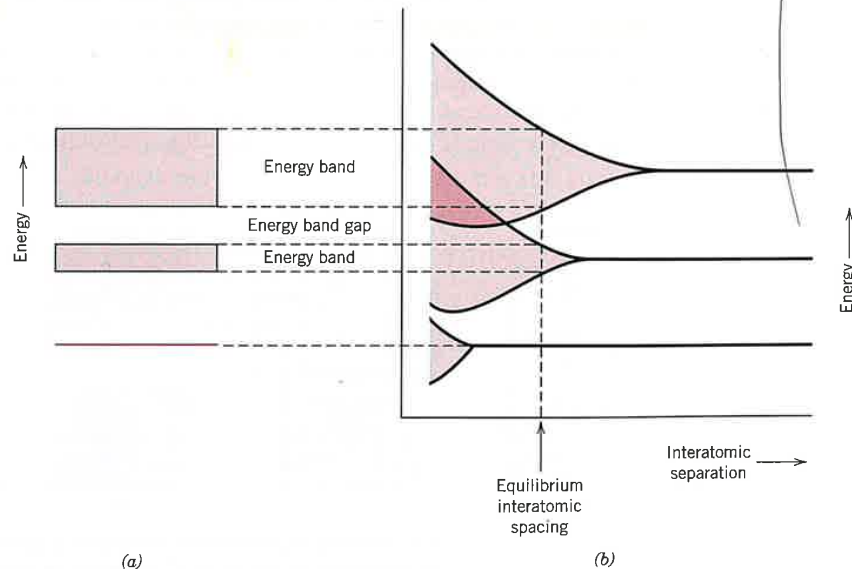


**FIGURE 19.3** (a) The conventional representation of the electron energy band structure for a solid material at the equilibrium interatomic separation. (b) Electron energy versus interatomic separation for an aggregate of atoms, illustrating how the energy band structure at the equilibrium separation in (a) is generated. (From Z. D. Jastrzebski, *The Nature and Properties of Engineering Materials*, 3rd edition. Copyright © 1987 by John Wiley & Sons, Inc. Reprinted by permission of John Wiley & Sons, Inc.)

The number of states within each band will equal the total of all states contributed by the  $N$  atoms. For example, an  $s$  band will consist of  $N$  states, and a  $p$  band of  $3N$  states. With regard to occupancy, each energy state may accommodate two electrons, which must have oppositely directed spins. Furthermore, bands will contain the electrons that resided in the corresponding levels of the isolated atoms; for example, a  $4s$  energy band in the solid will contain those isolated atom's  $4s$  electrons. Of course, there will be empty bands and, possibly, bands that are only partially filled.

The electrical properties of a solid material are a consequence of its electron band structure, that is, the arrangement of the outermost electron bands and the way in which they are filled with electrons.

Four different types of band structures are possible at 0 K. In the first (Figure 19.4a), one outermost band is only partially filled with electrons. The energy corresponding to the highest filled state at 0 K is called the **Fermi energy**  $E_f$ , as indicated. This energy band structure is typified by some metals, in particular those that have a single  $s$  valence electron (e.g., copper). Each copper atom has one  $4s$  electron; however, for a solid comprised of  $N$  atoms, the  $4s$  band is capable of accommodating  $2N$  electrons. Thus only half the available electron positions within this  $4s$  band are filled.

For the second band structure, also found in metals (Figure 19.4b), there is an overlap of an empty band and a filled band. Magnesium has this band structure. Each isolated Mg atom has two  $3s$  electrons. However, when a solid is formed, the  $3s$  and  $3p$  bands overlap. In this instance and at 0 K, the Fermi energy is taken as that energy below which, for  $N$  atoms,  $N$  states are filled, two electrons per state.

The final two band structures are similar; one band (the **valence band**) that is completely filled with electrons is separated from an empty **conduction band**; and an **energy band gap** lies between them. For very pure materials, electrons may not have energies within this gap. The difference between the two band structures lies in the magnitude of the energy gap; for materials that are insulators, the band gap is relatively wide (Figure 19.4c), whereas for semiconductors it is narrow (Figure

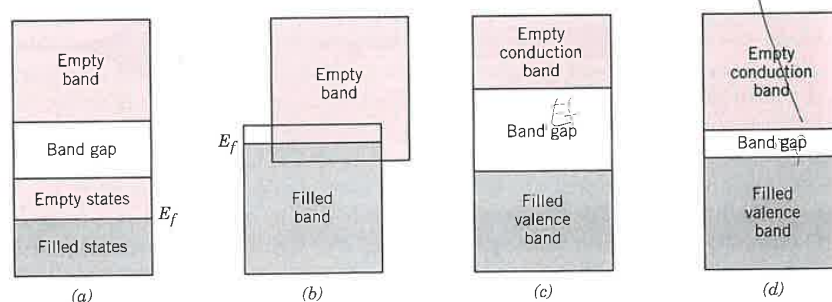


**FIGURE 19.4** The various possible electron band structures in solids at 0 K. (a) The electron band structure found in metals such as copper, in which there are available electron states above and adjacent to filled states, in the same band. (b) The electron band structure of metals such as magnesium, wherein there is an overlap of filled and empty outer bands. (c) The electron band structure characteristic of insulators; the filled valence band is separated from the empty conduction band by a relatively large band gap ( $>2$  eV). (d) The electron band structure found in the semiconductors, which is the same as for insulators except that the band gap is relatively narrow ( $<2$  eV).

19.4d). The Fermi energy for these two band structures lies within the band gap—near its center.

## 19.6 CONDUCTION IN TERMS OF BAND AND ATOMIC BONDING MODELS

At this point in the discussion, it is vital that another concept be understood, namely, that only electrons with energies greater than the Fermi energy may be acted on and accelerated in the presence of an electric field. These are the electrons that participate in the conduction process, which are termed **free electrons**. Another charged electronic entity called a **hole** is found in semiconductors and insulators. Holes have energies less than  $E_f$  and also participate in electronic conduction. As the ensuing discussion reveals, the electrical conductivity is a direct function of the numbers of free electrons and holes. In addition, the distinction between conductors and nonconductors (insulators and semiconductors) lies in the numbers of these free electron and hole charge carriers.

### METALS

For an electron to become free, it must be excited or promoted into one of the empty and available energy states above  $E_f$ . For metals having either of the band structures shown in Figures 19.4a and 19.4b, there are vacant energy states adjacent to the highest filled state at  $E_f$ . Thus, very little energy is required to promote electrons into the low-lying empty states, as shown in Figure 19.5. Generally, the energy provided by an electric field is sufficient to excite large numbers of electrons into these conducting states.

For the metallic bonding model discussed in Section 2.6, it was assumed that all the valence electrons have freedom of motion and form an “electron gas,” which is uniformly distributed throughout the lattice of ion cores. Even though these electrons are not locally bound to any particular atom, they, nevertheless, must experience some excitation to become conducting electrons that are truly free. Thus, although only a fraction are excited, this still gives rise to a relatively large number of free electrons and, consequently, a high conductivity.

### INSULATORS AND SEMICONDUCTORS

For insulators and semiconductors, empty states adjacent to the top of the filled valence band are not available. To become free, therefore, electrons must be pro-

FIGURE 19.5 For a metal, occupancy of electron states (a) before and (b) after an electron excitation.

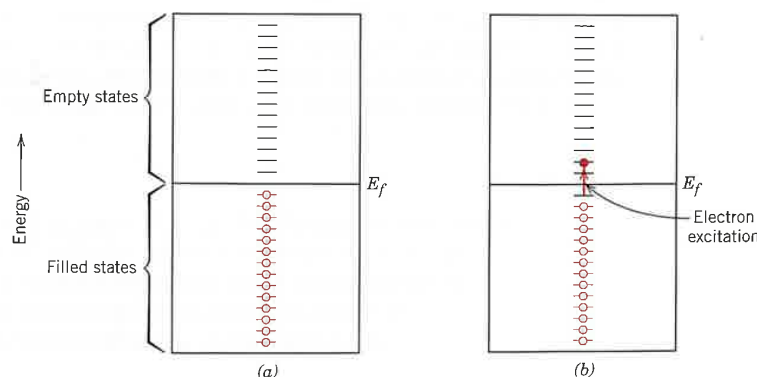
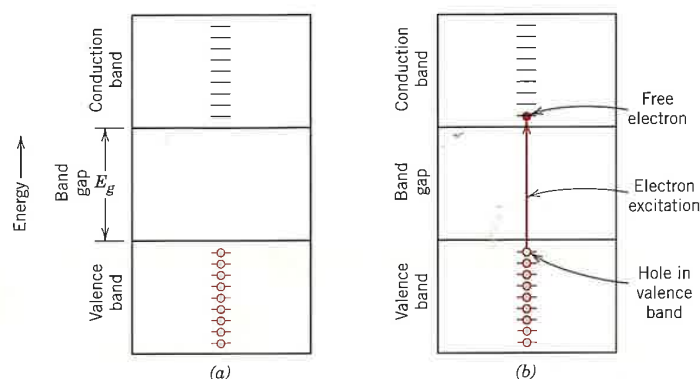


**FIGURE 19.6**  
For an insulator or semiconductor, occupancy of electron states (a) before and (b) after an electron excitation from the valence band into the conduction band, in which both a free electron and a hole are generated.



moted across the energy band gap and into empty states at the bottom of the conduction band. This is possible only by supplying to an electron the difference in energy between these two states, which is approximately equal to the band gap energy  $E_g$ . This excitation process is demonstrated in Figure 19.6. For many materials this band gap is several electron volts wide. Most often the excitation energy is from a nonelectrical source such as heat or light, usually the former.

The number of electrons excited thermally (by heat energy) into the conduction band depends on the energy band gap width as well as temperature. At a given temperature, the larger the  $E_g$ , the lower the probability that a valence electron will be promoted into an energy state within the conduction band; this results in fewer conduction electrons. In other words, the larger the band gap, the lower the electrical conductivity at a given temperature. Thus, the distinction between semiconductors and insulators lies in the width of the band gap; for semiconductors it is narrow, whereas for insulating materials it is relatively wide.

Increasing the temperature of either a semiconductor or an insulator results in an increase in the thermal energy that is available for electron excitation. Thus, more electrons are promoted into the conduction band, which gives rise to an enhanced conductivity.

The conductivity of insulators and semiconductors may also be viewed from the perspective of atomic bonding models discussed in Section 2.6. For electrically insulating materials, interatomic bonding is ionic or strongly covalent. Thus, the valence electrons are tightly bound to or shared with the individual atoms. In other words, these electrons are highly localized and are not in any sense free to wander throughout the crystal. The bonding in semiconductors is covalent (or predominantly covalent) and relatively weak, which means that the valence electrons are not as strongly bound to the atoms. Consequently, these electrons are more easily removed by thermal excitation than they are for insulators.

## 19.7 ELECTRON MOBILITY

When an electric field is applied, a force is brought to bear on the free electrons; as a consequence, they all experience an acceleration in a direction opposite to that of the field, by virtue of their negative charge. According to quantum mechanics, there is no interaction between an accelerating electron and atoms in a perfect crystal lattice. Under such circumstances all the free electrons should accelerate as

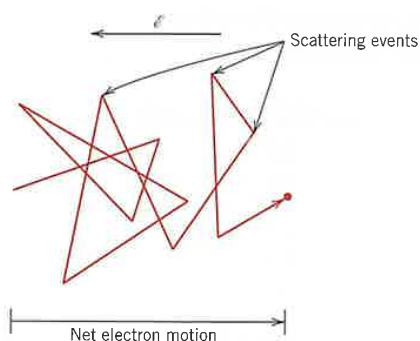


FIGURE 19.7 Schematic diagram showing the path of an electron that is deflected by scattering events.

long as the electric field is applied, which would give rise to a continuously increasing electric current with time. However, we know that a current reaches a constant value the instant that a field is applied, indicating that there exist what might be termed “frictional forces,” which counter this acceleration from the external field. These frictional forces result from the scattering of electrons by imperfections in the crystal lattice, including impurity atoms, vacancies, interstitial atoms, dislocations, and even the thermal vibrations of the atoms themselves. Each scattering event causes an electron to lose kinetic energy and to change its direction of motion, as represented schematically in Figure 19.7. There is, however, some net electron motion in the direction opposite to the field, and this flow of charge is the electric current.

The scattering phenomenon is manifested as a resistance to the passage of an electric current. Several parameters are used to describe the extent of this scattering; these include the *drift velocity* and the **mobility** of an electron. The drift velocity  $v_d$  represents the average electron velocity in the direction of the force imposed by the applied field. It is directly proportional to the electric field as follows:

$$v_d = \mu_e \mathcal{E} \quad (19.7)$$

The constant of proportionality  $\mu_e$  is called the electron mobility, which is an indication of the frequency of scattering events; its units are square meters per volt-second ( $\text{m}^2/\text{V}\cdot\text{s}$ ).

The conductivity  $\sigma$  of most materials may be expressed as

$$\sigma = n|e|\mu_e \quad (19.8)$$

where  $n$  is the number of free or conducting electrons per unit volume (e.g., per cubic meter), and  $|e|$  is the absolute magnitude of the electrical charge on an electron ( $1.6 \times 10^{-19}$  C). Thus, the electrical conductivity is proportional to both the number of free electrons and the electron mobility.

## 19.8 ELECTRICAL RESISTIVITY OF METALS

As mentioned previously, most metals are extremely good conductors of electricity; room-temperature conductivities for several of the more common metals are contained in Table 19.1. (Table B.9 in Appendix B lists the electrical resistivities of a

**Table 19.1** Room-Temperature Electrical Conductivities for Nine Common Metals and Alloys

| <i>Metal</i>        | <i>Electrical Conductivity</i><br>[( $\Omega\cdot m$ ) <sup>-1</sup> ] |
|---------------------|------------------------------------------------------------------------|
| Silver              | $6.8 \times 10^7$                                                      |
| Copper              | $6.0 \times 10^7$                                                      |
| Gold                | $4.3 \times 10^7$                                                      |
| Aluminum            | $3.8 \times 10^7$                                                      |
| Iron                | $1.0 \times 10^7$                                                      |
| Brass (70 Cu–30 Zn) | $1.6 \times 10^7$                                                      |
| Platinum            | $0.94 \times 10^7$                                                     |
| Plain carbon steel  | $0.6 \times 10^7$                                                      |
| Stainless steel     | $0.2 \times 10^7$                                                      |

large number of metals and alloys.) Again, metals have high conductivities because of the large numbers of free states that have been excited into empty states above the Fermi energy. Thus  $n$  has a large value in the conductivity expression, Equation 19.8.

At this point it is convenient to discuss conduction in metals in terms of the resistivity, the reciprocal of conductivity; the reason for this switch should become apparent in the ensuing discussion.

Since crystalline defects serve as scattering centers for conduction electrons in metals, increasing their number raises the resistivity (or lowers the conductivity). The concentration of these imperfections depends on temperature, composition, and the degree of cold work of a metal specimen. In fact, it has been observed experimentally that the total resistivity of a metal is the sum of the contributions from thermal vibrations, impurities, and plastic deformation; that is, the scattering mechanisms act independently of one another. This may be represented in mathematical form as follows:

$$\rho_{\text{total}} = \rho_t + \rho_i + \rho_d \quad (19.9)$$

in which  $\rho_t$ ,  $\rho_i$ , and  $\rho_d$  represent the individual thermal, impurity, and deformation resistivity contributions, respectively. Equation 19.9 is sometimes known as **Matthiessen's rule**. The influence of each  $\rho$  variable on the total resistivity is demonstrated in Figure 19.8, as a plot of resistivity versus temperature for copper and several copper–nickel alloys in annealed and deformed states. The additive nature of the individual resistivity contributions is demonstrated at  $-100^\circ\text{C}$ .

### INFLUENCE OF TEMPERATURE

For the pure metal and all the copper–nickel alloys shown in Figure 19.8, the resistivity rises linearly with temperature above about  $-200^\circ\text{C}$ . Thus,

$$\rho_t = \rho_0 + aT \quad (19.10)$$

where  $\rho_0$  and  $a$  are constants for each particular metal. This dependence of the thermal resistivity component on temperature is due to the increase with temperature in thermal vibrations and other lattice irregularities (e.g., vacancies), which serve as electron-scattering centers.

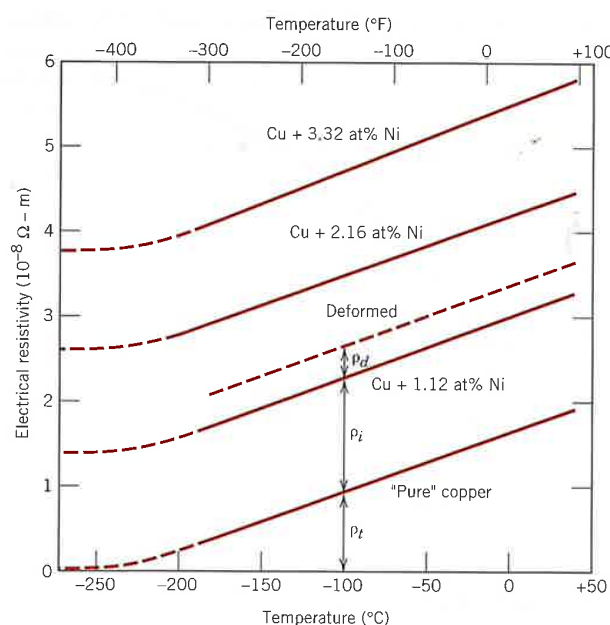


**FIGURE 19.8** The electrical resistivity versus temperature for copper and three copper–nickel alloys, one of which has been deformed. Thermal, impurity, and deformation contributions to the resistivity are indicated at  $-100^{\circ}\text{C}$ . [Adapted from J. O. Linde, *Ann. Physik*, **5**, 219 (1932); and C. A. Wert and R. M. Thomson, *Physics of Solids*, 2nd edition, McGraw-Hill Book Company, New York, 1970.]

### INFLUENCE OF IMPURITIES

For additions of a single impurity that forms a solid solution, the impurity resistivity  $\rho_i$  is related to the impurity concentration  $c_i$  in terms of the atom fraction (at%/100) as follows:

$$\rho_i = A c_i (1 - c_i) \quad (19.11)$$

where  $A$  is a composition-independent constant that is a function of both the impurity and host metals. The influence of nickel impurity additions on the room-temperature resistivity of copper is demonstrated in Figure 19.9, up to 50 wt% Ni; over this composition range nickel is completely soluble in copper (Figure 9.2). Again, nickel atoms in copper act as scattering centers, and increasing the concentration of nickel in copper results in an enhancement of resistivity.

For a two-phase alloy consisting of  $\alpha$  and  $\beta$  phases, a rule-of-mixtures expression may be utilized to approximate the resistivity as follows:

$$\rho_i = \rho_{\alpha} V_{\alpha} + \rho_{\beta} V_{\beta} \quad (19.12)$$

where the  $V$ 's and  $\rho$ 's represent volume fractions and individual resistivities for the respective phases.

### INFLUENCE OF PLASTIC DEFORMATION

Plastic deformation also raises the electrical resistivity as a result of increased numbers of electron-scattering dislocations. The effect of deformation on resistivity is also represented in Figure 19.8.

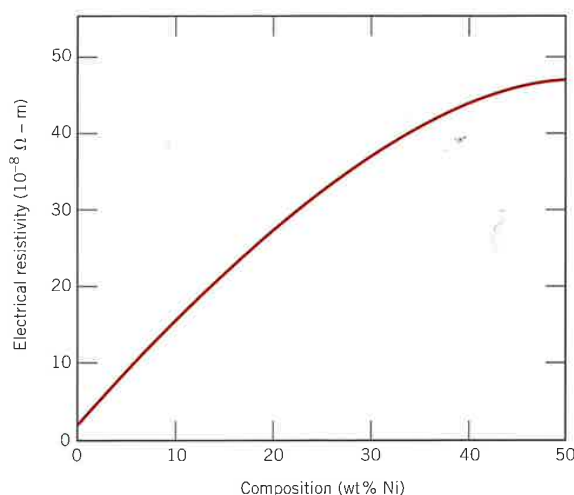


**FIGURE 19.9** Room-temperature electrical resistivity versus composition for copper–nickel alloys.

## 19.9 ELECTRICAL CHARACTERISTICS OF COMMERCIAL ALLOYS

Electrical and other properties of copper render it the most widely used metallic conductor. Oxygen-free high-conductivity (OFHC) copper, having extremely low oxygen and other impurity contents, is produced for many electrical applications. Aluminum, having a conductivity only about one half that of copper, is also frequently used as an electrical conductor. Silver has a higher conductivity than either copper or aluminum; however, its use is restricted on the basis of cost.

On occasion, it is necessary to improve the mechanical strength of a metal alloy without impairing significantly its electrical conductivity. Both solid solution alloying and cold working improve strength at the expense of conductivity, and thus, a tradeoff must be made for these two properties. Most often, strength is enhanced by introducing a second phase that does not have so adverse an effect on conductivity. For example, copper–beryllium alloys are precipitation hardened; but even so, the conductivity is reduced by about a factor of 5 over high-purity copper.

For some applications, such as furnace heating elements, a high electrical resistivity is desirable. The energy loss by electrons that are scattered is dissipated as heat energy. Such materials must have not only a high resistivity, but also a resistance to oxidation at elevated temperatures and, of course, a high melting temperature. Nichrome, a nickel–chromium alloy, is commonly employed in heating elements.

## SEMICONDUCTIVITY

The electrical conductivity of the semiconducting materials is not as high as that of the metals; nevertheless, they have some unique electrical characteristics that render them especially useful. The electrical properties of these materials are extremely sensitive to the presence of even minute concentrations of impurities. **Intrinsic semiconductors** are those in which the electrical behavior is based on the electronic structure inherent to the pure material. When the electrical

**Table 19.2** Band Gap Energies, Electron and Hole Mobilities, and Intrinsic Electrical Conductivities at Room Temperature for Semiconducting Materials

| <i>Material</i>        | <i>Band Gap<br/>(eV)</i> | <i>Electrical<br/>Conductivity<br/>[(<math>\Omega</math>-m)<sup>-1</sup>]</i> | <i>Electron Mobility<br/>(m<sup>2</sup>/V-s)</i> | <i>Hole Mobility<br/>(m<sup>2</sup>/V-s)</i> |
|------------------------|--------------------------|-------------------------------------------------------------------------------|--------------------------------------------------|----------------------------------------------|
| <b>Elemental</b>       |                          |                                                                               |                                                  |                                              |
| Si                     | 1.11                     | $4 \times 10^{-4}$                                                            | 0.14                                             | 0.05                                         |
| Ge                     | 0.67                     | 2.2                                                                           | 0.38                                             | 0.18                                         |
| <b>III-V Compounds</b> |                          |                                                                               |                                                  |                                              |
| GaP                    | 2.25                     | —                                                                             | 0.05                                             | 0.002                                        |
| GaAs                   | 1.42                     | $10^{-6}$                                                                     | 0.85                                             | 0.45                                         |
| InSb                   | 0.17                     | $2 \times 10^4$                                                               | 7.7                                              | 0.07                                         |
| <b>II-VI Compounds</b> |                          |                                                                               |                                                  |                                              |
| CdS                    | 2.40                     | —                                                                             | 0.03                                             | —                                            |
| ZnTe                   | 2.26                     | —                                                                             | 0.03                                             | 0.01                                         |

characteristics are dictated by impurity atoms, the semiconductor is said to be **extrinsic**.

## 19.10 INTRINSIC SEMICONDUCTION

Intrinsic semiconductors are characterized by the electron band structure shown in Figure 19.4*d*: at 0 K, a completely filled valence band, separated from an empty conduction band by a relatively narrow forbidden band gap, generally less than 2 eV. The two elemental semiconductors are silicon (Si) and germanium (Ge), having band gap energies of approximately 1.1 and 0.7 eV, respectively. Both are found in Group IVA of the periodic table (Figure 2.6) and are covalently bonded.<sup>1</sup> In addition, a host of compound semiconducting materials also display intrinsic behavior. One such group is formed between elements of Groups IIIA and VA, for example, gallium arsenide (GaAs) and indium antimonide (InSb); these are frequently called III-V compounds. The compounds composed of elements of Groups IIB and VIA also display semiconducting behavior; these include cadmium sulfide (CdS) and zinc telluride (ZnTe). As the two elements forming these compounds become more widely separated with respect to their relative positions in the periodic table (i.e., the electronegativities become more dissimilar, Figure 2.7), the atomic bonding becomes more ionic and the magnitude of the band gap energy increases—the materials tend to become more insulative. Table 19.2 gives the band gaps for some compound semiconductors.

### CONCEPT OF A HOLE

In intrinsic semiconductors, for every electron excited into the conduction band there is left behind a missing electron in one of the covalent bonds, or in the band scheme, a vacant electron state in the valence band, as shown in Figure 19.6*b*. Under the influence of an electric field, the position of this missing electron within the crystalline lattice may be thought of as moving by the motion of other valence electrons that repeatedly fill in the incomplete bond (Figure 19.10). This process

<sup>1</sup> The valence bands in silicon and germanium correspond to  $sp^3$  hybrid energy levels for the isolated atom; these hybridized valence bands are completely filled at 0 K.

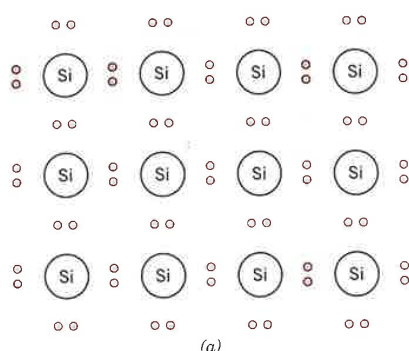
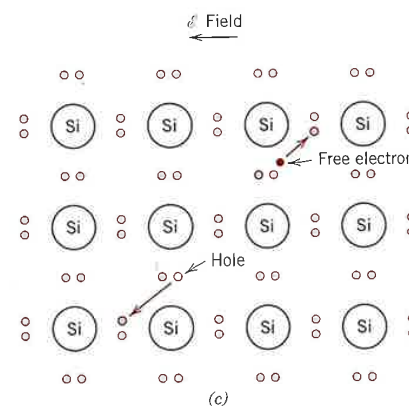
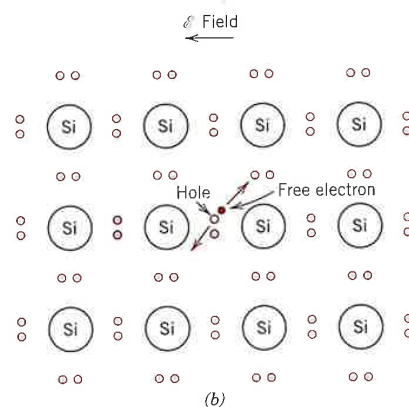


**FIGURE 19.10** Electron bonding model of electrical conduction in intrinsic silicon: (a) before excitation; (b) and (c) after excitation (the subsequent free-electron and hole motions in response to an external electric field).



is expedited by treating a missing electron from the valence band as a positively charged particle called a *hole*. A hole is considered to have a charge that is of the same magnitude as that for an electron, but of opposite sign ( $+1.6 \times 10^{-19}$  C). Thus, in the presence of an electric field, excited electrons and holes move in opposite directions. Furthermore, in semiconductors both electrons and holes are scattered by lattice imperfections.

**INTRINSIC CONDUCTIVITY**

Since there are two types of charge carrier (free electrons and holes) in an intrinsic semiconductor, the expression for electrical conduction, Equation 19.8, must be modified to include a term to account for the contribution of the hole current. Therefore, we write

$$\sigma = n|e|\mu_e + p|e|\mu_h \quad (19.13)$$

where  $p$  is the number of holes per cubic meter and  $\mu_h$  is the hole mobility. The magnitude of  $\mu_h$  is always less than  $\mu_e$  for semiconductors. For intrinsic semiconductors, every electron promoted across the band gap leaves behind a hole in the valence band, thus,

$$n = p \quad (19.14)$$

and

$$\sigma = n|e|(\mu_e + \mu_h) = p|e|(\mu_e + \mu_h) \quad (19.15)$$

The room-temperature intrinsic conductivities and electron and hole mobilities for several semiconducting materials are also presented in Table 19.2.

**EXAMPLE PROBLEM 19.1**

For intrinsic silicon, the room-temperature electrical conductivity is  $4 \times 10^{-4} (\Omega\text{-m})^{-1}$ ; the electron and hole mobilities are, respectively, 0.14 and 0.048  $\text{m}^2/\text{V}\cdot\text{s}$ . Compute the electron and hole concentrations at room temperature.

**SOLUTION**

Since the material is intrinsic, electron and hole concentrations will be the same, and therefore, from Equation 19.15,

$$\begin{aligned} n = p &= \frac{\sigma}{|e|(\mu_e + \mu_h)} \\ &= \frac{4 \times 10^{-4} (\Omega\text{-m})^{-1}}{(1.6 \times 10^{-19} \text{ C})(0.14 + 0.048 \text{ m}^2/\text{V}\cdot\text{s})} \\ &= 1.33 \times 10^{16} \text{ m}^{-3} \end{aligned}$$

**19.11 EXTRINSIC SEMICONDUCTION**

Virtually all commercial semiconductors are extrinsic; that is, the electrical behavior is determined by impurities, which, when present in even minute concentrations, introduce excess electrons or holes. For example, an impurity concentration of one atom in  $10^{12}$  is sufficient to render silicon extrinsic at room temperature.

**n-TYPE EXTRINSIC SEMICONDUCTION**

To illustrate how extrinsic semiconduction is accomplished, consider again the elemental semiconductor silicon. An Si atom has four electrons, each of which is covalently bonded with one of four adjacent Si atoms. Now, suppose that an impurity atom with a valence of 5 is added as a substitutional impurity; possibilities would

include atoms from the Group VA column of the periodic table (e.g., P, As, and Sb). Only four of five valence electrons of these impurity atoms can participate in the bonding because there are only four possible bonds with neighboring atoms. The extra nonbonding electron is loosely bound to the region around the impurity atom by a weak electrostatic attraction, as illustrated in Figure 19.11a. The binding energy of this electron is relatively small (on the order of 0.01 eV); thus, it is easily removed from the impurity atom, in which case it becomes a free or conducting electron (Figures 19.11b and 19.11c).

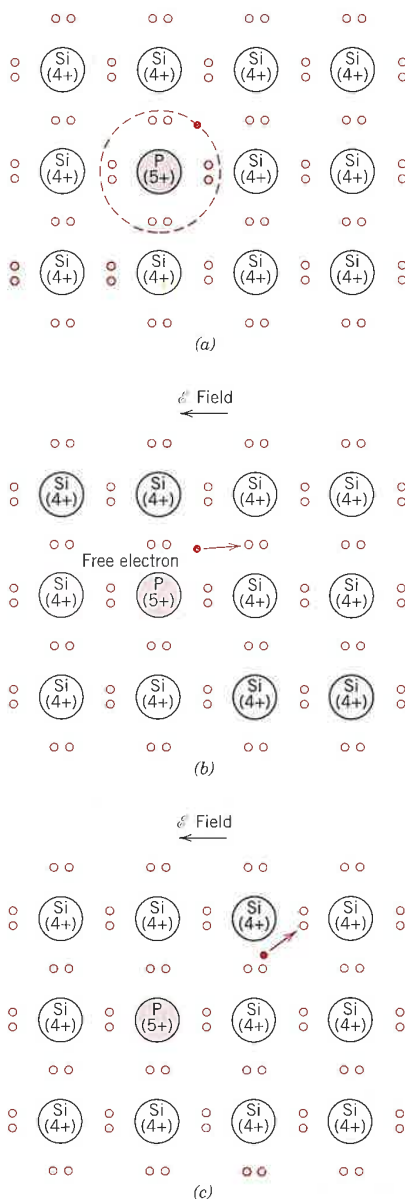
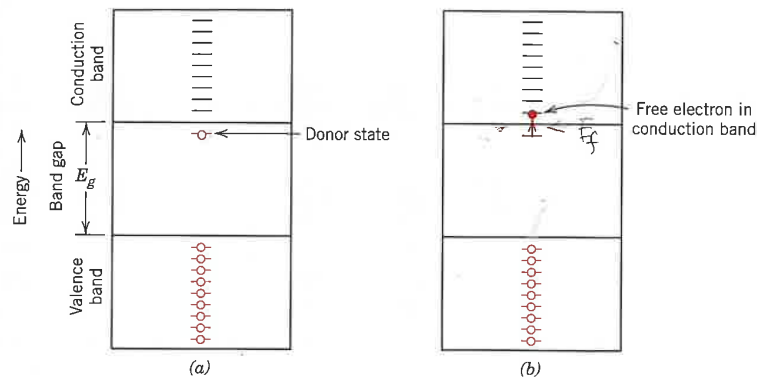


**FIGURE 19.11** Extrinsic *n*-type semiconduction model (electron bonding). (a) An impurity atom such as phosphorus, having five valence electrons, may substitute for a silicon atom. This results in an extra bonding electron, which is bound to the impurity atom and orbits it. (b) Excitation to form a free electron. (c) The motion of this free electron in response to an electric field.

**FIGURE 19.12** (a) Electron energy band scheme for a donor impurity level located within the band gap and just below the bottom of the conduction band. (b) Excitation from a donor state in which a free electron is generated in the conduction band.



The energy state of such an electron may be viewed from the perspective of the electron band model scheme. For each of the loosely bound electrons, there exists a single energy level, or energy state, which is located within the forbidden band gap just below the bottom of the conduction band (Figure 19.12a). The electron binding energy corresponds to the energy required to excite the electron from one of these impurity states to a state within the conduction band. Each excitation event (Figure 19.12b), supplies or donates a single electron to the conduction band; an impurity of this type is aptly termed a *donor*. Since each donor electron is excited from an impurity level, no corresponding hole is created within the valence band.

At room temperature, the thermal energy available is sufficient to excite large numbers of electrons from **donor states**; in addition, some intrinsic valence-conduction band transitions occur, as in Figure 19.6b, but to a negligible degree. Thus, the number of electrons in the conduction band far exceeds the number of holes in the valence band (or  $n \gg p$ ), and the first term on the right-hand side of Equation 19.13 overwhelms the second; that is,

$$\sigma \cong n|e|\mu_e \quad (19.16)$$

A material of this type is said to be an *n-type* extrinsic semiconductor. The electrons are *majority carriers* by virtue of their density or concentration; holes, on the other hand, are the *minority charge carriers*. For *n-type* semiconductors, the Fermi level is shifted upward in the band gap, to within the vicinity of the donor state; its exact position is a function of both temperature and donor concentration.

### **p-TYPE EXTRINSIC SEMICONDUCTION**

An opposite effect is produced by the addition to silicon or germanium of trivalent substitutional impurities such as aluminum, boron, and gallium from Group IIIA of the periodic table. One of the covalent bonds around each of these atoms is deficient in an electron; such a deficiency may be viewed as a hole that is weakly bound to the impurity atom. This hole may be liberated from the impurity atom by the transfer of an electron from an adjacent bond as illustrated in Figure 19.13. In essence, the electron and the hole exchange positions. A moving hole is considered to be in an excited state and participates in the conduction process, in a manner analogous to an excited donor electron, as described above.

Extrinsic excitations, in which holes are generated, may also be represented using the band model. Each impurity atom of this type introduces an energy level

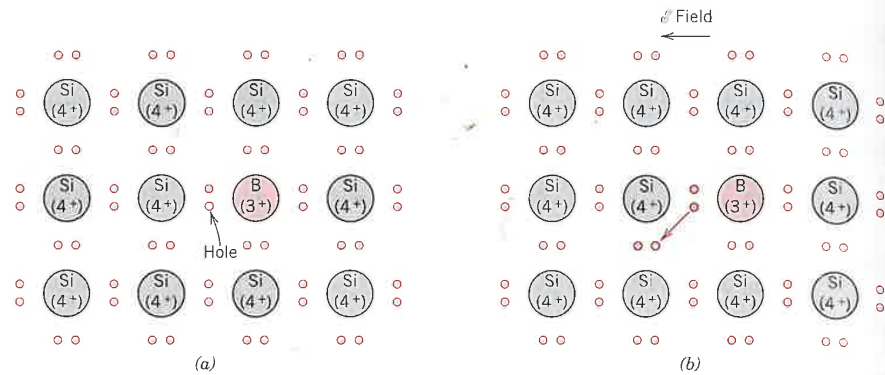


**FIGURE 19.13** Extrinsic *p*-type semiconductor model (electron bonding).

(a) An impurity atom such as boron, having three valence electrons, may substitute for a silicon atom. This results in a deficiency of one valence electron, or a hole associated with the impurity atom. (b) The motion of this hole in response to an electric field.

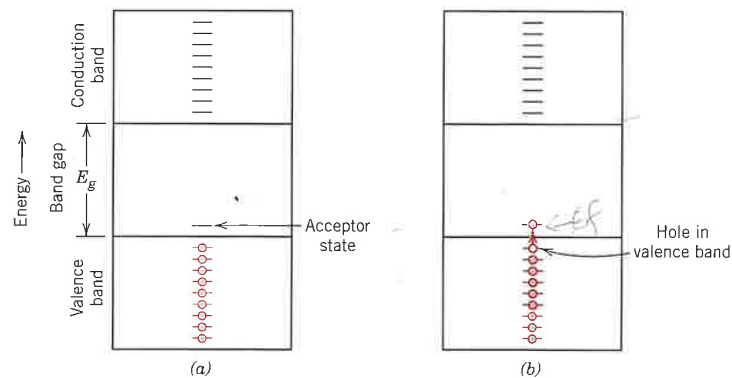
within the band gap, above yet very close to the top of the valence band (Figure 19.14a). A hole is imagined to be created in the valence band by the thermal excitation of an electron from the valence band into this impurity electron state, as demonstrated in Figure 19.14b. With such a transition, only one carrier is produced—a hole in the valence band; a free electron is *not* created in either the impurity level or the conduction band. An impurity of this type is called an *acceptor*, because it is capable of accepting an electron from the valence band, leaving behind a hole. It follows that the energy level within the band gap introduced by this type of impurity is called an **acceptor state**.

For this type of extrinsic conduction, holes are present in much higher concentrations than electrons (i.e.,  $p \gg n$ ), and under these circumstances a material is termed *p-type* because positively charged particles are primarily responsible for electrical conduction. Of course, holes are the majority carriers, and electrons are present in minority concentrations. This gives rise to a predominance of the second term on the right-hand side of Equation 19.13, or

$$\sigma \cong p|e|\mu_h \quad (19.17)$$

**FIGURE 19.14**

(a) Energy band scheme for an acceptor impurity level located within the band gap and just above the top of the valence band. (b) Excitation of an electron into the acceptor level, leaving behind a hole in the valence band.



For *p*-type semiconductors, the Fermi level is positioned within the band gap and near to the acceptor level.

Extrinsic semiconductors (both *n*- and *p*-type) are produced from materials that are initially of extremely high purity, commonly having total impurity contents on the order of  $10^{-7}$  at%. Controlled concentrations of specific donors or acceptors are then intentionally added, using various techniques. Such an alloying process in semiconducting materials is termed **doping**.

In extrinsic semiconductors, large numbers of charge carriers (either electrons or holes, depending on the impurity type) are created at room temperature, by the available thermal energy. As a consequence, relatively high room-temperature electrical conductivities are obtained in extrinsic semiconductors. Most of these materials are designed for use in electronic devices to be operated at ambient conditions.

### EXAMPLE PROBLEM 19.2

Phosphorus is added to high-purity silicon to give a concentration of  $10^{23} \text{ m}^{-3}$  of charge carriers at room temperature.

- Is this material *n*-type or *p*-type?
- Calculate the room-temperature conductivity of this material, assuming that electron and hole mobilities are the same as for the intrinsic material.

#### SOLUTION

(a) Phosphorus is a Group VA element (Figure 2.6) and, therefore, will act as a donor in silicon. Thus, the  $10^{23} \text{ m}^{-3}$  charge carriers will be virtually all electrons. This electron concentration is greater than that for the intrinsic case ( $1.33 \times 10^{16} \text{ m}^{-3}$ , Example Problem 19.1); hence, this material is extrinsically *n*-type.

(b) In this case the conductivity may be determined using Equation 19.16, as follows:

$$\begin{aligned}\sigma &= n|e|\mu_e = (10^{23} \text{ m}^{-3})(1.6 \times 10^{-19} \text{ C})(0.14 \text{ m}^2/\text{V}\cdot\text{s}) \\ &= 2240 (\Omega\cdot\text{m})^{-1}\end{aligned}$$

## 19.12 THE TEMPERATURE VARIATION OF CONDUCTIVITY AND CARRIER CONCENTRATION

Figure 19.15 plots the logarithm of the electrical conductivity as a function of the logarithm of absolute temperature for intrinsic silicon, and also for silicon that has been doped with 0.0013 and 0.0052 at% boron; again, boron acts as an acceptor in silicon. Worth noting from this figure is that the electrical conductivity in the intrinsic specimen increases dramatically with rising temperature. The numbers of both electrons and holes increase with temperature because more thermal energy is available to excite electrons from the valence to the conduction band. Thus, both the values of *n* and *p* in the intrinsic conductivity expression, Equation 19.15, are enhanced. The magnitudes of electron and hole mobilities decrease slightly with temperature as a result of more effective electron and hole scattering by the thermal vibrations. However, these reductions in  $\mu_e$  and  $\mu_h$  by no means offset the increase in *n* and *p*, and the net effect of a rise in temperature is to produce a conductivity increase.

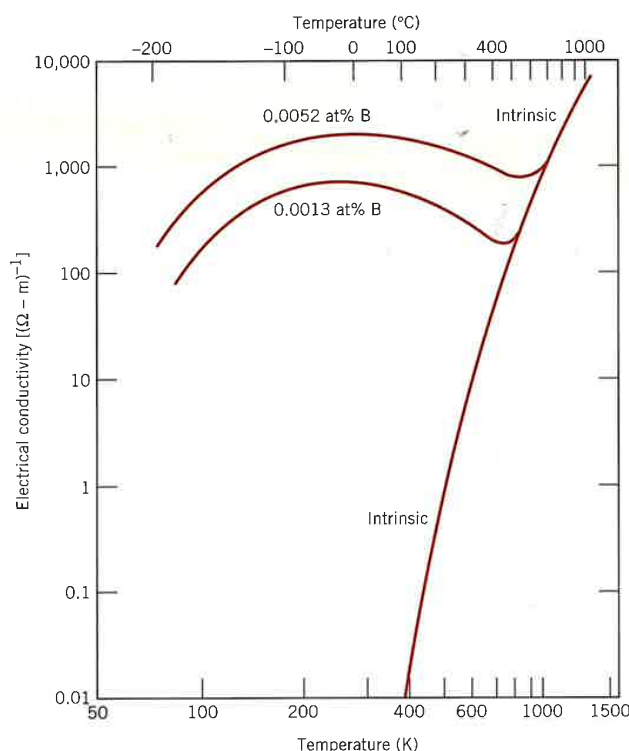


**FIGURE 19.15** The temperature dependence of the electrical conductivity (log-log scales) for intrinsic silicon and boron-doped silicon at two doping levels. [Adapted from G. L. Pearson and J. Bardeen, *Phys. Rev.*, **75**, 865 (1949).]

Mathematically, the dependence of intrinsic conductivity  $\sigma$  on the absolute temperature  $T$  is approximately

$$\ln \sigma \cong C - \frac{E_g}{2kT} \quad (19.18)$$

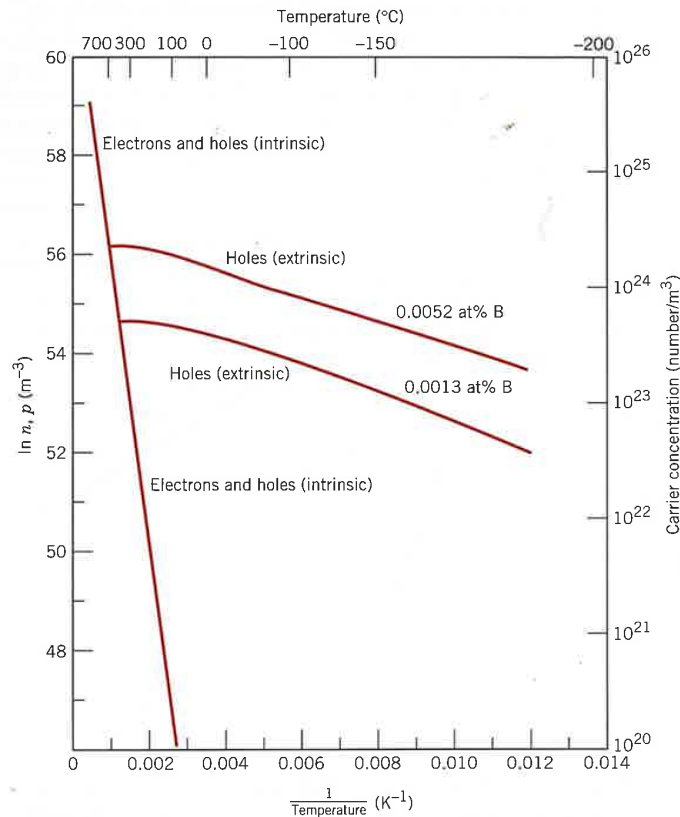
where  $C$  represents a temperature-independent constant and  $E_g$  and  $k$  are the band gap energy and Boltzmann's constant, respectively. Since the increase of  $n$  and  $p$  with rising temperature is so much greater than the decrease in  $\mu_e$  and  $\mu_h$ , the dependence of carrier concentration on temperature for intrinsic behavior is virtually the same as for the conductivity, or

$$\ln n = \ln p \cong C' - \frac{E_g}{2kT} \quad (19.19)$$

The parameter  $C'$  is a constant that is independent of temperature, yet is different from  $C$  in Equation 19.18.

In light of Equation 19.19, another method of representing the temperature dependence of the electrical behavior of semiconductors is as the natural logarithm of electron and hole concentrations versus the reciprocal of the absolute temperature. Figure 19.16 is such a plot using data taken from Figure 19.15; and, as may be noted (Figure 19.16), a straight line segment results for the intrinsic material; such a plot expedites the determination of the band gap energy. According to

**FIGURE 19.16**  
The logarithm of carrier (electron and hole) concentration as a function of the reciprocal of the absolute temperature for intrinsic silicon and two boron-doped silicon materials. (Adapted from G. L. Pearson and J. Bardeen, *Phys. Rev.*, **75**, 865, 1949.)



Equation 19.19, the slope of this line segment is equal to  $-E_g/2k$ , or  $E_g$  may be determined as follows:

$$E_g = -2k \left( \frac{\Delta \ln p}{\Delta(1/T)} \right) \quad (19.20)$$

$$= -2k \left( \frac{\Delta \ln n}{\Delta(1/T)} \right)$$

This is indicated in the schematic plot of Figure 19.17.

Another important feature of the behavior shown in Figures 19.15 and 19.16 is that at temperatures below about 800 K (527°C), the boron-doped materials are extrinsically *p*-type; that is, virtually all the carrier holes result from extrinsic excitations—electron transitions from the valence band into the boron acceptor level, which leave behind valence band holes (Figure 19.14). The available thermal energies at these temperatures are sufficient to promote significant numbers of these excitations, yet insufficient to stimulate many electrons from the valence band across the band gap. Thus, the extrinsic conductivity far exceeds that of the intrinsic material. For example, at 400 K (127°C) the conductivities for intrinsic silicon and extrinsic 0.0013 at% boron-doped material are approximately  $10^{-2}$  and  $600 (\Omega\text{-m})^{-1}$ ,

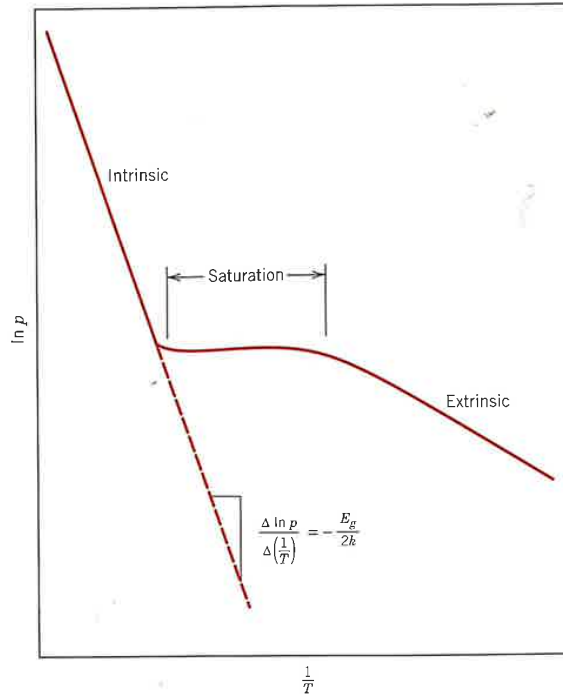


**FIGURE 19.17** Schematic plot of the natural logarithm of hole concentration as a function of the reciprocal of absolute temperature for a  $p$ -type semiconductor that exhibits extrinsic, saturation, and intrinsic behavior.

respectively (Figure 19.15). This comparison indicates the sensitivity of conductivity to even extremely small concentrations of some impurity elements.

Furthermore, the extrinsic conductivity is also sensitive to temperature, as indicated in Figure 19.15, for both boron-doped materials. Beginning at about 75 K ( $-200^{\circ}\text{C}$ ), the conductivity first increases with temperature, reaches a maximum, and then decreases slightly prior to becoming intrinsic. Or, in terms of carrier (i.e., hole) concentration, Figure 19.16,  $\ln p$  first increases linearly with decreasing  $1/T$  (or increasing temperature). Large numbers of extrinsic excitations are possible even at these relatively low temperatures inasmuch as the acceptor level lies just above the top of the valence band. With further temperature increase ( $1/T$  decrease), the hole concentration eventually becomes independent of temperature, Figure 19.16. At this point virtually all of the boron atoms have *accepted* electrons from the valence band, or are said to be *saturated*; this is appropriately termed the *saturation region* (Figure 19.17). (Donor impurities become *exhausted* instead of saturated.) The number of holes in this region is approximately equal to the number of dopant impurity (i.e., boron) atoms.

The decrease of conductivity with increasing temperature within the saturation region for the two extrinsic curves in Figure 19.15 may be explained by the reduction in hole mobility with rising temperature. From the extrinsic conductivity expression, Equation 19.17, both  $e$  and  $p$  are independent of temperature in this region, and the only temperature dependence comes from the mobility.

Also worth noting from Figures 19.15 and 19.16 is that at about 800 K ( $527^{\circ}\text{C}$ ), the conductivity of both boron-doped materials becomes intrinsic. At the outset of intrinsic behavior, the number of intrinsic valence band-to-conduction band transitions becomes greater than the number of holes that are extrinsically generated.

A couple of final comments relate to the influence of boron acceptor content on the electrical behavior of silicon. First, the extrinsic and saturation conductivities and hole concentrations are greater for the material with the higher boron content (Figures 19.15 and 19.16), a result not unexpected, since more B atoms are present from which holes may be produced. Also, the intrinsic onset temperature becomes elevated as the dopant content increases.

### EXAMPLE PROBLEM 19.3

If the room-temperature [25°C (298 K)] electrical conductivity of intrinsic germanium is  $2.2 (\Omega\text{-m})^{-1}$ , estimate its conductivity at 150°C (423 K).

#### SOLUTION

This problem is solved by employment of Equation 19.18. First, we determine the value of the constant  $C$  using the room-temperature data, after which the value at 150°C may be computed. From Table 19.2, the value of  $E_g$  for germanium is 0.67 eV, and, therefore,

$$\begin{aligned} C &= \ln \sigma + \frac{E_g}{2kT} \\ &= \ln(2.2) + \frac{0.67 \text{ eV}}{(2)(8.62 \times 10^{-5} \text{ eV/K})(298 \text{ K})} = 13.83 \end{aligned}$$

Now, at 150°C (423 K),

$$\begin{aligned} \ln \sigma &= C - \frac{E_g}{2kT} \\ &= 13.83 - \frac{0.67 \text{ eV}}{(2)(8.62 \times 10^{-5} \text{ eV/K})(423 \text{ K})} = 4.64 \end{aligned}$$

or

$$\sigma = 103.8 (\Omega\text{-m})^{-1}$$

### DESIGN EXAMPLE 19.1

The room-temperature electrical conductivity of intrinsic silicon is  $4 \times 10^{-4} (\Omega\text{-m})^{-1}$  (Table 19.2). An extrinsic  $n$ -type silicon material is desired having a room-temperature conductivity of  $150 (\Omega\text{-m})^{-1}$ . Specify a donor impurity type that may be used as well as its concentration in atom percent to yield these electrical characteristics. Assume that the electron and hole mobilities are the same as for the intrinsic material, and that at room temperature the donor impurities are exhausted.

#### SOLUTION

First of all, those elements which, when added to silicon render it  $n$ -type, lie one group to the right of silicon in the periodic table; these include the group VA elements (Figure 2.6)—i.e., nitrogen, phosphorus, arsenic, and antimony.

Since this material is extrinsic and  $n$ -type,  $n \gg p$ , the electrical conductivity is a function of the free electron concentration according to Equation 19.16. Furthermore, the design stipulates that the donor impurity atoms are exhausted; therefore,

the number of free electrons is about equal to the number of donor impurities,  $N_d$ . That is

$$n \sim N_d$$

We now solve Equation 19.16 for  $n$  using the stipulated conductivity [ $150 (\Omega\text{-m})^{-1}$ ] and the electron mobility value provided in Table 19.2 ( $0.14 \text{ m}^2/\text{V}\cdot\text{s}$ ). Thus

$$\begin{aligned} n &= N_d = \frac{\sigma}{|e|\mu_e} \\ &= \frac{150 (\Omega\text{-m})^{-1}}{(1.6 \times 10^{-19} \text{ C})(0.14 \text{ m}^2/\text{V}\cdot\text{s})} \\ &= 6.7 \times 10^{21} \text{ m}^{-3} \end{aligned}$$

It next becomes necessary to calculate the concentration of donor impurities in atom percent. This computation first requires the determination of the number of silicon atoms per cubic meter,  $N_{\text{Si}}$ , using Equation 4.2, which is as follows:

$$\begin{aligned} N_{\text{Si}} &= \frac{N_A \rho_{\text{Si}}}{A_{\text{Si}}} \\ &= \frac{(6.023 \times 10^{23} \text{ atoms/mol})(2.33 \text{ g/cm}^3)(10^6 \text{ cm}^3/\text{m}^3)}{28.09 \text{ g/mol}} \\ &= 5 \times 10^{28} \text{ m}^{-3} \end{aligned}$$

The concentration of donor impurities in atom percent ( $C'_d$ ) is just the ratio of  $N_d$  and  $N_d + N_{\text{Si}}$  multiplied by 100 as

$$\begin{aligned} C'_d &= \frac{N_d}{N_d + N_{\text{Si}}} \times 100 \\ &= \frac{6.7 \times 10^{21} \text{ m}^{-3}}{(6.7 \times 10^{21} \text{ m}^{-3}) + (5 \times 10^{28} \text{ m}^{-3})} \times 100 = 1.34 \times 10^{-5} \end{aligned}$$

Thus, a silicon material having a room-temperature  $n$ -type electrical conductivity of  $150 (\Omega\text{-m})^{-1}$  must contain  $1.34 \times 10^{-5} \text{ at\%}$  nitrogen, phosphorus, arsenic, or antimony.

### 19.13 THE HALL EFFECT

For some material, it is on occasion desired to determine its majority charge carrier type, concentration, and mobility. Such determinations are not possible from a simple electrical conductivity measurement; a **Hall effect** experiment must also be conducted. This Hall effect is a result of the phenomenon whereby a magnetic field applied perpendicular to the direction of motion of a charged particle exerts a force on the particle perpendicular to both the magnetic field and the particle motion directions.

In demonstrating the Hall effect, consider the specimen geometry shown in Figure 19.18, a parallelepiped specimen having one corner situated at the origin of a Cartesian coordinate system. In response to an externally applied electric field, the electrons and/or holes move in the  $x$  direction and give rise to a current  $I_x$ . When a magnetic field is imposed in the positive  $z$  direction (denoted as  $B_z$ ), the

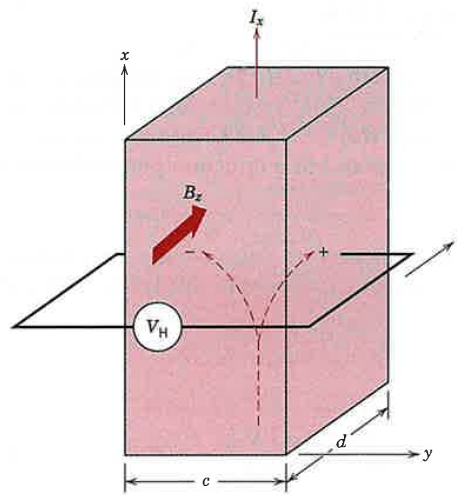


**FIGURE 19.18** Schematic demonstration of the Hall effect. Positive and/or negative charge carriers that are part of the  $I_x$  current are deflected by the magnetic field  $B_z$  and give rise to the Hall voltage,  $V_H$ .

resulting force brought to bear on the charge carriers will cause them to be deflected in the  $y$  direction—holes (positively charged carriers) to the right specimen face and electrons (negatively charged carriers) to the left face, as indicated in the figure. Thus, a voltage, termed the *Hall voltage*  $V_H$ , will be established in the  $y$  direction. The magnitude of  $V_H$  will depend on  $I_x$ ,  $B_z$ , and the specimen thickness  $d$  as follows:

$$V_H = \frac{R_H I_x B_z}{d} \quad (19.21)$$

In this expression  $R_H$  is termed the *Hall coefficient*, which is a constant for a given material. For metals, wherein conduction is by electrons,  $R_H$  is negative and equal to

$$R_H = \frac{1}{n|e|} \quad (19.22)$$

Thus,  $n$  may be determined, inasmuch as  $R_H$  may be measured using Equation 19.21 and the magnitude of  $e$ , the charge on an electron, is known.

Furthermore, from Equation 19.8, the electron mobility  $\mu_e$  is just

$$\mu_e = \frac{\sigma}{n|e|} \quad (19.23a)$$

Or, using Equation 19.22,

$$\mu_e = |R_H| \sigma \quad (19.23b)$$

Thus, the magnitude of  $\mu_e$  may also be determined if the conductivity  $\sigma$  has also been measured.

For semiconducting materials, the determination of majority carrier type and computation of carrier concentration and mobility are more complicated and will not be discussed here.

**EXAMPLE PROBLEM 19.4**

The electrical conductivity and electron mobility for aluminum are  $3.8 \times 10^7 (\Omega\text{-m})^{-1}$  and  $0.0012 \text{ m}^2/\text{V}\cdot\text{s}$ , respectively. Calculate the Hall voltage for an aluminum specimen that is 15 mm thick for a current of 25 A and a magnetic field of 0.6 tesla (imposed in a direction perpendicular to the current).

**SOLUTION**

The Hall voltage  $V_H$  may be determined using Equation 19.21. However, it first becomes necessary to compute the Hall coefficient ( $R_H$ ) from Equation 19.23b as

$$\begin{aligned} R_H &= -\frac{\mu_e}{\sigma} \\ &= -\frac{0.0012 \text{ m}^2/\text{V}\cdot\text{s}}{3.8 \times 10^7 (\Omega\text{-m})^{-1}} = -3.16 \times 10^{-11} \text{ V}\cdot\text{m}/\text{A}\cdot\text{tesla} \end{aligned}$$

Now, employment of Equation 19.21 leads to

$$\begin{aligned} V_H &= \frac{R_H I_x B_z}{d} \\ &= \frac{(-3.16 \times 10^{-11} \text{ V}\cdot\text{m}/\text{A}\cdot\text{tesla})(25 \text{ A})(0.6 \text{ tesla})}{15 \times 10^{-3} \text{ m}} \\ &= -3.16 \times 10^{-8} \text{ V} \end{aligned}$$

**19.14 SEMICONDUCTOR DEVICES**

The unique electrical properties of semiconductors permit their use in devices to perform specific electronic functions. Diodes and transistors, which have replaced old-fashioned vacuum tubes, are two familiar examples. Advantages of semiconductor devices (sometimes termed solid-state devices) include small size, low power consumption, and no warmup time. Vast numbers of extremely small circuits, each consisting of numerous electronic devices, may be incorporated onto a small silicon chip. The invention of semiconductor devices, which has given rise to miniaturized circuitry, is responsible for the advent and extremely rapid growth of a host of new industries in the past few years.

**THE  $p$ - $n$  RECTIFYING JUNCTION**

A rectifier, or **diode**, is an electronic device that allows the current to flow in one direction only; for example, a rectifier transforms an alternating current into direct current. Before the advent of the  $p$ - $n$  junction semiconductor rectifier, this operation was carried out using the vacuum tube diode. The  **$p$ - $n$  rectifying junction** is constructed from a single piece of semiconductor that is doped so as to be  $n$ -type on one side and  $p$ -type on the other (Figure 19.19a). If pieces of  $n$ - and  $p$ -type materials are joined together, a poor rectifier results, since the presence of a surface between the two sections renders the device very inefficient. Also, single crystals of semiconducting materials must be used in all devices because electronic phenomena that are deleterious to operation occur at grain boundaries.

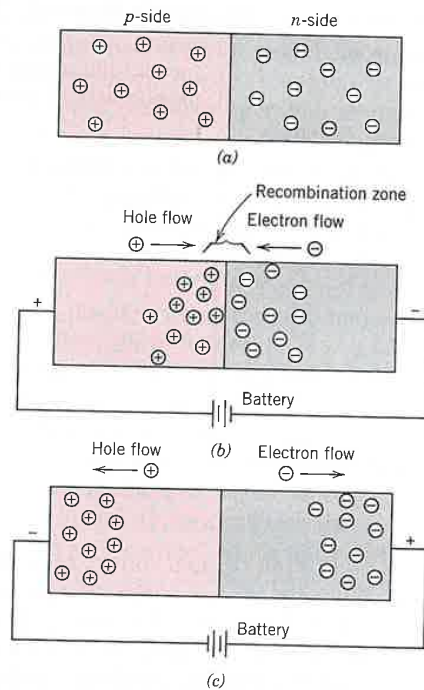
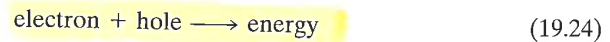


**FIGURE 19.19** For a  $p$ - $n$  rectifying junction, representations of electron and hole distributions for (a) no electrical potential, (b) forward bias, and (c) reverse bias.

Before the application of any potential across the  $p$ - $n$  specimen, holes will be the dominant carriers on the  $p$ -side, and electrons will predominate in the  $n$ -region, as illustrated in Figure 19.19a. An external electric potential may be established across a  $p$ - $n$  junction with two different polarities. When a battery is used, the positive terminal may be connected to the  $p$ -side, and the negative terminal to the  $n$ -side; this is referred to as a **forward bias**. The opposite polarity (minus to  $p$  and plus to  $n$ ) is termed **reverse bias**.

The response of the charge carriers to the application of a forward-biased potential is demonstrated in Figure 19.19b. The holes on the  $p$ -side and the electrons on the  $n$ -side are attracted to the junction. As electrons and holes encounter one another near the junction, they continuously recombine and annihilate one another, according to



Thus for this bias, large numbers of charge carriers flow across the semiconductor and to the junction, as evidenced by an appreciable current and a low resistivity. The current-voltage characteristics for forward bias are shown on the right-hand half of Figure 19.20.

For reverse bias (Figure 19.19c), both holes and electrons, as majority carriers, are rapidly drawn away from the junction; this separation of positive and negative charges (or polarization) leaves the junction region relatively free of mobile charge carriers. Recombination will not occur to any appreciable extent, so that the junction is now highly insulative. Figure 19.20 also illustrates the current-voltage behavior for reverse bias.

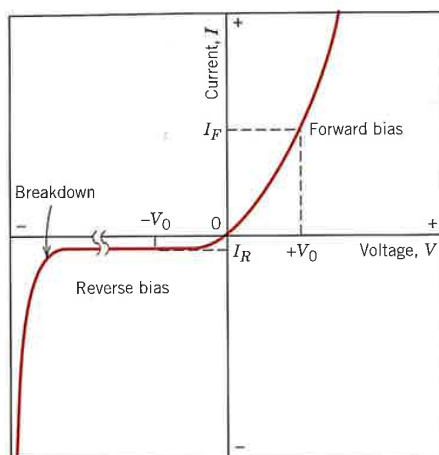


**FIGURE 19.20** The current–voltage characteristics of a  $p$ – $n$  junction for forward and reverse biases. The phenomenon of breakdown is also shown.

The rectification process in terms of input voltage and output current is demonstrated in Figure 19.21. Whereas voltage varies sinusoidally with time (Figure 19.21a), maximum current flow for reverse bias voltage  $I_R$  is extremely small in comparison to that for forward bias  $I_F$  (Figure 19.21b). Furthermore, correspondence between  $I_F$  and  $I_R$  and the imposed maximum voltage ( $\pm V_0$ ) is noted in Figure 19.20.

At high reverse bias voltages, sometimes on the order of several hundred volts, large numbers of charge carriers (electrons and holes) are generated. This gives rise to a very abrupt increase in current, a phenomenon known as *breakdown*, also shown in Figure 19.20, and discussed in more detail in Section 19.21.

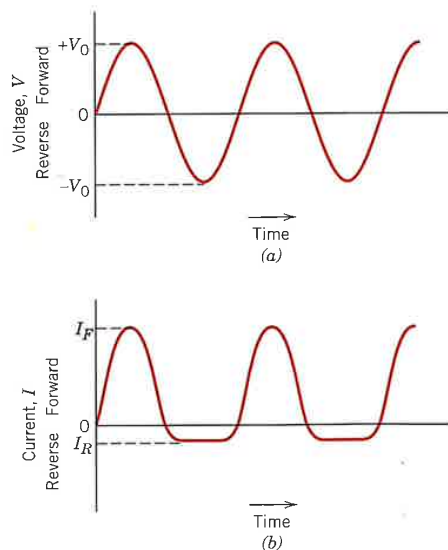


**FIGURE 19.21** (a) Voltage versus time for the input to a  $p$ – $n$  rectifying junction. (b) Current versus time, showing rectification of voltage in (a) by a  $p$ – $n$  rectifying junction having the voltage–current characteristics shown in Figure 19.20.

## THE TRANSISTOR

Transistors, which are extremely important semiconducting devices in today's micro-electronic circuitry, are capable of two primary types of function. First, they can perform the same operation as their vacuum tube precursor, the triode; that is, they can amplify an electrical signal. In addition, they serve as switching devices in computers for the processing and storage of information. The two major types are the **junction** (or bimodal) **transistor** and the *metal-oxide-semiconductor field-effect transistor* (abbreviated as **MOSFET**).

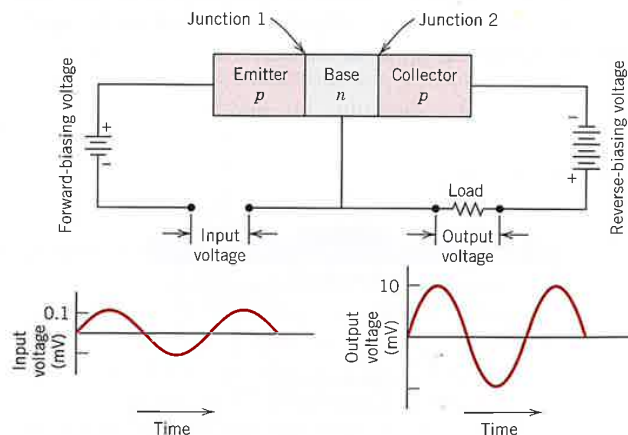
### Junction Transistors

The junction transistor is composed of two  $p$ - $n$  junctions arranged back to back in either the  $n$ - $p$ - $n$  or the  $p$ - $n$ - $p$  configuration; the latter variety is discussed here. Figure 19.22 is a schematic representation of a  $p$ - $n$ - $p$  junction transistor along with its attendant circuitry. A very thin  $n$ -type *base* region is sandwiched in between  $p$ -type *emitter* and *collector* regions. The circuit that includes the emitter-base junction (junction 1) is forward biased, whereas a reverse bias voltage is applied across the base-collector junction (junction 2).

Figure 19.23 illustrates the mechanics of operation in terms of the motion of charge carriers. Since the emitter is  $p$ -type and junction 1 is forward biased, large numbers of holes enter the base region. These injected holes are minority carriers in the  $n$ -type base, and some will combine with the majority electrons. However, if the base is extremely narrow and the semiconducting materials have been properly prepared, most of these holes will be swept through the base without recombination, then across junction 2 and into the  $p$ -type collector. The holes now become a part of the emitter-collector circuit. A small increase in input voltage within the emitter-base circuit produces a large increase in current across junction 2. This large increase in collector current is also reflected by a large increase in voltage across the load resistor, which is also shown in the circuit (Figure 19.22). Thus, a voltage signal that passes through a junction transistor experiences amplification; this effect is also illustrated in Figure 19.22 by the two voltage-time plots.

Similar reasoning applies to the operation of an  $n$ - $p$ - $n$  transistor, except that electrons instead of holes are injected across the base and into the collector.

**FIGURE 19.22**  
Schematic diagram of a  $p$ - $n$ - $p$  junction transistor and its associated circuitry, including input and output voltage-time characteristics showing voltage amplification. (Adapted from A. G. Guy, *Essentials of Materials Science*, McGraw-Hill Book Company, New York, 1976.)



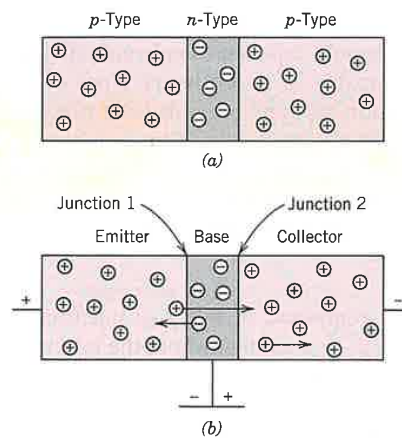


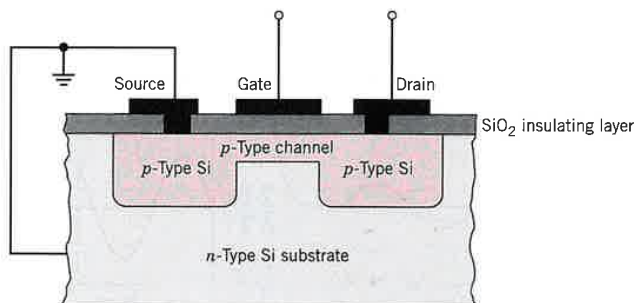
**FIGURE 19.23** For a junction transistor ( $p$ - $n$ - $p$  type), the distributions and directions of electron and hole motion (a) when no potential is applied and (b) with appropriate bias for voltage amplification.

### The MOSFET

One variety of MOSFET consists of two small islands of  $p$ -type semiconductor that are created within a substrate of  $n$ -type silicon, as shown in cross section in Figure 19.24; the islands are joined by a narrow  $p$ -type channel. Appropriate metal connections (source and drain) are made to these islands; an insulating layer of silicon dioxide is formed by the surface oxidation of the silicon. A final connector (gate) is then fashioned onto the surface of this insulating layer.

The operation of a MOSFET differs from that of the junction transistor in that a single type of charge carrier (either electron or hole) is active. The conductivity of the channel is varied by the presence of an electric field imposed on the gate. For example, imposition of a positive field on the gate will drive charge carriers (in this case holes) out of the channel, thereby reducing the electrical conductivity. Thus, a small alteration in the field at the gate will produce a relatively large variation in current between the source and the drain. In some respects, then, the operation of a MOSFET is very similar to that described for the junction transistor. The primary difference is that the gate current is exceedingly small in comparison to the base current of a junction transistor. MOSFETs are, therefore, used where the signal sources to be amplified cannot sustain an appreciable current.

**FIGURE 19.24** Schematic cross-sectional view of a MOSFET transistor.



### *Semiconductors in Computers*

In addition to their ability to amplify an imposed electrical signal, transistors and diodes may also act as switching devices, a feature utilized for arithmetic and logical operations, and also for information storage in computers. Computer numbers and functions are expressed in terms of a binary code (i.e., numbers written to the base 2). Within this framework, numbers are represented by a series of two states (sometimes designated 0 and 1). Now, transistors and diodes within a digital circuit operate as switches that also have two states—on and off, or conducting and nonconducting; “off” corresponds to one binary number state, and “on” to the other. Thus, a single number may be represented by a collection of circuit elements containing transistors that are appropriately switched.

### **MICROELECTRONIC CIRCUITRY**

During the past few years, the advent of microelectronic circuitry, where thousands of electronic components and circuits are incorporated into a very small space, has revolutionized the field of electronics. This revolution was precipitated, in part, by aerospace technology, which necessitated computers and electronic devices that were small and had low power requirements. As a result of refinement in processing and fabrication techniques, there has been an astonishing depreciation in the cost of integrated circuitry. Consequently, at the time of this writing, personal computers are affordable to a large segment of the population in the United States. Also, the use of **integrated circuits** has become infused into many other facets of our lives—calculators, communications, watches, industrial production and control, and all phases of the electronics industry.

Inexpensive microelectronic circuits are mass produced by using some very ingenious fabrication techniques. The process begins with the growth of relatively large cylindrical single crystals of high-purity silicon from which thin circular wafers are cut. Many microelectronic or integrated circuits, sometimes called “chips,” are prepared on a single wafer; a photograph of one such wafer containing numerous chips is shown in Figure 23.20. A chip is rectangular, typically on the order of 6 mm ( $\frac{1}{4}$  in.) on a side and contains thousands of circuit elements: diodes, transistors, resistors, and capacitors. One such microprocessor chip is shown in its entirety in Figure 23.22*b*; also shown are the numerous electrical leads that are used to connect this chip to its leadframe, which in turn is bonded to a printed circuit board. Enlarged photographs of microprocessor chips at different magnifications are presented in Figures 19.25*a* and 19.25*b*; these micrographs reveal the intricacy of integrated circuits. At this time, 175,000,000 component chips are being produced, and memory capabilities currently double about every 12 months.

Microelectronic circuits consist of many layers that lie within or are stacked on top of the silicon wafer in a precisely detailed pattern. Using photolithographic techniques, for each layer, very small elements are masked in accordance with a microscopic pattern. Circuit elements are constructed by the selective introduction of specific materials (by diffusion or ion implantation) into unmasked regions to create localized *n*-type, *p*-type, high-resistivity, or conductive areas. This procedure is repeated layer by layer until the total integrated circuit has been fabricated, as illustrated in the MOSFET schematic (Figure 19.24). Elements of integrated circuits are shown in Figure 19.25 and on page 605.

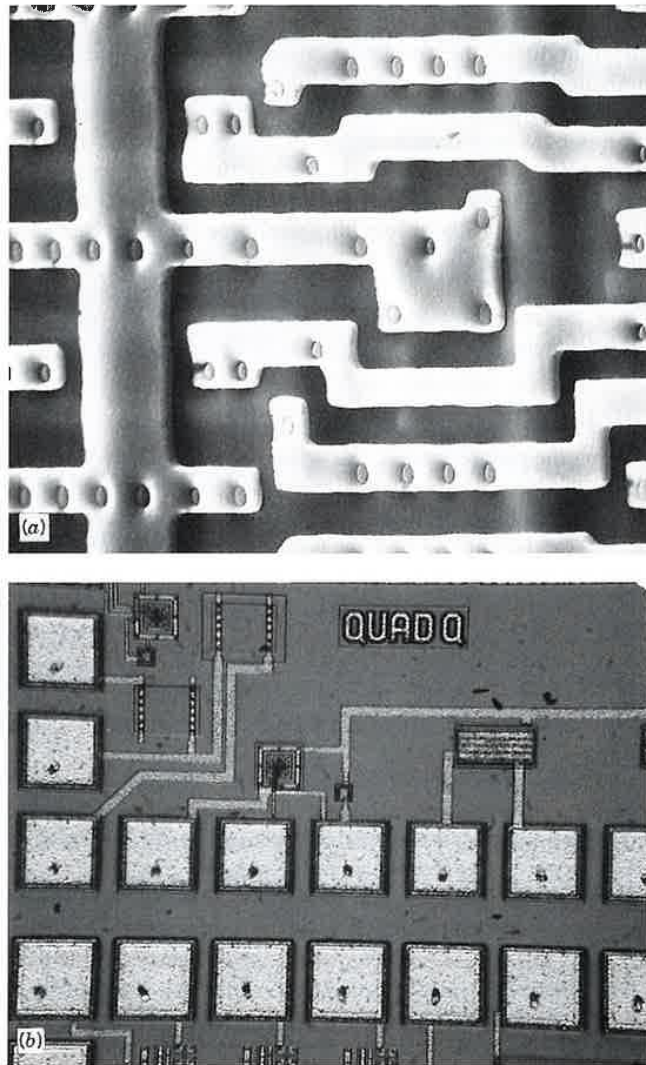


**FIGURE 19.25** (a) Scanning electron micrograph showing a small region of a microprocessing chip (a 0.5 MB selected address device). The narrow, white regions are an aluminum top layer that serves as the wiring for this device. The gray regions are diffusion-layer doped silicon that have been coated with an interlayer dielectric. Approximately 2000 $\times$ . (b) An optical photomicrograph showing a portion of a circuit that is used to test microprocessing chips. The narrow, light regions are aluminum connectors, while the white, square areas are test pads (semiconductor devices); test circuits (also composed of semiconductor devices) appear in the upper left-hand corner of the photograph. Approximately 50 $\times$ . (Both photographs courtesy of Nick Gonzales of National Semiconductor Corporation, West Jordan, Utah.)

## ELECTRICAL CONDUCTION IN IONIC CERAMICS AND IN POLYMERS

Most polymers and ionic ceramics are insulating materials at room temperature and, therefore, have electron energy band structures similar to that represented in Figure 19.4c; a filled valence band is separated from an empty conduction band by a relatively large band gap, usually greater than 2 eV. Thus, at normal temperatures only very few electrons may be excited across the band gap by the available thermal energy, which accounts for the very small values of conductivity; Table 19.3 gives the room-temperature electrical conductivity of several of these materials. (The electrical resistivities of a large number of ceramic and polymeric materials are provided in Table B.9, Appendix B.) Of course, many materials are utilized on the basis of their ability to insulate, and thus a high electrical resistivity is desirable. With rising temperature insulating materials experience an increase in electrical conductivity, which may ultimately be greater than that for semiconductors.

### 19.15 CONDUCTION IN IONIC MATERIALS

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

$$\sigma_{\text{total}} = \sigma_{\text{electronic}} + \sigma_{\text{ionic}} \quad (19.25)$$

**Table 19.3** Typical Room-Temperature Electrical Conductivities for 13 Nonmetallic Materials

| Material                | Electrical Conductivity<br>[( $\Omega \cdot m$ ) <sup>-1</sup> ] |
|-------------------------|------------------------------------------------------------------|
| Graphite                | $3 \times 10^4$ – $2 \times 10^5$                                |
| <i>Ceramics</i>         |                                                                  |
| Concrete (dry)          | $10^{-9}$                                                        |
| Soda-lime glass         | $10^{-10}$ – $10^{-11}$                                          |
| Porcelain               | $10^{-10}$ – $10^{-12}$                                          |
| Borosilicate glass      | $\sim 10^{-13}$                                                  |
| Aluminum oxide          | $< 10^{-13}$                                                     |
| Fused silica            | $< 10^{-18}$                                                     |
| <i>Polymers</i>         |                                                                  |
| Phenol-formaldehyde     | $10^{-9}$ – $10^{-10}$                                           |
| Polymethyl methacrylate | $< 10^{-12}$                                                     |
| Nylon 6,6               | $10^{-12}$ – $10^{-13}$                                          |
| Polystyrene             | $< 10^{-14}$                                                     |
| Polyethylene            | $10^{-15}$ – $10^{-17}$                                          |
| Polytetrafluoroethylene | $< 10^{-17}$                                                     |

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

A mobility  $\mu_i$  may be associated with each of the ionic species as follows:

$$\mu_i = \frac{n_i e D_i}{kT} \quad (19.26)$$

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

## 19.16 ELECTRICAL PROPERTIES OF POLYMERS

Most polymeric materials are poor conductors of electricity (Table 19.3) because of the unavailability of large numbers of free electrons to participate in the conduction process. The mechanism of electrical conduction in these materials is not well understood, but it is felt that conduction in polymers of high purity is electronic.

### CONDUCTING POLYMERS

Within the past several years, polymeric materials have been synthesized that have electrical conductivities on par with metallic conductors; they are appropriately termed *conducting polymers*. Conductivities as high as  $1.5 \times 10^7 (\Omega\text{-m})^{-1}$  have been achieved in these materials; on a volume basis, this value corresponds to one fourth of the conductivity of copper, or twice its conductivity on the basis of weight.

This phenomenon is observed in a dozen or so polymers, including polyacetylene, polyparaphenylene, polypyrrole, and polyaniline that have been doped with appropriate impurities. As is the case with semiconductors, these polymers may be made either *n*-type (i.e., free-electron dominant) or *p*-type (i.e., hole dominant) depending on the dopant. However, unlike semiconductors, the dopant atoms or molecules do not substitute for or replace any of the polymer atoms.

High-purity polymers have electron band structures characteristic of electrical insulators (Figure 19.4c). The mechanism by which large numbers of free electrons and holes are generated in these conducting polymers is complex and not well understood. In very simple terms, it appears that the dopant atoms lead to the formation of new energy bands that overlap the valence and conduction bands of the intrinsic polymer, giving rise to a partially filled band, and the production at room temperature of a high concentration of free electrons or holes. Orienting the polymer chains, either mechanically (Section 16.3) or magnetically, during synthesis results in a highly anisotropic material having a maximum conductivity along the direction of orientation.

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

## DIELECTRIC BEHAVIOR

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

### 19.17 CAPACITANCE

When a voltage is applied across a capacitor, one plate becomes positively charged, the other negatively charged, with the corresponding electric field directed from the positive to the negative. The **capacitance**  $C$  is related to the quantity of charge stored on either plate  $Q$  by<sup>2</sup>

$$C = \frac{Q}{V} \quad (19.27)$$

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

Now, consider a parallel-plate capacitor with a vacuum in the region between the plates (Figure 19.26a). The capacitance may be computed from the relationship

$$C = \epsilon_0 \frac{A}{l} \quad (19.28)$$

where  $A$  represents the area of the plates and  $l$  is the distance between them. The parameter  $\epsilon_0$ , called the **permittivity** of a vacuum, is a universal constant having the value of  $8.85 \times 10^{-12}$  F/m.

If a dielectric material is inserted into the region within the plates (Figure 19.26b), then

$$C = \epsilon \frac{A}{l} \quad (19.29)$$

where  $\epsilon$  is the permittivity of this dielectric medium, which will be greater in magnitude than  $\epsilon_0$ . The relative permittivity  $\epsilon_r$ , often called the **dielectric constant**, is equal to the ratio

$$\epsilon_r = \frac{\epsilon}{\epsilon_0} \quad (19.30)$$

which is greater than unity and represents the increase in charge storing capacity by insertion of the dielectric medium between the plates. The dielectric constant is one material property that is of prime consideration for capacitor design. The  $\epsilon_r$  values of a number of dielectric materials are contained in Table 19.4.

<sup>2</sup> By convention, the uppercase "C" is used to represent both capacitance and the unit of charge, coulomb. To minimize confusion in this discussion, the capacitance designation will be italicized, as  $C$ .

FIGURE 19.26

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

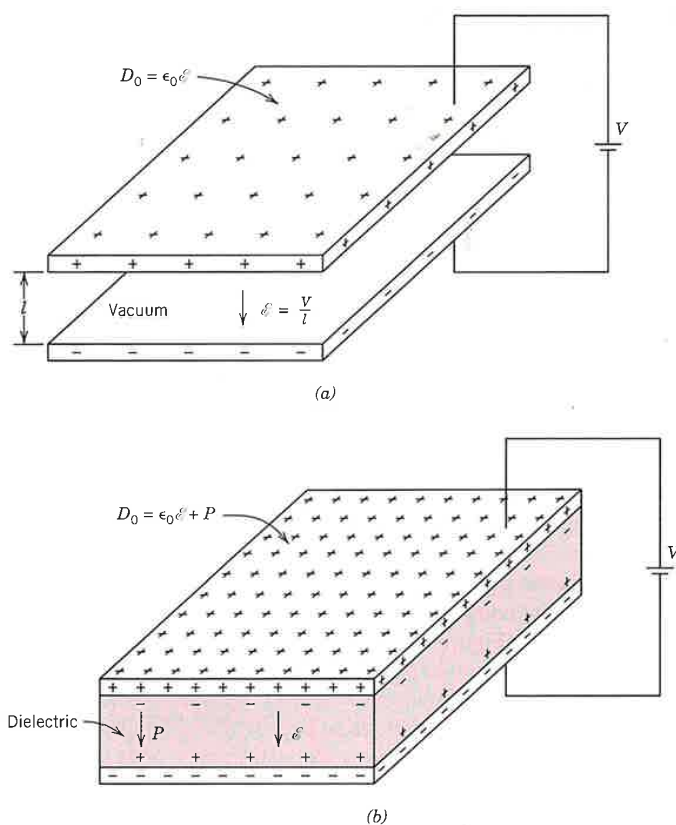


**Table 19.4** Dielectric Constants and Strengths for Some Dielectric Materials

| Material                         | Dielectric Constant |           | Dielectric Strength<br>(V/mil) <sup>a</sup> |
|----------------------------------|---------------------|-----------|---------------------------------------------|
|                                  | 60 Hz               | 1 MHz     |                                             |
| Ceramics                         |                     |           |                                             |
| Titanate ceramics                | —                   | 15–10,000 | 50–300                                      |
| Mica                             | —                   | 5.4–8.7   | 1000–2000                                   |
| Steatite (MgO–SiO <sub>2</sub> ) | —                   | 5.5–7.5   | 200–350                                     |
| Soda–lime glass                  | 6.9                 | 6.9       | 250                                         |
| Porcelain                        | 6.0                 | 6.0       | 40–400                                      |
| Fused silica                     | 4.0                 | 3.8       | 250                                         |
| Polymers                         |                     |           |                                             |
| Phenol-formaldehyde              | 5.3                 | 4.8       | 300–400                                     |
| Nylon 6,6                        | 4.0                 | 3.6       | 400                                         |
| Polystyrene                      | 2.6                 | 2.6       | 500–700                                     |
| Polyethylene                     | 2.3                 | 2.3       | 450–500                                     |
| Polytetrafluoroethylene          | 2.1                 | 2.1       | 400–500                                     |

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

## 19.18 FIELD VECTORS AND POLARIZATION

Perhaps the best approach to an explanation of the phenomenon of capacitance is with the aid of field vectors. To begin, for every electric dipole, there is a separation between a positive and a negative electric charge as demonstrated in Figure 19.27. An electric dipole moment  $p$  is associated with each dipole as follows:

$$p = qd \quad (19.31)$$

where  $q$  is the magnitude of each dipole charge and  $d$  is the distance of separation between them. In reality, a dipole moment is a vector that is directed from the negative to the positive charge, as indicated in Figure 19.27. In the presence of an electric field  $\mathcal{E}$ , which is also a vector quantity, a force (or torque) will come to bear on an electric dipole to orient it with the applied field; this phenomenon is illustrated in Figure 19.28. The process of dipole alignment is termed **polarization**.

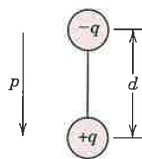


**FIGURE 19.27** Schematic representation of an electric dipole generated by two electric charges (of magnitude  $q$ ) separated by the distance  $d$ ; the associated polarization vector  $p$  is also shown.

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

$$D_0 = \epsilon_0 \mathcal{E} \quad (19.32)$$

the constant of proportionality being  $\epsilon_0$ . Furthermore, an analogous expression exists for the dielectric case, that is,

$$D = \epsilon \mathcal{E} \quad (19.33)$$

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

The increase in capacitance, or dielectric constant, can be explained using a simplified model of polarization within a dielectric material. Consider the capacitor in Figure 19.29a, the vacuum situation, wherein a charge of  $+Q_0$  is stored on the top plate, and  $-Q_0$  on the bottom one. When a dielectric is introduced and an electric field is applied, the entire solid within the plates becomes polarized (Figure 19.29c). As a result of this polarization, there is a net accumulation of negative

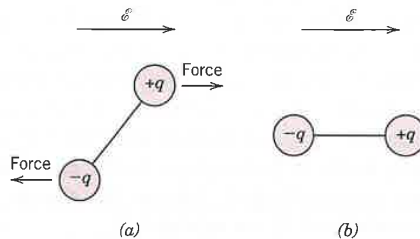


**FIGURE 19.28** (a) Imposed forces (torque) acting on a dipole by an electric field. (b) Final dipole alignment with the field.

tric

ic Strength  
(mil)<sup>a</sup>

0-300  
0-2000  
0-350  
250  
0-400  
250

0-400  
400  
0-700  
0-500  
0-500

he magni-  
ate of appli-

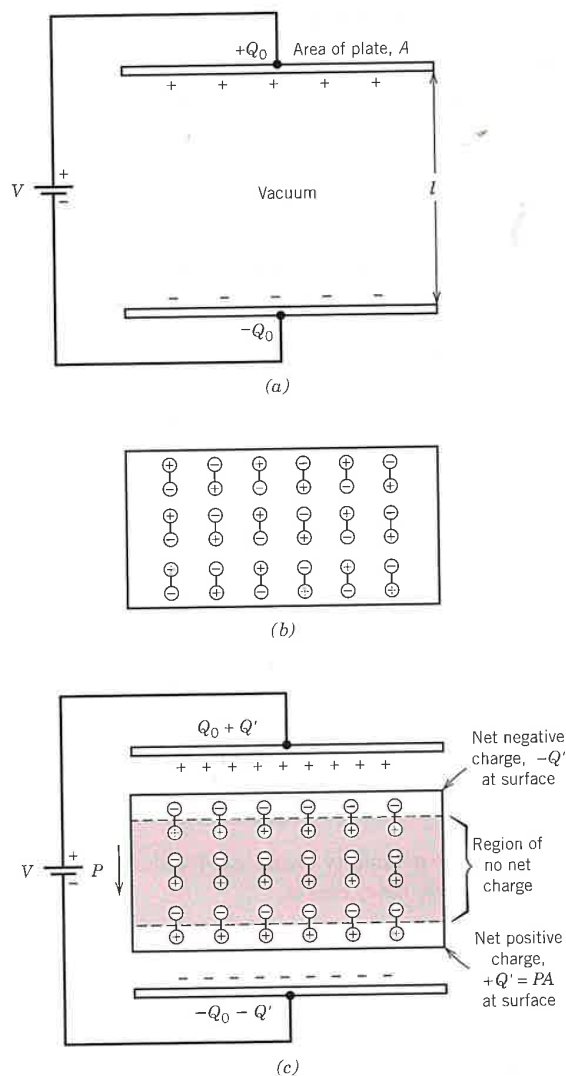


**FIGURE 19.29** Schematic representations of (a) the charge stored on capacitor plates for a vacuum, (b) the dipole arrangement in an unpolarized dielectric, and (c) the increased charge storing capacity resulting from the polarization of a dielectric material. (Adapted from A. G. Guy, *Essentials of Materials Science*, McGraw-Hill Book Company, New York, 1976.)

charge of magnitude  $-Q'$  at the dielectric surface near the positively charged plate and, in a similar manner, a surplus of  $+Q'$  charge at the surface adjacent to the negative plate. For the region of dielectric removed from these surfaces, polarization effects are not important. Thus, if each plate and its adjacent dielectric surface are considered to be a single entity, the induced charge from the dielectric ( $+Q'$  or  $-Q'$ ) may be thought of as nullifying some of the charge that originally existed on the plate for a vacuum ( $-Q_0$  or  $+Q_0$ ). The voltage imposed across the plates is maintained at the vacuum value by increasing the charge at the negative (or bottom) plate by an amount  $-Q'$ , and the top plate by  $+Q'$ . Electrons are caused to flow from the positive to the negative plate by the external voltage source such that the proper voltage is reestablished. And so the charge on each plate is now  $Q_0 + Q'$ , having been increased by an amount  $Q'$ .

**Table 19.5** Primary and Derived Units for Various Electrical Parameters and Field Vectors

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

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

$$D = \epsilon_0 \mathcal{E} + P \quad (19.34)$$

where  $P$  is the *polarization*, or the increase in charge density above that for a vacuum because of the presence of the dielectric; or, from Figure 19.29c,  $P = Q'/A$ , where  $A$  is the area of each plate. The units of  $P$  are the same as for  $D$  ( $\text{C}/\text{m}^2$ ).

The polarization  $P$  may also be thought of as the total dipole moment per unit volume of the dielectric material, or as a polarization electric field within the dielectric that results from the mutual alignment of the many atomic or molecular dipoles with the externally applied field  $\mathcal{E}$ . For many dielectric materials,  $P$  is proportional to  $\mathcal{E}$  through the relationship

$$P = \epsilon_0 (\epsilon_r - 1) \mathcal{E} \quad (19.35)$$

in which case  $\epsilon_r$  is independent of the magnitude of the electric field.

Table 19.5 lists the several dielectric parameters along with their units.

### EXAMPLE PROBLEM 19.5

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

- The capacitance.
- The magnitude of the charge stored on each plate.
- The dielectric displacement  $D$ .
- The polarization.

**SOLUTION**

(a) Capacitance is calculated using Equation 19.29; however, the permittivity  $\epsilon$  of the dielectric medium must first be determined from Equation 19.30 as follows:

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

Thus, the capacitance is

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

(b) Since the capacitance has been determined, the charge stored may be computed using Equation 19.27, according to

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

(c) The dielectric displacement is calculated from Equation 19.33, which yields

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

(d) Using Equation 19.34, the polarization may be determined as follows:

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

## 19.19 TYPES OF POLARIZATION

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

### ELECTRONIC POLARIZATION

**Electronic polarization** may be induced to one degree or another in all atoms. It results from a displacement of the center of the negatively charged electron cloud relative to the positive nucleus of an atom by the electric field (Figure 19.30a). This polarization type is found in all dielectric materials, and, of course, exists only while an electric field is present.

### IONIC POLARIZATION

**Ionic polarization** occurs only in materials that are ionic. An applied field acts to displace cations in one direction and anions in the opposite direction, which gives

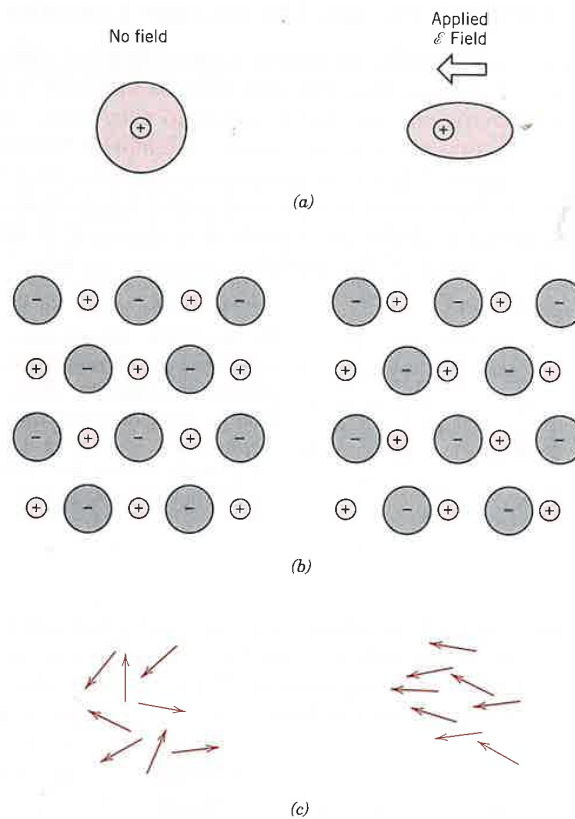


**FIGURE 19.30** (a) Electronic polarization that results from the distortion of an atomic electron cloud by an electric field. (b) Ionic polarization that results from the relative displacement of electrically charged ions in response to an electric field. (c) Response of permanent electric dipoles (arrows) to an applied electric field, producing orientation polarization. (From O. H. Wyatt and D. Dew-Hughes, *Metals, Ceramics and Polymers*, Cambridge University Press, 1974.)

rise to a net dipole moment. This phenomenon is illustrated in Figure 19.30b. The magnitude of the dipole moment for each ion pair  $p_i$  is equal to the product of the relative displacement  $d_i$  and the charge on each ion, or

$$p_i = qd_i \quad (19.36)$$

### ORIENTATION POLARIZATION

The third type, **orientation polarization**, is found only in substances that possess permanent dipole moments. Polarization results from a rotation of the permanent moments into the direction of the applied field, as represented in Figure 19.30c. This alignment tendency is counteracted by the thermal vibrations of the atoms, such that polarization decreases with increasing temperature.

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

$$P = P_e + P_i + P_o \quad (19.37)$$

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

## 19.20 FREQUENCY DEPENDENCE OF THE DIELECTRIC CONSTANT

In many practical situations the current is alternating (ac); that is, an applied voltage or electric field changes direction with time, as indicated in Figure 19.21a. Now, consider a dielectric material that is subject to polarization by an ac electric field. With each direction reversal, the dipoles attempt to reorient with the field, as illustrated in Figure 19.31, a process requiring some finite time. For each polarization type, some minimum reorientation time exists, which depends on the ease with which the particular dipoles are capable of realignment. A **relaxation frequency** is taken as the reciprocal of this minimum reorientation time.

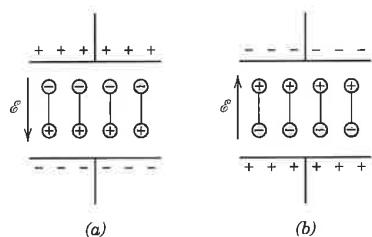


**FIGURE 19.31** Dipole orientations for (a) one polarity of an alternating electric field and (b) for the reversed polarity. (From Richard A. Flinn and Paul K. Trojan, *Engineering Materials and Their Applications*, 4th edition. Copyright © 1990 by John Wiley & Sons, Inc. Adapted by permission of John Wiley & Sons, Inc.)

A dipole cannot keep shifting orientation direction when the frequency of the applied electric field exceeds its relaxation frequency, and therefore, will not make a contribution to the dielectric constant. The dependence of  $\epsilon_r$  on the field frequency is represented schematically in Figure 19.32 for a dielectric medium that exhibits all three types of polarization; note that the frequency axis is scaled logarithmically. As indicated in Figure 19.32, when a polarization mechanism ceases to function, there is an abrupt drop in the dielectric constant; otherwise,  $\epsilon_r$  is virtually frequency independent. Table 19.4 gave values of the dielectric constant at 60 Hz and 1 MHz; these provide an indication of this frequency dependence at the low end of the frequency spectrum.

The absorption of electrical energy by a dielectric material that is subjected to an alternating electric field is termed *dielectric loss*. This loss may be important at

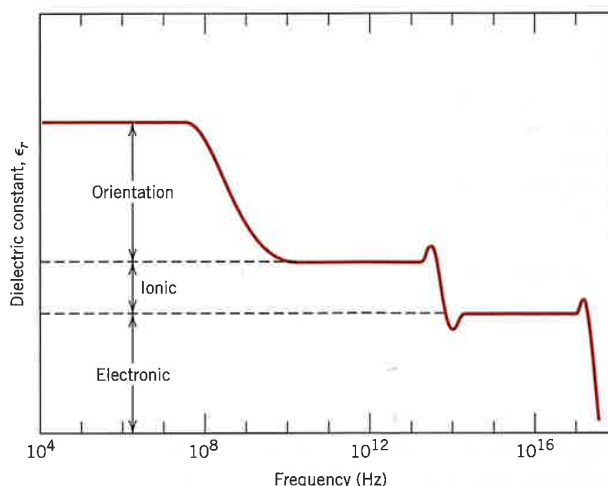


**FIGURE 19.32** Variation of dielectric constant with frequency of an alternating electric field. Electronic, ionic, and orientation polarization contributions to the dielectric constant are indicated.

electric field frequencies in the vicinity of the relaxation frequency for each of the operative dipole types for a specific material. A low dielectric loss is desired at the frequency of utilization.

## 19.21 DIELECTRIC STRENGTH

When very high electric fields are applied across dielectric materials, large numbers of electrons may suddenly be excited to energies within the conduction band. As a result, the current through the dielectric by the motion of these electrons increases dramatically; sometimes localized melting, burning, or vaporization produces irreversible degradation and perhaps even failure of the material. This phenomenon is known as dielectric breakdown. The **dielectric strength**, sometimes called the breakdown strength, represents the magnitude of an electric field necessary to produce breakdown. Table 19.4 presented dielectric strengths for several materials.

## 19.22 DIELECTRIC MATERIALS

A number of ceramics and polymers are utilized as insulators and/or in capacitors. Many of the ceramics, including glass, porcelain, steatite, and mica, have dielectric constants within the range of 6 to 10 (Table 19.4). These materials also exhibit a high degree of dimensional stability and mechanical strength. Typical applications include powerline and electrical insulation, switch bases, and light receptacles. The titania ( $\text{TiO}_2$ ) and titanate ceramics, such as barium titanate ( $\text{BaTiO}_3$ ), can be made to have extremely high dielectric constants, which render them especially useful for some capacitor applications.

The magnitude of the dielectric constant for most polymers is less than for ceramics, since the latter may exhibit greater dipole moments;  $\epsilon_r$  values for polymers generally lie between 2 and 5. These materials are commonly utilized for insulation of wires, cables, motors, generators, and so on, and, in addition, for some capacitors.

## OTHER ELECTRICAL CHARACTERISTICS OF MATERIALS

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

## 19.23 FERROELECTRICITY

The group of dielectric materials called **ferroelectrics** exhibit spontaneous polarization, that is, polarization in the absence of an electric field. They are the dielectric analogue of ferromagnetic materials, which may display permanent magnetic behavior. There must exist in ferroelectric materials permanent electric dipoles, the origin of which is explained for barium titanate, one of the most common ferroelectrics. The spontaneous polarization is a consequence of the positioning of the  $\text{Ba}^{2+}$ ,  $\text{Ti}^{4+}$ , and  $\text{O}^{2-}$  ions within the unit cell, as represented in Figure 19.33. The  $\text{Ba}^{2+}$  ions are located at the corners of the unit cell, which is of tetragonal symmetry (a cube that has been elongated slightly in one direction). The dipole moment results from the relative displacements of the  $\text{O}^{2-}$  and  $\text{Ti}^{4+}$  ions from their symmetrical positions as shown in the side view of the unit cell. The  $\text{O}^{2-}$  ions are located near, but slightly below, the centers of each of the six faces, whereas the  $\text{Ti}^{4+}$  ion is displaced upward

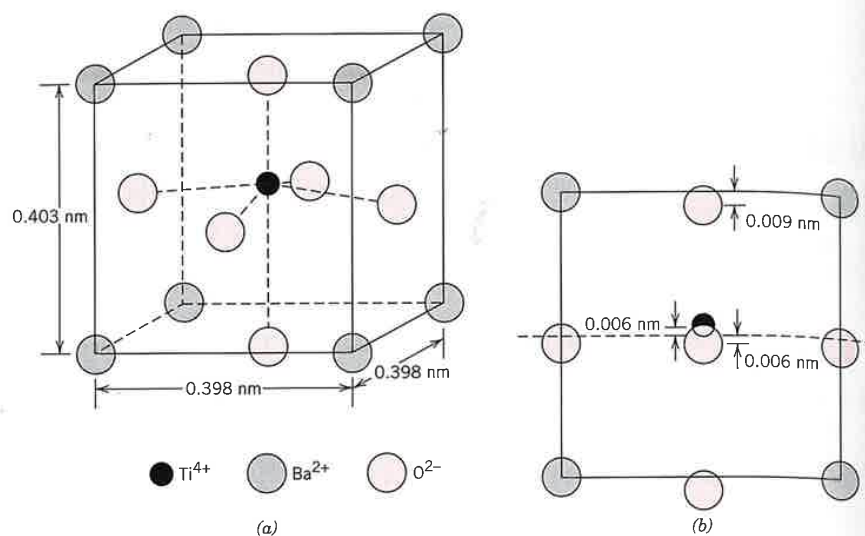


**FIGURE 19.33** A barium titanate ( $\text{BaTiO}_3$ ) unit cell (a) in an isometric projection, and (b) looking at one face, which shows the displacements of  $\text{Ti}^{4+}$  and  $\text{O}^{2-}$  ions from the center of the face.

from the unit cell center. Thus, a permanent ionic dipole moment is associated with each unit cell. However, when barium titanate is heated above its *ferroelectric Curie temperature* [ $120^\circ\text{C}$  ( $250^\circ\text{F}$ )], the unit cell becomes cubic, and all ions assume symmetric positions within the cubic unit cell; the material now has a perovskite crystal structure (Section 13.2), and the ferroelectric behavior ceases.

Spontaneous polarization of this group of materials results as a consequence of interactions between adjacent permanent dipoles wherein they mutually align, all in the same direction. For example, with barium titanate, the relative displacements of  $\text{O}^{2-}$  and  $\text{Ti}^{4+}$  ions are in the same direction for all the unit cells within some volume region of the specimen. Other materials display ferroelectricity; these include Rochelle salt ( $\text{NaKC}_4\text{H}_4\text{O}_6 \cdot 4\text{H}_2\text{O}$ ), potassium dihydrogen phosphate ( $\text{KH}_2\text{PO}_4$ ), potassium niobate ( $\text{KNbO}_3$ ), and lead zirconate–titanate ( $\text{Pb}[\text{ZrO}_3, \text{TiO}_3]$ ). Ferroelectrics have extremely high dielectric constants at relatively low applied field frequencies; for example, at room temperature,  $\epsilon_r$  for barium titanate may be as high as 5000. Consequently, capacitors made from these materials can be significantly smaller than capacitors made from other dielectric materials.

## 19.24 PIEZOELECTRICITY

An unusual property exhibited for a few ceramic materials is piezoelectricity, or, literally, pressure electricity: polarization is induced and an electric field is established across a specimen by the application of external forces. Reversing the sign of an external force (i.e., from tension to compression) reverses the direction of the field. The piezoelectric effect is demonstrated in Figure 19.34.

**Piezoelectric** materials are utilized in transducers, devices that convert electrical energy into mechanical strains, or vice versa. Familiar applications that employ piezoelectrics include phonograph pickups, microphones, ultrasonic generators, strain gages, and sonar detectors. In a phonograph cartridge, as the stylus traverses

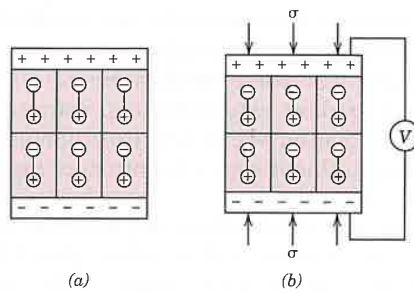


**FIGURE 19.34** (a) Dipoles within a piezoelectric material. (b) A voltage is generated when the material is subjected to a compressive stress. (From *Elements of Materials Science and Engineering*, 6th edition by Lawrence H. Van Vlack; copyright © 1989 by Addison-Wesley Publishing Company. Reprinted by permission.)

the grooves on a record, a pressure variation is imposed on a piezoelectric material located in the cartridge, which is then transformed into an electric signal, and amplified before going to the speaker.

Piezoelectric materials include titanates of barium and lead, lead zirconate ( $\text{PbZrO}_3$ ), ammonium dihydrogen phosphate ( $\text{NH}_4\text{H}_2\text{PO}_4$ ), and quartz. This property is characteristic of materials having complicated crystal structures with a low degree of symmetry. The piezoelectric behavior of a polycrystalline specimen may be improved by heating above its Curie temperature and then cooling to room temperature in a strong electric field.

## SUMMARY

The ease with which a material is capable of transmitting an electric current is expressed in terms of electrical conductivity or its reciprocal, resistivity. On the basis of its conductivity, a solid material may be classified as a metal, a semiconductor, or an insulator.

For most materials, an electric current results from the motion of free electrons, which are accelerated in response to an applied electric field. The number of these free electrons depends on the electron energy band structure of the material. An electron band is just a series of electron states that are closely spaced with respect to energy, and one such band may exist for each electron subshell found in the isolated atom. By "electron energy band structure" is meant the manner in which the outermost bands are arranged relative to one another and then filled with electrons. A distinctive band structure type exists for metals, for semiconductors, and for insulators. An electron becomes free by being excited from a filled state in one band, to an available empty state above the Fermi energy. Relatively small energies are required for electron excitations in metals, giving rise to large numbers of free electrons. Larger energies are required for electron excitations in semiconductors and insulators, which accounts for their lower free electron concentrations and smaller conductivity values.

Free electrons being acted on by an electric field are scattered by imperfections in the crystal lattice. The magnitude of electron mobility is indicative of the frequency of these scattering events. In many materials, the electrical conductivity is proportional to the product of the electron concentration and the mobility.

For metallic materials, electrical resistivity increases with temperature, impurity content, and plastic deformation. The contribution of each to the total resistivity is additive.

Semiconductors may be either elements (Si and Ge) or covalently bonded compounds. With these materials, in addition to free electrons, holes (missing electrons in the valence band) may also participate in the conduction process. On

the basis of electrical behavior, semiconductors are classified as either intrinsic or extrinsic. For intrinsic behavior, the electrical properties are inherent to the pure material, and electron and hole concentrations are equal; electrical behavior is dictated by impurities for extrinsic semiconductors. Extrinsic semiconductors may be either  $n$ - or  $p$ -type depending on whether electrons or holes, respectively, are the predominant charge carriers. Donor impurities introduce excess electrons; acceptor impurities, excess holes.

The electrical conductivity of semiconducting materials is particularly sensitive to impurity type and content, as well as to temperature. The addition of even minute concentrations of some impurities enhances the conductivity drastically. Furthermore, with rising temperature, intrinsic conductivity experiences an exponential increase. Extrinsic conductivity may also increase with temperature.

A number of semiconducting devices employ the unique electrical characteristics of these materials to perform specific electronic functions. Included are the  $p$ - $n$  rectifying junction, and junction and MOSFET transistors. Transistors are used for amplification of electrical signals, as well as for switching devices in computer circuits.

Dielectric materials are electrically insulative, yet susceptible to polarization in the presence of an electric field. This polarization phenomenon accounts for the ability of the dielectrics to increase the charge storing capability of capacitors, the efficiency of which is expressed in terms of a dielectric constant. Polarization results from the inducement by, or orientation with the electric field of atomic or molecular dipoles; a dipole is said to exist when there is a net spatial separation of positively and negatively charged entities. Possible polarization types include electronic, ionic, and orientation; not all types need be present in a particular dielectric. For alternating electric fields, whether a specific polarization type contributes to the total polarization and dielectric constant depends on frequency; each polarization mechanism ceases to function when the applied field frequency exceeds its relaxation frequency.

This chapter concluded with brief discussions of two other electrical phenomena. Ferroelectric materials are those that may exhibit polarization spontaneously, that is, in the absence of any external electric field. Finally, piezoelectricity is the phenomenon whereby polarization is induced in a material by the imposition of external forces.

### IMPORTANT TERMS AND CONCEPTS

|                          |                         |                          |
|--------------------------|-------------------------|--------------------------|
| Acceptor state           | Electrical resistance   | Intrinsic semiconductor  |
| Capacitance              | Electron energy band    | Ionic conduction         |
| Conduction band          | Energy band gap         | Junction transistor      |
| Conductivity, electrical | Extrinsic semiconductor | Matthiessen's rule       |
| Dielectric               | Fermi energy            | Metal                    |
| Dielectric constant      | Ferroelectric           | Mobility                 |
| Dielectric displacement  | Forward bias            | MOSFET                   |
| Dielectric strength      | Free electron           | Ohm's law                |
| Diode                    | Hall effect             | Permittivity             |
| Dipole, electric         | Hole                    | Piezoelectric            |
| Donor state              | Insulator               | Polarization             |
| Doping                   | Integrated circuit      | Polarization, electronic |

Polarization, ionic  
Polarization, orientation  
Rectifying junction

Relaxation frequency  
Resistivity, electrical  
Reverse bias

Semiconductor  
Valence band

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## QUESTIONS AND PROBLEMS

- 19.1 (a)** Compute the electrical conductivity of a 5.1-mm (0.2-in.) diameter cylindrical silicon specimen 51 mm (2 in.) long in which a current of 0.1 A passes in an axial direction. A voltage of 12.5 V is measured across two probes that are separated by 38 mm (1.5 in.). **(b)** Compute the resistance over the entire 51 mm (2 in.) of the specimen.
- 19.2** A copper wire 100 m long must experience a voltage drop of less than 1.5 V when a current of 2.5 A passes through it. Using the data in Table 19.1, compute the minimum diameter of the wire.
- 19.3** An aluminum wire 4 mm in diameter is to offer a resistance of no more than 2.5  $\Omega$ . Using the data in Table 19.1, compute the maximum wire length.
- 19.4** Demonstrate that the two Ohm's law expressions, Equations 19.1 and 19.5, are equivalent.
- 19.5 (a)** Using the data in Table 19.1, compute the resistance of a copper wire 3 mm (0.12

- in.) in diameter and 2 m (78.7 in.) long. **(b)** What would be the current flow if the potential drop across the ends of the wire is 0.05 V? **(c)** What is the current density? **(d)** What is the magnitude of the electric field across the ends of the wire?
- 19.6** What is the distinction between electronic and ionic conduction?
- 19.7** How does the electron structure of an isolated atom differ from that of a solid material?
- 19.8** In terms of electron energy band structure, discuss reasons for the difference in electrical conductivity between metals, semiconductors, and insulators.
- 19.9** If a metallic material is cooled through its melting temperature at an extremely rapid rate, it will form a noncrystalline solid (i.e., a metallic glass). Will the electrical conductivity of the noncrystalline metal be greater or less than its crystalline counterpart? Why?
- 19.10** Briefly tell what is meant by the drift velocity and mobility of a free electron.
- 19.11** **(a)** Calculate the drift velocity of electrons in germanium at room temperature and when the magnitude of the electric field is 1000 V/m. **(b)** Under these circumstances, how long does it take an electron to traverse a 25 mm (1 in.) length of crystal?
- 19.12** An *n*-type semiconductor is known to have an electron concentration of  $3 \times 10^{18} \text{ m}^{-3}$ . If the electron drift velocity is 100 m/s in an electric field of 500 V/m, calculate the conductivity of this material.
- 19.13** At room temperature the electrical conductivity and the electron mobility for copper are  $6.0 \times 10^7 (\Omega\text{-m})^{-1}$  and  $0.0030 \text{ m}^2/\text{V}\cdot\text{s}$ , respectively. **(a)** Compute the number of free electrons per cubic meter for copper at room temperature. **(b)** What is the number of free electrons per copper atom? Assume a density of  $8.9 \text{ g/cm}^3$ .
- 19.14** **(a)** Calculate the number of free electrons per cubic meter for gold assuming that there are 1.5 free electrons per gold atom. The electrical conductivity and density for Au are  $4.3 \times 10^7 (\Omega\text{-m})^{-1}$  and  $19.32 \text{ g/cm}^3$ , respectively. **(b)** Now compute the electron mobility for Au.
- 19.15** From Figure 19.35, estimate the value of *A* in Equation 19.11 for zinc as an impurity in copper–zinc alloys.

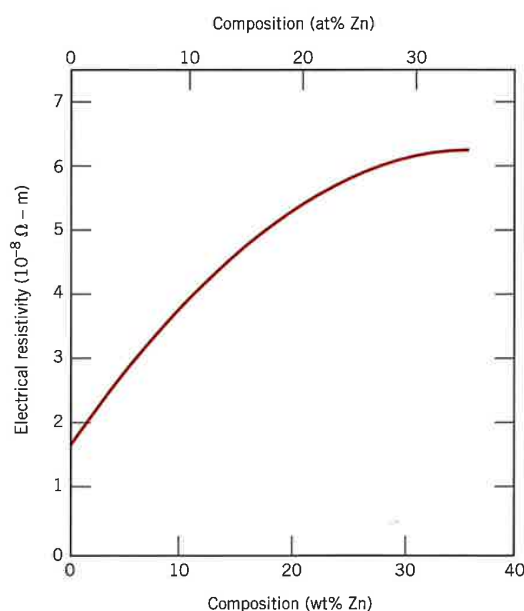


**FIGURE 19.35** Room-temperature electrical resistivity versus composition for copper–zinc alloys. (Adapted from *Metals Handbook: Properties and Selection: Nonferrous Alloys and Pure Metals*, Vol. 2, 9th edition, H. Baker, Managing Editor, American Society for Metals, 1979, p. 315.)

**19.16 (a)** Using the data in Figure 19.8, determine the values of  $\rho_0$  and  $a$  from Equation 19.10 for pure copper. Take the temperature  $T$  to be in degrees Celsius. **(b)** Determine the value of  $A$  in Equation 19.11 for nickel as an impurity in copper, using the data in Figure 19.8. **(c)** Using the results of parts a and b, estimate the electrical resistivity of copper containing 1.75 at% Ni at 100°C.

**19.17** Determine the electrical conductivity of a Cu-Ni alloy that has a yield strength of 125 MPa (18,000 psi). You will find Figure 7.16b helpful.

**19.18** Tin bronze has a composition of 92 wt% Cu and 8 wt% Sn, and consists of two phases at room temperature: an  $\alpha$  phase, which is copper containing a very small amount of tin in solid solution, and an  $\epsilon$  phase, which consists of approximately 37 wt% Sn. Compute the room temperature conductivity of this alloy given the following data:

| Phase      | Electrical Resistivity ( $\Omega\text{-m}$ ) | Density ( $\text{g/cm}^3$ ) |
|------------|----------------------------------------------|-----------------------------|
| $\alpha$   | $1.88 \times 10^{-8}$                        | 8.94                        |
| $\epsilon$ | $5.32 \times 10^{-7}$                        | 8.25                        |

**19.19** The room-temperature electrical resistivities of pure lead and pure tin are  $2.06 \times 10^{-7}$  and  $1.11 \times 10^{-7} \Omega\text{-m}$ , respectively.

**(a)** Make a schematic graph of the room-temperature electrical resistivity versus composition for all compositions between pure lead and pure tin.

**(b)** On this same graph schematically plot electrical resistivity versus composition at 150°C.

**(c)** Explain the shapes of these two curves, as well as any differences between them.

**19.20** A cylindrical metal wire 2 mm (0.08 in.) in diameter is required to carry a current of 10 A with a minimum of 0.03 V drop per foot (300 mm) of wire. Which of the metals and alloys listed in Table 19.1 are possible candidates?

**19.21 (a)** Compute the number of free electrons and holes that exist in intrinsic germanium at room temperature, using the data in Table

19.2. **(b)** Now calculate the number of free electrons per atom for germanium and silicon (Example Problem 19.1). **(c)** Explain the difference. You will need the densities for Ge and Si, which are 5.32 and 2.33 g/cm<sup>3</sup>, respectively.

**19.22** For intrinsic semiconductors, both electron and hole concentrations depend on temperature as follows:

$$n, p \propto \exp\left(-\frac{E_g}{2kT}\right) \quad (19.38)$$

or, taking natural logarithms,

$$\ln n, \ln p \propto -\frac{E_g}{2kT}$$

Thus, a plot of the intrinsic  $\ln n$  (or  $\ln p$ ) versus  $1/T$  (K)<sup>-1</sup> should be linear and yield a slope of  $-E_g/2k$ . Using this information and Figure 19.16, determine the band gap energy for silicon. Compare this value with the one given in Table 19.2.

**19.23** Define the following terms as they pertain to semiconducting materials: intrinsic, extrinsic, compound, elemental. Now provide an example of each.

**19.24** Is it possible for compound semiconductors to exhibit intrinsic behavior? Explain your answer.

**19.25** For each of the following pairs of semiconductors, decide which will have the smaller band gap energy  $E_g$  and then cite the reason for your choice: **(a)** ZnS and CdSe, **(b)** Si and C (diamond), **(c)** Al<sub>2</sub>O<sub>3</sub> and ZnTe, **(d)** InSb and ZnSe, and **(e)** GaAs and AlP.

**19.26 (a)** In your own words, explain how donor impurities in semiconductors give rise to free electrons in numbers in excess of those generated by valence band-conduction band excitations. **(b)** Also explain how acceptor impurities give rise to holes in numbers in excess of those generated by valence band-conduction band excitations.

**19.27 (a)** Explain why no hole is generated by the electron excitation involving a donor impurity atom. **(b)** Explain why no free electron is generated by the electron excitation involving an acceptor impurity atom.

- 19.28** Will each of the following elements act as a donor or an acceptor when added to the indicated semiconducting material? Assume that the impurity elements are substitutional.

| Impurity | Semiconductor |
|----------|---------------|
| N        | Si            |
| B        | Ge            |
| Zn       | GaAs          |
| S        | InSb          |
| In       | CdS           |
| As       | ZnTe          |

- 19.29** (a) At approximately what position is the Fermi energy for an intrinsic semiconductor? (b) At approximately what position is the Fermi energy for an  $n$ -type semiconductor? (c) Make a schematic plot of Fermi energy versus temperature for an  $n$ -type semiconductor up to a temperature at which it becomes intrinsic. Also note on this plot energy positions corresponding to the top of the valence band and the bottom of the conduction band.
- 19.30** (a) The room-temperature electrical conductivity of a silicon specimen is  $10^3 (\Omega\cdot\text{m})^{-1}$ . The hole concentration is known to be  $1.0 \times 10^{23} \text{ m}^{-3}$ . Using the electron and hole mobilities for silicon in Table 19.2, compute the electron concentration. (b) On the basis of the result in part a, is the specimen intrinsic,  $n$ -type extrinsic, or  $p$ -type extrinsic? Why?
- 19.31** Using the data in Table 19.2, compute the electron and hole concentrations for intrinsic InSb at room temperature.
- 19.32** Germanium to which  $5 \times 10^{22} \text{ m}^{-3}$  Sb atoms have been added is an extrinsic semiconductor at room temperature, and virtually all the Sb atoms may be thought of as being ionized (i.e., one charge carrier exists for each Sb atom). (a) Is this material  $n$ -type or  $p$ -type? (b) Calculate the electrical conductivity of this material, assuming electron and hole mobilities of 0.1 and  $0.05 \text{ m}^2/\text{V}\cdot\text{s}$ , respectively.
- 19.33** The following electrical characteristics have been determined for both intrinsic and  $p$ -type extrinsic indium phosphide (InP) at room temperature:

|                           | $\sigma (\Omega\cdot\text{m})^{-1}$ | $n (\text{m}^{-3})$  | $p (\text{m}^{-3})$  |
|---------------------------|-------------------------------------|----------------------|----------------------|
| Intrinsic                 | $2.5 \times 10^{-6}$                | $3.0 \times 10^{13}$ | $3.0 \times 10^{13}$ |
| Extrinsic<br>( $n$ -type) | $3.6 \times 10^{-5}$                | $4.5 \times 10^{14}$ | $2.0 \times 10^{12}$ |

Calculate electron and hole mobilities.

- 19.34** Compare the temperature dependence of the conductivity for metals and intrinsic semiconductors. Briefly explain the difference in behavior.
- 19.35** Using the data in Table 19.2, estimate the electrical conductivity of intrinsic GaAs at  $150^\circ\text{C}$  ( $423 \text{ K}$ ).
- 19.36** Briefly explain the presence of the factor 2 in the denominator of the second term on the right-hand side of Equation 19.19.
- 19.37** Using the data in Table 19.2, estimate the temperature at which the electrical conductivity of intrinsic GaAs is  $4 \times 10^{-4} (\Omega\cdot\text{m})^{-1}$ .
- 19.38** The intrinsic electrical conductivities of a semiconductor at 20 and  $100^\circ\text{C}$  (293 and 373 K) are 1.0 and  $500 (\Omega\cdot\text{m})^{-1}$ , respectively. Determine the approximate band gap energy for this material.
- 19.39** Below, the intrinsic electrical conductivity of a semiconductor at two temperatures is tabulated:

| $T (\text{K})$ | $\sigma (\Omega\cdot\text{m})^{-1}$ |
|----------------|-------------------------------------|
| 450            | 0.12                                |
| 550            | 2.25                                |

- (a) Determine the band gap energy (in eV) for this material.
- (b) Estimate the electrical conductivity at 300 K ( $27^\circ\text{C}$ ).
- 19.40** At room temperature, the temperature dependence of electron and hole mobilities for intrinsic germanium is found to be proportional to  $T^{-3/2}$  for  $T$  in Kelvins; thus, a more accurate form of Equation 19.18 is as follows:

$$\sigma = C'' T^{-3/2} \exp\left(-\frac{E_g}{2kT}\right) \quad (19.39a)$$

or, in logarithmic form

$$\ln \sigma = \ln C'' - \frac{3}{2} \ln T - \frac{E_g}{2kT} \quad (19.39b)$$

where  $C'$  is a temperature-independent constant.

(a) Calculate the intrinsic electrical conductivity for intrinsic germanium at  $150^\circ\text{C}$ , and compare this value with that obtained in Example Problem 19.3, which uses Equation 19.18.

(b) Now compute the number of free electrons and holes for intrinsic germanium at  $150^\circ\text{C}$  assuming this  $T^{-3/2}$  dependence of electron and hole mobilities.

**19.41** Estimate the temperature at which GaAs has an electrical conductivity of  $3.7 \times 10^{-3} (\Omega\text{-m})^{-1}$  assuming the temperature dependence for  $\sigma$  of Equation 19.39a. The data shown in Table 19.2 might prove helpful.

**19.42** The slope of the extrinsic portions of the curves in Figure 19.16 is related to the position of the acceptor level in the band gap (Figure 19.14). Write an expression for the dependence of  $p$  on the position of this level.

**19.43** We noted in Section 13.5 (Figure 13.21) that in FeO (wüstite), the iron ions can exist in both  $\text{Fe}^{2+}$  and  $\text{Fe}^{3+}$  states. The number of each of these ion types depends on temperature and the ambient oxygen pressure. Furthermore, it was also noted that in order to retain electroneutrality, one  $\text{Fe}^{2+}$  vacancy will be created for every two  $\text{Fe}^{3+}$  ions that are formed; consequently, in order to reflect the existence of these vacancies the formula for wüstite is often represented as  $\text{Fe}_{(1-x)}\text{O}$  where  $x$  is some small fraction less than unity.

In this nonstoichiometric  $\text{Fe}_{(1-x)}\text{O}$  material, conduction is electronic, and, in fact, it behaves as a  $p$ -type semiconductor. That is, the  $\text{Fe}^{3+}$  ions act as electron acceptors, and it is relatively easy to excite an electron from the valence band into an  $\text{Fe}^{3+}$  acceptor state, with the formation of a hole. Determine the electrical conductivity of a specimen of wüstite that has a hole mobility of  $1.0 \times 10^{-5} \text{ m}^2/\text{V}\cdot\text{s}$  and for which the value of  $x$  is 0.060. Assume that the acceptor states are saturated (i.e., one hole exists for every  $\text{Fe}^{3+}$  ion). Wüstite has the sodium chloride crystal structure with a unit cell edge length of 0.437 nm.

**19.44** Some hypothetical metal is known to have an electrical resistivity of  $4 \times 10^{-8} (\Omega\text{-m})$ . Through a specimen of this metal that is 25 mm thick is passed a current of 30 A; when a magnetic field of 0.75 tesla is simultaneously imposed in a direction perpendicular to that of the current, a Hall voltage of  $-1.26 \times 10^{-7} \text{ V}$  is measured. Compute (a) the electron mobility for this metal, and (b) the number of free electrons per cubic meter.

**19.45** Some metal alloy is known to have electrical conductivity and electron mobility values of  $1.5 \times 10^7 (\Omega\text{-m})^{-1}$  and  $0.0020 \text{ m}^2/\text{V}\cdot\text{s}$ , respectively. Through a specimen of this alloy that is 35 mm thick is passed a current of 45 A. What magnetic field would need to be imposed to yield a Hall voltage of  $-1.0 \times 10^{-7} \text{ V}$ ?

**19.46** Briefly describe electron and hole motions in a  $p$ - $n$  junction for forward and reverse biases; then explain how these lead to rectification.

**19.47** How is the energy in the reaction described by Equation 19.24 dissipated?

**19.48** What are the two functions that a transistor may perform in an electronic circuit?

**19.49** Would you expect increasing temperature to influence the operation of  $p$ - $n$  junction rectifiers and transistors? Explain.

**19.50** Cite the differences in operation and application for junction transistors and MOSFETs.

**19.51** At temperatures between  $775^\circ\text{C}$  (1048 K) and  $1100^\circ\text{C}$  (1373 K), the activation energy and preexponential for the diffusion coefficient of  $\text{Fe}^{2+}$  in FeO are 102,000 J/mol and  $7.3 \times 10^{-8} \text{ m}^2/\text{s}$ , respectively. Compute the mobility for an  $\text{Fe}^{2+}$  ion at  $1000^\circ\text{C}$  (1273 K).

**19.52** A parallel-plate capacitor using a dielectric material having an  $\epsilon_r$  of 2.5 has a plate spacing of 1 mm (0.04 in.). If another material having a dielectric constant of 4.0 is used and the capacitance is to be unchanged, what must be the new spacing between the plates?

**19.53** A parallel-plate capacitor with dimensions of 100 mm by 25 mm and a plate separation of 3 mm must have a minimum capacitance of 38 pF ( $3.8 \times 10^{-11} \text{ F}$ ) when an ac potential of 500 V is applied at a frequency

of 1 MHz. Which of those materials listed in Table 19.4 are possible candidates? Why?

- 19.54** Consider a parallel-plate capacitor having an area of  $2500 \text{ mm}^2$  and a plate separation of 2 mm, and with a material of dielectric constant 4.0 positioned between the plates. **(a)** What is the capacitance of this capacitor? **(b)** Compute the electric field that must be applied for a charge of  $8.0 \times 10^{-9} \text{ C}$  to be stored on each plate.

- 19.55** In your own words, explain the mechanism by which charge storing capacity is increased by the insertion of a dielectric material within the plates of a capacitor.

- 19.56** For NaCl, the ionic radii for  $\text{Na}^+$  and  $\text{Cl}^-$  ions are 0.102 and 0.181 nm, respectively. If an externally applied electric field produces a 5% expansion of the lattice, compute the dipole moment for each  $\text{Na}^+-\text{Cl}^-$  pair. Assume that this material is completely unpolarized in the absence of an electric field.

- 19.57** The polarization  $P$  of a dielectric material positioned within a parallel-plate capacitor is to be  $1.0 \times 10^{-6} \text{ C/m}^2$ .

**(a)** What must be the dielectric constant if an electric field of  $5 \times 10^4 \text{ V/m}$  is applied?  
**(b)** What will be the dielectric displacement  $D$ ?

- 19.58** A charge of  $3.5 \times 10^{-11} \text{ C}$  is to be stored on each plate of a parallel-plate capacitor having an area of  $160 \text{ mm}^2$  ( $0.25 \text{ in.}^2$ ) and a plate separation of 3.5 mm ( $0.14 \text{ in.}$ ).

**(a)** What voltage is required if a material having a dielectric constant of 5.0 is positioned within the plates?  
**(b)** What voltage would be required if a vacuum is used?  
**(c)** What are the capacitances for parts a and b?  
**(d)** Compute the dielectric displacement for part a.  
**(e)** Compute the polarization for part a.

- 19.59** **(a)** For each of the three types of polarization, briefly describe the mechanism by which dipoles are induced and/or oriented by the action of an applied electric field. **(b)** For solid lead titanate ( $\text{PbTiO}_3$ ), gaseous

neon, diamond, solid KCl, and liquid  $\text{NH}_3$  what kind(s) of polarization is (are) possible? Why?

- 19.60** The dielectric constant for a soda-lime glass measured at very high frequencies (on the order of  $10^{15} \text{ Hz}$ ) is approximately 2.3. What fraction of the dielectric constant at relatively low frequencies (1 MHz) is attributed to ionic polarization? Neglect any orientation polarization contributions.

- 19.61** **(a)** Compute the magnitude of the dipole moment associated with each unit cell of  $\text{BaTiO}_3$ , as illustrated in Figure 19.33.

**(b)** Compute the maximum polarization that is possible for this material.

- 19.62** Briefly explain why the ferroelectric behavior of  $\text{BaTiO}_3$  ceases above its ferroelectric Curie temperature.

- 19.63** Would you expect the physical dimensions of a piezoelectric material such as  $\text{BaTiO}_3$  to change when it is subjected to an electric field? Why or why not?

### Design Problems

- 19.D1** A 95 wt% Pt-5 wt% Ni alloy is known to have an electrical resistivity of  $2.35 \times 10^{-7} \Omega\text{-m}$  at room temperature ( $25^\circ\text{C}$ ). Calculate the composition of a platinum-nickel alloy that gives a room-temperature resistivity of  $1.75 \times 10^{-7} \Omega\text{-m}$ . The room-temperature resistivity of pure platinum may be determined from the data in Table 19.1; assume that platinum and nickel form a solid solution.

- 19.D2** Using information contained in Figures 19.8 and 19.35, determine the electrical conductivity of an 80 wt% Cu-20 wt% Zn alloy at  $-150^\circ\text{C}$  ( $-240^\circ\text{F}$ ).

- 19.D3** Is it possible to alloy copper with nickel to achieve a minimum tensile strength of 375 MPa (54,400 psi) and yet maintain an electrical conductivity of  $2.5 \times 10^6 (\Omega\text{-m})^{-1}$ ? If not, why? If so, what concentration of nickel is required? You may want to consult Figure 7.16a.

- 19.D4** Specify an acceptor impurity type and concentration (in weight percent) that will pro-

duce a *p*-type silicon material having a room temperature electrical conductivity of  $50 (\Omega\text{-m})^{-1}$ . Use intrinsic electron and hole mobilities, and assume that the acceptor impurities are saturated.

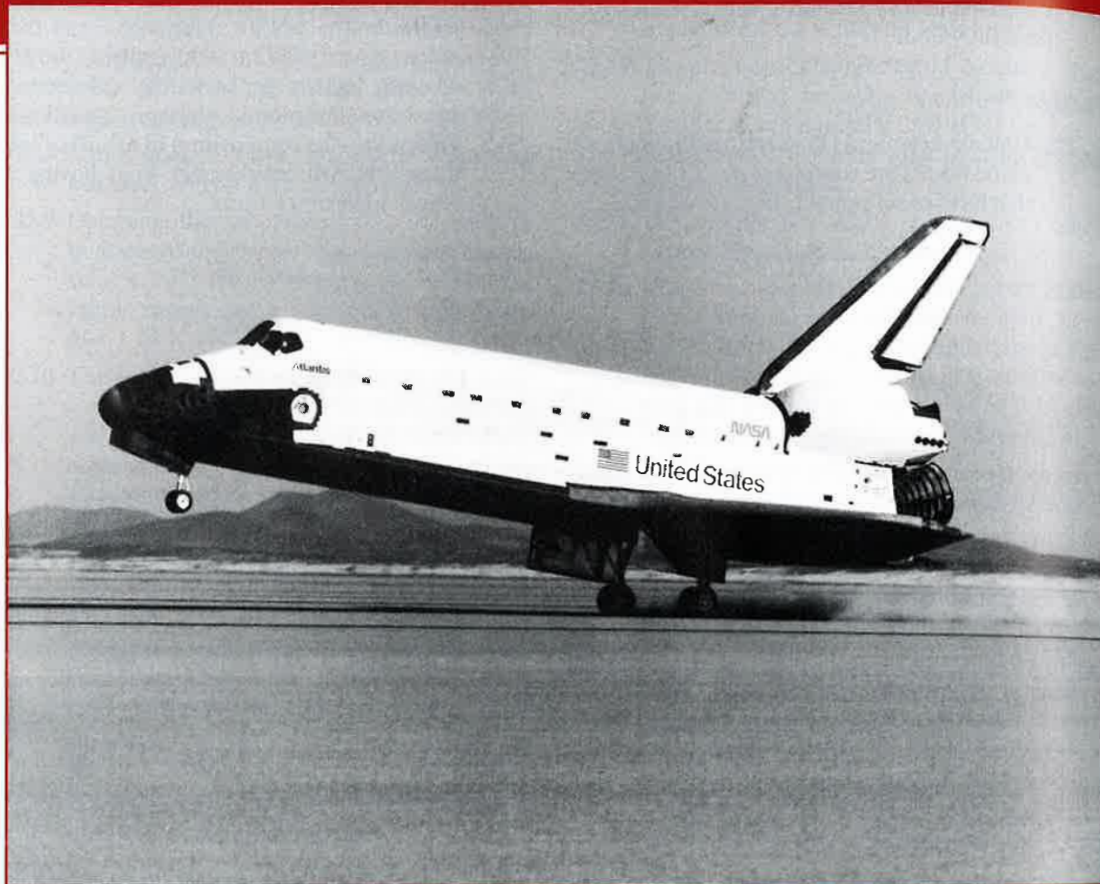
- 19.D5** One integrated circuit design calls for diffusing boron into very high purity silicon at an elevated temperature. It is necessary that at a distance  $0.2 \mu\text{m}$  from the surface of the silicon wafer, the room-temperature electrical conductivity be  $1.2 \times 10^4 (\Omega\text{-m})^{-1}$ . The concentration of B at the surface of the Si is maintained at a constant level of  $1.0 \times 10^{25} \text{m}^{-3}$ ; furthermore, it is assumed that the concentration of B in the original Si material is negligible, and that at room temperature the boron atoms are saturated. Specify the temperature at which this diffusion heat treatment is to take place if the treatment time is to be one hour. The diffusion coefficient for the diffusion of B in Si is a function of temperature as

$$D(\text{m}^2/\text{s}) = 2.4 \times 10^{-4} \exp\left(-\frac{347 \text{ kJ/mol}}{RT}\right)$$

- 19.D6** Problem 19.43 noted that FeO (wüstite) may behave as a semiconductor by virtue of the transformation of  $\text{Fe}^{2+}$  to  $\text{Fe}^{3+}$  and the creation of  $\text{Fe}^{2+}$  vacancies; the maintenance of electroneutrality requires that for every two  $\text{Fe}^{3+}$  ions, one vacancy is formed. The existence of these vacancies is reflected in the chemical formula of this nonstoichiometric wüstite as  $\text{Fe}_{(1-x)}\text{O}$ , where  $x$  is a small number having a value less than unity. The degree of nonstoichiometry (i.e., the value of  $x$ ) may be varied by changing temperature and oxygen partial pressure. Compute the value of  $x$  that is required to produce an  $\text{Fe}_{(1-x)}\text{O}$  material having a *p*-type electrical conductivity of  $2000 (\Omega\text{-m})^{-1}$ ; assume that the hole mobility is  $1.0 \times 10^{-5} \text{m}^2/\text{V-s}$ , and that the acceptor states are saturated.

- 19.D7** The base semiconducting material used in virtually all of our modern integrated circuits is silicon. However, silicon has some limitations and restrictions. Write an essay comparing the properties and applications (and/or potential applications) of silicon and gallium arsenide.

## Chapter 23 / Materials Selection and Design Considerations



**S**hown in this photograph is the landing of the *Atlantis* Space Shuttle Orbiter. This chapter discusses the materials that are used for its outer airframe's thermal protection system. [Photograph courtesy the National Aeronautics and Space Administration (NASA).]

### Why Study *Materials Selection and Design Considerations*?

Perhaps one of the most important tasks that an engineer may be called upon to perform is that of materials selection with regard to component design. Inappropriate or improper decisions can be disastrous from both economic and safety perspectives. Therefore, it is essential that the engineering stu-

dent become familiar with and versed in the procedures and protocols that are normally employed in this process. This chapter discusses materials selection issues in several contexts and from various perspectives.

## Learning Objectives

After careful study of this chapter you should be able to do the following:

1. Describe how the strength performance index for a solid cylindrical shaft is determined.
2. Describe the manner in which materials selection charts are employed in the materials selection process.
3. Briefly describe the steps that are used to ascertain whether or not a particular metal alloy is suitable for use in an automobile valve spring.
4. List and briefly explain six biocompatibility considerations relative to materials that are employed in artificial hip replacements.
5. Name the four components found in the artificial hip replacement, and, for each, list its specific material requirements.
6. (a) Name the three components of the thermal protection system for the Space Shuttle Orbiter. (b) Describe the composition, microstructure, and general properties of the ceramic tiles that are used on the Space Shuttle Orbiter.
7. Describe the components and their functions for an integrated circuit leadframe.
8. (a) Name and briefly describe the three processes that are carried out during integrated circuit packaging. (b) Note property requirements for each of these processes, and, in addition, cite at least two materials that are employed.

## 23.1 INTRODUCTION

Virtually the entire book to this point has dealt with the properties of various materials, how the properties of a specific material are dependent on its structure, and, in many cases, how structure may be fashioned by the processing technique that is employed during production. Of late, there has been a trend to emphasize the element of *design* in engineering pedagogy. To a materials scientist or materials engineer, design can be taken in several contexts. First of all, it can mean designing new materials having unique property combinations. Alternatively, design can involve selecting a new material having a better combination of characteristics for a specific application; choice of material cannot be made without consideration of necessary manufacturing processes (e.g., forming, welding, etc.), which also rely on material properties. Or, finally, design might mean developing a process for producing a material having better properties.

One particularly effective technique for teaching design principles is the case study method. With this technique, the solutions to real-life engineering problems are carefully analyzed in detail so that the student may observe the procedures and rationale that are involved in the decision-making process. We have chosen to perform five case studies which draw upon principles that were introduced in previous chapters. These five studies involve materials that are used for the following: (1) a torsionally stressed cylindrical shaft; (2) an automobile valve spring; (3) the artificial total hip replacement; (4) the thermal protection system on the Space Shuttle Orbiter; and (5) integrated circuit packages.

## MATERIALS SELECTION FOR A TORSIONALLY STRESSED CYLINDRICAL SHAFT

We begin by addressing the design process from the perspective of materials selection; that is, for some application, selecting a material having a desirable or optimum property or combination of properties. Elements of this materials selection process involve deciding on the constraints of the problem, and, from these, establishing criteria that can be used in materials selection to maximize performance.

The component or structural element we have chosen to discuss is a solid

cylindrical shaft that is subjected to a torsional stress. Strength of the shaft will be considered in detail, and criteria will be developed for the maximization of strength with respect to both minimum material mass and minimum cost. Other parameters and properties that may be important in this selection process are also discussed briefly.

## 23.2 STRENGTH

For this portion of the problem, we will establish a criterion for selection of light and strong materials for this shaft. It will be assumed that the twisting moment and length of the shaft are **specified**, whereas the radius (or cross-sectional area) may be varied. We develop an expression for the mass of material required in terms of twisting moment, shaft length, and density and strength of the material. Using this expression, it will be possible to evaluate the performance—that is, maximize the strength of this torsionally stressed shaft with respect to mass and, in addition, relative to material cost.

Consider the cylindrical shaft of length  $L$  and radius  $r$ , as shown in Figure 23.1. The application of twisting moment (or torque),  $M_t$ , produces an angle of twist  $\phi$ . Shear stress  $\tau$  at radius  $r$  is defined by the equation

$$\tau = \frac{M_t r}{J} \quad (23.1)$$

Here,  $J$  is the polar moment of inertia, which for a solid cylinder is

$$J = \frac{\pi r^4}{2} \quad (23.2)$$

Thus,

$$\tau = \frac{2M_t}{\pi r^3} \quad (23.3)$$

A safe design calls for the shaft to be able to sustain some twisting moment without fracture. In order to establish a materials selection criterion for a light and strong material, we replace the shear stress in Equation 23.3 with the shear strength of the material  $\tau_f$  divided by a factor of safety  $N$ , as

$$\frac{\tau_f}{N} = \frac{2M_t}{\pi r^3} \quad (23.4)$$

It is now necessary to take into consideration material mass. The mass  $m$  of any given quantity of material is just the product of its density ( $\rho$ ) and volume. Since the volume of a cylinder is just  $\pi r^2 L$ , then

$$m = \pi r^2 L \rho \quad (23.5)$$

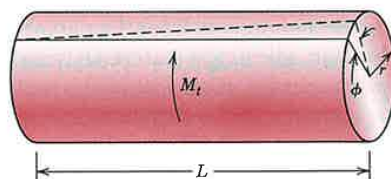


**FIGURE 23.1** A solid cylindrical shaft that experiences an angle of twist  $\phi$  in response to the application of a twisting moment  $M_t$ .

Or, the radius of the shaft in terms of its mass is just

$$r = \sqrt{\frac{m}{\pi L \rho}} \quad (23.6)$$

Substitution of this  $r$  expression into Equation 23.4 leads to

$$\begin{aligned} \frac{\tau_f}{N} &= \frac{2M_t}{\pi \left( \sqrt{\frac{m}{\pi L \rho}} \right)^3} \\ &= 2M_t \sqrt{\frac{\pi L^3 \rho^3}{m^3}} \end{aligned} \quad (23.7)$$

Solving this expression for the mass  $m$  yields

$$m = (2NM_t)^{2/3} (\pi^{1/3} L) \left( \frac{\rho}{\tau_f^{2/3}} \right) \quad (23.8)$$

The parameters on the right-hand side of this equation are grouped into three sets of parentheses. Those contained within the first set (i.e.,  $N$  and  $M_t$ ) relate to the safe functioning of the shaft. Within the second parentheses is  $L$ , a geometric parameter. And, finally, the material properties of density and strength are contained within the last set.

The upshot of Equation 23.8 is that the best materials to be used for a light shaft which can safely sustain a specified twisting moment are those having low  $\rho/\tau_f^{2/3}$  ratios. In terms of material suitability, it is sometimes preferable to work with what is termed a *performance index*,  $P$ , which is just the reciprocal of this ratio; that is

$$P = \frac{\tau_f^{2/3}}{\rho} \quad (23.9)$$

In this context we want to utilize a material having a large performance index.

At this point it becomes necessary to examine the performance indices of a variety of potential materials. This procedure is expedited by the utilization of what are termed *materials selection charts*.<sup>1</sup> These are plots of the values of one material property versus those of another property. Both axes are scaled logarithmically and usually span about five orders of magnitude, so as to include the properties of virtually all materials. For example, for our problem, the chart of interest is logarithm of strength versus logarithm of density, which is shown in Figure 23.2.<sup>2</sup> It may be noted on this plot that materials of a particular type (e.g., woods, engineering polymers, etc.) cluster together and are enclosed within an envelope delineated with a bold line. Subclasses within these clusters are enclosed using finer lines.

<sup>1</sup> A comprehensive collection of these charts may be found in M. F. Ashby, *Materials Selection in Mechanical Design*, Pergamon Press, Oxford, 1992.

<sup>2</sup> Strength for metals and polymers is taken as yield strength, for ceramics and glasses, compressive strength, for elastomers, tear strength, and for composites, tensile failure strength.

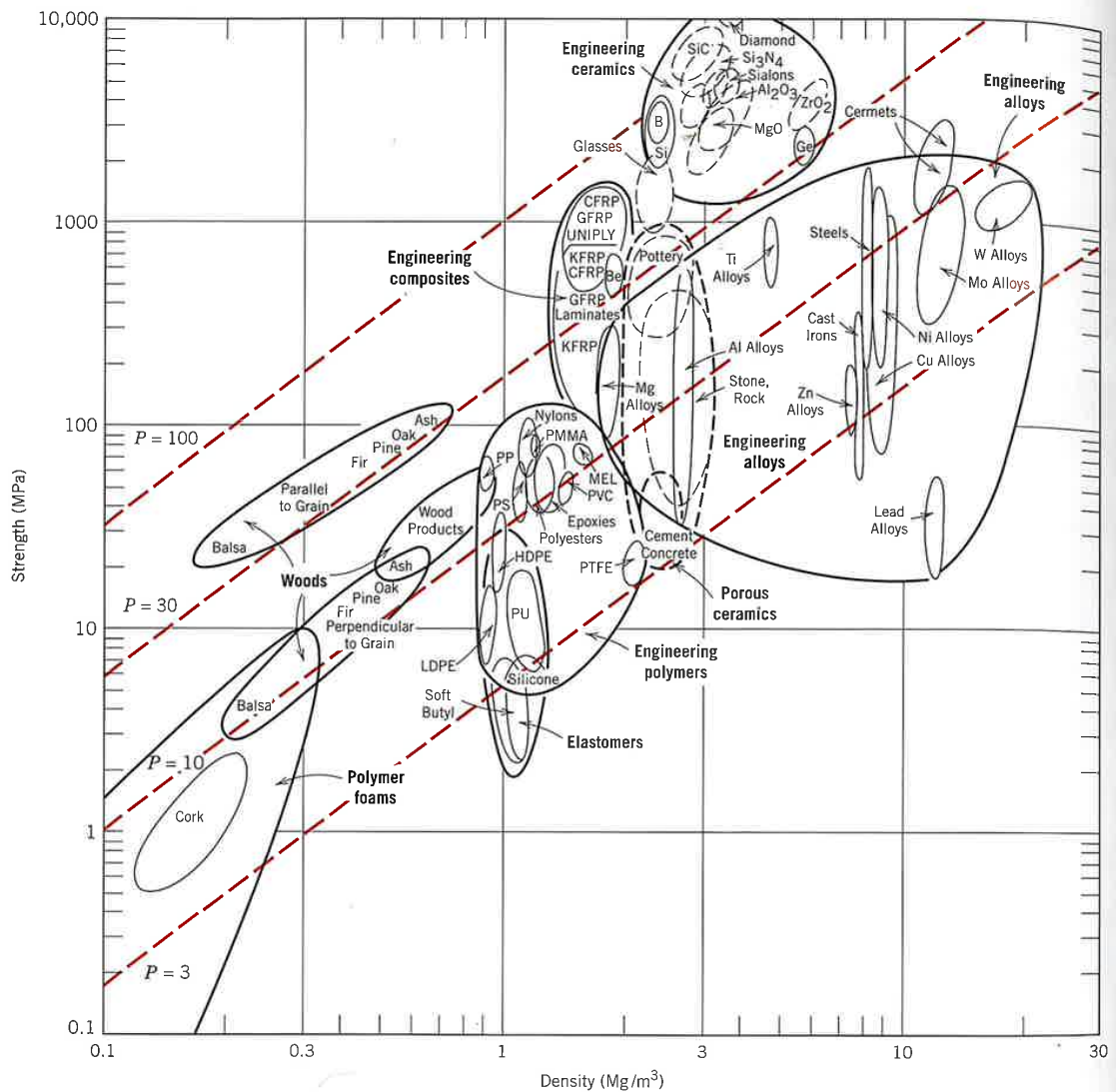


**FIGURE 23.2** Strength versus density materials selection chart. Design guidelines for performance indices of 3, 10, 30, and 100  $(\text{MPa})^{2/3} \text{m}^3/\text{Mg}$  have been constructed, all having a slope of  $\frac{2}{3}$ . (Adapted from M. F. Ashby, *Materials Selection in Mechanical Design*. Copyright © 1992. Reprinted by permission of Butterworth-Heinemann Ltd.)

Now, taking the logarithm of both sides of Equation 23.9 and rearranging yields

$$\log \tau_f = \frac{2}{3} \log \rho + \frac{2}{3} \log P \quad (23.10)$$

This expression tells us that a plot of  $\log \tau_f$  versus  $\log \rho$  will yield a family of straight and parallel lines all having a slope of  $\frac{2}{3}$ ; each line in the family corresponds to a different performance index,  $P$ . These lines are termed *design guidelines*, and four have been included in Figure 23.2 for  $P$  values of 3, 10, 30, and 100  $(\text{MPa})^{2/3} \text{m}^3/\text{Mg}$ . All materials that lie on one of these lines will perform equally well in terms

of strength-per-mass basis; materials whose positions lie above a particular line will have higher performance indices, while those lying below will exhibit poorer performances. For example, a material on the  $P = 30$  line will yield the same strength with one-third the mass as another material that lies along the  $P = 10$  line.

The selection process now involves choosing one of these lines, a “selection line” that includes some subset of these materials; for the sake of argument let us pick  $P = 10 \text{ (MPa)}^{2/3} \text{ m}^3/\text{Mg}$ , which is represented in Figure 23.3. Materials lying

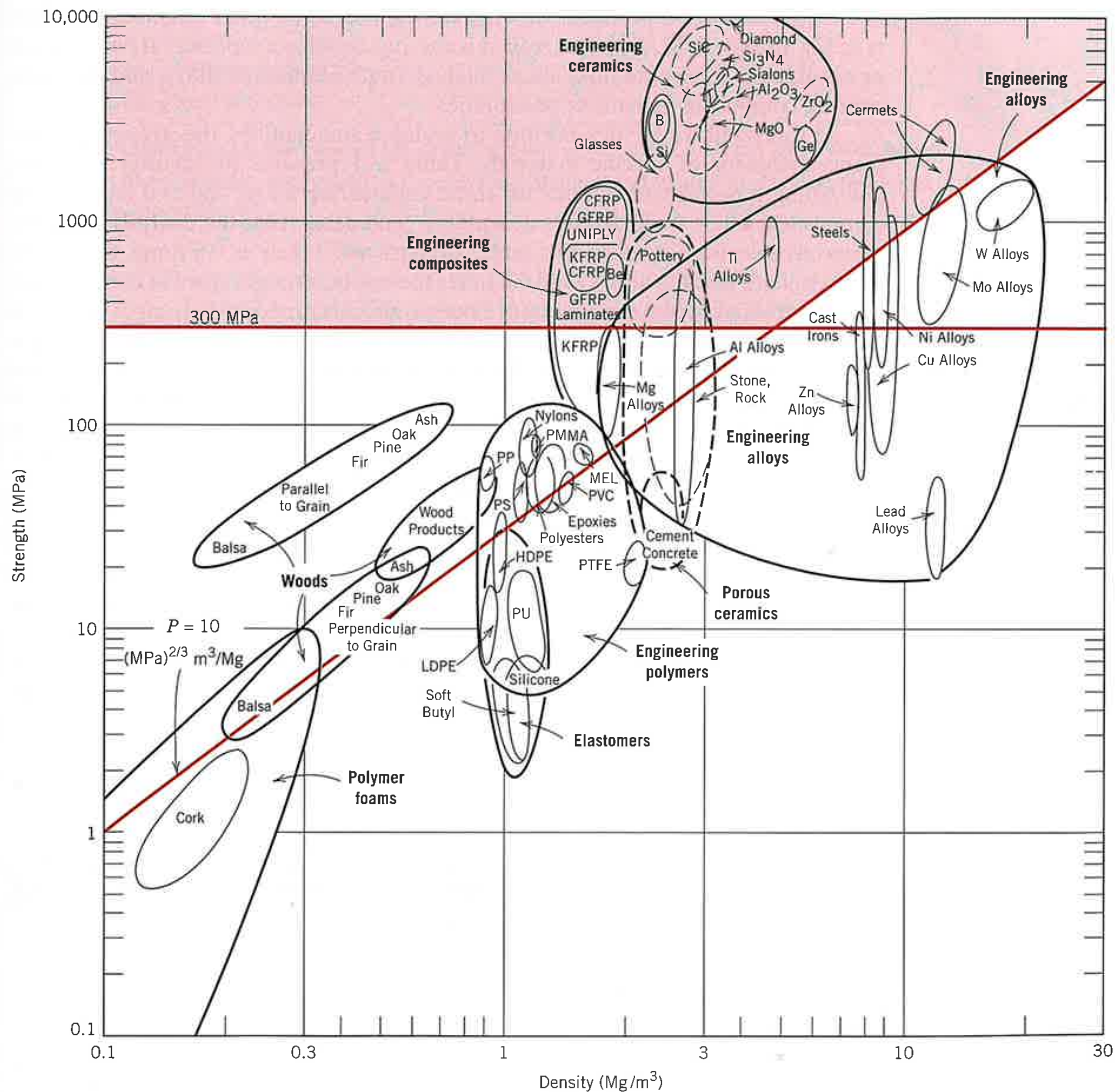


**FIGURE 23.3** Strength versus density materials selection chart. Those materials lying within the shaded region are acceptable candidates for a solid cylindrical shaft which has a mass-strength performance index in excess of  $10 \text{ (MPa)}^{2/3} \text{ m}^3/\text{Mg}$ , and a strength of at least 300 MPa (43,500 psi). (Adapted from M. F. Ashby, *Materials Selection in Mechanical Design*. Copyright © 1992. Reprinted by permission of Butterworth-Heinemann Ltd.)

along this line or above it are in the “search region” of the diagram and are possible candidates for this rotating shaft. These include wood products, some plastics, a number of engineering alloys, the engineering composites, and glasses and engineering ceramics. On the basis of fracture toughness considerations, the engineering ceramics and glasses are ruled out as possibilities.

Let us now impose a further constraint on the problem, namely that the strength of the shaft must equal or exceed 300 MPa (43,500 psi). This may be represented on the materials selection chart by a horizontal line constructed at 300 MPa, Figure 23.3. Now the search region is further restricted to that area above both of these lines. Thus, all wood products, all engineering polymers, other engineering alloys (viz. Mg and some Al alloys), as well as some engineering composites are eliminated as candidates; steels, titanium alloys, high-strength aluminum alloys, and the engineering composites remain as possibilities.

At this point we are in a position to evaluate and compare the strength performance behavior of specific materials. Table 23.1 presents the density, strength, and strength performance index for three engineering alloys and two engineering composites, which were deemed acceptable candidates from the analysis using the materials selection chart. In this table, strength was taken as 0.6 times the tensile yield strength (for the alloys) and 0.6 times the tensile strength (for the composites); these approximations were necessary since we are concerned with strength in torsion and torsional strengths are not readily available. Furthermore, for the two engineering composites, it is assumed that the continuous and aligned glass and carbon fibers are wound in a helical fashion (Figure 17.14), and at a 45° angle referenced to the shaft axis. The five materials in Table 23.1 are ranked according to strength performance index, from highest to lowest: carbon fiber-reinforced and glass fiber-reinforced composites, followed by aluminum, titanium, and 4340 steel alloys.

Material cost is another important consideration in the selection process. In real-life engineering situations, economics of the application often is the overriding issue and normally will dictate the material of choice. One way to determine materials cost is by taking the product of the price (on a per-unit mass basis) and the required mass of material.

Cost considerations for these five remaining candidate materials—steel, aluminum, and titanium alloys, and two engineering composites—are presented in Table

**Table 23.1** Density ( $\rho$ ), Strength ( $\tau_f$ ), the Performance Index ( $P$ ) for Five Engineering Materials

| Material                                                             | $\rho$<br>(Mg/m <sup>3</sup> ) | $\tau_f$<br>(MPa) | $\frac{\tau_f^{2/3}}{\rho} = P$<br>[(MPa) <sup>2/3</sup> /Mg] |
|----------------------------------------------------------------------|--------------------------------|-------------------|---------------------------------------------------------------|
| Carbon fiber-reinforced composite (0.65 fiber fraction) <sup>a</sup> | 1.5                            | 1140              | 72.8                                                          |
| Glass fiber-reinforced composite (0.65 fiber fraction) <sup>a</sup>  | 2.0                            | 1060              | 52.0                                                          |
| Aluminum alloy (2024-T6)                                             | 2.8                            | 300               | 16.0                                                          |
| Titanium alloy (Ti-6Al-4V)                                           | 4.4                            | 525               | 14.8                                                          |
| 4340 Steel (oil-quenched and tempered)                               | 7.8                            | 780               | 10.9                                                          |

<sup>a</sup> The fibers in these composites are continuous, aligned, and wound in a helical fashion at a 45° angle relative to the shaft axis.

**Table 23.2** Tabulation of the  $\rho/\tau_f^{2/3}$  Ratio, Relative Cost ( $\bar{c}$ ), and the Product of  $\rho/\tau_f^{2/3}$  and  $\bar{c}$  for Five Engineering Materials<sup>a</sup>

| Material                                                             | $\rho/\tau_f^{2/3}$<br>[ $10^{-2} \{ \text{Mg}/(\text{MPa})^{2/3} \text{m}^3 \}$ ] | $\bar{c}$<br>(\$/\$) | $\bar{c}(\rho/\tau_f^{2/3})$<br>[ $10^{-2} (\text{Mg}/(\text{MPa})^{2/3} \text{m}^3) (\text{Mg}/(\text{MPa})^{2/3} \text{m}^3)$ ] |
|----------------------------------------------------------------------|------------------------------------------------------------------------------------|----------------------|-----------------------------------------------------------------------------------------------------------------------------------|
| 4340 Steel (oil-quenched and tempered)                               | 9.2                                                                                | 5                    | 46                                                                                                                                |
| Glass fiber-reinforced composite (0.65 fiber fraction) <sup>b</sup>  | 1.9                                                                                | 40                   | 76                                                                                                                                |
| Aluminum alloy (2024-T6)                                             | 6.2                                                                                | 15                   | 93                                                                                                                                |
| Carbon fiber-reinforced composite (0.65 fiber fraction) <sup>b</sup> | 1.4                                                                                | 80                   | 112                                                                                                                               |
| Titanium alloy (Ti-6Al-4V)                                           | 6.8                                                                                | 110                  | 748                                                                                                                               |

<sup>a</sup> The relative cost is the ratio of the prices per unit mass of the material and low-carbon steel.

<sup>b</sup> The fibers in these composites are continuous, aligned, and wound in a helical fashion at a 45° angle relative to the shaft axis.

23.2. In the first column is tabulated  $\rho/\tau_f^{2/3}$ . The next column lists the approximate relative cost, denoted as  $\bar{c}$ ; this parameter is simply the per-unit mass cost of material divided by the per-unit mass cost for low-carbon steel, one of the common engineering materials. The underlying rationale for using  $\bar{c}$  is that while the price of a specific material will vary over time, the price ratio between that material and another will, most likely, change more slowly.

Finally, the right-hand column of Table 23.2 shows the product of  $\rho/\tau_f^{2/3}$  and  $\bar{c}$ . This product provides a comparison of these several materials on the basis of the cost of materials for a cylindrical shaft that would not fracture in response to the twisting moment  $M_t$ . We use this product inasmuch as  $\rho/\tau_f^{2/3}$  is proportional to the mass of material required (Equation 23.8) and  $\bar{c}$  is the relative cost on a per-unit mass basis. Now the most economical is the 4340 steel, followed by the glass fiber-reinforced composite, 2024-T6 aluminum, the carbon fiber-reinforced composite, and the titanium alloy. Thus, when the issue of economics is considered, there is a significant alteration within the ranking scheme. For example, inasmuch as the carbon fiber-reinforced composite is relatively expensive, it is significantly less desirable; or, in other words, the higher cost of this material may not outweigh the enhanced strength it provides.

### 23.3 OTHER PROPERTY CONSIDERATIONS AND THE FINAL DECISION

To this point in our materials selection process we have considered only the strength of materials. Other properties relative to the performance of the cylindrical shaft may be important—for example, stiffness, and, if the shaft rotates, fatigue behavior. Furthermore, fabrication costs should also be considered; in our analysis they have been neglected.

Relative to stiffness, a stiffness-to-mass performance analysis similar to that above could be conducted. For this case, the stiffness performance index  $P_s$  is

$$P_s = \frac{\sqrt{G}}{\rho} \quad (23.11)$$

where  $G$  is the shear modulus. The appropriate materials selection chart ( $\log G$  versus  $\log \rho$ ) would be used in the preliminary selection process. Subsequently, performance index and per-unit-mass cost data would be collected on specific candidate materials; from these analyses the materials would be ranked on the basis of stiffness performance and cost.

In deciding on the best material, it may be worthwhile to make a table employing the results of the various criteria that were used. The tabulation would include, for all candidate materials, performance index, cost, etc. for each criterion, as well as comments relative to any other important considerations. This table puts in perspective the important issues and facilitates the final decision process.

## AUTOMOBILE VALVE SPRING

### 23.4 INTRODUCTION

The basic function of a spring is to store mechanical energy as it is initially elastically deformed and then recoup this energy at a later time as the spring recoils. In this section helical springs that are used in mattresses and in retractable pens and as suspension springs in automobiles are discussed. A stress analysis will be conducted on this type of spring, and the results will then be applied to a valve spring that is utilized in automobile engines.

Consider the helical spring shown in Figure 23.4, which has been constructed of wire having a circular cross section of diameter  $d$ ; the coil center-to-center diameter is denoted as  $D$ . The application of a compressive force  $F$  causes a twisting force, or moment, denoted as  $T$ , as shown in the figure. A combination of shear stresses result, the sum of which,  $\tau$ , is

$$\tau = \frac{8FD}{\pi d^3} K_w \quad (23.12)$$

where  $K_w$  is a force-independent constant that is a function of the  $D/d$  ratio:

$$K_w = 1.60 \left( \frac{D}{d} \right)^{-0.140} \quad (23.13)$$

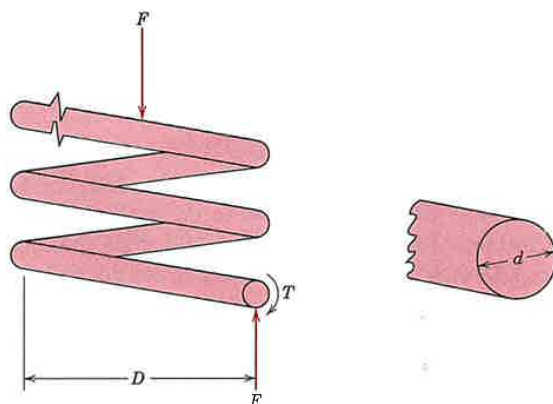


**FIGURE 23.4** Schematic diagram of a helical spring showing the twisting moment  $T$  that results from the compressive force  $F$ . (Adapted from K. Edwards and P. McKee, *Fundamentals of Mechanical Component Design*. Copyright © 1991 by McGraw-Hill, Inc. Reproduced with permission of The McGraw-Hill Companies.)

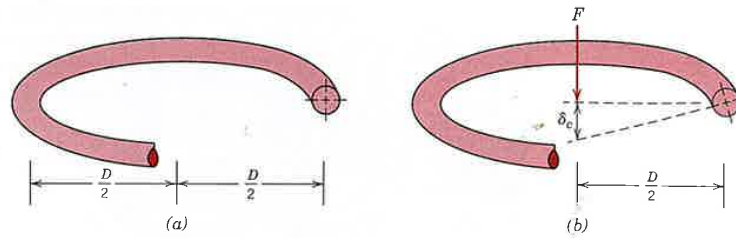


**FIGURE 23.5** Schematic diagrams of one coil of a helical spring, (a) prior to being compressed, and (b) showing the deflection  $\delta_c$  produced from the compressive force  $F$ . (Adapted from K. Edwards and P. McKee, *Fundamentals of Mechanical Component Design*. Copyright © 1991 by McGraw-Hill, Inc. Reproduced with permission of The McGraw-Hill Companies.)

In response to the force  $F$ , the coiled spring will experience deflection, which will be assumed to be totally elastic. The amount of deflection per coil of spring,  $\delta_c$ , as indicated in Figure 23.5, is given by the expression

$$\delta_c = \frac{8FD^3}{d^4G} \quad (23.14)$$

where  $G$  is the shear modulus of the material from which the spring is constructed. Furthermore,  $\delta_c$  may be computed from the total spring deflection,  $\delta_s$ , and the number of effective spring coils,  $N_c$ , as

$$\delta_c = \frac{\delta_s}{N_c} \quad (23.15)$$

Now, solving for  $F$  in Equation 23.14 gives

$$F = \frac{d^4\delta_c G}{8D^3} \quad (23.16)$$

and substituting for  $F$  in Equation 23.12 leads to

$$\tau = \frac{\delta_c G d}{\pi D^2} K_w \quad (23.17)$$

Under normal circumstances, it is desired that a spring experience no permanent deformation upon loading; this means that the right-hand side of Equation 23.17 must be less than the shear yield strength  $\tau_y$  of the spring material, or that

$$\tau_y > \frac{\delta_c G d}{\pi D^2} K_w \quad (23.18)$$

## 23.5 AUTOMOBILE VALVE SPRING

We shall now apply the results of the preceding section to an automobile valve spring. A cut-away schematic diagram of an automobile engine showing these springs is presented in Figure 23.6. Functionally, springs of this type permit both

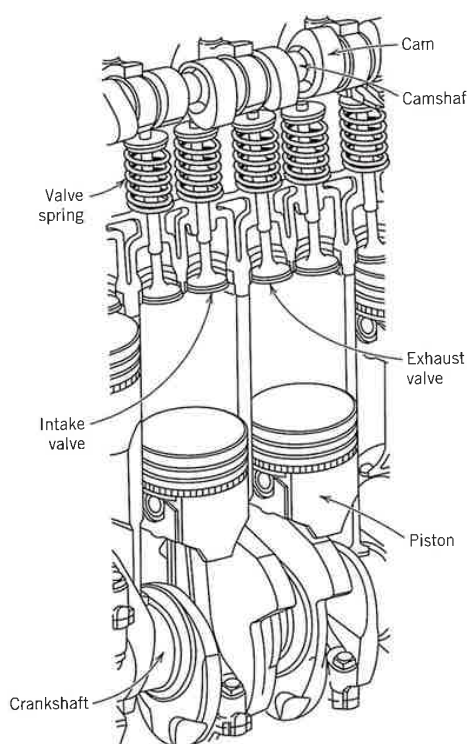


**FIGURE 23.6** Cutaway drawing of a section of an automobile engine in which various components including valves and valve springs are shown.

intake and exhaust valves to alternately open and close as the engine is in operation. Rotation of the camshaft causes a valve to open and its spring to be compressed, so that the load on the spring is increased. The stored energy in the spring then forces the valve to close as the camshaft continues its rotation. This process occurs for each valve for each engine cycle, and over the lifetime of the engine it occurs many millions of times. Furthermore, during normal engine operation, the temperature of the springs is approximately 80°C (175°F).

A photograph of a typical valve spring is shown in Figure 23.7. The spring has a total length of 1.67 in. (42 mm), is constructed of wire having a diameter  $d$  of 0.170 in. (4.3 mm), has six coils (only four of which are active), and has a center-to-center diameter  $D$  of 1.062 in. (27 mm). Furthermore, when installed and when a valve is completely closed, its spring is compressed a total of 0.24 in. (6.1 mm), which, from Equation 23.15, gives an installed deflection per coil  $\delta_{ic}$  of

$$\delta_{ic} = \frac{0.24 \text{ in.}}{4 \text{ coils}} = 0.060 \text{ in./coil (1.5 mm/coil)}$$

The cam lift is 0.30 in. (7.6 mm), which means that when the cam completely opens a valve, the spring experiences a maximum total deflection equal to the sum of the valve lift and the compressed deflection, namely, 0.30 in. + 0.24 in. = 0.54 in. (13.7 mm). Hence, the maximum deflection per coil,  $\delta_{mc}$ , is

$$\delta_{mc} = \frac{0.54 \text{ in.}}{4 \text{ coils}} = 0.135 \text{ in./coil (3.4 mm/coil)}$$



FIGURE 23.7 Photograph of a typical automobile valve spring.

Thus, we have available all of the parameters in Equation 23.18 (taking  $\delta_c = \delta_{mc}$ ), except for  $\tau_y$ , the required shear yield strength of the spring material.

However, the material parameter of interest is really not  $\tau_y$  inasmuch as the spring is continually stress cycled as the valve opens and closes during engine operation; this necessitates designing against the possibility of failure by fatigue rather than against the possibility of yielding. This fatigue complication is handled by choosing a metal alloy that has a fatigue limit (Figure 8.22a) that is greater than the cyclic stress amplitude to which the spring will be subjected. For this reason, steel alloys, which have fatigue limits, are normally employed for valve springs.

When using steel alloys in spring design, two assumptions may be made if the stress cycle is reversed (if  $\tau_m = 0$ , where  $\tau_m$  is the mean stress, or, equivalently, if  $\tau_{\max} = -\tau_{\min}$ , in accordance with Equation 8.21 and as noted in Figure 23.8). The first of these assumptions is that the fatigue limit of the alloy (expressed as stress amplitude) is 45,000 psi (310 MPa), the threshold of which occurs at about  $10^6$  cycles. Secondly, for torsion and on the basis of experimental data, it has been found that the fatigue strength at  $10^3$  cycles is  $0.67TS$ , where  $TS$  is the tensile strength of the material (as measured from a pure tension test). The  $S$ - $N$  fatigue diagram (i.e., stress amplitude versus logarithm of the number of cycles to failure) for these alloys is shown in Figure 23.9.

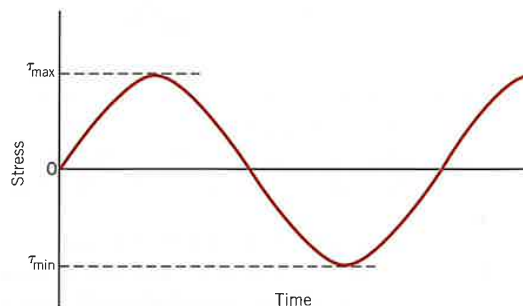


FIGURE 23.8 Stress versus time for a reversed cycle in shear.

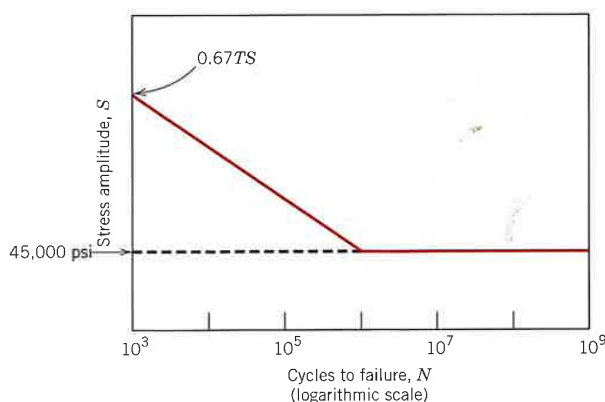


**FIGURE 23.9** Shear stress amplitude versus logarithm of the number of cycles to fatigue failure for typical ferrous alloys.

Now let us estimate the number of cycles to which a typical valve spring may be subjected in order to determine whether it is permissible to operate within the fatigue limit regime of Figure 23.9 (i.e., if the number of cycles exceeds  $10^6$ ). For the sake of argument, assume that the automobile in which the spring is mounted travels a minimum of 100,000 miles (161,000 km) at an average speed of 40 mph (64.4 km/h), with an average engine speed of 3000 rpm (rev/min). The total time it takes the automobile to travel this distance is 2500 h (100,000 mi/40 mph), or 150,000 min. At 3000 rpm, the total number of revolutions is (3000 rev/min)(150,000 min) =  $4.5 \times 10^8$  rev, and since there are 2 rev/cycle, the total number of cycles is  $2.25 \times 10^8$ . This result means that we may use the fatigue limit as the design stress inasmuch as the limit cycle threshold has been exceeded for the 100,000-mile distance of travel (i.e., since  $2.25 \times 10^8$  cycles  $> 10^6$  cycles).

Furthermore, this problem is complicated by the fact that the stress cycle is not completely reversed (i.e.,  $\tau_m \neq 0$ ) inasmuch as between minimum and maximum deflections the spring remains in compression; thus, the 45,000 psi (310 MPa) fatigue limit is not valid. What we would now like to do is first to make an appropriate extrapolation of the fatigue limit for this  $\tau_m \neq 0$  case and then compute and compare with this limit the actual stress amplitude for the spring; if the stress amplitude is significantly below the extrapolated limit, then the spring design is satisfactory.

A reasonable extrapolation of the fatigue limit for this  $\tau_m \neq 0$  situation may be made using the following expression (termed Goodman's law):

$$\tau_{al} = \tau_e \left( 1 - \frac{\tau_m}{0.67TS} \right) \quad (23.19)$$

where  $\tau_{al}$  is the fatigue limit for the mean stress  $\tau_m$ ;  $\tau_e$  is the fatigue limit for  $\tau_m = 0$  [i.e., 45,000 psi (310 MPa)]; and, again,  $TS$  is the tensile strength of the alloy. To determine the new fatigue limit  $\tau_{al}$  from the above expression necessitates the computation of both the tensile strength of the alloy and the mean stress for the spring.

One common spring alloy is an ASTM 232 chrome–vanadium steel, having a composition of 0.48–0.53 wt% C, 0.80–1.10 wt% Cr, a minimum of 0.15 wt% V, and the balance being Fe. Spring wire is normally cold drawn (Section 12.2) to the desired diameter; consequently, tensile strength will increase with the amount of

drawing (i.e., with decreasing diameter). For this alloy it has been experimentally verified that, for the diameter  $d$  in inches, the tensile strength is

$$TS \text{ (psi)} = 169,000(d)^{-0.167} \quad (23.20)$$

Since  $d = 0.170$  in. for this spring,

$$\begin{aligned} TS &= (169,000)(0.170 \text{ in.})^{-0.167} \\ &= 227,200 \text{ psi (1570 MPa)} \end{aligned}$$

Computation of the mean stress  $\tau_m$  is made using Equation 8.21 modified to the shear stress situation as follows:

$$\tau_m = \frac{\tau_{\min} + \tau_{\max}}{2} \quad (23.21)$$

It now becomes necessary to determine the minimum and maximum shear stresses for the spring, using Equation 23.17. The value of  $\tau_{\min}$  may be calculated from Equations 23.17 and 23.13 inasmuch as the minimum  $\delta_c$  is known (i.e.,  $\delta_{ic} = 0.060$  in.). A shear modulus of  $11.5 \times 10^6$  psi (79 GPa) will be assumed for the steel; this is the room-temperature value, which is also valid at the 80°C service temperature. Thus,  $\tau_{\min}$  is just

$$\begin{aligned} \tau_{\min} &= \frac{\delta_{ic} G d}{\pi D^2} K_w \\ &= \frac{\delta_{ic} G d}{\pi D^2} \left[ 1.60 \left( \frac{D}{d} \right)^{-0.140} \right] \\ &= \left[ \frac{(0.060 \text{ in.})(11.5 \times 10^6 \text{ psi})(0.170 \text{ in.})}{\pi (1.062 \text{ in.})^2} \right] \left[ 1.60 \left( \frac{1.062 \text{ in.}}{0.170 \text{ in.}} \right)^{-0.140} \right] \\ &= 41,000 \text{ psi (280 MPa)} \end{aligned} \quad (23.22a)$$

Now  $\tau_{\max}$  may be determined taking  $\delta_c = \delta_{mc} = 0.135$  in. as follows:

$$\begin{aligned} \tau_{\max} &= \frac{\delta_{mc} G d}{\pi D^2} \left[ 1.60 \left( \frac{D}{d} \right)^{-0.140} \right] \\ &= \left[ \frac{(0.135 \text{ in.})(11.5 \times 10^6 \text{ psi})(0.170 \text{ in.})}{\pi (1.062 \text{ in.})^2} \right] \left[ 1.60 \left( \frac{1.062 \text{ in.}}{0.170 \text{ in.}} \right)^{-0.140} \right] \\ &= 92,200 \text{ psi (635 MPa)} \end{aligned} \quad (23.22b)$$

Now, from Equation 23.21,

$$\begin{aligned} \tau_m &= \frac{\tau_{\min} + \tau_{\max}}{2} \\ &= \frac{41,000 \text{ psi} + 92,200 \text{ psi}}{2} = 66,600 \text{ psi (460 MPa)} \end{aligned}$$

The variation of shear stress with time for this valve spring is noted in Figure 23.10; the time axis is not scaled, inasmuch as the time scale will depend on engine speed.

Our next objective is to determine the fatigue limit amplitude ( $\tau_{al}$ ) for this  $\tau_m = 66,600$  psi (460 MPa) using Equation 23.19 and for  $\tau_e$  and  $TS$  values of 45,000

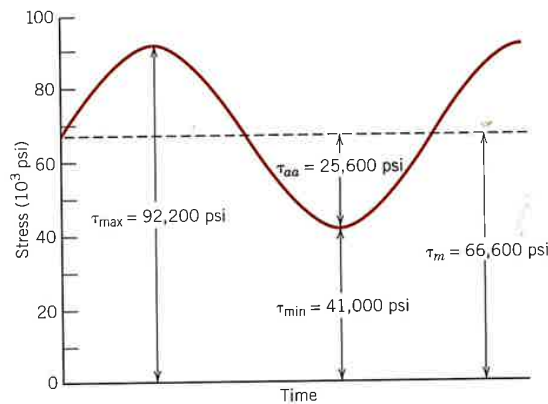


FIGURE 23.10 Shear stress versus time for an automobile valve spring.

psi (310 MPa) and 227,200 psi (1570 MPa), respectively. Thus,

$$\begin{aligned}\tau_{al} &= \tau_e \left[ 1 - \frac{\tau_m}{0.67TS} \right] \\ &= (45,000 \text{ psi}) \left[ 1 - \frac{66,600 \text{ psi}}{(0.67)(227,200 \text{ psi})} \right] \\ &= 25,300 \text{ psi (175 MPa)}\end{aligned}$$

Now let us determine the actual stress amplitude  $\tau_{aa}$  for the valve spring using Equation 8.23 modified to the shear stress condition:

$$\begin{aligned}\tau_{aa} &= \frac{\tau_{\max} - \tau_{\min}}{2} \\ &= \frac{92,200 \text{ psi} - 41,000 \text{ psi}}{2} = 25,600 \text{ psi (177 MPa)}\end{aligned}\quad (23.23)$$

Thus, the actual stress amplitude is slightly greater than the fatigue limit, which means that this spring design is marginal.

The fatigue limit of this alloy may be increased to greater than 25,300 psi (175 MPa) by shot peening, a procedure described in Section 8.11. Shot peening involves the introduction of residual compressive surface stresses by plastically deforming outer surface regions; small and very hard particles are projected onto the surface at high velocities. This is an automated procedure commonly used to improve the fatigue resistance of valve springs; in fact, the spring shown in Figure 23.7 has been shot peened, which accounts for its rough surface texture. Shot peening has been observed to increase the fatigue limit of steel alloys in excess of 50% and, in addition, to reduce significantly the degree of scatter of fatigue data.

This spring design, including shot peening, may be satisfactory; however, its adequacy should be verified by experimental testing. The testing procedure is relatively complicated and, consequently, will not be discussed in detail. In essence, it involves performing a relatively large number of fatigue tests (on the order of 1000) on this shot-peened ASTM 232 steel, in shear, using a mean stress of 66,600 psi (460 MPa) and a stress amplitude of 25,600 psi (177 MPa), and for  $10^6$  cycles. On the basis of the number of failures, an estimate of the survival probability can be

made. For the sake of argument, let us assume that this probability turns out to be 0.99999; this means that one spring in 100,000 produced will fail.

Suppose that you are employed by one of the large automobile companies that manufactures on the order of 1 million cars per year, and that the engine powering each automobile is a six-cylinder one. Since for each cylinder there are two valves, and thus two valve springs, a total of 12 million springs would be produced every year. For the above survival probability rate, the total number of spring failures would be approximately 120, which also corresponds to 120 engine failures. As a practical matter, one would have to weigh the cost of replacing these 120 engines against the cost of a spring redesign.

Redesign options would involve taking measures to reduce the shear stresses on the spring, by altering the parameters in Equations 23.13 and 23.17. This would include either (1) increasing the coil diameter  $D$ , which would also necessitate increasing the wire diameter  $d$ , or (2) increasing the number of coils  $N_c$ .

## ARTIFICIAL TOTAL HIP REPLACEMENT

### 23.6 ANATOMY OF THE HIP JOINT

As a prelude to discussing the artificial hip, let us first briefly address some of the anatomical features of joints in general and the hip joint in particular. The joint is an important component of the skeletal system. It is located at bone junctions, where loads may be transmitted from bone to bone by muscular action; this is normally accompanied by some relative motion of the component bones. Bone tissue is a complex natural composite consisting of soft and strong protein collagen and brittle apatite, which has a density between 1.6 and 1.7 g/cm<sup>3</sup>. Being an anisotropic material, the mechanical properties of bone differ in longitudinal (axial) and transverse (radial) directions (Table 23.3). The articulating (or connecting) surface of each joint is coated with cartilage, which consists of body fluids that lubricate and provide an interface having a very low coefficient of friction so as to facilitate the bone-sliding movement.

The human hip joint (Figure 23.11) occurs at the junction between the pelvis and the upper leg (thigh) bone, or femur. A relatively large range of rotary motion is permitted at the hip by a ball-and-socket type of joint; the top of the femur

**Table 23.3** Mechanical Characteristics of Human Long Bone Both Parallel and Perpendicular to the Bone Axis

| <i>Property</i>                              | <i>Parallel to<br/>Bone Axis</i> | <i>Perpendicular to<br/>Bone Axis</i> |
|----------------------------------------------|----------------------------------|---------------------------------------|
| Elastic modulus, GPa (psi)                   | 17.4<br>( $2.48 \times 10^6$ )   | 11.7<br>( $1.67 \times 10^6$ )        |
| Ultimate strength, tension, MPa<br>(ksi)     | 135<br>(19.3)                    | 61.8<br>(8.96)                        |
| Ultimate strength, compression,<br>MPa (ksi) | 196<br>(28.0)                    | 135<br>(19.3)                         |
| Elongation at fracture                       | 3–4%                             | —                                     |

**Source:** From D. F. Gibbons, "Biomedical Materials," pp. 253–254, in *Handbook of Engineering in Medicine and Biology*, D. G. Fleming, and B. N. Feinberg, CRC Press, Boca Raton, Florida, 1976. With permission.

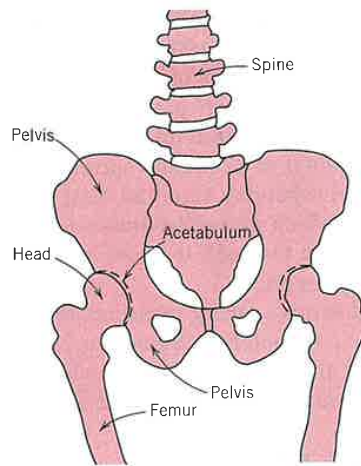


**FIGURE 23.11** Schematic diagram of human hip joints and adjacent skeletal components.

terminates in a ball-shaped head that fits into a cuplike cavity (the acetabulum) within the pelvis. An x-ray of a normal hip joint is shown in Figure 23.12a.

This joint is susceptible to fracture, which normally occurs at the narrow region just below the head. An x-ray of a fractured hip is shown in Figure 23.12b; the arrows show the two ends of the fracture line through the femoral neck. Furthermore, the hip may become diseased (osteoarthritis); in such a case small lumps of bone form on the rubbing surfaces of the joint, which causes pain as the head rotates in the acetabulum. Damaged and diseased hip joints have been replaced with artificial or prosthetic ones, with moderate success, beginning in the late 1950s. Total hip replacement surgery involves the removal of the head and the upper portion of the femur, and some of the bone marrow at the top of the remaining femur segment. Into this hole within the center of the femur is secured a metal anchorage stem

**FIGURE 23.12** X-Rays of (a) a normal hip joint and (b) a fractured hip joint. The arrows in (b) show the two ends of the fracture line through the femoral neck.

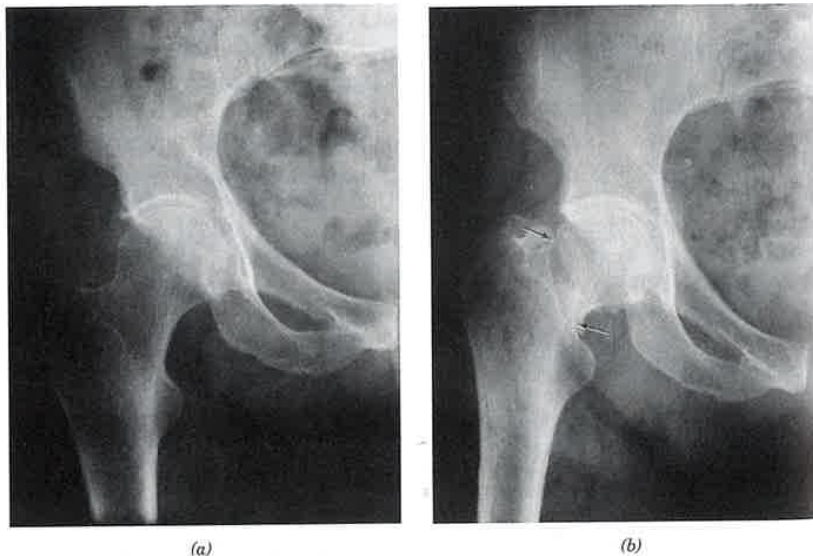
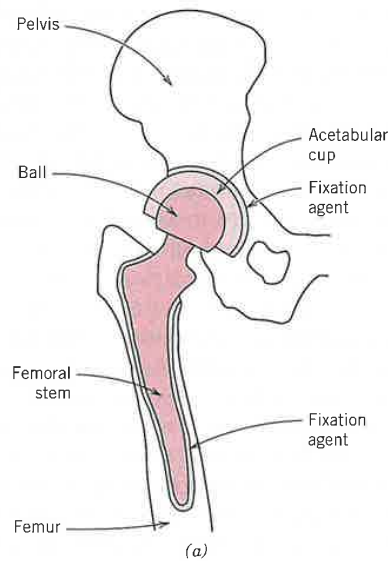


**FIGURE 23.13**  
(a) Schematic diagram and (b) x-ray of an artificial total hip replacement.



onto which is attached, at its other end, the ball portion of the joint. In addition, the replacement cup socket must be attached to the pelvis. This is accomplished by removal of the old cup and its surrounding bone tissue. The new socket is affixed into this recess. A schematic diagram of the artificial hip joint is presented in Figure 23.13a; and Figure 23.13b shows an x-ray of a total hip replacement. In the remainder of this section we discuss material constraints and those materials that have been used with the greatest degree of success for the various artificial hip components.

## 23.7 MATERIAL REQUIREMENTS

In essence, there are four basic components to the artificial hip: (1) the femoral stem, (2) the ball that attaches to this stem, (3) the acetabular cup that is affixed to the pelvis, and (4) a fixation agent that secures the stem into the femur and the cup to the pelvis. The property constraints on the materials to be used for these elements are very stringent because of the chemical and mechanical complexity of the hip joint. Some of the requisite material characteristics will now be discussed.

Whenever any foreign material is introduced into the body environment, rejection reactions occur. The magnitude of rejection may range from mild irritation or inflammation to death. Any implant material must be *biocompatible*, that is, it must produce a minimum degree of rejection. Products resulting from reactions with body fluids must be tolerated by the surrounding body tissues such that normal tissue function is unimpaired. Biocompatibility is a function of the location of the implant, as well as of its chemistry and shape.

The body fluid consists of an aerated and warm solution containing approximately 1 wt% NaCl in addition to other salts and organic compounds in relatively minor concentrations. Thus, the body fluids are very corrosive, which, for metal alloys can lead not only to uniform corrosion, but also to crevice attack and pitting and, when stresses are present, to fretting, stress corrosion cracking, and corrosion fatigue. It has been estimated that the maximum tolerable corrosion rate for implant metal alloys is on the order of 0.01 mil per year ( $2.5 \times 10^{-4}$  mm per year).

Another adverse consequence of corrosion is the generation of corrosion products that are either toxic or interfere with normal body functions. These substances are rapidly transported throughout the body; some may segregate in specific organs. Even though others may be excreted from the body, they may nevertheless still persist in relatively high concentrations by virtue of the ongoing corrosion process.

The bones and replacement components within the hip joint must support forces that originate from without the body, such as those due to gravity; in addition, they must transmit forces that result from muscular action such as walking. These forces are complex in nature and fluctuate with time in magnitude, in direction, and in rate of application. Thus, mechanical characteristics such as modulus of elasticity, yield strength, tensile strength, fatigue strength, fracture toughness, and ductility are all important considerations relative to the materials of choice for the prosthetic hip. For example, the material used for the femoral stem should have minimum yield and tensile strengths of approximately 500 MPa (72,500 psi) and 650 MPa (95,000 psi), respectively, and a minimum ductility of about 8%EL. In addition, the fatigue strength (for bending stresses that are fully reversed [Figure 8.20a]) should be at least 400 MPa (60,000 psi) at  $10^7$  cycles. For the average person, the load on the hip joint fluctuates on the order of  $10^6$  times per year. Furthermore, the modulus of elasticity of the prosthetic material should match that of bone; a significant difference can lead to deterioration of the bone tissue surrounding the implant.

Furthermore, since the ball-and-cup articulating surfaces rub against one another, wear of these surfaces is minimized by the employment of very hard materials. Excessive and uneven wear can lead to a change in shape of the articulating surfaces and cause the prosthesis to malfunction. In addition, particulate debris will be generated as the articulating surfaces wear against one another; accumulation of this debris in the surrounding tissues can also lead to inflammation.

Frictional forces at these rubbing counterfaces should also be minimized to prevent loosening of the femoral stem and acetabular cup assembly from their positions secured by the fixation agent. If these components do become loose over time, the hip will experience premature degradation that may require it to be replaced.

Three final important material factors are density, property reproducibility, and cost. It is highly desirable that lightweight components be used, that material properties from prosthesis to prosthesis remain consistent over time, and, of course, that the cost of the prosthesis components be reasonable.

Ideally, an artificial hip that has been surgically implanted should function satisfactorily for the lifetime of the recipient and not require replacement. For current designs, lifetimes range between only five and ten years; certainly longer ones are desirable.

Several final comments are in order relative to biocompatibility assessment. Biocompatibility of materials is usually determined empirically; that is, tests are conducted wherein materials are implanted in laboratory animals and the biocompatibility of each material is judged on the basis of rejection reactions, level of corrosion, generation of toxic substances, etc. This procedure is then repeated on humans for those materials that were found to be relatively biocompatible in animals. It is difficult to *a priori* predict the biocompatibility of a material. For example, mercury, when ingested into the body, is poisonous; however, dental amalgams, which have high mercury contents, have generally been found to be very biocompatible.

## 23.8 MATERIALS EMPLOYED

### FEMORAL STEM AND BALL

Early prosthetic hip designs called for both the femoral stem and ball to be of the same material—a stainless steel. Subsequent improvements have been introduced, including the utilization of materials other than stainless steel and, in addition, constructing the stem and ball from different materials. Figure 23.14 is a photograph in which are shown two different hip replacement designs.

Currently, the femoral stem is constructed from a metal alloy of which there are three possible types: stainless steel, cobalt–nickel–chromium–molybdenum, and titanium. The most suitable stainless steel is 316L, which has a very low sulfur content ( $<0.002$  wt%); its composition is given in Table 12.4. The principal disadvantages of this alloy are its susceptibility to crevice corrosion and pitting, and its relatively low fatigue strength. Fabrication technique may also have a significant influence on its characteristics. Cast 316L typically has poor mechanical properties and inadequate corrosion resistance. Consequently, prosthetic femoral stems are either forged or cold worked. Furthermore, heat treatment may also influence the characteristics of the material and must be taken into consideration. Normally, 316L is implanted in older and less active persons. The mechanical characteristics and corrosion rate range of this alloy (in the cold-worked state) are supplied in Table 23.4.

Various Co–Cr–Mo and Co–Ni–Cr–Mo alloys have been employed for artificial hip prostheses; one that has been found to be especially suitable, designated MP35N, has a composition of 35 wt% Co, 35 wt% Ni, 20 wt% Cr, and 10 wt% Mo. It is formed by hot forging and, as such, has tensile and yield strengths that are superior to 316L stainless steel (Table 23.4). Furthermore, its corrosion and fatigue characteristics are excellent.

Of those metal alloys that are implanted for prosthetic hip joints, probably the most biocompatible is the titanium alloy Ti–6Al–4V; its composition is 90 wt% Ti, 6 wt% Al, and 4 wt% V. The optimal properties for this material are produced by hot forging; any subsequent deformation and/or heat treatment should be avoided to prevent the formation of microstructures that are deleterious to its bioperformance. The properties of this alloy are also listed in Table 23.4.

Recent improvements for this prosthetic device include using a ceramic material for the ball component rather than any of the aforementioned metal alloys. The ceramic of choice is a high-purity and polycrystalline aluminum oxide, which is



**FIGURE 23.14** Photograph showing two artificial total hip replacement designs.

**Table 23.4** Mechanical and Corrosion Characteristics of Three Metal Alloys That Are Commonly Used for the Femoral Stem Component of the Prosthetic Hip

| <i>Alloy</i>                       | <i>Elastic Modulus</i><br>[GPa (psi)] | <i>0.2% Yield Strength</i><br>[MPa (ksi)] | <i>Tensile Strength</i><br>[MPa (ksi)] | <i>Elongation at Fracture</i><br>(%) | <i>Fatigue Strength or Limit, 10<sup>7</sup> Cycles</i> [MPa (ksi)] | <i>Corrosion Rate</i><br>(mpy) <sup>a</sup> |
|------------------------------------|---------------------------------------|-------------------------------------------|----------------------------------------|--------------------------------------|---------------------------------------------------------------------|---------------------------------------------|
| 316L Stainless steel (cold worked) | 196<br>(28.4 × 10 <sup>6</sup> )      | 700<br>(102)                              | 875<br>(127)                           | 12                                   | 383<br>(55.5)                                                       | 0.001–0.002                                 |
| MP35N (hot forged)                 | 230<br>(33.4 × 10 <sup>6</sup> )      | 1000<br>(145)                             | 1200<br>(174)                          | 13                                   | 500<br>(72.5)                                                       | 0.0012–0.002                                |
| Ti-6Al-4V (hot forged)             | 120<br>(17.4 × 10 <sup>6</sup> )      | 950<br>(138)                              | 1075<br>(156)                          | 13                                   | 580<br>(84.1)                                                       | 0.007–0.04                                  |

<sup>a</sup> mpy means mils per year, or 0.001 in./yr

**Sources:** From Gladius Lewis, *Selection of Engineering Materials*, © 1990, p. 189. Adapted by permission of Prentice Hall, Englewood Cliffs, New Jersey. And D. F. Gibbons, "Materials for Orthopedic Joint Prostheses," Ch. 4, p. 116, in *Biocompatibility of Orthopedic Implants*, Vol. I, D. F. Williams, CRC Press, Boca Raton, Florida, 1982. With permission.

harder and more wear resistant, and generates lower frictional stresses at the joint. However, the fracture toughness of alumina is relatively low and its fatigue characteristics are poor. Hence, the femoral stem, being subjected to significant stress levels, is still fabricated from one of the above alloys, and is then attached to the ceramic ball; this femoral stem–ball component thus becomes a two-piece unit.

The materials selected for use in an orthopedic implant come after years of research into the chemical and physical properties of a host of different candidate materials. Ideally, the material(s) of choice will not only be biocompatible, but have mechanical properties that match the biomaterial being replaced—viz., bone. However, no man-made material is both biocompatible and possesses the property combination of bone and the natural hip joint—i.e., low modulus of elasticity, relatively high strength and fracture toughness, low coefficient of friction, and excellent wear resistance. Consequently, material property compromises and trade-offs must be made. For example, recall that the modulus of elasticity of bone and femoral stem materials should be closely matched such that accelerated deterioration of the bone tissue adjacent to the implant is avoided. Unfortunately, man-made materials that are both biocompatible and relatively strong, also have high moduli of elasticity. Thus, for this application, it was decided to trade off a low modulus for biocompatibility and strength.

### ACETABULAR CUP

Some acetabular cups are made from one of the biocompatible alloys or aluminum oxide. More commonly, however, ultrahigh molecular weight polyethylene (Section 16.18) is used. This material is virtually inert in the body environment and has excellent wear-resistance characteristics; furthermore, it has a very low coefficient of friction when in contact with the materials used for the ball component of the socket.

### FIXATION

Successful performance of the artificial hip joint calls for the secure attachment of both the femoral stem to the femur and the acetabular cup to the pelvis. Insecure attachment of either component ultimately leads to a loosening of that component

and the accelerated degradation of the joint. A fixation agent is sometimes used to bond these two prosthetic components to their surrounding bone structures. The most commonly used fixation agent is a polymethyl methacrylate (acrylic) bone cement that is polymerized *in situ* during surgery.

This acrylic bond cement has, in some cases, contributed to femoral stem loosening because it is brittle and does not bond well with the metallic implant and bone tissue. It has been found that a more secure implant–bone bond is formed when the stem is coated with a porous surface layer, consisting of a sintered metal powder. After implantation, bone tissue grows into the three-dimensional pore network, and thereby fixates the implant to the bone. Such a coating has been applied to the upper stem region of the right hip replacement shown in Figure 23.14.

## THERMAL PROTECTION SYSTEM ON THE SPACE SHUTTLE ORBITER

### 23.9 INTRODUCTION

In 1969, the National Aeronautics and Space Administration (NASA) of the United States decided to direct its primary mission to the development of a *Space Transportation System (STS)*, also commonly known as the *Space Shuttle Orbiter*. In essence, the Space Shuttle is a reusable cargo-carrying space vehicle that is launched aboard a rocket, and then orbits the earth. Upon mission completion, it reenters the atmosphere as a space craft, and, finally, once inside the lower atmosphere, lands in the manner of a normal aircraft. The maiden flight was made by the *Columbia* orbiter in April of 1981; since then, four other orbiters have been constructed—*Discovery*, *Atlantis*, *Endeavour*, and the ill-fated *Challenger*. A photograph of the *Atlantis* is shown on page 734.

The successful operation of the Space Shuttle is dependent on a fully reusable outer “skin,” termed a *Thermal Protection System (TPS)*, that protects the inner airframe and its occupants from the searing heat generated during the reentry phase from space into the earth’s atmosphere. The development of this Thermal Protection System evolved over a twenty-year period, and is a classical and somewhat involved materials selection and design problem. In this section the primary components of the Shuttle’s TPS are discussed.

In reading this section, keep in mind that cost constraints relative to the design and fabrication of these materials were not as rigid as would be expected for normal commercial applications.

### 23.10 THERMAL PROTECTION SYSTEM— DESIGN REQUIREMENTS

Material requirements on the Thermal Protection System are, to say the least, awesome. For example, the TPS must do the following:

1. Maintain the temperature on the inner airframe below that to which it was designed [viz., 175°C (350°F)] for a maximum outer surface temperature of 1260°C (2300°F).
2. Remain usable for 100 missions, with a maximum turnaround time of 160 h.
3. Provide and maintain an aerodynamically smooth outer surface.

4. Be constructed of low-density materials.
5. Withstand temperature extremes between  $-110^{\circ}\text{C}$  ( $-170^{\circ}\text{F}$ ) and  $1260^{\circ}\text{C}$  ( $2300^{\circ}\text{F}$ ).
6. Be resistant to severe thermal gradients and rapid temperature changes.
7. Be able to withstand stresses and vibrations that are experienced during launch, as well as thermally induced stresses imposed during temperature changes.
8. Experience a minimum absorption of moisture and other contaminants during storage between missions.
9. Be made to adhere to the airframe that is constructed of an aluminum alloy.

Thermal protection systems and materials developed previously by the aerospace industry proved unsuitable for the Space Shuttle because they were either too dense and/or nonreusable. Therefore, it became necessary to design a new set of complex materials. Furthermore, no single material is capable of meeting all of the criteria listed above. In addition, not all of these criteria are required over all surfaces of the spacecraft; for example, typical reentry maximum temperature profiles are shown in Figure 23.15.

Therefore, the philosophy adopted was to design several different thermal protection materials systems, each with its particular set of properties, that satisfy the required criteria for a specific region of the spacecraft surface. Several different materials systems are employed on the Space Shuttles, the designs of which depend

**FIGURE 23.15**  
Approximate maximum outer surface temperature profiles for the Space Shuttle Orbiter during reentry: (a) upper and lower views; (b) side view. (From "The Shuttle Orbiter Thermal Protection System," L. J. Korb, C. A. Morant, R. M. Calland, and C. S. Thatcher, *Ceramic Bulletin*, No. 11, Nov. 1981, p. 1188. Copyright 1981. Reprinted by permission of the American Ceramic Society.)

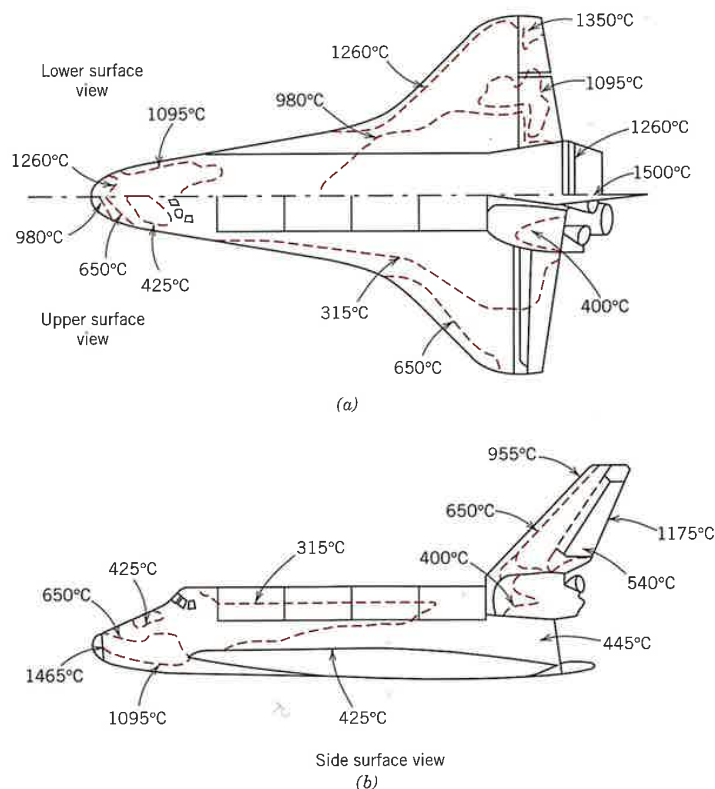


**Table 23.5** Thermal Protection Systems Employed on the Space Shuttle Orbiter

| <i>Material Generic Name</i>                          | <i>Minimum Operating Temperature, °C (°F)</i> | <i>Maximum Operating Temperature, °C (°F)</i> | <i>Material Composition</i>                                          | <i>Orbiter Locations</i>                                  |
|-------------------------------------------------------|-----------------------------------------------|-----------------------------------------------|----------------------------------------------------------------------|-----------------------------------------------------------|
| Felt reusable surface insulation (FRSI)               | -130 (-200)                                   | 400 (750)                                     | Nylon felt, silicone rubber coating                                  | Wing upper surface, upper sides, cargo bay doors          |
| Advanced flexible reusable surface insulation (AFRSI) | -130 (-200)                                   | 815 (1500)                                    | Quartz batting sandwiched between quartz and glass fabrics           | Upper surface regions                                     |
| Low-temperature reusable surface insulation (LRSI)    | -130 (-200)                                   | 650 (1200)                                    | Silica tiles, borosilicate glass coating                             | Upper wing surfaces, tail surfaces, upper vehicle sides   |
| High-temperature reusable insulation (HRSI)           | -130 (-200)                                   | 1260 (2300)                                   | Silica tiles, borosilicate glass coating with SiB <sub>4</sub> added | Lower surfaces and sides, tail leading and trailing edges |
| Reinforced carbon-carbon (RCC)                        | No lower limit identified                     | 1650 (3000)                                   | Pyrolyzed carbon-carbon, coated with SiC                             | Nose cap and wing leading edges                           |

**Source:** Adapted from L. J. Korb, C. A. Morant, R. M. Calland and C. S. Thatcher, "The Shuttle Orbiter Thermal Protection System," *Ceramic Bulletin*, No. 11, Nov. 1981, p. 1188. Copyright 1981. Reprinted by permission of the American Ceramic Society.

on the maximum outer surface temperature generated during vehicle reentry. These systems and their temperature ranges of operation, material compositions, and orbiter areas are listed in Table 23.5. Furthermore, the locations of these various systems are indicated in Figure 23.16.

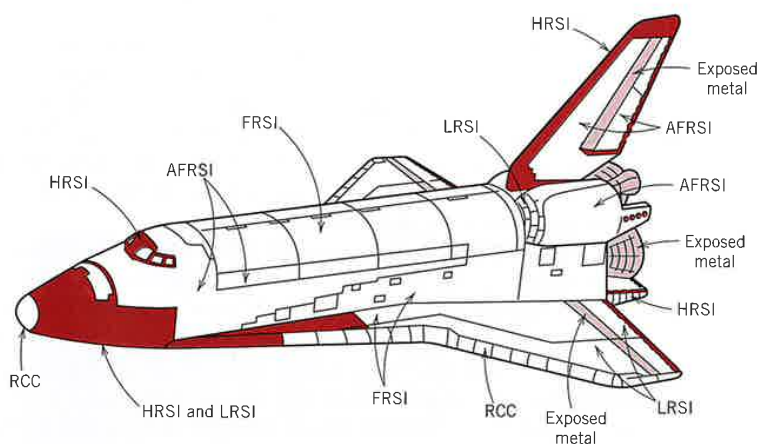


**FIGURE 23.16** Locations of the various components of the thermal protection system on the Space Shuttle Orbiter: FRSI, felt reusable surface insulation; AFRSI, advanced flexible reusable surface insulation; LRSI, low-temperature reusable surface insulation; HRSI, high-temperature reusable surface insulation; RCC, reinforced carbon-carbon composite. (Adapted from L. J. Korb, C. A. Morant, R. M. Calland, and C. S. Thatcher, "The Shuttle Orbiter Thermal Protection System," *Ceramic Bulletin*, No. 11, Nov. 1981, p. 1189. Copyright 1981. Reprinted by permission of the American Ceramic Society.)

## 23.11 THERMAL PROTECTION SYSTEM—COMPONENTS

### FELT REUSABLE SURFACE INSULATION

Upper surface regions exposed up to temperatures of 400°C (750°F) are covered with what is termed *felt reusable surface insulation (FRSI)*. This insulation consists of felt blankets of a nylon material the outer surface of which is coated with a silicone elastomer to achieve the necessary surface thermal properties. These blankets come in two thicknesses, 4 and 8 mm (0.16 and 0.32 in.), and are bonded to the aluminum airframe by a room-temperature vulcanizing (RTV) silicone adhesive.

Other upper surface regions that are exposed to higher temperatures, not to exceed 815°C (1500°F), are protected by blankets of an *advanced flexible reusable surface insulation (AFRSI)*. These blankets consist of a quartz fiber batting that is sandwiched between a high-temperature woven quartz fabric on the outer side and a lower-temperature glass fabric on the inner side. The outer surface of some regions is also protected with a ceramic coating. Furthermore, these three layers are stitched together using quartz and glass threads in a one-inch square pattern. AFRSI blanket thicknesses range between 10 mm (0.41 in.) and just under 50 mm (2 in.). Over most vehicle regions, these AFRSI blankets are bonded to the structure by a silicone RTV adhesive, as with the FRSI insulation.

### CERAMIC TILE SYSTEMS

More rigid material restrictions are imposed on regions of the Space Shuttle that are exposed to temperatures in the range of 400 to 1260°C (750 to 2300°F). For these areas it was decided to use a relatively complex ceramic material in the form of tiles. Ceramics are intrinsically thermal insulators and, furthermore, will withstand these elevated temperatures. The tile design is utilized for the protection system to conform to the contours of the Shuttle's surface, and also to accommodate the thermal dimensional changes accompanying the extremes of temperature that are experienced during a typical mission.

Each Shuttle has on the average of 24,300 of these tiles, which comprise approximately 70% of the total orbiter exterior area. No two tiles have exactly the same configuration, but sizes range from between about 150 mm by 150 mm (6 in. by 6 in.) to about 200 mm by 200 mm (8 in. by 8 in.). Tile thicknesses vary between 5 mm (0.2 in.) and 90 mm (3.5 in.). Each tile is precisely machined to its individual shape using diamond tools on a computer-controlled mill. Figure 23.17 is a photograph that shows the tiles being installed.

Tiles having three densities are used, which are designated by LI-900, FRCI-12, and LI-2200; the respective densities of these materials are 0.14 g/cm<sup>3</sup> (9 lb<sub>m</sub>/ft<sup>3</sup>), 0.19 g/cm<sup>3</sup> (12 lb<sub>m</sub>/ft<sup>3</sup>), and 0.35 g/cm<sup>3</sup> (22 lb<sub>m</sub>/ft<sup>3</sup>). The LI-900 and LI-2200 materials are fabricated using very high-purity silica fibers, having diameters ranging between 1 and 4 μm and lengths on the order of 3 mm (0.13 in.). Fiber-to-fiber bonds are established by a sintering heat treatment at 1370°C (2500°F), which gives rise to a very porous and lightweight material. The microstructure of a typical tile is shown in the scanning electron micrograph, Figure 23.18. On the other hand, FRCI tiles are composed of a 78% silica fiber-22% aluminum borosilicate fiber composite; the FRCI designation comes from *Fibrous Refractory Composite Insulation*.

The strengths of the LI-2200 and FRCI tiles are virtually equivalent, being greater than that of LI-900. LI-2200 and FRCI are used in those locations where a higher strength is required, such as around doors and access panels. Employment



**FIGURE 23.17** Photograph showing the installation of thermal protection ceramic tiles on the Space Shuttle Orbiter. [Photograph courtesy the National Aeronautics and Space Administration (NASA).]

of FRCI instead of LI-2200 reduced orbiter weight by approximately 450 kg (1000 lb<sub>m</sub>). Most tiles on the orbiters are the LI-900 type.

These low-density silica fiber materials are ideal for the Shuttle's Thermal Protection System. Being approximately 93 vol% void, they are excellent thermal insulators; this is confirmed by the photograph on page 658, which shows a man holding a very hot cube of the tile material in his bare hands. Furthermore, silica has an extremely low coefficient of thermal expansion (Table 20.1) as well as a relatively small modulus of elasticity (Table 13.5); thus, it is very resistant to thermal shock associated with rapid temperature changes (Equation 20.8). Also, silica may be heated to relatively high temperatures without softening; short-term exposures to temperatures as high as 1480°C (2700°F) are possible.

The properties of the tiles are anisotropic; they are designed to be strongest in the plane of the tile and to be most thermally insulative in the direction perpendicular to this plane.



**FIGURE 23.18** Scanning electron micrograph of a Space Shuttle Orbiter ceramic tile showing silica fibers that were bonded to one another during a sintering heat treatment. 750×. (Photograph provided courtesy of Lockheed Aerospace Ceramics Systems, Sunnyvale, California.)

Tiles on surfaces exposed to maximum temperatures in the range of 400 to 650°C (750 to 1200°F) (i.e., upper vehicle sides, and upper wing and tail surfaces) are coated with a thin layer (0.30 mm [0.012 in.] thick) of a high-emittance borosilicate glass. This tile type is referred to as a *low-temperature reusable surface insulation (LRSI)*; the tile surface is white, which reflects the sun's rays and keeps the Shuttle relatively cool while in orbit. Locations of the LRSI tiles are indicated in Figure 23.16.

Those tiles that are exposed to higher maximum temperatures between 650°C (1200°F) and 1260°C (2300°F) (i.e., the vehicle underbody, and tail leading and trailing edges) receive a black coating consisting of the same borosilicate glass and, in addition, silicon tetraboride ( $\text{SiB}_4$ ); this coating material is sometimes termed a *reaction cured glass (RCG)*. Being of high optical emittance, this coating is able to radiate approximately 90% of the reentry heat generated away from the Shuttle either into the earth's atmosphere or into deep space. This type of tile is termed a *high-temperature reusable surface insulation (HRSI)*, and its locations on the Shuttle are also noted in Figure 23.16.

It is also necessary to isolate and cushion the brittle ceramic tiles from the mechanical and thermal strains sustained by the airframe and, in addition, to attach the tiles to the airframe. This is accomplished by an assembly consisting of a *strain isolator pad (SIP)*, a *filler bar*, and a silicone RTV adhesive that bonds the tile to the SIP and the SIP and filler bar to the airframe structure. A schematic diagram of this assembly is shown in Figure 23.19. The strain isolator pad is composed of a nylon felt that will sustain repeated heatings to 290°C (550°F); this pad isolates the tiles from airframe deflections.

Beneath the tile-to-tile junctions are located the filler bars. They are of the same nylon felt to which an RTV outer coating has been applied. The thickness of these bars is greater than the strain isolator pad, and, as such, they form a gasket seal to the undersurface of the tiles and protect the strain isolator pads from water or plasma penetration through the tile-to-tile junctions.

The adhesive that bonds this system together and to the airframe must survive repeated exposures to at least 290°C (550°F), must cure at room temperature, and

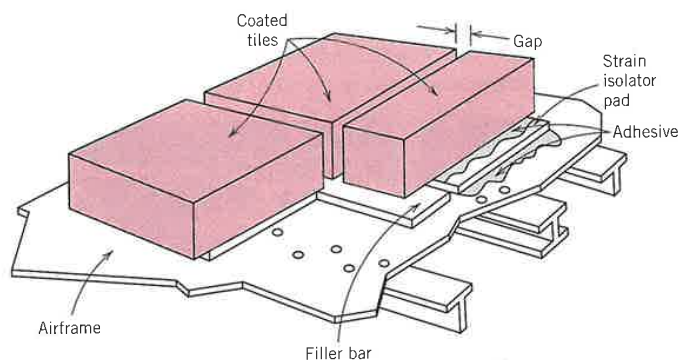


**FIGURE 23.19** Schematic cross section of the tile component of the Space Shuttle Orbiter's thermal protection system. (From L. J. Korb, C. A. Morant, R. M. Calland, and C. S. Thatcher, "The Shuttle Orbiter Thermal Protection System," *Ceramic Bulletin*, No. 11, Nov. 1981, p. 1189. Copyright 1981. Reprinted by permission of the American Ceramic Society.)

must be capable of filling any irregularities in the airframe structure. The only material that fulfills all these requirements is a silicone RTV adhesive.

### REINFORCED CARBON-CARBON

During reentry, some shuttle orbiter surface regions are exposed to temperatures in excess of those that the ceramic tiles are capable of sustaining ( $1260^{\circ}\text{C}$  [ $2300^{\circ}\text{F}$ ]). Specifically, these areas are the nose cap and wing leading edges, Figure 23.15, where temperatures may reach as high as  $1650^{\circ}\text{C}$  ( $3000^{\circ}\text{F}$ ). The material that was designed for use in these locations is a *reinforced carbon-carbon* (RCC) composite. It is also a relatively complex material consisting of a carbon matrix that is reinforced with graphite fibers; the surface is coated with a thin layer of silicon carbide (SiC) as a protection against oxidation. This composite material is suitable for these high-temperature locations for the following reasons: strength and stiffness are retained up to the maximum service temperatures; it has a low coefficient of thermal expansion, and thus will not experience significant thermal stresses and deflections; it is highly resistant to thermal shock and fatigue; its density is very low; and fabrication into complex shapes is possible. Figure 23.16 shows those areas where this RCC composite material is employed.

Of course, materials other than those already cited are used on the Orbiter. For example, window ports are made of glass materials. Also, as may be noted from Figure 23.16, metal alloys are used for some exposed surfaces. These alloys will typically have high melting temperatures and, preferably, relatively low densities. Examples include beryllium, niobium, titanium, stainless steel (alloys 316), and several superalloys (Inconel alloys 718, 625, 750, and Haynes alloy 188).

## MATERIALS FOR INTEGRATED CIRCUIT PACKAGES

### 23.12 INTRODUCTION

The microelectronic circuitry, including the integrated circuits that are used in our modern computers, calculators, and other electronic devices, was briefly discussed in Section 19.14. The heart of the integrated circuit (abbreviated *IC*) is the *chip*, a small rectangular substrate of high-purity and single-crystal silicon (or more recently gallium arsenide) onto which literally thousands of circuit elements are imprinted. Circuit elements (i.e., transistors, resistors, diodes, etc.) are created by selectively adding controlled concentrations of specific impurities to extremely minute and localized regions near the surface of the semiconducting material using involved photolithographic techniques. The chips are small in size, with the largest being on the order of 6 mm ( $\frac{1}{4}$  in.) on each side and approximately 0.4 mm (0.015 in.) thick. Photographs of a typical chip are shown in Figure 19.25.

Furthermore, chips are very fragile inasmuch as silicon is a relatively brittle material and gallium arsenide is even more brittle. It is also necessary to fabricate conducting circuit paths over the surface of the chip so as to facilitate the passage of current from device to device; on silicon ICs the metal conductor used is aluminum or an aluminum-silicon alloy (99 wt% Al, 1 wt% Si) which is metallized onto the chip surface to form a very thin film. The chip design also calls for these circuit paths to terminate at contact pads on the chip periphery, at which points electrical

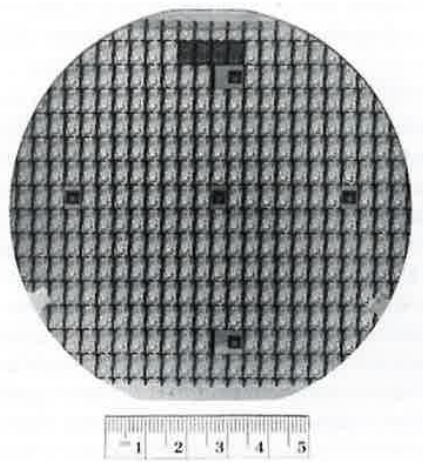


**FIGURE 23.20** Photograph of a 100-mm-diameter (4-in.-diameter) silicon wafer. Each of the small rectangles shown is an individual IC chip or die.

connections may be made with the macroscopic world. It should be obvious that a functioning microelectronic chip is a very sophisticated electronic entity, that materials requirements are very stringent, and that elegant processing techniques are involved in its fabrication.

A large number of IC chips are fabricated onto a circular thin wafer of single-crystal Si, as shown in the photograph in Figure 23.20. Single crystals of Si having diameters as large as 200 mm (8 in.) are routinely grown. The small rectangular ICs arrayed in the manner shown in the photograph are collectively referred to as *dice*. Each IC or *die* (singular of dice) is first tested for functionality, after which it is removed from the wafer in a meticulous sawing or “scribe and break” operation. Next, the die is mounted in some type of *package*. The packaged IC may then be bonded to a printed circuit board. The purpose of this section is to discuss the material requirements and some of the materials that are used for the various IC package components.

Some of the functions that an integrated circuit package must perform include the following:

1. To permit electrical contact between the devices on the chip and the macroscopic world. The contact pads on the surface of the IC are so minuscule and numerous that accommodation of macroscopic wiring is simply not possible.
2. To dissipate excess heat. While in operation, the many electronic devices generate significant quantities of heat, which must be dissipated away from the chip.
3. To protect delicate electrical connections on the chip from chemical degradation and contamination.
4. To provide mechanical support so that the small and fragile chip may be handled.
5. To provide an adequate electrical interface such that the performance of the IC itself is not significantly degraded by the package design.

Thus, IC packaging also poses a host of material demands that are very challenging. In fact, it has been noted that the performance of some ICs is limited, not by

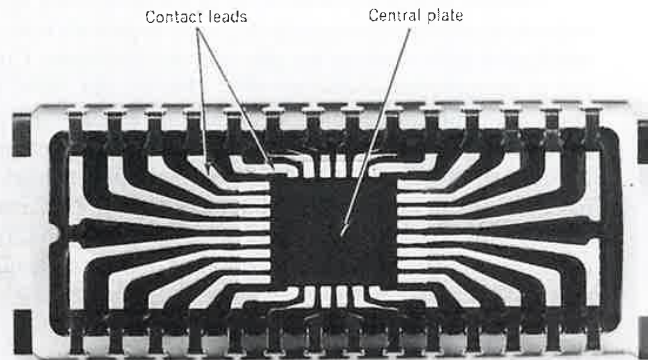
the characteristics of the semiconducting materials nor by the metallization process, but rather by the quality of the package. There are a number of different package designs used by the various IC manufacturers. For one of the common designs, the *leadframe*, we have elected to discuss the various components and, for each component, the materials that are employed along with their property limitations. This package design is popular with digital IC manufacturers primarily because its production can be highly automated.

### 23.13 LEADFRAME DESIGN AND MATERIALS

The leadframe, as the name suggests, is a frame to which electrical leads may be made from the IC chip. A photograph of a leadframe-type package is shown in Figure 23.21. In essence, the leadframe consists of a central plate onto which the die is mounted, and an array of contact leads to which wire connections may be made from the contact pads on the chip. Some leadframe designs also call for a substrate onto which the die is mounted, which substrate is, in turn, bonded to the central plate. During the packaging process, and after the chip has been attached to the central plate (a procedure termed *die bonding*), the contact pads on the IC chip are cleaned, wires are attached to both the contact pads and the leadframe leads (called *wire bonding*), and, finally, this package is encapsulated in a protective enclosure so as to seal out moisture, dust, and other contaminants. This procedure is called *hermetic sealing*.

There are some rather stringent requirements on the properties of the material to be used for the leadframe; these are as follows: (1) The leadframe material must have a high electrical conductivity, inasmuch as there will be current passage through its leads. (2) The leadframe, the die attach central plate, substrate (if present), and die-bonding adhesive must also be thermally conductive so as to facilitate the dissipation of heat generated by the IC. (3) A coefficient of thermal expansion comparable to that of Si is highly desirable; a thermal expansion mismatch could destroy the integrity of the bond between the IC and the central plate as a result of thermal cycling during normal operation. (4) The leadframe material and sub-

**FIGURE 23.21**  
Photograph of a leadframe on which the central plate and contact leads are labeled. 2×.  
(Leadframe supplied by National Semiconductor Corporation. Photograph by Dennis Haynes.)



strate must also adhere to the die-bonding adhesive, and the adhesive and substrate must also be electrically conductive. (5) A secure and electrically conductive joint between the leadframe and the connecting wires must be possible. (6) The leadframe must be resistant to oxidation and retain its mechanical strength during any thermal cycling that may accompany the die-bonding and encapsulation procedures. (7) The leadframe must also withstand corrosive environments at high temperatures and high humidities. (8) It must be possible to mass produce the leadframes economically. Normally, they are stamped from thin metal sheets.

A parenthetical comment is in order relative to the electrical characteristics of the substrate and die-bonding adhesive. In the preceding paragraph it was noted that the materials used for these two leadframe components must be electrically conductive. This is inconsistent with the ceramic materials used for packaging substrates which, as discussed in Section 14.18, must be electrical insulators. This discrepancy is resolved when it is realized that some package designs call for grounding of the IC chip through the substrate, whereas for other designs, grounding is through the contact wires.

Several alloys have been used for the leadframe with varying degrees of success. The most commonly used materials are copper-based alloys; the compositions, electrical and thermal conductivities, and coefficients of thermal expansion for two of the most popular ones (C19400 and C19500) are listed in Table 23.6. For the most part, they satisfy the criteria listed in the preceding paragraph. Also listed in the table are the compositions of two other alloys (Kovar and Alloy 42) that have been used extensively in leadframes. The desirability of these latter two alloys lies in their relatively low coefficients of thermal expansion, which are closely matched to that of Si [i.e.,  $2.5 \times 10^{-6} (\text{°C})^{-1}$ ]. However, from Table 23.6 it may also be noted that both electrical and thermal conductivities for Kovar and Alloy 42 are inferior to the conductivity values for the C19400 and C19500 alloys.

### 23.14 DIE BONDING

The die-bonding operation consists of attaching the IC chip to the central supporting leadframe plate. For the copper alloys noted in Table 23.6, attachment may be made using a gold–silicon eutectic solder; however, melting of the solder requires heating the assembly to 500°C (900°F).

Another adhesive possibility is an epoxy bonding agent, which is normally filled with metal particles (frequently Ag) so as to provide both a thermally and electrically conductive path between the chip and the leadframe. Curing of the epoxy is carried out at temperatures between 60°C (140°F) and 350°C (660°F) depending on the application. Since the amounts of thermal expansion are different for the Cu alloy leadframe plate and Si chip, the epoxy adhesive must be capable of absorbing any thermal strains produced during temperature changes such that the mechanical integrity of the junction is maintained. Figure 23.22a shows a schematic diagram of a chip that is bonded to a substrate layer that is, in turn, bonded to the leadframe plate. Figure 23.22b is a photograph of a chip, its leadframe, and the connecting wires.

### 23.15 WIRE BONDING

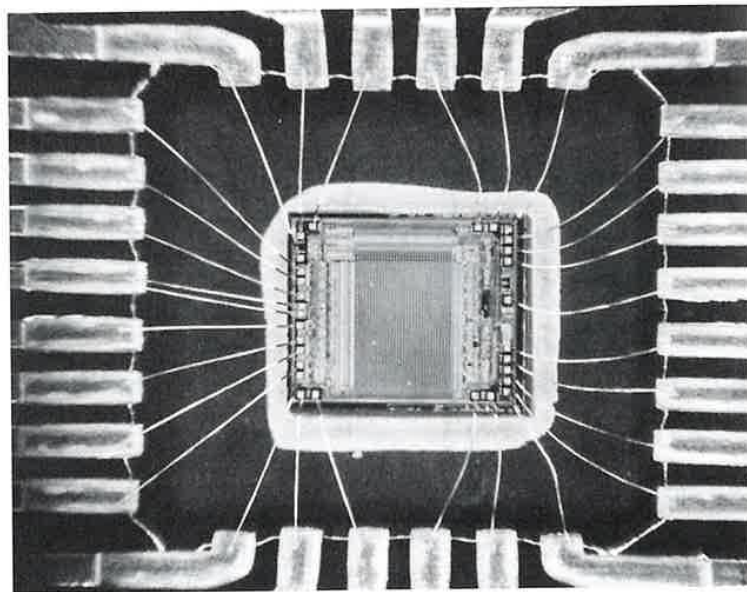
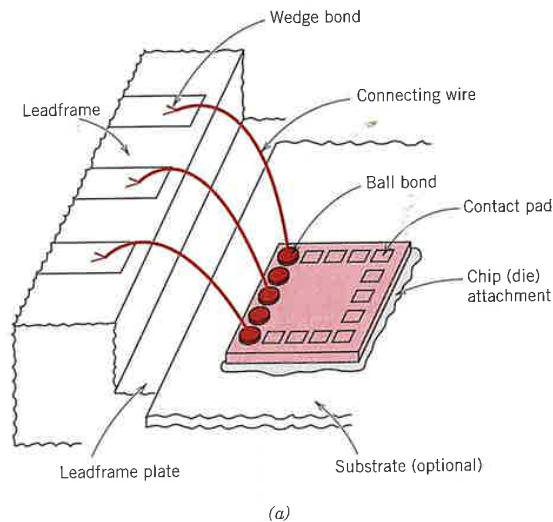
The next step in the packaging process involves making electrical connections between the metallized chip pads and the leadframe; this is accomplished using connecting wires (Figures 23.22a and 23.22b). A wire-bonding procedure is normally

**Table 23.6** Designations, Compositions, Electrical and Thermal Conductivities, and Coefficients of Thermal Expansion for Common IC Leadframe Alloys

| Alloy Designation   | Composition (wt%) |    |     |                                | Electrical Conductivity<br>[ $10^6 (\Omega \cdot m)^{-1}$ ] | Thermal Conductivity<br>(W/m-K) | Coefficient of Thermal Expansion <sup>a</sup><br>[ $10^{-6} (^\circ C)^{-1}$ ] |
|---------------------|-------------------|----|-----|--------------------------------|-------------------------------------------------------------|---------------------------------|--------------------------------------------------------------------------------|
|                     | Fe                | Ni | Co  | Cu                             |                                                             |                                 |                                                                                |
| C19400              | 2.35              |    |     | Balance                        | 39.4                                                        | 260                             | 16.3                                                                           |
|                     |                   |    |     | 0.03 P, 0.12 Zn, 0.03 Pb (max) |                                                             |                                 |                                                                                |
| C19500              | 1.5               |    | 0.8 | Balance                        | 29.1                                                        | 200                             | 16.9                                                                           |
| Kovar (ASTM F15)    | 54                | 29 | 17  | 0.6 Sn, 0.03 P                 | 2.0                                                         | 17                              | 5.1                                                                            |
| Alloy 42 (ASTM F30) | 58                | 42 |     |                                | 1.4                                                         | 12                              | 4.9                                                                            |

<sup>a</sup> Coefficient of thermal expansion values are averages measured between 20°C and 300°C.

**FIGURE 23.22** (a) Schematic diagram showing the IC chip, its attachment to the substrate (or leadframe plate), and the connecting wires that run to the leadframe contact leads. (Adapted from *Electronic Materials Handbook*, Vol. 1, *Packaging*, C. A. Dostal, editor, ASM International, 1989, p. 225.) (b) Photograph showing a portion of a leadframe package. Included is the IC chip along with its connecting wires. One end of each wire is bonded to a chip pad; the other wire extremity is bonded to a leadframe contact lead.  $7\frac{1}{2}\times$ . (Photograph courtesy of National Semiconductor Corporation.)



carried out using a microjoining operation, since very fine wires are used to make the connections. Wire bonding is the slow step in the packaging process because several hundred wires may need to be installed; this procedure is usually automated.

Several important considerations must be taken into account relative to the choice of wire alloy. Of course, a high electrical conductivity is the prime prerequisite. In addition, consideration must be given to the ability of the alloy to bond, by welding or brazing, with both the Al alloy at the chip pad and the Cu alloy on the leadframe; the formation of a microjoint that is both mechanically and electrically stable is an absolute necessity.

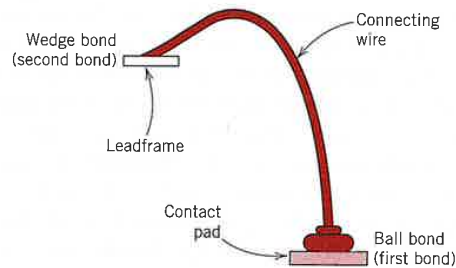


**FIGURE 23.23** Schematic diagram showing a connecting wire that is ball bonded to the IC contact pad and wedge bonded to the leadframe. (Adapted from *Electronic Materials Handbook*, Vol. 1, *Packaging*, C. A. Dostal, editor, ASM International, 1989, p. 225.)

The most commonly used wire material is gold—actually a gold alloy containing a small amount of beryllium–copper that is added to inhibit grain growth. Gold wires are round and have diameters that are typically  $18\text{ }\mu\text{m}$  (0.0007 in.),  $25\text{ }\mu\text{m}$  (0.001 in.), or  $50\text{ }\mu\text{m}$  (0.002 in.). Less costly Cu and Al have also been employed for contact wires. Prior to making the microjoint, regions of the chip pad and leadframe surfaces at which the junctions are to be made may be coated with Au so as to improve bondability. During the actual microjoining process, one wire end is brought into the vicinity of one of the joint regions using a special tool. This wire end is then melted with a spark or flame heat source.

Two different types of microjoints are possible: ball and wedge. Figure 23.23 is a schematic diagram showing a connecting wire having a ball microjoint at its contact pad end and a wedge microjoint at the leadframe connection. Ball joints are possible for gold wires since the melted wire end forms into a small ball because of the high surface tension of gold. Bonding of this molten ball with the contact pad or leadframe is accomplished by making mechanical contact with the bonding surface while both wire and surface are subjected to ultrasonic vibrations. A scanning electron micrograph of a ball microjoint is shown in Figure 23.24a. This type of

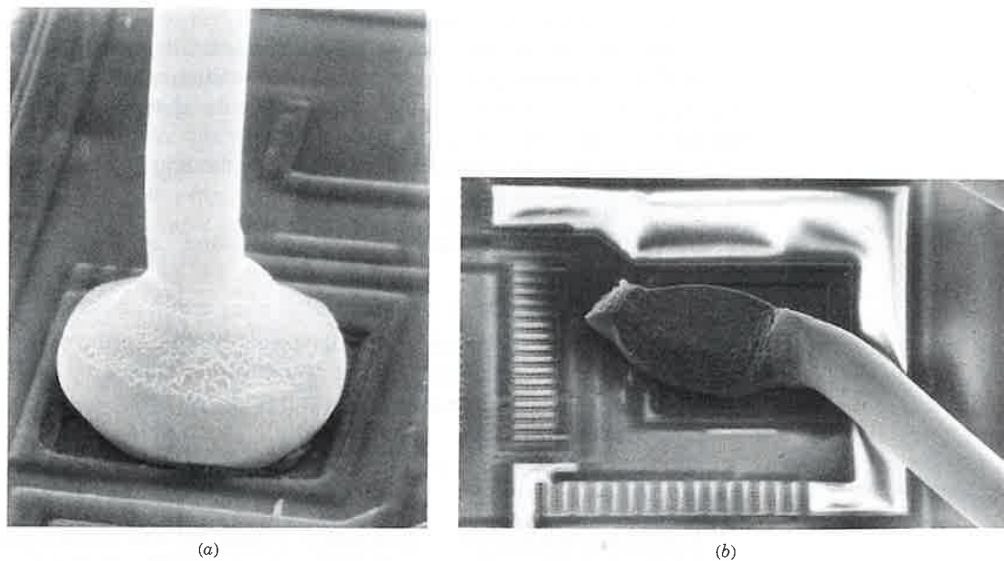


**FIGURE 23.24** Scanning electron micrographs of (a) a ball bond (475 $\times$ ), and (b) a wedge bond (275 $\times$ ). (Photographs courtesy of National Semiconductor Corporation.)

microjoint is especially desirable since, after the first of the two microjoints for each wire has been made (usually on the IC contact pad), the wire may then be bent in any direction in preparation for the microjoining of its other extremity.

The ends of copper and aluminum wires do not form balls upon melting. They are wedge microjoined by positioning the wire between a vibrating probe and the contact pad or leadframe surface; the vibrations loosen and remove surface contaminants, which results in intimate contact of the two surfaces. An electric current is then applied through the probe, which welds the wire to the surface. Unfortunately, the bending motion of wedge-bonded wires is restricted to a single direction. Gold wires may also be bonded using wedge microjoints. Figure 23.24b is a scanning electron micrograph of a wedge microjoint.

There are other considerations relative to wire bonding that deserve mentioning. Microjunction alloy combinations that form intermetallic phases should be avoided because these phases are normally brittle and yield microjoints lacking long-term mechanical stability. For example, Au and Al may react at elevated temperatures to form  $\text{AuAl}_2$ , termed the "purple plague"; this compound is not only very brittle (and purple), but also highly electrically resistive. Furthermore, mechanical integrity at each microjoint is important so as to (1) withstand vibrations that the package may experience, and (2) survive thermal stresses that are generated as the packaging materials change temperature.

## 23.16 PACKAGE ENCAPSULATION

The microelectronic package, as now constituted, must be provided some type of protection from corrosion, contamination, and damage during handling and while in service. The wire interconnection microjunctions are extremely fragile and may be easily damaged. Especially vulnerable to corrosion are the narrow Al circuit paths that have been metallized onto the surface of the IC chip; even the slightest corrosion of these elements will impair the operation of the chip. These Al-metallized layers experience corrosion when atmospheric moisture in which even minute concentrations of ionic contaminants are dissolved (especially chlorine and phosphorus) condenses on the chip surface. Furthermore, the corrosive reactions are accelerated as a consequence of electric currents that pass through these circuit paths. In addition, any sodium (as  $\text{Na}^+$ ) that gets on the chip surface will eventually diffuse into the chip and destroy its operation.

The material used to encapsulate the package should:

1. Be electrically insulating;
2. Be easily molded to the desired shape around the chip die and its wire leads;
3. Be highly impervious to the penetration of moisture and contaminants;
4. Be able to form strong adhesive bonds with the chip surface, wires, and other leadframe components;
5. Exhibit mechanical and chemical stability for the expected lifetime of the package;
6. Not require exposure to excessively high temperatures during installation;
7. Have a coefficient of thermal expansion similar to those of other package components so as to avoid thermal stresses capable of fracturing the wire leads.

Figure 23.25 shows a schematic diagram of an encapsulated IC package.

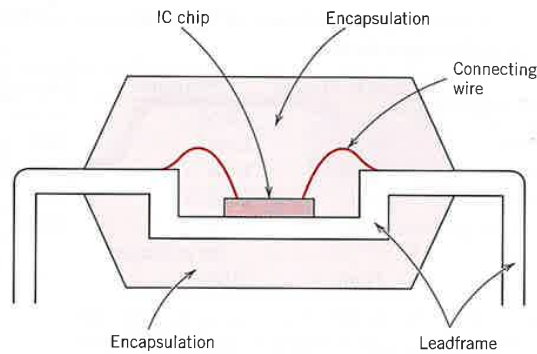


**FIGURE 23.25** Schematic diagram showing an encapsulated IC leadframe package. (Adapted from *Electronic Materials Handbook*, Vol. 1, *Packaging*, C. A. Dostal, editor, ASM International, 1989, p. 241.)

Both ceramic and polymeric materials are used to encapsulate IC packages; of course each of these material types has its own set of assets and liabilities. Ceramics are extremely resistant to moisture penetration and are chemically stable and chemically inert. Glasses are the most commonly utilized ceramic materials. The principal disadvantage of glass is the requirement that it be heated to moderately high temperatures to lower its viscosity to the point where it will flow around and make intimate contact with all of the wires that are microjoined to the chip surface. Some common glass constituents should be avoided (notably  $\text{Na}_2\text{O}$  and  $\text{K}_2\text{O}$ ) since volatile cation species ( $\text{Na}^+$  and  $\text{K}^+$ ) may be emitted from the molten glass. These species are notorious in accelerating corrosion reactions, and the ions will degrade the chip performance.

Polymeric materials are used in the largest volume for packaging encapsulation because they are not as costly as the ceramics, and they may be produced in a low-viscosity state at lower temperatures. Epoxies and polyurethanes are commonly used, with the former being the most common. However, these materials have a tendency to absorb water and do not form moisture-tight bonds with the lead wires. Some of these polymers require curing at a temperature on the order of  $150^\circ\text{C}$ , and during cooling to room temperature will shrink more than other package components to which they are attached. This difference in amounts of contraction can give rise to mechanical strains of sufficient magnitude to damage the connecting wires as well as other electronic components. The addition of appropriate fillers (such as fine silica or alumina particles) to the polymer can alleviate this problem but often has undesirable electrical consequences. A comparison of the important encapsulation characteristics of four different polymer types is given in Table 23.7.

## 23.17 TAPE AUTOMATED BONDING

Another packaging design, *tape automated bonding* (or *TAB*), a variation of the leadframe discussed above, has found widespread use by virtue of its low cost. The tape-bonded package consists of a thin and flexible polyimide polymer backing film substrate; onto this substrate surface is patterned an array of copper “finger” high-conductivity conduction paths similar in configuration to the contact leads for the conventional leadframe. A schematic diagram of a tape-bonded film leadframe is shown in Figure 23.26.

Mechanical support for the assembly is provided by the polyimide film, onto which the die is bonded using an adhesive. Polyimide strip widths are typically 35 mm (1.38 in.), and sprocket holes are incorporated along opposing edges so as to facilitate movement and positioning of the TAB leadframes. Literally thousands

**Table 23.7** Property Comparisons of Four Classes of Polymers Used for IC Package Encapsulation

|                         | <i>Epoxy Resins</i> | <i>Silicones</i>      | <i>Polyurethanes</i> | <i>Polysulphides</i> |
|-------------------------|---------------------|-----------------------|----------------------|----------------------|
| Dielectric strength     | Good                | Good                  | Good                 | Good                 |
| Elastic modulus         | High                | Low                   | Wide range           | Low                  |
| Tensile strength        | High                | Low                   | Wide range           | —                    |
| Precursor viscosity     | Low                 | Low                   | Low                  | High                 |
| Adhesion to package     | Excellent           | Poor<br>(to ceramics) | Good                 | Good                 |
| Moisture diffusion rate | High                | High                  | Low                  | Very low             |

**Source:** From C. R. M. Grovenor, *Microelectronic Materials*.  
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of these individual units, attached end to end, are spooled onto reels in preparation for automated processing.

The copper fingers are extremely narrow and positioned close together. Separation distances of the inner contact leads are on the order of  $50\text{ }\mu\text{m}$ , which is much smaller than is possible for the stamped leadframe. Furthermore, each die chip contact pad is microjoined directly to one of these copper fingers, which eliminates the need for any connecting wires. The copper fingers are very thin, so that, for this direct bonding to be achieved, the chip pad bonding sites must be raised above the metallized coating. This is accomplished using “solder bumps,” which are normally layers of gold (or gold-plated copper) approximately  $25\text{ }\mu\text{m}$  thick. Schematic representations illustrating this attachment design are presented in Figure 23.27. The finger contacts are bonded to these raised bumps by soldering using a thermal-compression bonding tool. This tape-bonding design is fully automated in that all of the hundred or so microjoints can be made in a single step, a feature not possible with leadframes that require multiple wire-bonding operations.

The packaging operation for the TAB leadframe is completed, as with the stamped leadframe, by encapsulation of the assembly (i.e., tape leadframe and its

**FIGURE 23.26**  
Schematic diagram of  
a complete tape-bonded  
(TAB) leadframe.  
(From *Electronic  
Materials Handbook*,  
Vol. 1, *Packaging*, C.  
A. Dostal, editor, ASM  
International, 1989, p.  
233.)

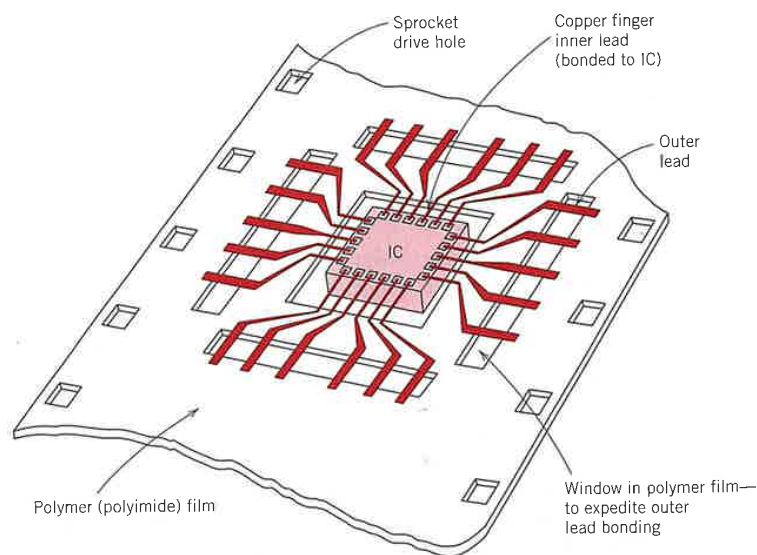
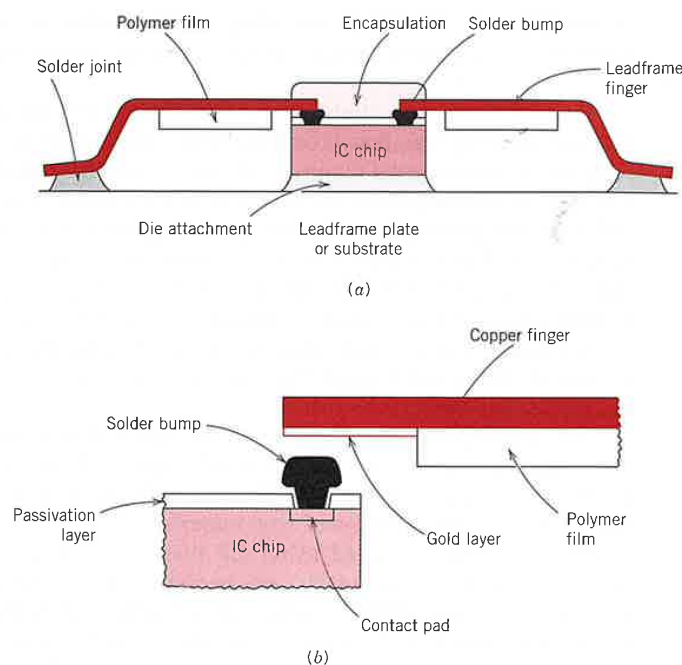


**FIGURE 23.27**

Schematic diagrams showing (a) the cross section of an encapsulated TAB leadframe package, and (b) how bonding between the IC chip and a copper finger is achieved with a solder bump. (Adapted from *Electronic Materials Handbook*, Vol. 1, Packaging, C. A. Dostal, editor, ASM International, 1989, pp. 233, 234.)



attached chip) within a fluid polymeric material that subsequently cures so as to form a protective shield. Protruding from this package are the copper finger conducting paths to which external electrical connections are made. Furthermore, excess heat generated by the chip must be dissipated along these copper fingers inasmuch as the polymer tape backing does not provide an effective thermal conduction path because of its low thermal conductivity.

The ultimate design goal of the IC package is to allow for the proper electrical operation of the packaged device. As frequencies and computing speeds creep ever higher, the mechanical and electrical design considerations of the package design must become more and more integrated. The overall electrical performance of the package is as important to the end user as the overall reliability.

## SUMMARY

In this chapter, we have illustrated the protocol of materials selection using five diverse examples. For the first case, a torsionally stressed cylindrical shaft, an expression for strength performance index was derived; then, using the appropriate materials selection chart, a preliminary candidate search was conducted. From the results of this search, several candidate engineering materials were ranked on both strength-per-unit mass and cost bases. Other factors that are relevant to the decision-making process were also discussed.

A stress analysis was next performed on a helical spring, which was then extended to an automobile valve spring. It was noted that the possibility of fatigue failure was crucial to the performance of this spring application. The shear stress amplitude was computed, the magnitude of which was almost identical to the calculated fatigue limit for a chrome–vanadium steel that is commonly used for valve springs. It was noted that the fatigue limit of valve springs is often enhanced

by shot peening. Finally, a procedure was suggested for assessing the economic feasibility of this spring design incorporating the shot-peened chrome–vanadium steel.

For the third case study, the artificial total hip replacement was explored. The hip anatomy was first presented, which was followed by a discussion of the components and material requirements for the artificial replacement. Implant materials must be biocompatible with body tissues and fluids, must be corrosion resistant, and must also be mechanically compatible with interfacing replacement/body components. The femoral stem and ball are normally made of a cold-worked stainless steel, a hot-forged Co–Ni–Cr–Mo alloy, or a hot-forged titanium alloy. Some recent designs call for a polycrystalline aluminum oxide ball. Ultrahigh molecular weight polyethylene is commonly used for the acetabular cup, whereas acrylic bone cement is normally the fixation agent for attachment of the femoral stem (to the femur) and acetabular cup (to the pelvis).

The thermal protection system on the Space Shuttle was the fourth materials case study considered. Its design presented some very restrictive materials requirements; these were overcome by the incorporation of several different systems as well as by the development of new materials. A felt reusable surface insulation, consisting of silicone-coated nylon felt blankets, is used for those surface areas exposed to relatively low reentry temperatures. The ceramic tiles cover the major portion of the Space Shuttle's surface, areas that are exposed to higher temperatures. This porous insulation is composed of either silica fibers or a combination of silica and aluminum borosilicate fibers. Tiles having several different strengths, densities, and thermal properties are fabricated for utilization at the various locations. A thin glass surface coating is applied to each tile so as to improve either its reflectance or emissive characteristics. Those surface regions of the Shuttle that experience the highest reentry temperatures are constructed of a reinforced carbon–carbon composite that is coated with a thin layer of silicon carbide.

Materials utilized for the integrated circuit package incorporating the leadframe design were the topic of the final case study. An IC chip is bonded to the leadframe plate using either a eutectic solder or an epoxy resin. The leadframe material must be both electrically and thermally conductive, and, ideally, have a coefficient of thermal expansion that matches the IC chip material (i.e., silicon or gallium arsenide); copper alloys are commonly used leadframe materials. Very thin wires (preferably of gold, but often of copper or aluminum) are used to make electrical connections from the microscopic IC chip contact pads to the leadframe. Ultrasonic microjoining welding/brazing techniques are used where each connection joint may be in the form of either a ball or wedge. The final step is package encapsulation, wherein this leadframe–wire–chip assembly is encased in a protective enclosure. Ceramic glasses and polymeric resins are the most common encapsulation materials. Resins are less expensive than glasses and require lower encapsulation temperatures; however, glasses normally offer a higher level of protection.

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## QUESTIONS AND PROBLEMS

### Design Problems

- 23.D1 (a)** Using the procedure as outlined in Section 23.2 ascertain which of the metal alloys listed in Appendix B (and also the database on the CD-ROM), have torsional strength performance indices greater than 12.5 (in SI units), and, in addition, shear strengths greater than 300 MPa. **(b)** Also using the cost database (Appendix C), conduct a cost analysis in the same manner as Section 23.2. For those materials that satisfy the criteria noted in part a, and,

on the basis of this cost analysis, which material would you select for a solid cylindrical shaft? Why?

- 23.D2** In a manner similar to the treatment of Section 23.2, perform a stiffness-to-mass performance analysis on a solid cylindrical shaft that is subjected to a torsional stress. Use the same engineering materials that are listed in Table 23.1. In addition, conduct a material cost analysis. Rank these materials both on the basis of mass of material required and material cost. For glass

and carbon fiber-reinforced composites, assume that the shear moduli are 8.6 and 9.2 GPa, respectively.

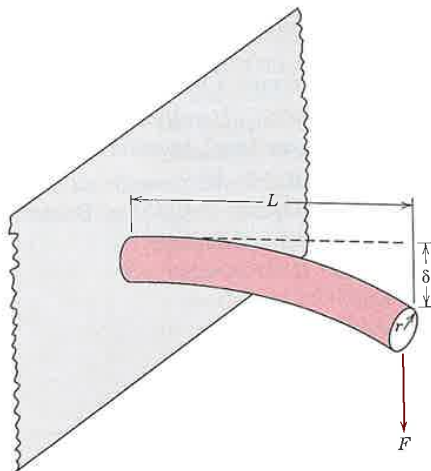
- 23.D3 (a)** A cylindrical cantilever beam is subjected to a force  $F$ , as indicated in the figure below. Derive strength and stiffness performance index expressions analogous to Equations 23.9 and 23.11 for this beam. The stress imposed on the unfixed end  $\sigma$  is

$$\sigma = \frac{FLr}{I} \quad (23.24)$$

$L$ ,  $r$ , and  $I$  are, respectively, the length, radius, and moment of inertia of the beam. Furthermore, the beam-end deflection  $\delta$  is

$$\delta = \frac{FL^3}{3EI} \quad (23.25)$$

where  $E$  is the modulus of elasticity of the beam.



- (b)** From the properties database presented in Appendix B (or on the CD-ROM), select those metal alloys with stiffness performance indices greater than 3.0 (in SI units).

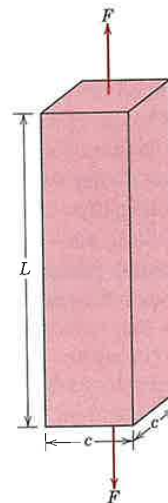
- (c)** Also using the cost database (Appendix C), conduct a cost analysis in the same manner as Section 23.2. Relative to this analysis and that in part b, which alloy would you select on a stiffness-per-mass basis?

- (d)** Now select those metal alloys having strength performance indices greater than 18.0 (in SI units), and rank them from highest to lowest  $P$ .

- (e)** And, using the cost database, rank the materials in part d from least to most costly. Relative to this analysis and that in part d, which alloy would you select on a strength-per-mass basis?

- (f)** Which material would you select if both stiffness and strength are to be considered relative to this application? Justify your choice.

- 23.D4 (a)** A bar specimen having a square cross section of edge length  $c$  is subjected to a uniaxial tensile force  $F$ , as shown in the following figure. Derive strength and stiffness performance index expressions analogous to Equations 23.9 and 23.11 for this bar.



- (b)** From the properties database presented in Appendix B (or on the CD-ROM), select those metal alloys with stiffness performance indices greater than 26.3 (in SI units).

- (c)** Also using the cost database (Appendix C), conduct a cost analysis in the same manner as Section 23.2. Relative to this analysis and that in part b, which alloy would you select on a stiffness-per-mass basis?

(d) Now select those metal alloys having strength performance indices greater than 100 (in SI units), and rank them from highest to lowest  $P$ .

(e) And, using the cost database, rank the materials in part d from least to most costly. Relative to this analysis and that in part d, which alloy would you select on a strength-per-mass basis?

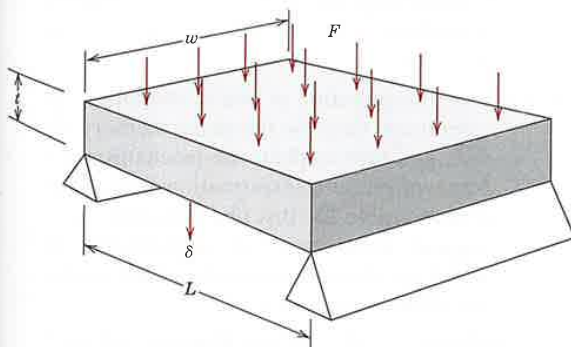
(f) Which material would you select if both stiffness and strength are to be considered relative to this application? Justify your choice.

**23.D5** Consider the plate shown below that is supported at its ends and subjected to a force  $F$  that is uniformly distributed over the upper face as indicated. The deflection  $\delta$  at the  $L/2$  position is given by the expression

$$\delta = \frac{5FL^3}{32Ewt^3} \quad (23.26)$$

Furthermore, the tensile stress at the underside and also at the  $L/2$  location is equal to

$$\sigma = \frac{3FL}{4wt^2} \quad (23.27)$$



(a) Derive stiffness and strength performance index expressions analogous to Equations 23.9 and 23.11 for this plate. (Hint: solve for  $t$  in these two equations, and then substitute the resulting expressions into the mass equation, as expressed in terms of density and plate dimensions.)

(b) From the properties database in Appendix B (or on the CD-ROM), select

those metal alloys with stiffness performance indices greater than 1.50 (in SI units)

(c) Also using the cost database (Appendix C), conduct a cost analysis in the same manner as Section 23.2. Relative to this analysis and that in part b, which alloy would you select on a stiffness-per-mass basis?

(d) Now select those metal alloys having strength performance indices greater than 6.0 (in SI units), and rank them from highest to lowest  $P$ .

(e) And, using the cost database, rank the materials in part d from least to most costly. Relative to this analysis and that in part d, which alloy would you select on a strength-per-mass basis?

(f) Which material would you select if both stiffness and strength are to be considered relative to this application? Justify your choice.

**23.D6** A spring having a center-to-center diameter of 15 mm (0.6 in.) is to be constructed of cold-worked ( $\frac{1}{4}$  hard) 304 stainless steel wire that is 2.0 mm (0.08 in.) in diameter; this spring design calls for ten coils.

(a) What is the maximum tensile load that may be applied such that the total spring deflection will be no more than 5 mm (0.2 in.)?

(b) What is the maximum tensile load that may be applied without any permanent deformation of the spring wire? Assume that the shear yield strength is  $0.6 \sigma_y$ , where  $\sigma_y$  is the yield strength in tension.

**23.D7** You have been asked to select a material for a spring that is to be stressed in tension. It is to consist of 8 coils, and the coil-to-coil diameter called for is 12 mm; furthermore, the diameter of the spring wire must be 1.75 mm. Upon application of a tensile force of 30 N, the spring is to experience a deflection of no more than 10 mm, and not plastically deform.

(a) From those materials included in the database in Appendix B (or on the CD-ROM), make a list of those candidate materials that meet the above criteria. As-

sume that the shear yield strength is  $0.6\sigma_y$ , where  $\sigma_y$  is the yield strength in tension, and that the shear modulus is equal to  $0.4E$ ,  $E$  being the modulus of elasticity.

(b) Now, from this list of candidate materials, select the one you would use for this spring application. In addition to the above criteria, the material must be relatively corrosion resistant, and, of course, capable of being fabricated into wire form. Justify your decision.

- 23.D8** A spring having 10 coils and a coil-to-coil diameter of 0.4 in. is to be made of cold-drawn steel wire. When a tensile load of 12.9 lb<sub>f</sub> is applied the spring is to deflect no more than 0.80 in. The cold drawing operation will, of course, increase the shear yield strength of the wire, and it has been observed that  $\tau_y$  (in ksi) depends on wire diameter  $d$  (in in.) according to

$$\tau_y = \frac{63}{d^{0.2}} \quad (23.28)$$

If the shear modulus for this steel is  $11.5 \times 10^6$  psi, calculate the minimum wire diameter required such that the spring will not plastically deform when subjected to the above load.

- 23.D9** A helical spring is to be constructed from a 4340 steel. The design calls for 12 coils, a coil-to-coil diameter of 12 mm, and a wire diameter of 2 mm. Furthermore, in response to a tensile force of 27 N, the total deflection is to be no more than 3.5 mm. Specify a heat treatment for this 4340 steel wire in order for the spring to meet the above criteria. Assume a shear modulus of 80 GPa for this steel alloy, and that  $\tau_y = 0.6\sigma_y$ .

- 23.D10** Using the *E-Z Solve* software included on the CD-ROM that accompanies this book, construct a routine for the automobile valve spring (Section 23.5) that allows the user to specify the number of effective coils ( $N$ ), the spring coil-to-coil diameter ( $D$ ), and the wire cross-section diameter ( $d$ ), and calculates the fatigue limit ( $\tau_{al}$ ) as well as the actual stress amplitude ( $\tau_{aa}$ ). Incorporate into this routine values cited for installed and maximum deflections per coil

(i.e.,  $\delta_{ic} = 0.24$  in. and  $\delta_{mc} = 0.54$  in.), as well as for the shear modulus of steel ( $G = 11.5 \times 10^6$  psi).

- 23.D11** You have been asked to select a metal alloy to be used as leadframe plate in an integrated circuit package that is to house a silicon chip.

(a) Using the database in Appendix B (or on the CD-ROM) list those materials that are electrically conductive [ $\sigma > 10 \times 10^6$  ( $\Omega\text{-m}$ )<sup>-1</sup>], have linear coefficients of thermal expansion of between  $2 \times 10^{-6}$  and  $10 \times 10^{-6}$  ( $^{\circ}\text{C}$ )<sup>-1</sup>, and thermal conductivities of greater than 100 W/m-K. On the bases of properties and cost, would you consider any of these materials in preference to those listed in Table 23.6? Why or why not?

(b) Repeat this procedure for potential insulating leadframe plate materials that must have electrical conductivities less than  $10^{-10}$  ( $\Omega\text{-m}$ )<sup>-1</sup>, as well as coefficients of thermal expansion between  $2 \times 10^{-6}$  and  $10 \times 10^{-6}$  ( $^{\circ}\text{C}$ )<sup>-1</sup>, and thermal conductivities of greater than 30 W/m-K. On the bases of properties and cost (Appendix C), would you consider any of the materials listed in Appendix B (or on the CD-ROM) in preference to aluminum oxide? Why or why not?

- 23.D12** After consultation of one of the following references, describe the shape memory effect, and then explain the mechanism (in terms of phase transformations, etc.) that is responsible for this phenomenon. Now suggest three practical applications in which an alloy displaying this shape memory effect may be utilized.

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- 23.D13** Write an essay on the replacement of metallic automobile components by polymers and composite materials. Address the following issues: (1) Which automotive

components (e.g., crankshaft) now use polymers and/or composites? (2) Specifically what materials (e.g., high-density polyethylene) are now being used? (3) What are the reasons for these replacements?

**23.D14** Perform a case study on material usage for the compact disc, after the manner of those studies described in this chapter. Begin with a brief description of the mechanism by which sounds are stored and then reproduced. Then, cite all of the requisite material properties for this application; finally, note which material is most commonly utilized, and the rationale for its use.

**23.D15** One of the critical components of our modern video cassette recorders (VCRs) is the magnetic recording/playback head. Write an essay in which you address the following issues: (1) the mechanism by which the head records and plays back video/audio signals; (2) the requisite properties for the material from which the head is manufactured; then (3) present at least three likely candidate materials, and the property values for each that make it a viable candidate.

**23.D16** Another group of new materials are the metallic glasses (or amorphous metals).

Write an essay about these materials in which you address the following issues: (1) compositions of some of the common metallic glasses; (2) characteristics of these materials that make them technologically attractive; (3) characteristics that limit their utilization; (4) current and potential uses; and (5) at least one technique that is used to produce metallic glasses.

**23.D17** The transdermal patch has recently become popular as a mechanism for delivering drugs into the human body.

(a) Cite at least one advantage of this drug-delivery system over oral administration using pills and caplets.

(b) Note the limitations on drugs that are administered by transdermal patches.

(c) Make a list of the characteristics required of materials (other than the delivery drug) that are incorporated in the transdermal patch.

**23.D18** Glass, aluminum, and various plastic materials are utilized for beverage containers (page 1). Make a list of the advantages and disadvantages of using each of these three material types; include such factors as cost, recyclability, and energy consumption for container production.

# Appendix A / The International System of Units (SI)

Units in the *International System of Units* fall into two classifications: base and derived. Base units are fundamental and not reducible. Table A.1 lists the base units of interest in the discipline of materials science and engineering.

Derived units are expressed in terms of the base units, using mathematical signs for multiplication and division. For example, the SI units for density are kilogram per cubic meter ( $\text{kg}/\text{m}^3$ ). For some derived units, special names and symbols exist; for example, N is used to denote the newton, the unit of force, which is equivalent to  $1 \text{ kg}\cdot\text{m}/\text{s}^2$ . Table A.2 contains a number of the important derived units.

It is sometimes necessary, or convenient, to form names and symbols that are decimal multiples or submultiples of SI units. Only one prefix is used when a multiple of an SI unit is formed, which should be in the numerator. These prefixes and their approved symbols are given in Table A.3. Symbols for all units used in this book, SI or otherwise, are contained inside the front cover.

**Table A.1** The SI Base Units

| <i>Quantity</i>           | <i>Name</i>  | <i>Symbol</i> |
|---------------------------|--------------|---------------|
| Length                    | meter, metre | m             |
| Mass                      | kilogram     | kg            |
| Time                      | second       | s             |
| Electric current          | ampere       | A             |
| Thermodynamic temperature | kelvin       | K             |
| Amount of substance       | mole         | mol           |

**Table A.2** Some of the SI Derived Units

| <i>Quantity</i>                      | <i>Name</i>              | <i>Formula</i>                                    | <i>Special Symbol<sup>a</sup></i> |
|--------------------------------------|--------------------------|---------------------------------------------------|-----------------------------------|
| Area                                 | square meter             | m <sup>2</sup>                                    | —                                 |
| Volume                               | cubic meter              | m <sup>3</sup>                                    | —                                 |
| Velocity                             | meter per second         | m/s                                               | —                                 |
| Density                              | kilogram per cubic meter | kg/m <sup>3</sup>                                 | —                                 |
| Concentration                        | moles per cubic meter    | mol/m <sup>3</sup>                                | —                                 |
| Force                                | newton                   | kg·m/s <sup>2</sup>                               | N                                 |
| Energy                               | joule                    | kg·m <sup>2</sup> /s <sup>2</sup> , N·m           | J                                 |
| Stress                               | pascal                   | kg/m·s <sup>2</sup> , N/m <sup>2</sup>            | Pa                                |
| Strain                               | —                        | m/m                                               | —                                 |
| Power, radiant flux                  | watt                     | kg·m <sup>2</sup> /s <sup>3</sup> , J/s           | W                                 |
| Viscosity                            | pascal-second            | kg/m·s                                            | Pa·s                              |
| Frequency (of a periodic phenomenon) | hertz                    | s <sup>-1</sup>                                   | Hz                                |
| Electric charge                      | coulomb                  | A·s                                               | C                                 |
| Electric potential                   | volt                     | kg·m <sup>2</sup> /s <sup>2</sup> ·C              | V                                 |
| Capacitance                          | farad                    | s <sup>2</sup> ·C/kg·m <sup>2</sup>               | F                                 |
| Electric resistance                  | ohm                      | kg·m <sup>2</sup> /s <sup>2</sup> ·C <sup>2</sup> | Ω                                 |
| Magnetic flux                        | weber                    | kg·m <sup>2</sup> /s·C                            | Wb                                |
| Magnetic flux density                | tesla                    | kg/s·C, Wb/m <sup>2</sup>                         | (T)                               |

<sup>a</sup> Special symbols in parentheses are approved in the SI but not used in this text; here, the name is used.

**Table A.3** SI Multiple and Submultiple Prefixes

| <i>Factor by Which Multiplied</i> | <i>Prefix</i>      | <i>Symbol</i> |
|-----------------------------------|--------------------|---------------|
| 10 <sup>9</sup>                   | giga               | G             |
| 10 <sup>6</sup>                   | mega               | M             |
| 10 <sup>3</sup>                   | kilo               | k             |
| 10 <sup>-2</sup>                  | centi <sup>a</sup> | c             |
| 10 <sup>-3</sup>                  | milli              | m             |
| 10 <sup>-6</sup>                  | micro              | μ             |
| 10 <sup>-9</sup>                  | nano               | n             |
| 10 <sup>-12</sup>                 | pico               | p             |

<sup>a</sup> Avoided when possible.

Table B.1 (Continued)

| Material                               | Density  |              |
|----------------------------------------|----------|--------------|
|                                        | $g/cm^3$ | $lb_m/in.^3$ |
| Stainless alloy 405                    | 7.80     | 0.282        |
| Stainless alloy 440A                   | 7.80     | 0.282        |
| Stainless alloy 17-7PH                 | 7.65     | 0.276        |
| <b>Cast Irons</b>                      |          |              |
| Gray irons                             |          |              |
| • Grade G1800                          | 7.30     | 0.264        |
| • Grade G3000                          | 7.30     | 0.264        |
| • Grade G4000                          | 7.30     | 0.264        |
| Ductile irons                          |          |              |
| • Grade 60-40-18                       | 7.10     | 0.256        |
| • Grade 80-55-06                       | 7.10     | 0.256        |
| • Grade 120-90-02                      | 7.10     | 0.256        |
| <b>Aluminum Alloys</b>                 |          |              |
| Alloy 1100                             | 2.71     | 0.0978       |
| Alloy 2024                             | 2.77     | 0.100        |
| Alloy 6061                             | 2.70     | 0.0975       |
| Alloy 7075                             | 2.80     | 0.101        |
| Alloy 356.0                            | 2.69     | 0.0971       |
| <b>Copper Alloys</b>                   |          |              |
| C11000 (electrolytic tough pitch)      | 8.89     | 0.321        |
| C17200 (beryllium-copper)              | 8.25     | 0.298        |
| C26000 (cartridge brass)               | 8.53     | 0.308        |
| C36000 (free-cutting brass)            | 8.50     | 0.307        |
| C71500 (copper-nickel, 30%)            | 8.94     | 0.323        |
| C93200 (bearing bronze)                | 8.93     | 0.322        |
| <b>Magnesium Alloys</b>                |          |              |
| Alloy AZ31B                            | 1.77     | 0.0639       |
| Alloy AZ91D                            | 1.81     | 0.0653       |
| <b>Titanium Alloys</b>                 |          |              |
| Commercially pure (ASTM grade 1)       | 4.51     | 0.163        |
| Alloy Ti-5Al-2.5Sn                     | 4.48     | 0.162        |
| Alloy Ti-6Al-4V                        | 4.43     | 0.160        |
| <b>Precious Metals</b>                 |          |              |
| Gold (commercially pure)               | 19.32    | 0.697        |
| Platinum (commercially pure)           | 21.45    | 0.774        |
| Silver (commercially pure)             | 10.49    | 0.379        |
| <b>Refractory Metals</b>               |          |              |
| Molybdenum (commercially pure)         | 10.22    | 0.369        |
| Tantalum (commercially pure)           | 16.6     | 0.599        |
| Tungsten (commercially pure)           | 19.3     | 0.697        |
| <b>Miscellaneous Nonferrous Alloys</b> |          |              |
| Nickel 200                             | 8.89     | 0.321        |
| Inconel 625                            | 8.44     | 0.305        |
| Monel 400                              | 8.80     | 0.318        |
| Haynes alloy 25                        | 9.13     | 0.330        |
| Invar                                  | 8.05     | 0.291        |

**Table B.1** (Continued)

| <b>Material</b>                                           | <b>Density</b>          |                                       |
|-----------------------------------------------------------|-------------------------|---------------------------------------|
|                                                           | <b>g/cm<sup>3</sup></b> | <b>lb<sub>m</sub>/in.<sup>3</sup></b> |
| Super invar                                               | 8.10                    | 0.292                                 |
| Kovar                                                     | 8.36                    | 0.302                                 |
| Chemical lead                                             | 11.34                   | 0.409                                 |
| Antimonial lead (6%)                                      | 10.88                   | 0.393                                 |
| Tin (commercially pure)                                   | 7.17                    | 0.259                                 |
| Lead-Tin solder (60Sn-40Pb)                               | 8.52                    | 0.308                                 |
| Zinc (commercially pure)                                  | 7.14                    | 0.258                                 |
| Zirconium, reactor grade 702                              | 6.51                    | 0.235                                 |
| <b>GRAPHITE, CERAMICS, AND SEMICONDUCTING MATERIALS</b>   |                         |                                       |
| Aluminum oxide                                            |                         |                                       |
| • 99.9% pure                                              | 3.98                    | 0.144                                 |
| • 96%                                                     | 3.72                    | 0.134                                 |
| • 90%                                                     | 3.60                    | 0.130                                 |
| Concrete                                                  | 2.4                     | 0.087                                 |
| Diamond                                                   |                         |                                       |
| • Natural                                                 | 3.51                    | 0.127                                 |
| • Synthetic                                               | 3.20–3.52               | 0.116–0.127                           |
| Gallium arsenide                                          | 5.32                    | 0.192                                 |
| Glass, borosilicate (Pyrex)                               | 2.23                    | 0.0805                                |
| Glass, soda-lime                                          | 2.5                     | 0.0903                                |
| Glass ceramic (Pyroceram)                                 | 2.60                    | 0.0939                                |
| Graphite                                                  |                         |                                       |
| • Extruded                                                | 1.71                    | 0.0616                                |
| • Isostatically molded                                    | 1.78                    | 0.0643                                |
| Silica, fused                                             | 2.2                     | 0.079                                 |
| Silicon                                                   | 2.33                    | 0.0841                                |
| Silicon carbide                                           |                         |                                       |
| • Hot pressed                                             | 3.3                     | 0.119                                 |
| • Sintered                                                | 3.2                     | 0.116                                 |
| Silicon nitride                                           |                         |                                       |
| • Hot pressed                                             | 3.3                     | 0.119                                 |
| • Reaction bonded                                         | 2.7                     | 0.0975                                |
| • Sintered                                                | 3.3                     | 0.119                                 |
| Zirconia, 3 mol% Y <sub>2</sub> O <sub>3</sub> , sintered | 6.0                     | 0.217                                 |
| <b>POLYMERS</b>                                           |                         |                                       |
| Elastomers                                                |                         |                                       |
| • Butadiene-acrylonitrile (nitrile)                       | 0.98                    | 0.0354                                |
| • Styrene-butadiene (SBR)                                 | 0.94                    | 0.0339                                |
| • Silicone                                                | 1.1–1.6                 | 0.040–0.058                           |
| Epoxy                                                     | 1.11–1.40               | 0.0401–0.0505                         |
| Nylon 6,6                                                 | 1.14                    | 0.0412                                |
| Phenolic                                                  | 1.28                    | 0.0462                                |
| Polybutylene terephthalate (PBT)                          | 1.34                    | 0.0484                                |
| Polycarbonate (PC)                                        | 1.20                    | 0.0433                                |
| Polyester (thermoset)                                     | 1.04–1.46               | 0.038–0.053                           |
| Polyetheretherketone (PEEK)                               | 1.31                    | 0.0473                                |
| Polyethylene                                              |                         |                                       |
| • Low density (LDPE)                                      | 0.925                   | 0.0334                                |
| • High density (HDPE)                                     | 0.959                   | 0.0346                                |

**Table B.1** (Continued)

| <i>Material</i>                                          | <i>Density</i>          |                                       |
|----------------------------------------------------------|-------------------------|---------------------------------------|
|                                                          | <i>g/cm<sup>3</sup></i> | <i>lb<sub>m</sub>/in.<sup>3</sup></i> |
| • Ultrahigh molecular weight (UHMWPE)                    | 0.94                    | 0.0339                                |
| Polyethylene terephthalate (PET)                         | 1.35                    | 0.0487                                |
| Polymethyl methacrylate (PMMA)                           | 1.19                    | 0.0430                                |
| Polypropylene (PP)                                       | 0.905                   | 0.0327                                |
| Polystyrene (PS)                                         | 1.05                    | 0.0379                                |
| Polytetrafluoroethylene (PTFE)                           | 2.17                    | 0.0783                                |
| Polyvinyl chloride (PVC)                                 | 1.30–1.58               | 0.047–0.057                           |
| <b>FIBER MATERIALS</b>                                   |                         |                                       |
| Aramid (Kevlar 49)                                       | 1.44                    | 0.0520                                |
| Carbon (PAN precursor)                                   |                         |                                       |
| • Standard modulus                                       | 1.78                    | 0.0643                                |
| • Intermediate modulus                                   | 1.78                    | 0.0643                                |
| • High modulus                                           | 1.81                    | 0.0653                                |
| E Glass                                                  | 2.58                    | 0.0931                                |
| <b>COMPOSITE MATERIALS</b>                               |                         |                                       |
| Aramid fibers-epoxy matrix ( $V_f = 0.60$ )              | 1.4                     | 0.050                                 |
| High modulus carbon fibers-epoxy matrix ( $V_f = 0.60$ ) | 1.7                     | 0.061                                 |
| E glass fibers-epoxy matrix ( $V_f = 0.60$ )             | 2.1                     | 0.075                                 |
| Wood                                                     |                         |                                       |
| • Douglas fir (12% moisture)                             | 0.46–0.50               | 0.017–0.018                           |
| • Red oak (12% moisture)                                 | 0.61–0.67               | 0.022–0.024                           |

**Sources:** *ASM Handbooks, Volumes 1 and 2, Engineered Materials Handbook, Volume 4, Metals Handbook: Properties and Selection: Non-ferrous Alloys and Pure Metals*, Vol. 2, 9th edition, and *Advanced Materials & Processes*, Vol. 146, No. 4, ASM International Materials Park, OH; *Modern Plastics Encyclopedia '96*, The McGraw-Hill Companies, New York, NY; R. F. Floral and S. T. Peters, "Composite Structures and Technologies," tutorial notes, 1989; and manufacturers' technical data sheets.

**Table B.2** Room-Temperature Modulus of Elasticity Values for Various Engineering Materials

| <i>Material</i>                          | <i>Modulus of Elasticity</i> |                           |
|------------------------------------------|------------------------------|---------------------------|
|                                          | <i>GPa</i>                   | <i>10<sup>6</sup> psi</i> |
| <b>METALS AND METAL ALLOYS</b>           |                              |                           |
| <b>Plain Carbon and Low Alloy Steels</b> |                              |                           |
| Steel alloy A36                          | 207                          | 30                        |
| Steel alloy 1020                         | 207                          | 30                        |
| Steel alloy 1040                         | 207                          | 30                        |
| Steel alloy 4140                         | 207                          | 30                        |
| Steel alloy 4340                         | 207                          | 30                        |

Table B.2 (Continued)

| Material                               | Modulus of Elasticity |                        |
|----------------------------------------|-----------------------|------------------------|
|                                        | GPa                   | 10 <sup>6</sup> psi    |
| <b>Stainless Steels</b>                |                       |                        |
| Stainless alloy 304                    | 193                   | 28                     |
| Stainless alloy 316                    | 193                   | 28                     |
| Stainless alloy 405                    | 200                   | 29                     |
| Stainless alloy 440A                   | 200                   | 29                     |
| Stainless alloy 17-7PH                 | 204                   | 29.5                   |
| <b>Cast Irons</b>                      |                       |                        |
| Gray irons                             |                       |                        |
| • Grade G1800                          | 66–97 <sup>a</sup>    | 9.6–14 <sup>a</sup>    |
| • Grade G3000                          | 90–113 <sup>a</sup>   | 13.0–16.4 <sup>a</sup> |
| • Grade G4000                          | 110–138 <sup>a</sup>  | 16–20 <sup>a</sup>     |
| Ductile irons                          |                       |                        |
| • Grade 60-40-18                       | 169                   | 24.5                   |
| • Grade 80-55-06                       | 168                   | 24.4                   |
| • Grade 120-90-02                      | 164                   | 23.8                   |
| <b>Aluminum Alloys</b>                 |                       |                        |
| Alloy 1100                             | 69                    | 10                     |
| Alloy 2024                             | 72.4                  | 10.5                   |
| Alloy 6061                             | 69                    | 10                     |
| Alloy 7075                             | 71                    | 10.3                   |
| Alloy 356.0                            | 72.4                  | 10.5                   |
| <b>Copper Alloys</b>                   |                       |                        |
| C11000 (electrolytic tough pitch)      | 115                   | 16.7                   |
| C17200 (beryllium–copper)              | 128                   | 18.6                   |
| C26000 (cartridge brass)               | 110                   | 16                     |
| C36000 (free-cutting brass)            | 97                    | 14                     |
| C71500 (copper–nickel, 30%)            | 150                   | 21.8                   |
| C93200 (bearing bronze)                | 100                   | 14.5                   |
| <b>Magnesium Alloys</b>                |                       |                        |
| Alloy AZ31B                            | 45                    | 6.5                    |
| Alloy AZ91D                            | 45                    | 6.5                    |
| <b>Titanium Alloys</b>                 |                       |                        |
| Commercially pure (ASTM grade 1)       | 103                   | 14.9                   |
| Alloy Ti-5Al-2.5Sn                     | 110                   | 16                     |
| Alloy Ti-6Al-4V                        | 114                   | 16.5                   |
| <b>Precious Metals</b>                 |                       |                        |
| Gold (commercially pure)               | 77                    | 11.2                   |
| Platinum (commercially pure)           | 171                   | 24.8                   |
| Silver (commercially pure)             | 74                    | 10.7                   |
| <b>Refractory Metals</b>               |                       |                        |
| Molybdenum (commercially pure)         | 320                   | 46.4                   |
| Tantalum (commercially pure)           | 185                   | 27                     |
| Tungsten (commercially pure)           | 400                   | 58                     |
| <b>Miscellaneous Nonferrous Alloys</b> |                       |                        |
| Nickel 200                             | 204                   | 29.6                   |
| Inconel 625                            | 207                   | 30                     |
| Monel 400                              | 180                   | 26                     |
| Haynes alloy 25                        | 236                   | 34.2                   |

**Table B.2** (Continued)

| <i>Material</i>                                         | <i>Modulus of Elasticity</i> |                            |
|---------------------------------------------------------|------------------------------|----------------------------|
|                                                         | <i>GPa</i>                   | <i>10<sup>6</sup> psi</i>  |
| Invar                                                   | 141                          | 20.5                       |
| Super invar                                             | 144                          | 21                         |
| Kovar                                                   | 207                          | 30                         |
| Chemical lead                                           | 13.5                         | 2                          |
| Tin (commercially pure)                                 | 44.3                         | 6.4                        |
| Lead-Tin solder (60Sn-40Pb)                             | 30                           | 4.4                        |
| Zinc (commercially pure)                                | 104.5                        | 15.2                       |
| Zirconium, reactor grade 702                            | 99.3                         | 14.4                       |
| <b>GRAPHITE, CERAMICS, AND SEMICONDUCTING MATERIALS</b> |                              |                            |
| Aluminum oxide                                          |                              |                            |
| • 99.9% pure                                            | 380                          | 55                         |
| • 96%                                                   | 303                          | 44                         |
| • 90%                                                   | 275                          | 40                         |
| Concrete                                                | 25.4–36.6 <sup>a</sup>       | 3.7–5.3 <sup>a</sup>       |
| Diamond                                                 |                              |                            |
| • Natural                                               | 700–1200                     | 102–174                    |
| • Synthetic                                             | 800–925                      | 116–134                    |
| Gallium arsenide, single crystal                        |                              |                            |
| • In the $\langle 100 \rangle$ direction                | 85                           | 12.3                       |
| • In the $\langle 110 \rangle$ direction                | 122                          | 17.7                       |
| • In the $\langle 111 \rangle$ direction                | 142                          | 20.6                       |
| Glass, borosilicate (Pyrex)                             | 70                           | 10.1                       |
| Glass, soda-lime                                        | 69                           | 10                         |
| Glass ceramic (Pyroceram)                               | 120                          | 17.4                       |
| Graphite                                                |                              |                            |
| • Extruded                                              | 11                           | 1.6                        |
| • Isostatically molded                                  | 11.7                         | 1.7                        |
| Silica, fused                                           | 73                           | 10.6                       |
| Silicon, single crystal                                 |                              |                            |
| • In the $\langle 100 \rangle$ direction                | 129                          | 18.7                       |
| • In the $\langle 110 \rangle$ direction                | 168                          | 24.4                       |
| • In the $\langle 111 \rangle$ direction                | 187                          | 27.1                       |
| Silicon carbide                                         |                              |                            |
| • Hot pressed                                           | 207–483                      | 30–70                      |
| • Sintered                                              | 207–483                      | 30–70                      |
| Silicon nitride                                         |                              |                            |
| • Hot pressed                                           | 304                          | 44.1                       |
| • Reaction bonded                                       | 304                          | 44.1                       |
| • Sintered                                              | 304                          | 44.1                       |
| Zirconia, 3 mol% $Y_2O_3$                               | 205                          | 30                         |
| <b>POLYMERS</b>                                         |                              |                            |
| Elastomers                                              |                              |                            |
| • Butadiene-acrylonitrile (nitrile)                     | 0.0034 <sup>b</sup>          | 0.00049 <sup>b</sup>       |
| • Styrene-butadiene (SBR)                               | 0.002–0.010 <sup>b</sup>     | 0.0003–0.0015 <sup>b</sup> |
| Epoxy                                                   | 2.41                         | 0.35                       |
| Nylon 6,6                                               | 1.59–3.79                    | 0.230–0.550                |
| Phenolic                                                | 2.76–4.83                    | 0.40–0.70                  |
| Polybutylene terephthalate (PBT)                        | 1.93–3.00                    | 0.280–0.435                |
| Polycarbonate (PC)                                      | 2.38                         | 0.345                      |
| Polyester (thermoset)                                   | 2.06–4.41                    | 0.30–0.64                  |

**Table B.2** (Continued)

| <b>Material</b>                                          | <b>Modulus of Elasticity</b> |                           |
|----------------------------------------------------------|------------------------------|---------------------------|
|                                                          | <b>GPa</b>                   | <b>10<sup>6</sup> psi</b> |
| Polyetheretherketone (PEEK)                              | 1.10                         | 0.16                      |
| Polyethylene                                             |                              |                           |
| • Low density (LDPE)                                     | 0.172–0.282                  | 0.025–0.041               |
| • High density (HDPE)                                    | 1.08                         | 0.157                     |
| • Ultrahigh molecular weight (UHMWPE)                    | 0.69                         | 0.100                     |
| Polyethylene terephthalate (PET)                         | 2.76–4.14                    | 0.40–0.60                 |
| Polymethyl methacrylate (PMMA)                           | 2.24–3.24                    | 0.325–0.470               |
| Polypropylene (PP)                                       | 1.14–1.55                    | 0.165–0.225               |
| Polystyrene (PS)                                         | 2.28–3.28                    | 0.330–0.475               |
| Polytetrafluoroethylene (PTFE)                           | 0.40–0.55                    | 0.058–0.080               |
| Polyvinyl chloride (PVC)                                 | 2.41–4.14                    | 0.35–0.60                 |
| <b>FIBER MATERIALS</b>                                   |                              |                           |
| Aramid (Kevlar 49)                                       | 131                          | 19                        |
| Carbon (PAN precursor)                                   |                              |                           |
| • Standard modulus                                       | 230                          | 33.4                      |
| • Intermediate modulus                                   | 285                          | 41.3                      |
| • High modulus                                           | 400                          | 58                        |
| E Glass                                                  | 72.5                         | 10.5                      |
| <b>COMPOSITE MATERIALS</b>                               |                              |                           |
| Aramid fibers-epoxy matrix ( $V_f = 0.60$ )              |                              |                           |
| Longitudinal                                             | 76                           | 11                        |
| Transverse                                               | 5.5                          | 0.8                       |
| High modulus carbon fibers-epoxy matrix ( $V_f = 0.60$ ) |                              |                           |
| Longitudinal                                             | 220                          | 32                        |
| Transverse                                               | 6.9                          | 1.0                       |
| E glass fibers-epoxy matrix ( $V_f = 0.60$ )             |                              |                           |
| Longitudinal                                             | 45                           | 6.5                       |
| Transverse                                               | 12                           | 1.8                       |
| Wood                                                     |                              |                           |
| • Douglas fir (12% moisture)                             |                              |                           |
| Parallel to grain                                        | 10.8–13.6 <sup>c</sup>       | 1.57–1.97 <sup>c</sup>    |
| Perpendicular to grain                                   | 0.54–0.68 <sup>c</sup>       | 0.078–0.10 <sup>c</sup>   |
| • Red oak (12% moisture)                                 |                              |                           |
| Parallel to grain                                        | 11.0–14.1 <sup>c</sup>       | 1.60–2.04 <sup>c</sup>    |
| Perpendicular to grain                                   | 0.55–0.71 <sup>c</sup>       | 0.08–0.10 <sup>c</sup>    |

<sup>a</sup> Secant modulus taken at 25% of ultimate strength.<sup>b</sup> Modulus taken at 100% elongation.<sup>c</sup> Measured in bending.

**Sources:** *ASM Handbooks, Volumes 1 and 2, Engineered Materials Handbooks, Volumes 1 and 4, Metals Handbook: Properties and Selection: Nonferrous Alloys and Pure Metals*, Vol. 2, 9th edition, and *Advanced Materials & Processes*, Vol. 146, No. 4, ASM International, Materials Park, OH; *Modern Plastics Encyclopedia '96*, The McGraw-Hill Companies, New York, NY; R. F. Floral and S. T. Peters, "Composite Structures and Technologies," tutorial notes, 1989; and manufacturers' technical data sheets.

**Table B.3** Room-Temperature Poisson's Ratio Values for Various Engineering Materials

| <i>Material</i>                          | <i>Poisson's Ratio</i> | <i>Material</i>                                         | <i>Poisson's Ratio</i> |
|------------------------------------------|------------------------|---------------------------------------------------------|------------------------|
| <b>METALS AND METAL ALLOYS</b>           |                        | <b>Refractory Metals</b>                                |                        |
| <b>Plain Carbon and Low Alloy Steels</b> |                        | Molybdenum (commercially pure)                          | 0.32                   |
| Steel alloy A36                          | 0.30                   | Tantalum (commercially pure)                            | 0.35                   |
| Steel alloy 1020                         | 0.30                   | Tungsten (commercially pure)                            | 0.28                   |
| Steel alloy 1040                         | 0.30                   |                                                         |                        |
| Steel alloy 4140                         | 0.30                   | <b>Miscellaneous Nonferrous Alloys</b>                  |                        |
| Steel alloy 4340                         | 0.30                   | Nickel 200                                              | 0.31                   |
| <b>Stainless Steels</b>                  |                        | Inconel 625                                             | 0.31                   |
| Stainless alloy 304                      | 0.30                   | Monel 400                                               | 0.32                   |
| Stainless alloy 316                      | 0.30                   | Chemical lead                                           | 0.44                   |
| Stainless alloy 405                      | 0.30                   | Tin (commercially pure)                                 | 0.33                   |
| Stainless alloy 440A                     | 0.30                   | Zinc (commercially pure)                                | 0.25                   |
| Stainless alloy 17-7PH                   | 0.30                   | Zirconium, reactor grade 702                            | 0.35                   |
| <b>Cast Irons</b>                        |                        | <b>GRAPHITE, CERAMICS, AND SEMICONDUCTING MATERIALS</b> |                        |
| Gray irons                               |                        | Aluminum oxide                                          |                        |
| • Grade G1800                            | 0.26                   | • 99.9% pure                                            | 0.22                   |
| • Grade G3300                            | 0.26                   | • 96%                                                   | 0.21                   |
| • Grade G4000                            | 0.26                   | • 90%                                                   | 0.22                   |
| Ductile irons                            |                        | Concrete                                                | 0.20                   |
| • Grade 60-40-18                         | 0.29                   | Diamond                                                 |                        |
| • Grade 80-55-06                         | 0.31                   | • Natural                                               | 0.10–0.30              |
| • Grade 120-90-02                        | 0.28                   | • Synthetic                                             | 0.20                   |
| <b>Aluminum Alloys</b>                   |                        | Gallium arsenide                                        |                        |
| Alloy 1100                               | 0.33                   | • $\langle 100 \rangle$ orientation                     | 0.30                   |
| Alloy 2024                               | 0.33                   | Glass, borosilicate (Pyrex)                             | 0.20                   |
| Alloy 6061                               | 0.33                   | Glass, soda-lime                                        | 0.23                   |
| Alloy 7075                               | 0.33                   | Glass ceramic (Pyroceram)                               | 0.25                   |
| Alloy 356.0                              | 0.33                   | Silica, fused                                           | 0.17                   |
| <b>Copper Alloys</b>                     |                        | Silicon                                                 |                        |
| C11000 (electrolytic tough pitch)        | 0.33                   | • $\langle 100 \rangle$ orientation                     | 0.28                   |
| C17200 (beryllium-copper)                | 0.30                   | • $\langle 111 \rangle$ orientation                     | 0.36                   |
| C26000 (cartridge brass)                 | 0.35                   | Silicon carbide                                         |                        |
| C36000 (free-cutting brass)              | 0.34                   | • Hot pressed                                           | 0.17                   |
| C71500 (copper-nickel, 30%)              | 0.34                   | • Sintered                                              | 0.16                   |
| C93200 (bearing bronze)                  | 0.34                   | Silicon nitride                                         |                        |
| <b>Magnesium Alloys</b>                  |                        | • Hot pressed                                           | 0.30                   |
| Alloy AZ31B                              | 0.35                   | • Reaction bonded                                       | 0.22                   |
| Alloy AZ91D                              | 0.35                   | • Sintered                                              | 0.28                   |
| <b>Titanium Alloys</b>                   |                        | Zirconia, 3 mol% $Y_2O_3$                               | 0.31                   |
| Commercially pure (ASTM grade 1)         | 0.34                   | <b>POLYMERS</b>                                         |                        |
| Alloy Ti-5Al-2.5Sn                       | 0.34                   | Nylon 6,6                                               | 0.39                   |
| Alloy Ti-6Al-4V                          | 0.34                   | Polycarbonate (PC)                                      | 0.36                   |
| <b>Precious Metals</b>                   |                        | Polystyrene (PS)                                        | 0.33                   |
| Gold (commercially pure)                 | 0.42                   | Polytetrafluoroethylene (PTFE)                          | 0.46                   |
| Platinum (commercially pure)             | 0.39                   | Polyvinyl chloride (PVC)                                | 0.38                   |
| Silver (commercially pure)               | 0.37                   | <b>FIBER MATERIALS</b>                                  |                        |
|                                          |                        | E Glass                                                 | 0.22                   |

**Table B.3** (Continued)

| <i>Material</i>                                             | <i>Poisson's Ratio</i> | <i>Material</i>                                | <i>Poisson's Ratio</i> |
|-------------------------------------------------------------|------------------------|------------------------------------------------|------------------------|
| <b>COMPOSITE MATERIALS</b>                                  |                        |                                                |                        |
| Aramid fibers-epoxy matrix<br>( $V_f = 0.6$ )               | 0.34                   | E glass fibers-epoxy matrix<br>( $V_f = 0.6$ ) | 0.19                   |
| High modulus carbon fibers-<br>epoxy matrix ( $V_f = 0.6$ ) | 0.25                   |                                                |                        |

**Sources:** *ASM Handbooks, Volumes 1 and 2*, and *Engineered Materials Handbooks, Volumes 1 and 4*, ASM International, Materials Park, OH; R. F. Floral and S. T. Peters, "Composite Structures and Technologies," tutorial notes, 1989; and manufacturers' technical data sheets.

**Table B.4** Typical Room-Temperature Yield Strength, Tensile Strength, and Ductility (Percent Elongation) Values for Various Engineering Materials

| <i>Material/Condition</i>                | <i>Yield Strength<br/>(MPa [ksi])</i> | <i>Tensile Strength<br/>(MPa [ksi])</i> | <i>Percent Elongation</i> |
|------------------------------------------|---------------------------------------|-----------------------------------------|---------------------------|
| <b>METALS AND METAL ALLOYS</b>           |                                       |                                         |                           |
| <b>Plain Carbon and Low Alloy Steels</b> |                                       |                                         |                           |
| Steel alloy A36                          |                                       |                                         |                           |
| • Hot rolled                             | 220–250 (32–36)                       | 400–500 (58–72.5)                       | 23                        |
| Steel alloy 1020                         |                                       |                                         |                           |
| • Hot rolled                             | 210 (30) (min)                        | 380 (55) (min)                          | 25 (min)                  |
| • Cold drawn                             | 350 (51) (min)                        | 420 (61) (min)                          | 15 (min)                  |
| • Annealed (@ 870°C)                     | 295 (42.8)                            | 395 (57.3)                              | 36.5                      |
| • Normalized (@ 925°C)                   | 345 (50.3)                            | 440 (64)                                | 38.5                      |
| Steel alloy 1040                         |                                       |                                         |                           |
| • Hot rolled                             | 290 (42) (min)                        | 520 (76) (min)                          | 18 (min)                  |
| • Cold drawn                             | 490 (71) (min)                        | 590 (85) (min)                          | 12 (min)                  |
| • Annealed (@ 785°C)                     | 355 (51.3)                            | 520 (75.3)                              | 30.2                      |
| • Normalized (@ 900°C)                   | 375 (54.3)                            | 590 (85)                                | 28.0                      |
| Steel alloy 4140                         |                                       |                                         |                           |
| • Annealed (@ 815°C)                     | 417 (60.5)                            | 655 (95)                                | 25.7                      |
| • Normalized (@ 870°C)                   | 655 (95)                              | 1020 (148)                              | 17.7                      |
| • Oil-quenched and tempered (@ 315°C)    | 1570 (228)                            | 1720 (250)                              | 11.5                      |
| Steel alloy 4340                         |                                       |                                         |                           |
| • Annealed (@ 810°C)                     | 472 (68.5)                            | 745 (108)                               | 22                        |
| • Normalized (@ 870°C)                   | 862 (125)                             | 1280 (185.5)                            | 12.2                      |
| • Oil-quenched and tempered (@ 315°C)    | 1620 (235)                            | 1760 (255)                              | 12                        |
| <b>Stainless Steels</b>                  |                                       |                                         |                           |
| Stainless alloy 304                      |                                       |                                         |                           |
| • Hot finished and annealed              | 205 (30) (min)                        | 515 (75) (min)                          | 40 (min)                  |
| • Cold worked ( $\frac{1}{4}$ hard)      | 515 (75) (min)                        | 860 (125) (min)                         | 10 (min)                  |
| Stainless alloy 316                      |                                       |                                         |                           |
| • Hot finished and annealed              | 205 (30) (min)                        | 515 (75) (min)                          | 40 (min)                  |
| • Cold drawn and annealed                | 310 (45) (min)                        | 620 (90) (min)                          | 30 (min)                  |
| Stainless alloy 405                      |                                       |                                         |                           |
| • Annealed                               | 170 (25)                              | 415 (60)                                | 20                        |

**Table B.4** (Continued)

| <i>Material/Condition</i>                     | <i>Yield<br/>Strength<br/>(MPa [ksi])</i> | <i>Tensile<br/>Strength<br/>(MPa [ksi])</i> | <i>Percent<br/>Elongation</i> |
|-----------------------------------------------|-------------------------------------------|---------------------------------------------|-------------------------------|
| Stainless alloy 440A                          |                                           |                                             |                               |
| • Annealed                                    | 415 (60)                                  | 725 (105)                                   | 20                            |
| • Tempered @ 315°C                            | 1650 (240)                                | 1790 (260)                                  | 5                             |
| Stainless alloy 17-7PH                        |                                           |                                             |                               |
| • Cold rolled                                 | 1210 (175) (min)                          | 1380 (200) (min)                            | 1 (min)                       |
| • Precipitation hardened @ 510°C              | 1310 (190) (min)                          | 1450 (210) (min)                            | 3.5 (min)                     |
| <b>Cast Irons</b>                             |                                           |                                             |                               |
| Gray irons                                    |                                           |                                             |                               |
| • Grade G1800 (as cast)                       | —                                         | 124 (18) (min)                              | —                             |
| • Grade G3000 (as cast)                       | —                                         | 207 (30) (min)                              | —                             |
| • Grade G4000 (as cast)                       | —                                         | 276 (40) (min)                              | —                             |
| Ductile irons                                 |                                           |                                             |                               |
| • Grade 60-40-18 (annealed)                   | 276 (40) (min)                            | 414 (60) (min)                              | 18 (min)                      |
| • Grade 80-55-06 (as cast)                    | 379 (55) (min)                            | 552 (80) (min)                              | 6 (min)                       |
| • Grade 120-90-02 (oil quenched and tempered) | 621 (90) (min)                            | 827 (120) (min)                             | 2 (min)                       |
| <b>Aluminum Alloys</b>                        |                                           |                                             |                               |
| Alloy 1100                                    |                                           |                                             |                               |
| • Annealed (O temper)                         | 34 (5)                                    | 90 (13)                                     | 40                            |
| • Strain hardened (H14 temper)                | 117 (17)                                  | 124 (18)                                    | 15                            |
| Alloy 2024                                    |                                           |                                             |                               |
| • Annealed (O temper)                         | 75 (11)                                   | 185 (27)                                    | 20                            |
| • Heat treated and aged (T3 temper)           | 345 (50)                                  | 485 (70)                                    | 18                            |
| • Heat treated and aged (T351 temper)         | 325 (47)                                  | 470 (68)                                    | 20                            |
| Alloy 6061                                    |                                           |                                             |                               |
| • Annealed (O temper)                         | 55 (8)                                    | 124 (18)                                    | 30                            |
| • Heat treated and aged (T6 and T651 tempers) | 276 (40)                                  | 310 (45)                                    | 17                            |
| Alloy 7075                                    |                                           |                                             |                               |
| • Annealed (O temper)                         | 103 (15)                                  | 228 (33)                                    | 17                            |
| • Heat treated and aged (T6 temper)           | 505 (73)                                  | 572 (83)                                    | 11                            |
| Alloy 356.0                                   |                                           |                                             |                               |
| • As cast                                     | 124 (18)                                  | 164 (24)                                    | 6                             |
| • Heat treated and aged (T6 temper)           | 164 (24)                                  | 228 (33)                                    | 3.5                           |
| <b>Copper Alloys</b>                          |                                           |                                             |                               |
| C11000 (electrolytic tough pitch)             |                                           |                                             |                               |
| • Hot rolled                                  | 69 (10)                                   | 220 (32)                                    | 50                            |
| • Cold worked (H04 temper)                    | 310 (45)                                  | 345 (50)                                    | 12                            |
| C17200 (beryllium-copper)                     |                                           |                                             |                               |
| • Solution heat treated                       | 195–380 (28–55)                           | 415–540 (60–78)                             | 35–60                         |
| • Solution heat treated, aged @ 330°C         | 965–1205 (140–175)                        | 1140–1310 (165–190)                         | 4–10                          |
| C26000 (cartridge brass)                      |                                           |                                             |                               |
| • Annealed                                    | 75–150 (11–22)                            | 300–365 (43.5–53.0)                         | 54–68                         |
| • Cold worked (H04 temper)                    | 435 (63)                                  | 525 (76)                                    | 8                             |
| C36000 (free-cutting brass)                   |                                           |                                             |                               |
| • Annealed                                    | 125 (18)                                  | 340 (49)                                    | 53                            |
| • Cold worked (H02 temper)                    | 310 (45)                                  | 400 (58)                                    | 25                            |
| C71500 (copper-nickel, 30%)                   |                                           |                                             |                               |
| • Hot rolled                                  | 140 (20)                                  | 380 (55)                                    | 45                            |
| • Cold worked (H80 temper)                    | 545 (79)                                  | 580 (84)                                    | 3                             |

Table B.4 (Continued)

| <i>Material/Condition</i>              | <i>Yield Strength<br/>(MPa [ksi])</i> | <i>Tensile Strength<br/>(MPa [ksi])</i> | <i>Percent Elongation</i> |
|----------------------------------------|---------------------------------------|-----------------------------------------|---------------------------|
| C93200 (bearing bronze)                |                                       |                                         |                           |
| • Sand cast                            | 125 (18)                              | 240 (35)                                | 20                        |
| <b>Magnesium Alloys</b>                |                                       |                                         |                           |
| Alloy AZ31B                            |                                       |                                         |                           |
| • Rolled                               | 220 (32)                              | 290 (42)                                | 15                        |
| • Extruded                             | 200 (29)                              | 262 (38)                                | 15                        |
| Alloy AZ91D                            |                                       |                                         |                           |
| • As cast                              | 97–150 (14–22)                        | 165–230 (24–33)                         | 3                         |
| <b>Titanium Alloys</b>                 |                                       |                                         |                           |
| Commercially pure (ASTM grade 1)       |                                       |                                         |                           |
| • Annealed                             | 170 (25) (min)                        | 240 (35) (min)                          | 30                        |
| Alloy Ti-5Al-2.5Sn                     |                                       |                                         |                           |
| • Annealed                             | 760 (110) (min)                       | 790 (115) (min)                         | 16                        |
| Alloy Ti-6Al-4V                        |                                       |                                         |                           |
| • Annealed                             | 830 (120) (min)                       | 900 (130) (min)                         | 14                        |
| • Solution heat treated and aged       | 1103 (160)                            | 1172 (170)                              | 10                        |
| <b>Precious Metals</b>                 |                                       |                                         |                           |
| Gold (commercially pure)               |                                       |                                         |                           |
| • Annealed                             | nil                                   | 130 (19)                                | 45                        |
| • Cold worked (60% reduction)          | 205 (30)                              | 220 (32)                                | 4                         |
| Platinum (commercially pure)           |                                       |                                         |                           |
| • Annealed                             | <13.8 (2)                             | 125–165 (18–24)                         | 30–40                     |
| • Cold worked (50%)                    | —                                     | 205–240 (30–35)                         | 1–3                       |
| Silver (commercially pure)             |                                       |                                         |                           |
| • Annealed                             | —                                     | 170 (24.6)                              | 44                        |
| • Cold worked (50%)                    | —                                     | 296 (43)                                | 3.5                       |
| <b>Refractory Metals</b>               |                                       |                                         |                           |
| Molybdenum (commercially pure)         | 500 (72.5)                            | 630 (91)                                | 25                        |
| Tantalum (commercially pure)           | 165 (24)                              | 205 (30)                                | 40                        |
| Tungsten (commercially pure)           | 760 (110)                             | 960 (139)                               | 2                         |
| <b>Miscellaneous Nonferrous Alloys</b> |                                       |                                         |                           |
| Nickel 200 (annealed)                  | 148 (21.5)                            | 462 (67)                                | 47                        |
| Inconel 625 (annealed)                 | 517 (75)                              | 930 (135)                               | 42.5                      |
| Monel 400 (annealed)                   | 240 (35)                              | 550 (80)                                | 40                        |
| Haynes alloy 25                        | 445 (65)                              | 970 (141)                               | 62                        |
| Invar (annealed)                       | 276 (40)                              | 517 (75)                                | 30                        |
| Super invar (annealed)                 | 276 (40)                              | 483 (70)                                | 30                        |
| Kovar (annealed)                       | 276 (40)                              | 517 (75)                                | 30                        |
| Chemical lead                          | 6–8 (0.9–1.2)                         | 16–19 (2.3–2.7)                         | 30–60                     |
| Antimonial lead (6%) (chill cast)      | —                                     | 47.2 (6.8)                              | 24                        |
| Tin (commercially pure)                | 11 (1.6)                              | —                                       | 57                        |
| Lead–Tin solder (60Sn–40Pb)            | —                                     | 52.5 (7.6)                              | 30–60                     |
| Zinc (commercially pure)               |                                       |                                         |                           |
| • Hot rolled (anisotropic)             | —                                     | 134–159 (19.4–23.0)                     | 50–65                     |
| • Cold rolled (anisotropic)            | —                                     | 145–186 (21–27)                         | 40–50                     |
| Zirconium, reactor grade 702           |                                       |                                         |                           |
| • Cold worked and annealed             | 207 (30) (min)                        | 379 (55) (min)                          | 16 (min)                  |

Table B.4 (Continued)

| Material/Condition                                                  | Yield Strength<br>(MPa [ksi]) | Tensile Strength<br>(MPa [ksi]) | Percent Elongation |
|---------------------------------------------------------------------|-------------------------------|---------------------------------|--------------------|
| <b>GRAPHITE, CERAMICS, AND SEMICONDUCTING MATERIALS<sup>a</sup></b> |                               |                                 |                    |
| Aluminum oxide                                                      |                               |                                 |                    |
| • 99.9% pure                                                        | —                             | 282–551 (41–80)                 | —                  |
| • 96%                                                               | —                             | 358 (52)                        | —                  |
| • 90%                                                               | —                             | 337 (49)                        | —                  |
| Concrete <sup>b</sup>                                               | —                             | 37.3–41.3 (5.4–6.0)             | —                  |
| Diamond                                                             |                               |                                 |                    |
| • Natural                                                           | —                             | 1050 (152)                      | —                  |
| • Synthetic                                                         | —                             | 800–1400 (116–203)              | —                  |
| Gallium arsenide                                                    |                               |                                 |                    |
| • {100} orientation, polished surface                               | —                             | 66 (9.6) <sup>c</sup>           | —                  |
| • {100} orientation, as-cut surface                                 | —                             | 57 (8.3) <sup>c</sup>           | —                  |
| Glass, borosilicate (Pyrex)                                         | —                             | 69 (10)                         | —                  |
| Glass, soda-lime                                                    | —                             | 69 (10)                         | —                  |
| Glass ceramic (Pyroceram)                                           | —                             | 123–370 (18–54)                 | —                  |
| Graphite                                                            |                               |                                 |                    |
| • Extruded (with the grain direction)                               | —                             | 13.8–34.5 (2.0–5.0)             | —                  |
| • Isostatically molded                                              | —                             | 31–69 (4.5–10)                  | —                  |
| Silica, fused                                                       | —                             | 104 (15)                        | —                  |
| Silicon                                                             |                               |                                 |                    |
| • {100} orientation, as-cut surface                                 | —                             | 130 (18.9)                      | —                  |
| • {100} orientation, laser scribed                                  | —                             | 81.8 (11.9)                     | —                  |
| Silicon carbide                                                     |                               |                                 |                    |
| • Hot pressed                                                       | —                             | 230–825 (33–120)                | —                  |
| • Sintered                                                          | —                             | 96–520 (14–75)                  | —                  |
| Silicon nitride                                                     |                               |                                 |                    |
| • Hot pressed                                                       | —                             | 700–1000 (100–150)              | —                  |
| • Reaction bonded                                                   | —                             | 250–345 (36–50)                 | —                  |
| • Sintered                                                          | —                             | 414–650 (60–94)                 | —                  |
| Zirconia, 3 mol% Y <sub>2</sub> O <sub>3</sub> (sintered)           | —                             | 800–1500 (116–218)              | —                  |
| <b>POLYMERS</b>                                                     |                               |                                 |                    |
| Elastomers                                                          |                               |                                 |                    |
| • Butadiene-acrylonitrile (nitrile)                                 | —                             | 6.9–24.1 (1.0–3.5)              | 400–600            |
| • Styrene-butadiene (SBR)                                           | —                             | 12.4–20.7 (1.8–3.0)             | 450–500            |
| • Silicone                                                          | —                             | 10.3 (1.5)                      | 100–800            |
| Epoxy                                                               | —                             | 27.6–90.0 (4.0–13)              | 3–6                |
| Nylon 6,6                                                           |                               |                                 |                    |
| • Dry, as molded                                                    | 55.1–82.8 (8–12)              | 94.5 (13.7)                     | 15–80              |
| • 50% relative humidity                                             | 44.8–58.6 (6.5–8.5)           | 75.9 (11)                       | 150–300            |
| Phenolic                                                            | —                             | 34.5–62.1 (5.0–9.0)             | 1.5–2.0            |
| Polybutylene terephthalate (PBT)                                    | 56.6–60.0 (8.2–8.7)           | 56.6–60.0 (8.2–8.7)             | 50–300             |
| Polycarbonate (PC)                                                  | 62.1 (9)                      | 62.8–72.4 (9.1–10.5)            | 110–150            |
| Polyester (thermoset)                                               | —                             | 41.4–89.7 (6.0–13.0)            | <2.6               |
| Polyetheretherketone (PEEK)                                         | 91 (13.2)                     | 70.3–103 (10.2–15.0)            | 30–150             |
| Polyethylene                                                        |                               |                                 |                    |
| • Low density (LDPE)                                                | 9.0–14.5 (1.3–2.1)            | 8.3–31.4 (1.2–4.55)             | 100–650            |
| • High density (HDPE)                                               | 26.2–33.1 (3.8–4.8)           | 22.1–31.0 (3.2–4.5)             | 10–1200            |
| • Ultrahigh molecular weight (UHMWPE)                               | 21.4–27.6 (3.1–4.0)           | 38.6–48.3 (5.6–7.0)             | 350–525            |
| Polyethylene terephthalate (PET)                                    | 59.3 (8.6)                    | 48.3–72.4 (7.0–10.5)            | 30–300             |

Table B.4 (Continued)

| Material/Condition                                              | Yield Strength<br>(MPa [ksi]) | Tensile Strength<br>(MPa [ksi]) | Percent Elongation |
|-----------------------------------------------------------------|-------------------------------|---------------------------------|--------------------|
| Polymethyl methacrylate (PMMA)                                  | 53.8–73.1 (7.8–10.6)          | 48.3–72.4 (7.0–10.5)            | 2.0–5.5            |
| Polypropylene (PP)                                              | 31.0–37.2 (4.5–5.4)           | 31.0–41.4 (4.5–6.0)             | 100–600            |
| Polystyrene (PS)                                                | —                             | 35.9–51.7 (5.2–7.5)             | 1.2–2.5            |
| Polytetrafluoroethylene (PTFE)                                  | —                             | 20.7–34.5 (3.0–5.0)             | 200–400            |
| Polyvinyl chloride (PVC)                                        | 40.7–44.8 (5.9–6.5)           | 40.7–51.7 (5.9–7.5)             | 40–80              |
| <b>FIBER MATERIALS</b>                                          |                               |                                 |                    |
| Aramid (Kevlar 49)                                              | —                             | 3600–4100 (525–600)             | 2.8                |
| Carbon (PAN precursor)                                          | —                             | —                               | —                  |
| • Standard modulus (longitudinal)                               | —                             | 3800–4200 (550–610)             | 2                  |
| • Intermediate modulus (longitudinal)                           | —                             | 4650–6350 (675–920)             | 1.8                |
| • High modulus (longitudinal)                                   | —                             | 2500–4500 (360–650)             | 0.6                |
| E Glass                                                         | —                             | 3450 (500)                      | 4.3                |
| <b>COMPOSITE MATERIALS</b>                                      |                               |                                 |                    |
| Aramid fibers-epoxy matrix (aligned, $V_f = 0.6$ )              | —                             | —                               | —                  |
| • Longitudinal direction                                        | —                             | 1380 (200)                      | 1.8                |
| • Transverse direction                                          | —                             | 30 (4.3)                        | 0.5                |
| High modulus carbon fibers-epoxy matrix (aligned, $V_f = 0.6$ ) | —                             | —                               | —                  |
| • Longitudinal direction                                        | —                             | 760 (110)                       | 0.3                |
| • Transverse direction                                          | —                             | 28 (4)                          | 0.4                |
| E glass fibers-epoxy matrix (aligned, $V_f = 0.6$ )             | —                             | —                               | —                  |
| • Longitudinal direction                                        | —                             | 1020 (150)                      | 2.3                |
| • Transverse direction                                          | —                             | 40 (5.8)                        | 0.4                |
| Wood                                                            | —                             | —                               | —                  |
| • Douglas fir (12% moisture)                                    | —                             | —                               | —                  |
| Parallel to grain                                               | —                             | 108 (15.6)                      | —                  |
| Perpendicular to grain                                          | —                             | 2.4 (0.35)                      | —                  |
| • Red oak (12% moisture)                                        | —                             | —                               | —                  |
| Parallel to grain                                               | —                             | 112 (16.3)                      | —                  |
| Perpendicular to grain                                          | —                             | 7.2 (1.05)                      | —                  |

<sup>a</sup> The strength of graphite, ceramics, and semiconducting materials is taken as flexural strength.

<sup>b</sup> The strength of concrete is measured in compression.

<sup>c</sup> Flexural strength value at 50% fracture probability.

**Sources:** *ASM Handbooks, Volumes 1 and 2, Engineered Materials Handbooks, Volumes 1 and 4, Metals Handbook: Properties and Selection: Nonferrous Alloys and Pure Metals*, Vol. 2, 9th edition, *Advanced Materials & Processes*, Vol. 146, No. 4, and *Materials & Processing Databook (1985)*, ASM International, Materials Park, OH; *Modern Plastics Encyclopedia '96*, The McGraw-Hill Companies, New York, NY; R. F. Floral and S. T. Peters, "Composite Structures and Technologies," tutorial notes, 1989; and manufacturers' technical data sheets.

**Table B.5** Room-Temperature Plane Strain Fracture Toughness and Strength Values for Various Engineering Materials

| Material                                         | Fracture Toughness |           | Strength <sup>a</sup><br>(MPa) |
|--------------------------------------------------|--------------------|-----------|--------------------------------|
|                                                  | MPa√m              | ksi√in.   |                                |
| METALS AND METAL ALLOYS                          |                    |           |                                |
| Plain Carbon and Low Alloy Steels                |                    |           |                                |
| Steel alloy 1040                                 | 54.0               | 49.0      | 260                            |
| Steel alloy 4140                                 |                    |           |                                |
| • Tempered @ 370°C                               | 55–65              | 50–59     | 1375–1585                      |
| • Tempered @ 482°C                               | 75–93              | 68.3–84.6 | 1100–1200                      |
| Steel alloy 4340                                 |                    |           |                                |
| • Tempered @ 260°C                               | 50.0               | 45.8      | 1640                           |
| • Tempered @ 425°C                               | 87.4               | 80.0      | 1420                           |
| Stainless Steels                                 |                    |           |                                |
| Stainless alloy 17-7PH                           |                    |           |                                |
| • Precipitation hardened @ 510°C                 | 76                 | 69        | 1310                           |
| Aluminum Alloys                                  |                    |           |                                |
| Alloy 2024-T3                                    | 44                 | 40        | 345                            |
| Alloy 7075-T651                                  | 24                 | 22        | 495                            |
| Magnesium Alloys                                 |                    |           |                                |
| Alloy AZ31B                                      |                    |           |                                |
| • Extruded                                       | 28.0               | 25.5      | 200                            |
| Titanium Alloys                                  |                    |           |                                |
| Alloy Ti-5Al-2.5Sn                               |                    |           |                                |
| • Air cooled                                     | 71.4               | 65.0      | 876                            |
| Alloy Ti-6Al-4V                                  |                    |           |                                |
| • Equiaxed grains                                | 44–66              | 40–60     | 910                            |
| GRAPHITE, CERAMICS, AND SEMICONDUCTING MATERIALS |                    |           |                                |
| Aluminum oxide                                   |                    |           |                                |
| • 99.9% pure                                     | 4.2–5.9            | 3.8–5.4   | 282–551                        |
| • 96%                                            | 3.85–3.95          | 3.5–3.6   | 358                            |
| Concrete                                         | 0.2–1.4            | 0.18–1.27 | —                              |
| Diamond                                          |                    |           |                                |
| • Natural                                        | 3.4                | 3.1       | 1050                           |
| • Synthetic                                      | 6.0–10.7           | 5.5–9.7   | 800–1400                       |
| Gallium arsenide                                 |                    |           |                                |
| • In the {100} orientation                       | 0.43               | 0.39      | 66                             |
| • In the {110} orientation                       | 0.31               | 0.28      | —                              |
| • In the {111} orientation                       | 0.45               | 0.41      | —                              |
| Glass, borosilicate (Pyrex)                      | 0.77               | 0.70      | 69                             |
| Glass, soda-lime                                 | 0.75               | 0.68      | 69                             |
| Glass ceramic (Pyroceram)                        | 1.6–2.1            | 1.5–1.9   | 123–370                        |
| Silica, fused                                    | 0.79               | 0.72      | 104                            |
| Silicon                                          |                    |           |                                |
| • In the {100} orientation                       | 0.95               | 0.86      | —                              |
| • In the {110} orientation                       | 0.90               | 0.82      | —                              |
| • In the {111} orientation                       | 0.82               | 0.75      | —                              |
| Silicon carbide                                  |                    |           |                                |
| • Hot pressed                                    | 4.8–6.1            | 4.4–5.6   | 230–825                        |
| • Sintered                                       | 4.8                | 4.4       | 96–520                         |

Table B.5 (Continued)

| Material                                       | Fracture Toughness |          | Strength <sup>a</sup><br>(MPa) |
|------------------------------------------------|--------------------|----------|--------------------------------|
|                                                | MPa√m              | ksi√in.  |                                |
| Silicon nitride                                |                    |          |                                |
| • Hot pressed                                  | 4.1–6.0            | 3.7–5.5  | 700–1000                       |
| • Reaction bonded                              | 3.6                | 3.3      | 250–345                        |
| • Sintered                                     | 5.3                | 4.8      | 414–650                        |
| Zirconia, 3 mol% Y <sub>2</sub> O <sub>3</sub> | 7.0–12.0           | 6.4–10.9 | 800–1500                       |
| <b>POLYMERS</b>                                |                    |          |                                |
| Epoxy                                          | 0.6                | 0.55     | —                              |
| Nylon 6,6                                      | 2.5–3.0            | 2.3–2.7  | 44.8–58.6                      |
| Polycarbonate (PC)                             | 2.2                | 2.0      | 62.1                           |
| Polyester (thermoset)                          | 0.6                | 0.55     | —                              |
| Polyethylene terephthalate (PET)               | 5.0                | 4.6      | 59.3                           |
| Polymethyl methacrylate (PMMA)                 | 0.7–1.6            | 0.6–1.5  | 53.8–73.1                      |
| Polypropylene (PP)                             | 3.0–4.5            | 2.7–4.1  | 31.0–37.2                      |
| Polystyrene (PS)                               | 0.7–1.1            | 0.6–1.0  | —                              |
| Polyvinyl chloride (PVC)                       | 2.0–4.0            | 1.8–3.6  | 40.7–44.8                      |

<sup>a</sup> For metal alloys and polymers, strength is taken as yield strength; for ceramic materials, flexural strength is used.

**Sources:** *ASM Handbooks, Volumes 1 and 19, Engineered Materials Handbooks, Volumes 2 and 4, and Advanced Materials & Processes, Vol. 137, No. 6, ASM International, Materials Park, OH.*

Table B.6 Room-Temperature Linear Coefficient of Thermal Expansion Values for Various Engineering Materials

| Material                                 | Coefficient of Thermal Expansion    |                                     |
|------------------------------------------|-------------------------------------|-------------------------------------|
|                                          | 10 <sup>-6</sup> (°C) <sup>-1</sup> | 10 <sup>-6</sup> (°F) <sup>-1</sup> |
| <b>METALS AND METAL ALLOYS</b>           |                                     |                                     |
| <b>Plain Carbon and Low Alloy Steels</b> |                                     |                                     |
| Steel alloy A36                          | 11.7                                | 6.5                                 |
| Steel alloy 1020                         | 11.7                                | 6.5                                 |
| Steel alloy 1040                         | 11.3                                | 6.3                                 |
| Steel alloy 4140                         | 12.3                                | 6.8                                 |
| Steel alloy 4340                         | 12.3                                | 6.8                                 |
| <b>Stainless Steels</b>                  |                                     |                                     |
| Stainless alloy 304                      | 17.2                                | 9.6                                 |
| Stainless alloy 316                      | 15.9                                | 8.8                                 |
| Stainless alloy 405                      | 10.8                                | 6.0                                 |
| Stainless alloy 440A                     | 10.2                                | 5.7                                 |
| Stainless alloy 17-7PH                   | 11.0                                | 6.1                                 |
| <b>Cast Irons</b>                        |                                     |                                     |
| Gray irons                               |                                     |                                     |
| • Grade G1800                            | 11.4                                | 6.3                                 |
| • Grade G3000                            | 11.4                                | 6.3                                 |
| • Grade G4000                            | 11.4                                | 6.3                                 |

Table B.6 (Continued)

| Material                               | Coefficient of<br>Thermal Expansion |                                   |
|----------------------------------------|-------------------------------------|-----------------------------------|
|                                        | $10^{-6} (^{\circ}\text{C})^{-1}$   | $10^{-6} (^{\circ}\text{F})^{-1}$ |
| Ductile irons                          |                                     |                                   |
| • Grade 60-40-18                       | 11.2                                | 6.2                               |
| • Grade 80-55-06                       | 10.6                                | 5.9                               |
| <b>Aluminum Alloys</b>                 |                                     |                                   |
| Alloy 1100                             | 23.6                                | 13.1                              |
| Alloy 2024                             | 22.9                                | 12.7                              |
| Alloy 6061                             | 23.6                                | 13.1                              |
| Alloy 7075                             | 23.4                                | 13.0                              |
| Alloy 356.0                            | 21.5                                | 11.9                              |
| <b>Copper Alloys</b>                   |                                     |                                   |
| C11000 (electrolytic tough pitch)      | 17.0                                | 9.4                               |
| C17200 (beryllium-copper)              | 16.7                                | 9.3                               |
| C26000 (cartridge brass)               | 19.9                                | 11.1                              |
| C36000 (free-cutting brass)            | 20.5                                | 11.4                              |
| C71500 (copper-nickel, 30%)            | 16.2                                | 9.0                               |
| C93200 (bearing bronze)                | 18.0                                | 10.0                              |
| <b>Magnesium Alloys</b>                |                                     |                                   |
| Alloy AZ31B                            | 26.0                                | 14.4                              |
| Alloy AZ91D                            | 26.0                                | 14.4                              |
| <b>Titanium Alloys</b>                 |                                     |                                   |
| Commercially pure (ASTM grade 1)       | 8.6                                 | 4.8                               |
| Alloy Ti-5Al-2.5Sn                     | 9.4                                 | 5.2                               |
| Alloy Ti-6Al-4V                        | 8.6                                 | 4.8                               |
| <b>Precious Metals</b>                 |                                     |                                   |
| Gold (commercially pure)               | 14.2                                | 7.9                               |
| Platinum (commercially pure)           | 9.1                                 | 5.1                               |
| Silver (commercially pure)             | 19.7                                | 10.9                              |
| <b>Refractory Metals</b>               |                                     |                                   |
| Molybdenum (commercially pure)         | 4.9                                 | 2.7                               |
| Tantalum (commercially pure)           | 6.5                                 | 3.6                               |
| Tungsten (commercially pure)           | 4.5                                 | 2.5                               |
| <b>Miscellaneous Nonferrous Alloys</b> |                                     |                                   |
| Nickel 200                             | 13.3                                | 7.4                               |
| Inconel 625                            | 12.8                                | 7.1                               |
| Monel 400                              | 13.9                                | 7.7                               |
| Haynes alloy 25                        | 12.3                                | 6.8                               |
| Invar                                  | 1.6                                 | 0.9                               |
| Super invar                            | 0.72                                | 0.40                              |
| Kovar                                  | 5.1                                 | 2.8                               |
| Chemical lead                          | 29.3                                | 16.3                              |
| Antimonial lead (6%)                   | 27.2                                | 15.1                              |
| Tin (commercially pure)                | 23.8                                | 13.2                              |
| Lead-Tin solder (60Sn-40Pb)            | 24.0                                | 13.3                              |
| Zinc (commercially pure)               | 23.0-32.5                           | 12.7-18.1                         |
| Zirconium, reactor grade 702           | 5.9                                 | 3.3                               |

Table B.6 (Continued)

| Material                                                | Coefficient of<br>Thermal Expansion |                                   |
|---------------------------------------------------------|-------------------------------------|-----------------------------------|
|                                                         | $10^{-6} (^{\circ}\text{C})^{-1}$   | $10^{-6} (^{\circ}\text{F})^{-1}$ |
| <b>GRAPHITE, CERAMICS, AND SEMICONDUCTING MATERIALS</b> |                                     |                                   |
| Aluminum oxide                                          |                                     |                                   |
| • 99.9% pure                                            | 7.4                                 | 4.1                               |
| • 96%                                                   | 7.4                                 | 4.1                               |
| • 90%                                                   | 7.0                                 | 3.9                               |
| Concrete                                                | 10.0–13.6                           | 5.6–7.6                           |
| Diamond (natural)                                       | 0.11–1.23                           | 0.06–0.68                         |
| Gallium arsenide                                        | 5.9                                 | 3.3                               |
| Glass, borosilicate (Pyrex)                             | 3.3                                 | 1.8                               |
| Glass, soda–lime                                        | 9.0                                 | 5.0                               |
| Glass ceramic (Pyroceram)                               | 6.5                                 | 3.6                               |
| Graphite                                                |                                     |                                   |
| • Extruded                                              | 2.0–2.7                             | 1.1–1.5                           |
| • Isostatically molded                                  | 2.2–6.0                             | 1.2–3.3                           |
| Silica, fused                                           | 0.4                                 | 0.22                              |
| Silicon                                                 | 2.5                                 | 1.4                               |
| Silicon carbide                                         |                                     |                                   |
| • Hot pressed                                           | 4.6                                 | 2.6                               |
| • Sintered                                              | 4.1                                 | 2.3                               |
| Silicon nitride                                         |                                     |                                   |
| • Hot pressed                                           | 2.7                                 | 1.5                               |
| • Reaction bonded                                       | 3.1                                 | 1.7                               |
| • Sintered                                              | 3.1                                 | 1.7                               |
| Zirconia, 3 mol% $\text{Y}_2\text{O}_3$                 | 9.6                                 | 5.3                               |
| <b>POLYMERS</b>                                         |                                     |                                   |
| Elastomers                                              |                                     |                                   |
| • Butadiene-acrylonitrile (nitrile)                     | 235                                 | 130                               |
| • Styrene-butadiene (SBR)                               | 220                                 | 125                               |
| • Silicone                                              | 270                                 | 150                               |
| Epoxy                                                   | 81–117                              | 45–65                             |
| Nylon 6,6                                               | 144                                 | 80                                |
| Phenolic                                                | 122                                 | 68                                |
| Polybutylene terephthalate (PBT)                        | 108–171                             | 60–95                             |
| Polycarbonate (PC)                                      | 122                                 | 68                                |
| Polyester (thermoset)                                   | 100–180                             | 55–100                            |
| Polyetheretherketone (PEEK)                             | 72–85                               | 40–47                             |
| Polyethylene                                            |                                     |                                   |
| • Low density (LDPE)                                    | 180–400                             | 100–220                           |
| • High density (HDPE)                                   | 106–198                             | 59–110                            |
| • Ultrahigh molecular weight (UHMWPE)                   | 234–360                             | 130–200                           |
| Polyethylene terephthalate (PET)                        | 117                                 | 65                                |
| Polymethyl methacrylate (PMMA)                          | 90–162                              | 50–90                             |
| Polypropylene (PP)                                      | 146–180                             | 81–100                            |
| Polystyrene (PS)                                        | 90–150                              | 50–83                             |
| Polytetrafluoroethylene (PTFE)                          | 126–216                             | 70–120                            |
| Polyvinyl chloride (PVC)                                | 90–180                              | 50–100                            |

Table B.6 (Continued)

| Material                                                | Coefficient of<br>Thermal Expansion |                                   |
|---------------------------------------------------------|-------------------------------------|-----------------------------------|
|                                                         | $10^{-6} (^{\circ}\text{C})^{-1}$   | $10^{-6} (^{\circ}\text{F})^{-1}$ |
| <b>FIBER MATERIALS</b>                                  |                                     |                                   |
| Aramid (Kevlar 49)                                      |                                     |                                   |
| • Longitudinal direction                                | -2.0                                | -1.1                              |
| • Transverse direction                                  | 60                                  | 33                                |
| Carbon (PAN precursor)                                  |                                     |                                   |
| • Standard modulus                                      |                                     |                                   |
| Longitudinal direction                                  | -0.6                                | -0.3                              |
| Transverse direction                                    | 10.0                                | 5.6                               |
| • Intermediate modulus                                  |                                     |                                   |
| Longitudinal direction                                  | -0.6                                | -0.3                              |
| • High modulus                                          |                                     |                                   |
| Longitudinal direction                                  | -0.5                                | -0.28                             |
| Transverse direction                                    | 7.0                                 | 3.9                               |
| E Glass                                                 | 5.0                                 | 2.8                               |
| <b>COMPOSITE MATERIALS</b>                              |                                     |                                   |
| Aramid fibers-epoxy matrix ( $V_f = 0.6$ )              |                                     |                                   |
| • Longitudinal direction                                | -4.0                                | -2.2                              |
| • Transverse direction                                  | 70                                  | 40                                |
| High modulus carbon fibers-epoxy matrix ( $V_f = 0.6$ ) |                                     |                                   |
| • Longitudinal direction                                | -0.5                                | -0.3                              |
| • Transverse direction                                  | 32                                  | 18                                |
| E glass fibers-epoxy matrix ( $V_f = 0.6$ )             |                                     |                                   |
| • Longitudinal direction                                | 6.6                                 | 3.7                               |
| • Transverse direction                                  | 30                                  | 16.7                              |
| Wood                                                    |                                     |                                   |
| • Douglas fir (12% moisture)                            |                                     |                                   |
| Parallel to grain                                       | 3.8-5.1                             | 2.2-2.8                           |
| Perpendicular to grain                                  | 25.4-33.8                           | 14.1-18.8                         |
| • Red oak (12% moisture)                                |                                     |                                   |
| Parallel to grain                                       | 4.6-5.9                             | 2.6-3.3                           |
| Perpendicular to grain                                  | 30.6-39.1                           | 17.0-21.7                         |

**Sources:** *ASM Handbooks, Volumes 1 and 2, Engineered Materials Handbooks, Volumes 1 and 4, Metals Handbook: Properties and Selection: Nonferrous Alloys and Pure Metals*, Vol. 2, 9th edition, and *Advanced Materials & Processes*, Vol. 146, No. 4, ASM International, Materials Park, OH; *Modern Plastics Encyclopedia '96*, The McGraw-Hill Companies, New York, NY; R. F. Floral and S. T. Peters, "Composite Structures and Technologies," tutorial notes, 1989; and manufacturers' technical data sheets.

**Table B.7** Room-Temperature Thermal Conductivity Values for Various Engineering Materials

| Material                                 | Thermal Conductivity |                    |
|------------------------------------------|----------------------|--------------------|
|                                          | <i>W/m-K</i>         | <i>Btu/ft-h-°F</i> |
| <b>METALS AND METAL ALLOYS</b>           |                      |                    |
| <b>Plain Carbon and Low Alloy Steels</b> |                      |                    |
| Steel alloy A36                          | 51.9                 | 30                 |
| Steel alloy 1020                         | 51.9                 | 30                 |
| Steel alloy 1040                         | 51.9                 | 30                 |
| <b>Stainless Steels</b>                  |                      |                    |
| Stainless alloy 304 (annealed)           | 16.2                 | 9.4                |
| Stainless alloy 316 (annealed)           | 16.2                 | 9.4                |
| Stainless alloy 405 (annealed)           | 27.0                 | 15.6               |
| Stainless alloy 440A (annealed)          | 24.2                 | 14.0               |
| Stainless alloy 17-7PH (annealed)        | 16.4                 | 9.5                |
| <b>Cast Irons</b>                        |                      |                    |
| Gray irons                               |                      |                    |
| • Grade G1800                            | 46.0                 | 26.6               |
| • Grade G3000                            | 46.0                 | 26.6               |
| • Grade G4000                            | 46.0                 | 26.6               |
| Ductile irons                            |                      |                    |
| • Grade 60-40-18                         | 36.0                 | 20.8               |
| • Grade 80-55-06                         | 36.0                 | 20.8               |
| • Grade 120-90-02                        | 36.0                 | 20.8               |
| <b>Aluminum Alloys</b>                   |                      |                    |
| Alloy 1100 (annealed)                    | 222                  | 128                |
| Alloy 2024 (annealed)                    | 190                  | 110                |
| Alloy 6061 (annealed)                    | 180                  | 104                |
| Alloy 7075-T6                            | 130                  | 75                 |
| Alloy 356.0-T6                           | 151                  | 87                 |
| <b>Copper Alloys</b>                     |                      |                    |
| C11000 (electrolytic tough pitch)        | 388                  | 224                |
| C17200 (beryllium-copper)                | 105-130              | 60-75              |
| C26000 (cartridge brass)                 | 120                  | 70                 |
| C36000 (free-cutting brass)              | 115                  | 67                 |
| C71500 (copper-nickel, 30%)              | 29                   | 16.8               |
| C93200 (bearing bronze)                  | 59                   | 34                 |
| <b>Magnesium Alloys</b>                  |                      |                    |
| Alloy AZ31B                              | 96 <sup>a</sup>      | 55 <sup>a</sup>    |
| Alloy AZ91D                              | 72 <sup>a</sup>      | 43 <sup>a</sup>    |
| <b>Titanium Alloys</b>                   |                      |                    |
| Commercially pure (ASTM grade 1)         | 16                   | 9.2                |
| Alloy Ti-5Al-2.5Sn                       | 7.6                  | 4.4                |
| Alloy Ti-6Al-4V                          | 6.7                  | 3.9                |
| <b>Precious Metals</b>                   |                      |                    |
| Gold (commercially pure)                 | 315                  | 182                |
| Platinum (commercially pure)             | 71 <sup>b</sup>      | 41 <sup>b</sup>    |
| Silver (commercially pure)               | 428                  | 247                |

Table B.7 (Continued)

| Material                                                | Thermal Conductivity |             |
|---------------------------------------------------------|----------------------|-------------|
|                                                         | W/m-K                | Btu/ft-h-°F |
| <b>Refractory Metals</b>                                |                      |             |
| Molybdenum (commercially pure)                          | 142                  | 82          |
| Tantalum (commercially pure)                            | 54.4                 | 31.4        |
| Tungsten (commercially pure)                            | 155                  | 89.4        |
| <b>Miscellaneous Nonferrous Alloys</b>                  |                      |             |
| Nickel 200                                              | 70                   | 40.5        |
| Inconel 625                                             | 9.8                  | 5.7         |
| Monel 400                                               | 21.8                 | 12.6        |
| Haynes alloy 25                                         | 9.8                  | 5.7         |
| Invar                                                   | 10                   | 5.8         |
| Super invar                                             | 10                   | 5.8         |
| Kovar                                                   | 17                   | 9.8         |
| Chemical lead                                           | 35                   | 20.2        |
| Antimonial lead (6%)                                    | 29                   | 16.8        |
| Tin (commercially pure)                                 | 60.7                 | 35.1        |
| Lead-Tin solder (60Sn-40Pb)                             | 50                   | 28.9        |
| Zinc (commercially pure)                                | 108                  | 62          |
| Zirconium, reactor grade 702                            | 22                   | 12.7        |
| <b>GRAPHITE, CERAMICS, AND SEMICONDUCTING MATERIALS</b> |                      |             |
| Aluminum oxide                                          |                      |             |
| • 99.9% pure                                            | 39                   | 22.5        |
| • 96%                                                   | 35                   | 20          |
| • 90%                                                   | 16                   | 9.2         |
| Concrete                                                | 1.25–1.75            | 0.72–1.0    |
| Diamond                                                 |                      |             |
| • Natural                                               | 1450–4650            | 840–2700    |
| • Synthetic                                             | 3150                 | 1820        |
| Gallium arsenide                                        | 45.5                 | 26.3        |
| Glass, borosilicate (Pyrex)                             | 1.4                  | 0.81        |
| Glass, soda-lime                                        | 1.7                  | 1.0         |
| Glass ceramic (Pyroceram)                               | 3.3                  | 1.9         |
| Graphite                                                |                      |             |
| • Extruded                                              | 130–190              | 75–110      |
| • Isostatically molded                                  | 104–130              | 60–75       |
| Silica, fused                                           | 1.4                  | 0.81        |
| Silicon                                                 | 141                  | 82          |
| Silicon carbide                                         |                      |             |
| • Hot pressed                                           | 80                   | 46.2        |
| • Sintered                                              | 71                   | 41          |
| Silicon nitride                                         |                      |             |
| • Hot pressed                                           | 29                   | 17          |
| • Reaction bonded                                       | 10                   | 6           |
| • Sintered                                              | 33                   | 19.1        |
| Zirconia, 3 mol% Y <sub>2</sub> O <sub>3</sub>          | 2.0–3.3              | 1.2–1.9     |
| <b>POLYMERS</b>                                         |                      |             |
| Elastomers                                              |                      |             |
| • Butadiene-acrylonitrile (nitrile)                     | 0.25                 | 0.14        |
| • Styrene-butadiene (SBR)                               | 0.25                 | 0.14        |
| • Silicone                                              | 0.23                 | 0.13        |

Table B.7 (Continued)

| Material                              | Thermal Conductivity |             |
|---------------------------------------|----------------------|-------------|
|                                       | W/m-K                | Btu/ft-h-°F |
| Epoxy                                 | 0.19                 | 0.11        |
| Nylon 6,6                             | 0.24                 | 0.14        |
| Phenolic                              | 0.15                 | 0.087       |
| Polybutylene terephthalate (PBT)      | 0.18–0.29            | 0.10–0.17   |
| Polycarbonate (PC)                    | 0.20                 | 0.12        |
| Polyester (thermoset)                 | 0.17                 | 0.10        |
| Polyethylene                          |                      |             |
| • Low density (LDPE)                  | 0.33                 | 0.19        |
| • High density (HDPE)                 | 0.48                 | 0.28        |
| • Ultrahigh molecular weight (UHMWPE) | 0.33                 | 0.19        |
| Polyethylene terephthalate (PET)      | 0.15                 | 0.087       |
| Polymethyl methacrylate (PMMA)        | 0.17–0.25            | 0.10–0.15   |
| Polypropylene (PP)                    | 0.12                 | 0.069       |
| Polystyrene (PS)                      | 0.13                 | 0.075       |
| Polytetrafluoroethylene (PTFE)        | 0.25                 | 0.14        |
| Polyvinyl chloride (PVC)              | 0.15–0.21            | 0.08–0.12   |
| <b>FIBER MATERIALS</b>                |                      |             |
| Carbon (PAN precursor), longitudinal  |                      |             |
| • Standard modulus                    | 11                   | 6.4         |
| • Intermediate modulus                | 15                   | 8.7         |
| • High modulus                        | 70                   | 40          |
| E Glass                               | 1.3                  | 0.75        |
| <b>COMPOSITE MATERIALS</b>            |                      |             |
| Wood                                  |                      |             |
| • Douglas fir (12% moisture)          |                      |             |
| Perpendicular to grain                | 0.14                 | 0.08        |
| • Red oak (12% moisture)              |                      |             |
| Perpendicular to grain                | 0.18                 | 0.11        |

<sup>a</sup> At 100°C.<sup>b</sup> At 0°C.

**Sources:** *ASM Handbooks, Volumes 1 and 2, Engineered Materials Handbooks, Volumes 1 and 4, Metals Handbook: Properties and Selection: Nonferrous Alloys and Pure Metals*, Vol. 2, 9th edition, and *Advanced Materials & Processes*, Vol. 146, No. 4, ASM International, Materials Park, OH; *Modern Plastics Encyclopedia '96* and *Modern Plastics Encyclopedia 1977–1978*, The McGraw-Hill Companies, New York, NY; and manufacturers' technical data sheets.

**Table B.8 Room-Temperature Specific Heat Values for Various Engineering Materials**

| <i>Material</i>                          | <i>Specific Heat</i> |                                             |
|------------------------------------------|----------------------|---------------------------------------------|
|                                          | <i>J/kg-K</i>        | <i>10<sup>-3</sup>Btu/lb<sub>m</sub>-°F</i> |
| <b>METALS AND METAL ALLOYS</b>           |                      |                                             |
| <b>Plain Carbon and Low Alloy Steels</b> |                      |                                             |
| Steel alloy A36                          | 486 <sup>a</sup>     | 11.6 <sup>a</sup>                           |
| Steel alloy 1020                         | 486 <sup>a</sup>     | 11.6 <sup>a</sup>                           |
| Steel alloy 1040                         | 486 <sup>a</sup>     | 11.6 <sup>a</sup>                           |
| <b>Stainless Steels</b>                  |                      |                                             |
| Stainless alloy 304                      | 500                  | 12.0                                        |
| Stainless alloy 316                      | 500                  | 12.0                                        |
| Stainless alloy 405                      | 460                  | 11.0                                        |
| Stainless alloy 440A                     | 460                  | 11.0                                        |
| Stainless alloy 17-7PH                   | 460                  | 11.0                                        |
| <b>Cast Irons</b>                        |                      |                                             |
| Gray irons                               |                      |                                             |
| • Grade G1800                            | 544                  | 13                                          |
| • Grade G3000                            | 544                  | 13                                          |
| • Grade G4000                            | 544                  | 13                                          |
| Ductile irons                            |                      |                                             |
| • Grade 60-40-18                         | 544                  | 13                                          |
| • Grade 80-55-06                         | 544                  | 13                                          |
| • Grade 120-90-02                        | 544                  | 13                                          |
| <b>Aluminum Alloys</b>                   |                      |                                             |
| Alloy 1100                               | 904                  | 21.6                                        |
| Alloy 2024                               | 875                  | 20.9                                        |
| Alloy 6061                               | 896                  | 21.4                                        |
| Alloy 7075                               | 960 <sup>b</sup>     | 23.0 <sup>b</sup>                           |
| Alloy 356.0                              | 963 <sup>b</sup>     | 23.0 <sup>b</sup>                           |
| <b>Copper Alloys</b>                     |                      |                                             |
| C11000 (electrolytic tough pitch)        | 385                  | 9.2                                         |
| C17200 (beryllium-copper)                | 420                  | 10.0                                        |
| C26000 (cartridge brass)                 | 375                  | 9.0                                         |
| C36000 (free-cutting brass)              | 380                  | 9.1                                         |
| C71500 (copper-nickel, 30%)              | 380                  | 9.1                                         |
| C93200 (bearing bronze)                  | 376                  | 9.0                                         |
| <b>Magnesium Alloys</b>                  |                      |                                             |
| Alloy AZ31B                              | 1024                 | 24.5                                        |
| Alloy AZ91D                              | 1050                 | 25.1                                        |
| <b>Titanium Alloys</b>                   |                      |                                             |
| Commercially pure (ASTM grade 1)         | 528 <sup>c</sup>     | 12.6 <sup>c</sup>                           |
| Alloy Ti-5Al-2.5Sn                       | 470 <sup>c</sup>     | 11.2 <sup>c</sup>                           |
| Alloy Ti-6Al-4V                          | 610 <sup>c</sup>     | 14.6 <sup>c</sup>                           |
| <b>Precious Metals</b>                   |                      |                                             |
| Gold (commercially pure)                 | 130                  | 3.1                                         |
| Platinum (commercially pure)             | 132 <sup>d</sup>     | 3.2 <sup>d</sup>                            |
| Silver (commercially pure)               | 235                  | 5.6                                         |

Table B.8 (Continued)

| Material                                                | Specific Heat |                                   |
|---------------------------------------------------------|---------------|-----------------------------------|
|                                                         | J/kg-K        | $10^{-3}$ Btu/lb <sub>m</sub> -°F |
| <b>Refractory Metals</b>                                |               |                                   |
| Molybdenum (commercially pure)                          | 276           | 6.6                               |
| Tantalum (commercially pure)                            | 139           | 3.3                               |
| Tungsten (commercially pure)                            | 138           | 3.3                               |
| <b>Miscellaneous Nonferrous Alloys</b>                  |               |                                   |
| Nickel 200                                              | 456           | 10.9                              |
| Inconel 625                                             | 410           | 9.8                               |
| Monel 400                                               | 427           | 10.2                              |
| Haynes alloy 25                                         | 377           | 9.0                               |
| Invar                                                   | 500           | 12.0                              |
| Super invar                                             | 500           | 12.0                              |
| Kovar                                                   | 460           | 11.0                              |
| Chemical lead                                           | 129           | 3.1                               |
| Antimonial lead (6%)                                    | 135           | 3.2                               |
| Tin (commercially pure)                                 | 222           | 5.3                               |
| Lead-Tin solder (60Sn-40Pb)                             | 150           | 3.6                               |
| Zinc (commercially pure)                                | 395           | 9.4                               |
| Zirconium, reactor grade 702                            | 285           | 6.8                               |
| <b>GRAPHITE, CERAMICS, AND SEMICONDUCTING MATERIALS</b> |               |                                   |
| Aluminum oxide                                          |               |                                   |
| • 99.9% pure                                            | 775           | 18.5                              |
| • 96%                                                   | 775           | 18.5                              |
| • 90%                                                   | 775           | 18.5                              |
| Concrete                                                | 850-1150      | 20.3-27.5                         |
| Diamond (natural)                                       | 520           | 12.4                              |
| Gallium arsenide                                        | 350           | 8.4                               |
| Glass, borosilicate (Pyrex)                             | 850           | 20.3                              |
| Glass, soda-lime                                        | 840           | 20.0                              |
| Glass ceramic (Pyroceram)                               | 975           | 23.3                              |
| Graphite                                                |               |                                   |
| • Extruded                                              | 830           | 19.8                              |
| • Isostatically molded                                  | 830           | 19.8                              |
| Silica, fused                                           | 740           | 17.7                              |
| Silicon                                                 | 700           | 16.7                              |
| Silicon carbide                                         |               |                                   |
| • Hot pressed                                           | 670           | 16.0                              |
| • Sintered                                              | 590           | 14.1                              |
| Silicon nitride                                         |               |                                   |
| • Hot pressed                                           | 750           | 17.9                              |
| • Reaction bonded                                       | 870           | 20.7                              |
| • Sintered                                              | 1100          | 26.3                              |
| Zirconia, 3 mol% Y <sub>2</sub> O <sub>3</sub>          | 481           | 11.5                              |
| <b>POLYMERS</b>                                         |               |                                   |
| Epoxy                                                   | 1050          | 25                                |
| Nylon 6,6                                               | 1670          | 40                                |
| Phenolic                                                | 1590-1760     | 38-42                             |
| Polybutylene terephthalate (PBT)                        | 1170-2300     | 28-55                             |
| Polycarbonate (PC)                                      | 840           | 20                                |

**Table B.8** (Continued)

| <i>Material</i>                  | <i>Specific Heat</i> |                                             |
|----------------------------------|----------------------|---------------------------------------------|
|                                  | <i>J/kg-K</i>        | <i>10<sup>-2</sup>Btu/lb<sub>m</sub>-°F</i> |
| Polyester (thermoset)            | 710–920 <sup>c</sup> | 17–22                                       |
| Polyethylene                     |                      |                                             |
| • Low density (LDPE)             | 2300                 | 55                                          |
| • High density (HDPE)            | 1850                 | 44.2                                        |
| Polyethylene terephthalate (PET) | 1170                 | 28                                          |
| Polymethyl methacrylate (PMMA)   | 1460                 | 35                                          |
| Polypropylene (PP)               | 1925                 | 46                                          |
| Polystyrene (PS)                 | 1170                 | 28                                          |
| Polytetrafluoroethylene (PTFE)   | 1050                 | 25                                          |
| Polyvinyl chloride (PVC)         | 1050–1460            | 25–35                                       |
| <b>FIBER MATERIALS</b>           |                      |                                             |
| Aramid (Kevlar 49)               | 1300                 | 31                                          |
| E Glass                          | 810                  | 19.3                                        |
| <b>COMPOSITE MATERIALS</b>       |                      |                                             |
| Wood                             |                      |                                             |
| • Douglas fir (12% moisture)     | 2900                 | 69.3                                        |
| • Red oak (12% moisture)         | 2900                 | 69.3                                        |

<sup>a</sup> At temperatures between 50°C and 100°C.<sup>b</sup> At 100°C.<sup>c</sup> At 50°C.<sup>d</sup> At 0°C.

**Sources:** *ASM Handbooks, Volumes 1 and 2, Engineered Materials Handbooks, Volumes 1, 2, and 4, Metals Handbook: Properties and Selection: Non-ferrous Alloys and Pure Metals*, Vol. 2, 9th edition, and *Advanced Materials & Processes*, Vol. 146, No. 4, ASM International, Materials Park, OH; *Modern Plastics Encyclopedia 1977–1978*, The McGraw-Hill Companies, New York, NY; and manufacturers' technical data sheets.

**Table B.9** Room-Temperature Electrical Resistivity Values for Various Engineering Materials

| <i>Material</i>                          | <i>Electrical Resistivity, Ω-m</i> |
|------------------------------------------|------------------------------------|
| <b>METALS AND METAL ALLOYS</b>           |                                    |
| <b>Plain Carbon and Low Alloy Steels</b> |                                    |
| Steel alloy A36 <sup>a</sup>             | $1.60 \times 10^{-7}$              |
| Steel alloy 1020 (annealed) <sup>a</sup> | $1.60 \times 10^{-7}$              |
| Steel alloy 1040 (annealed) <sup>a</sup> | $1.60 \times 10^{-7}$              |
| Steel alloy 4140 (quenched and tempered) | $2.20 \times 10^{-7}$              |
| Steel alloy 4340 (quenched and tempered) | $2.48 \times 10^{-7}$              |
| <b>Stainless Steels</b>                  |                                    |
| Stainless alloy 304 (annealed)           | $7.2 \times 10^{-7}$               |
| Stainless alloy 316 (annealed)           | $7.4 \times 10^{-7}$               |
| Stainless alloy 405 (annealed)           | $6.0 \times 10^{-7}$               |
| Stainless alloy 440A (annealed)          | $6.0 \times 10^{-7}$               |
| Stainless alloy 17-7PH (annealed)        | $8.3 \times 10^{-7}$               |

**Table B.9** (Continued)

| <b>Material</b>                             | <b>Electrical Resistivity, <math>\Omega\cdot m</math></b> |
|---------------------------------------------|-----------------------------------------------------------|
| <b>Cast Irons</b>                           |                                                           |
| Gray irons                                  |                                                           |
| • Grade G1800                               | $15.0 \times 10^{-7}$                                     |
| • Grade G3000                               | $9.5 \times 10^{-7}$                                      |
| • Grade G4000                               | $8.5 \times 10^{-7}$                                      |
| Ductile irons                               |                                                           |
| • Grade 60-40-18                            | $5.5 \times 10^{-7}$                                      |
| • Grade 80-55-06                            | $6.2 \times 10^{-7}$                                      |
| • Grade 120-90-02                           | $6.2 \times 10^{-7}$                                      |
| <b>Aluminum Alloys</b>                      |                                                           |
| Alloy 1100 (annealed)                       | $2.9 \times 10^{-8}$                                      |
| Alloy 2024 (annealed)                       | $3.4 \times 10^{-8}$                                      |
| Alloy 6061 (annealed)                       | $3.7 \times 10^{-8}$                                      |
| Alloy 7075 (T6 treatment)                   | $5.22 \times 10^{-8}$                                     |
| Alloy 356.0 (T6 treatment)                  | $4.42 \times 10^{-8}$                                     |
| <b>Copper Alloys</b>                        |                                                           |
| C11000 (electrolytic tough pitch, annealed) | $1.72 \times 10^{-8}$                                     |
| C172000 (beryllium-copper)                  | $5.7 \times 10^{-8}$ – $1.15 \times 10^{-7}$              |
| C26000 (cartridge brass)                    | $6.2 \times 10^{-8}$                                      |
| C36000 (free-cutting brass)                 | $6.6 \times 10^{-8}$                                      |
| C71500 (copper-nickel, 30%)                 | $37.5 \times 10^{-8}$                                     |
| C93200 (bearing bronze)                     | $14.4 \times 10^{-8}$                                     |
| <b>Magnesium Alloys</b>                     |                                                           |
| Alloy AZ31B                                 | $9.2 \times 10^{-8}$                                      |
| Alloy AZ91D                                 | $17.0 \times 10^{-8}$                                     |
| <b>Titanium Alloys</b>                      |                                                           |
| Commercially pure (ASTM grade 1)            | $4.2 \times 10^{-7}$ – $5.2 \times 10^{-7}$               |
| Alloy Ti-5Al-2.5Sn                          | $15.7 \times 10^{-7}$                                     |
| Alloy Ti-6Al-4V                             | $17.1 \times 10^{-7}$                                     |
| <b>Precious Metals</b>                      |                                                           |
| Gold (commercially pure)                    | $2.35 \times 10^{-8}$                                     |
| Platinum (commercially pure)                | $10.60 \times 10^{-8}$                                    |
| Silver (commercially pure)                  | $1.47 \times 10^{-8}$                                     |
| <b>Refractory Metals</b>                    |                                                           |
| Molybdenum (commercially pure)              | $5.2 \times 10^{-8}$                                      |
| Tantalum (commercially pure)                | $13.5 \times 10^{-8}$                                     |
| Tungsten (commercially pure)                | $5.3 \times 10^{-8}$                                      |
| <b>Miscellaneous Nonferrous Alloys</b>      |                                                           |
| Nickel 200                                  | $0.95 \times 10^{-7}$                                     |
| Inconel 625                                 | $12.90 \times 10^{-7}$                                    |
| Monel 400                                   | $5.47 \times 10^{-7}$                                     |
| Haynes alloy 25                             | $8.9 \times 10^{-7}$                                      |
| Invar                                       | $8.2 \times 10^{-7}$                                      |
| Super invar                                 | $8.0 \times 10^{-7}$                                      |
| Kovar                                       | $4.9 \times 10^{-7}$                                      |
| Chemical lead                               | $2.06 \times 10^{-7}$                                     |
| Antimonial lead (6%)                        | $2.53 \times 10^{-7}$                                     |
| Tin (commercially pure)                     | $1.11 \times 10^{-7}$                                     |
| Lead-Tin solder (60Sn-40Pb)                 | $1.50 \times 10^{-7}$                                     |

**Table B.9** (Continued)

| <b>Material</b>                                         | <b>Electrical Resistivity, <math>\Omega\cdot m</math></b> |
|---------------------------------------------------------|-----------------------------------------------------------|
| Zinc (commercially pure)                                | $62.0 \times 10^{-7}$                                     |
| Zirconium, reactor grade 702                            | $3.97 \times 10^{-7}$                                     |
| <b>GRAPHITE, CERAMICS, AND SEMICONDUCTING MATERIALS</b> |                                                           |
| Aluminum oxide                                          |                                                           |
| • 99.9% pure                                            | $>10^{13}$                                                |
| • 96%                                                   | $>10^{12}$                                                |
| • 90%                                                   | $>10^{12}$                                                |
| Concrete (dry)                                          | $10^9$                                                    |
| Diamond                                                 |                                                           |
| • Natural                                               | $10\text{--}10^{14}$                                      |
| • Synthetic                                             | $1.5 \times 10^{-2}$                                      |
| Gallium arsenide (intrinsic)                            | $10^6$                                                    |
| Glass, borosilicate (Pyrex)                             | $\sim 10^{13}$                                            |
| Glass, soda-lime                                        | $10^{10}\text{--}10^{11}$                                 |
| Glass ceramic (Pyroceram)                               | $2 \times 10^{14}$                                        |
| Graphite                                                |                                                           |
| • Extruded (with grain direction)                       | $7 \times 10^{-6}\text{--}20 \times 10^{-6}$              |
| • Isostatically molded                                  | $10 \times 10^{-6}\text{--}18 \times 10^{-6}$             |
| Silica, fused                                           | $>10^{18}$                                                |
| Silicon (intrinsic)                                     | 2500                                                      |
| Silicon carbide                                         |                                                           |
| • Hot pressed                                           | $1.0\text{--}10^9$                                        |
| • Sintered                                              | $1.0\text{--}10^9$                                        |
| Silicon nitride                                         |                                                           |
| • Hot isostatic pressed                                 | $>10^{12}$                                                |
| • Reaction bonded                                       | $>10^{12}$                                                |
| • Sintered                                              | $>10^{12}$                                                |
| Zirconia, 3 mol% $Y_2O_3$                               | $10^{10}$                                                 |
| <b>POLYMERS</b>                                         |                                                           |
| Elastomers                                              |                                                           |
| • Butadiene-acrylonitrile (nitrile)                     | $3.5 \times 10^8$                                         |
| • Styrene-butadiene (SBR)                               | $6 \times 10^{11}$                                        |
| • Silicone                                              | $10^{13}$                                                 |
| Epoxy                                                   | $10^{10}\text{--}10^{13}$                                 |
| Nylon 6,6                                               | $10^{12}\text{--}10^{13}$                                 |
| Phenolic                                                | $10^9\text{--}10^{10}$                                    |
| Polybutylene terephthalate (PBT)                        | $4 \times 10^{14}$                                        |
| Polycarbonate (PC)                                      | $2 \times 10^{14}$                                        |
| Polyester (thermoset)                                   | $10^{13}$                                                 |
| Polyetheretherketone (PEEK)                             | $6 \times 10^{14}$                                        |
| Polyethylene                                            |                                                           |
| • Low density (LDPE)                                    | $10^{15}\text{--}5 \times 10^{16}$                        |
| • High density (HDPE)                                   | $10^{15}\text{--}5 \times 10^{16}$                        |
| • Ultrahigh molecular weight (UHMWPE)                   | $>5 \times 10^{14}$                                       |
| Polyethylene terephthalate (PET)                        | $10^{12}$                                                 |
| Polymethyl methacrylate (PMMA)                          | $>10^{12}$                                                |
| Polypropylene (PP)                                      | $>10^{14}$                                                |
| Polystyrene (PS)                                        | $>10^{14}$                                                |
| Polytetrafluoroethylene (PTFE)                          | $10^{17}$                                                 |
| Polyvinyl chloride (PVC)                                | $>10^{14}$                                                |

**Table B.9** (Continued)

| Material                   | Electrical Resistivity, $\Omega\cdot m$ |
|----------------------------|-----------------------------------------|
| <b>FIBER MATERIALS</b>     |                                         |
| Carbon (PAN precursor)     |                                         |
| • Standard modulus         | $17 \times 10^{-6}$                     |
| • Intermediate modulus     | $15 \times 10^{-6}$                     |
| • High modulus             | $9.5 \times 10^{-6}$                    |
| E Glass                    | $4 \times 10^{14}$                      |
| <b>COMPOSITE MATERIALS</b> |                                         |
| Wood                       |                                         |
| • Douglas fir (oven dry)   |                                         |
| Parallel to grain          | $10^{14}\text{--}10^{16}$               |
| Perpendicular to grain     | $10^{14}\text{--}10^{16}$               |
| • Red oak (oven dry)       |                                         |
| Parallel to grain          | $10^{14}\text{--}10^{16}$               |
| Perpendicular to grain     | $10^{14}\text{--}10^{16}$               |

<sup>a</sup> At 0°C.

**Sources:** *ASM Handbooks, Volumes 1 and 2, Engineered Materials Handbooks, Volumes 1, 2, and 4, Metals Handbook: Properties and Selection: Non-ferrous Alloys and Pure Metals*, Vol. 2, 9th edition, and *Advanced Materials & Processes*, Vol. 146, No. 4, ASM International, Materials Park, OH; *Modern Plastics Encyclopedia 1977–1978*, The McGraw-Hill Companies, New York, NY; and manufacturers' technical data sheets.

**Table B.10** Compositions of Metal Alloys for Which Data Are Included in Tables B.1 through B.9

| Alloy<br>(UNS Designation)               | Composition (wt%)                                            |
|------------------------------------------|--------------------------------------------------------------|
| <b>PLAIN-CARBON AND LOW-ALLOY STEELS</b> |                                                              |
| A 36 (ASTM A 36)                         | 98.0 Fe (min), 0.29 C, 1.0 Mn, 0.28 Si                       |
| 1020 (G10200)                            | 99.1 Fe (min), 0.20 C, 0.45 Mn                               |
| 1040 (G10400)                            | 98.6 Fe (min), 0.40 C, 0.75 Mn                               |
| 4140 (G41400)                            | 96.8 Fe (min), 0.40 C, 0.90 Cr, 0.20 Mo, 0.9 Mn              |
| 4340 (G43400)                            | 95.2 Fe (min), 0.40 C, 1.8 Ni, 0.80 Cr, 0.25 Mo, 0.7 Mn      |
| <b>STAINLESS STEELS</b>                  |                                                              |
| 304 (S30400)                             | 66.4 Fe (min), 0.08 C, 19.0 Cr, 9.25 Ni, 2.0 Mn              |
| 316 (S31600)                             | 61.9 Fe (min), 0.08 C, 17.0 Cr, 12.0 Ni, 2.5 Mo, 2.0 Mn      |
| 405 (S40500)                             | 83.1 Fe (min), 0.08 C, 13.0 Cr, 0.20 Al, 1.0 Mn              |
| 440A (S44002)                            | 78.4 Fe (min), 0.70 C, 17.0 Cr, 0.75 Mo, 1.0 Mn              |
| 17-7PH (S17700)                          | 70.6 Fe (min), 0.09 C, 17.0 Cr, 7.1 Ni, 1.1 Al, 1.0 Mn       |
| <b>CAST IRONS</b>                        |                                                              |
| Grade G1800 (F10004)                     | Fe (bal), 3.4–3.7 C, 2.8–2.3 Si, 0.65 Mn, 0.15 P, 0.15 S     |
| Grade G3000 (F10006)                     | Fe (bal), 3.1–3.4 C, 2.3–1.9 Si, 0.75 Mn, 0.10 P, 0.15 S     |
| Grade G4000 (F10008)                     | Fe (bal), 3.0–3.3 C, 2.1–1.8 Si, 0.85 Mn, 0.07 P, 0.15 S     |
| Grade 60-40-18 (F32800)                  | Fe (bal), 3.4–4.0 C, 2.0–2.8 Si, 0–1.0 Ni, 0.05 Mg           |
| Grade 80-55-06 (F33800)                  | Fe (bal), 3.3–3.8 C, 2.0–3.0 Si, 0–1.0 Ni, 0.05 Mg           |
| Grade 120-90-02 (F36200)                 | Fe (bal), 3.4–3.8 C, 2.0–2.8 Si, 0–2.5 Ni, 0–1.0 Mo, 0.05 Mg |

**Table B.10** (Continued)

| <b>Alloy</b><br>(UNS Designation)     | <b>Composition (wt%)</b>                                      |
|---------------------------------------|---------------------------------------------------------------|
| <b>ALUMINUM ALLOYS</b>                |                                                               |
| 1100 (A91100)                         | 99.00 Al (min), 0.20 Cu (max)                                 |
| 2024 (A92024)                         | 90.75 Al (min), 4.4 Cu, 0.6 Mn, 1.5 Mg                        |
| 6061 (A96061)                         | 95.85 Al (min), 1.0 Mg, 0.6 Si, 0.30 Cu, 0.20 Cr              |
| 7075 (A97075)                         | 87.2 Al (min), 5.6 Zn, 2.5 Mg, 1.6 Cu, 0.23 Cr                |
| 356.0 (A03560)                        | 90.1 Al (min), 7.0 Si, 0.3 Mg                                 |
| <b>COPPER ALLOYS</b>                  |                                                               |
| (C11000)                              | 99.90 Cu (min), 0.04 O (max)                                  |
| (C17200)                              | 96.7 Cu (min), 1.9 Be, 0.20 Co                                |
| (C26000)                              | Zn (bal), 70 Cu, 0.07 Pb, 0.05 Fe (max)                       |
| (C36000)                              | 60.0 Cu (min), 35.5 Zn, 3.0 Pb                                |
| (C71500)                              | 63.75 Cu (min), 30.0 Ni                                       |
| (C93200)                              | 81.0 Cu (min), 7.0 Sn, 7.0 Pb, 3.0 Zn                         |
| <b>MAGNESIUM ALLOYS</b>               |                                                               |
| AZ31B (M11311)                        | 94.4 Mg (min), 3.0 Al, 0.20 Mn (min), 1.0 Zn, 0.1 Si (max)    |
| AZ91D (M11916)                        | 89.0 Mg (min), 9.0 Al, 0.13 Mn (min), 0.7 Zn, 0.1 Si (max)    |
| <b>TITANIUM ALLOYS</b>                |                                                               |
| Commercial, grade 1 (R50250)          | 99.5 Ti (min)                                                 |
| Ti-5Al-2.5Sn (R54520)                 | 90.2 Ti (min), 5.0 Al, 2.5 Sn                                 |
| Ti-6Al-4V (R56400)                    | 87.7 Ti (min), 6.0 Al, 4.0 V                                  |
| <b>MISCELLANEOUS ALLOYS</b>           |                                                               |
| Nickel 200                            | 99.0 Ni (min)                                                 |
| Inconel 625                           | 58.0 Ni (min), 21.5 Cr, 9.0 Mo, 5.0 Fe, 3.65 Nb + Ta, 1.0 Co  |
| Monel 400                             | 63.0 Ni (min), 31.0 Cu, 2.5 Fe, 0.2 Mn, 0.3 C, 0.5 Si         |
| Haynes alloy 25                       | 49.4 Co (min), 20 Cr, 15 W, 10 Ni, 3 Fe (max), 0.10 C, 1.5 Mn |
| Invar (K93601)                        | 64 Fe, 36 Ni                                                  |
| Super invar                           | 63 Fe, 32 Ni, 5 Co                                            |
| Kovar                                 | 54 Fe, 29 Ni, 17 Co                                           |
| Chemical lead (L51120)                | 99.90 Pb (min)                                                |
| Antimonial lead, 6% (L53105)          | 94 Pb, 6 Sb                                                   |
| Tin (commercially pure) (ASTM B339A)  | 98.85 Pb (min)                                                |
| Lead-Tin solder (60Sn-40Pb)           |                                                               |
| (ASTM B32 grade 60)                   | 60 Sn, 40 Pb                                                  |
| Zinc (commercially pure) (Z21210)     | 99.9 Zn (min), 0.10 Pb (max)                                  |
| Zirconium, reactor grade 702 (R60702) | 99.2 Zr + Hf (min), 4.5 Hf (max), 0.2 Fe + Cr                 |

**Sources:** ASM Handbooks, Volumes 1 and 2, ASM International, Materials Park, OH.

# Appendix C / Costs and Relative Costs for Selected Engineering Materials

**T**his appendix contains price information for the same set of materials for which the properties are included in Appendix B. The collection of valid cost data for materials is an extremely difficult task, which explains the dearth of materials-pricing information in the literature. One reason for this is that there are three pricing tiers: manufacturer, distributor, and retail. Under most circumstances, we have cited distributor prices. For some materials (e.g., specialized ceramics such as silicon carbide and silicon nitride), it was necessary to use manufacturer's prices. In addition, there may be significant variation in the cost for a specific material. There are several reasons for this. First, each vendor has its own pricing scheme. Furthermore, cost will depend on quantity of material purchased and, in addition, how it was processed or treated. We have endeavored to collect data for relatively large orders—i.e., quantities on the order of 900 kg (2000 lb<sub>m</sub>) for materials that are ordinarily sold in bulk lots—and, also, for common shapes/treatments. When possible, we obtained price quotes from at least three distributors/manufacturers.

This pricing information was collected between May and August of 1998. Cost data are in U.S. dollars per kilogram; in addition, these data are expressed as both price ranges and single-price values. The absence of a price range (i.e., when a single value is cited) means that either the variation is small, or that, on the basis of limited data, it is not possible to identify a range of prices. Furthermore, inasmuch as material prices change over time, it was decided to use a relative cost index; this index represents the per-unit mass cost (or average per-unit mass cost) of a material divided by the average per-unit mass cost of a common engineering material—A36 plain carbon steel. Although the price of a specific material will vary over time, the price ratio between that material and another will, most likely, change more slowly.

| <i>Material/Condition</i>                | <i>Cost (\$US/kg)</i> | <i>Relative Cost</i> |
|------------------------------------------|-----------------------|----------------------|
| <b>PLAIN CARBON AND LOW ALLOY STEELS</b> |                       |                      |
| Steel alloy A36                          |                       |                      |
| • Plate, hot rolled                      | 0.50–0.90             | 1.00                 |
| • Angle bar, hot rolled                  | 1.15                  | 1.6                  |
| Steel alloy 1020                         |                       |                      |
| • Plate, hot rolled                      | 0.50–0.60             | 0.8                  |
| • Plate, cold rolled                     | 0.85–1.45             | 1.6                  |
| Steel alloy 1040                         |                       |                      |
| • Plate, hot rolled                      | 0.75–0.85             | 1.1                  |
| • Plate, cold rolled                     | 1.30                  | 1.9                  |

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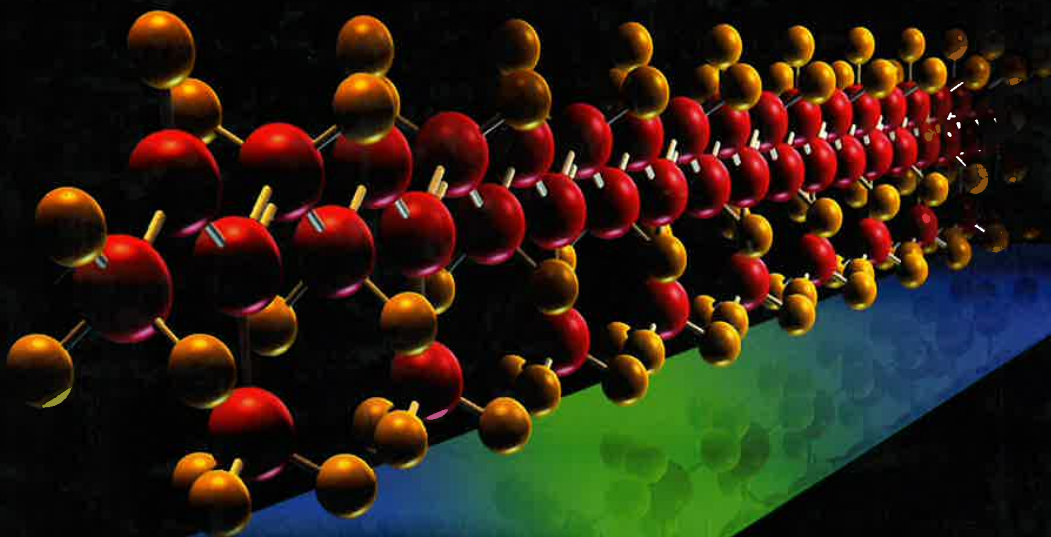
| <i>Material/Condition</i>                      | <i>Cost (\$US/kg)</i> | <i>Relative Cost</i> |
|------------------------------------------------|-----------------------|----------------------|
| Steel alloy 4140                               |                       |                      |
| • Bar, normalized                              | 1.75–1.95             | 2.6                  |
| • H grade (round), normalized                  | 2.85–3.05             | 4.2                  |
| Steel alloy 4340                               |                       |                      |
| • Bar, annealed                                | 2.45                  | 3.5                  |
| • Bar, normalized                              | 3.30                  | 4.7                  |
| <b>STAINLESS STEELS</b>                        |                       |                      |
| Stainless alloy 304                            |                       |                      |
| • Plate, hot finished and annealed             | 2.15–3.50             | 4.0                  |
| Stainless alloy 316                            |                       |                      |
| • Plate, hot finished and annealed             | 3.00–4.40             | 5.3                  |
| • Round, cold drawn and annealed               | 6.20                  | 8.9                  |
| Stainless alloy 440A                           |                       |                      |
| • Plate, annealed                              | 4.40–5.00             | 6.7                  |
| Stainless alloy 17-7PH                         |                       |                      |
| • Plate, cold rolled                           | 6.85–10.00            | 12.0                 |
| <b>CAST IRONS</b>                              |                       |                      |
| Gray irons (all grades)                        |                       |                      |
| • High production                              | 1.20–1.50             | 1.9                  |
| • Low production                               | 3.30                  | 4.7                  |
| Ductile irons (all grades)                     |                       |                      |
| • High production                              | 1.45–1.85             | 2.4                  |
| • Low production                               | 3.30–5.00             | 5.9                  |
| <b>ALUMINUM ALLOYS</b>                         |                       |                      |
| Alloy 1100                                     |                       |                      |
| • Sheet, annealed                              | 7.25–10.00            | 12.3                 |
| Alloy 2024                                     |                       |                      |
| • Sheet, T3 temper                             | 8.80–11.00            | 14.1                 |
| • Bar, T351 temper                             | 11.35                 | 16.2                 |
| Alloy 6061                                     |                       |                      |
| • Sheet, T6 temper                             | 4.40–6.20             | 7.6                  |
| • Bar, T651 temper                             | 6.10                  | 8.7                  |
| Alloy 7075                                     |                       |                      |
| • Sheet, T6 temper                             | 9.00–9.70             | 13.4                 |
| Alloy 356                                      |                       |                      |
| • As cast, high production                     | 4.40–6.60             | 7.9                  |
| • As cast, custom pieces                       | 11.00                 | 15.7                 |
| • T6 temper, custom pieces                     | 11.65                 | 16.6                 |
| <b>COPPER ALLOYS</b>                           |                       |                      |
| Alloy C11000 (electrolytic tough pitch), sheet | 4.00–7.00             | 7.9                  |
| Alloy C17200 (beryllium–copper), sheet         | 25.00–47.00           | 51.4                 |
| Alloy C26000 (cartridge brass), sheet          | 3.50–4.85             | 6.0                  |
| Alloy C36000 (free-cutting brass), sheet, rod  | 3.20–4.00             | 5.1                  |
| Alloy C71500 (copper–nickel, 30%), sheet       | 8.50–9.50             | 12.9                 |
| Alloy C93200 (bearing bronze)                  |                       |                      |
| • Bar                                          | 4.50–6.50             | 7.9                  |
| • As cast, custom piece                        | 12.20                 | 17.4                 |

| Material/Condition                                                           | Cost (\$US/kg) | Relative Cost |
|------------------------------------------------------------------------------|----------------|---------------|
| <b>MAGNESIUM ALLOYS</b>                                                      |                |               |
| Alloy AZ31B                                                                  | 11.00          | 15.7          |
| • Sheet (rolled)                                                             | 8.80           | 12.6          |
| • Extruded                                                                   | 3.80           | 5.4           |
| Alloy AZ91D (as cast)                                                        |                |               |
| <b>TITANIUM ALLOYS</b>                                                       |                |               |
| Commercially pure                                                            | 28.00–65.00    | 66.4          |
| • ASTM grade 1, annealed                                                     | 90.00–130.00   | 157           |
| Alloy Ti-5Al-2.5V                                                            | 55.00–130.00   | 132           |
| Alloy Ti-6Al-4V                                                              |                |               |
| <b>PRECIOUS METALS</b>                                                       |                |               |
| Gold, bullion                                                                | 9,500–10,250   | 14,100        |
| Platinum, bullion                                                            | 11,400–14,400  | 18,400        |
| Silver, bullion                                                              | 170–210        | 271           |
| <b>REFRACTORY METALS</b>                                                     |                |               |
| Molybdenum                                                                   | 85.00–115.00   | 143           |
| • Commercially pure, sheet and rod                                           |                |               |
| Tantalum                                                                     | 390–440        | 593           |
| • Commercially pure, sheet and rod                                           |                |               |
| Tungsten                                                                     | 77.50          | 111           |
| • Commercially pure, sheet                                                   | 97.00–135.00   | 166           |
| • Commercially pure, rod ( $1/2$ – $3/8$ in. dia.)                           |                |               |
| <b>MISCELLANEOUS NONFERROUS ALLOYS</b>                                       |                |               |
| Nickel 200                                                                   | 19.00–25.00    | 31.4          |
| Inconel 625                                                                  | 20.00–29.00    | 35.0          |
| Monel 400                                                                    | 15.50–16.50    | 22.9          |
| Haynes alloy 25                                                              | 85.50–103.50   | 135           |
| Invar                                                                        | 17.25–19.75    | 26.4          |
| Super invar                                                                  | 22.00–33.00    | 39.3          |
| Kovar                                                                        | 30.75–39.75    | 50.4          |
| Chemical lead                                                                | 1.20           | 1.7           |
| • Ingot                                                                      | 1.55–1.95      | 2.5           |
| • Plate                                                                      |                |               |
| Antimonial lead (6%)                                                         | 1.50           | 2.1           |
| • Ingot                                                                      | 2.00–2.70      | 3.4           |
| • Plate                                                                      | 6.85–8.85      | 11.2          |
| Tin, commercial purity (99.9+%), ingot                                       | 5.50–7.50      | 9.3           |
| Solder (60Sn-40Pb), bar                                                      |                |               |
| Zinc, commercial purity                                                      | 1.20           | 1.7           |
| • Ingot                                                                      | 1.65–2.45      | 2.9           |
| • Anode                                                                      | 44.00–48.50    | 66.1          |
| Zirconium, reactor grade 702 (plate)                                         |                |               |
| <b>GRAPHITE, CERAMICS, AND SEMICONDUCTING MATERIALS</b>                      |                |               |
| Aluminum oxide                                                               |                |               |
| • Calcined powder, 99.8% pure, particle size between 0.4 and 5 $\mu\text{m}$ | 1.40–1.60      | 2.1           |
| • Ball grinding media, 99% pure, $1/4$ in. dia.                              | 28.65          | 41            |
| • Ball grinding media, 96% pure, $1/4$ in. dia.                              | 29.75          | 42.5          |
| • Ball grinding media, 90% pure, $1/4$ in. dia.                              | 15.20          | 21.7          |

| <i>Material/Condition</i>                                                         | <i>Cost (\$US/kg)</i> | <i>Relative Cost</i> |
|-----------------------------------------------------------------------------------|-----------------------|----------------------|
| Concrete, mixed                                                                   | 0.04                  | 0.06                 |
| Diamond                                                                           |                       |                      |
| • Natural, 1/3 carat, industrial grade                                            | 36,000–90,000         | 90,000               |
| • Synthetic, 30–40 mesh, industrial grade                                         | 18,750                | 27,000               |
| • Natural, powder, 45 $\mu\text{m}$ , polishing abrasive                          | 5,000                 | 7,100                |
| Gallium arsenide                                                                  |                       |                      |
| • Mechanical grade, 75 mm dia. wafers, ~625 $\mu\text{m}$ thick                   | 1650–2700             | 3100                 |
| • Prime grade, 75 mm dia. wafers, ~625 $\mu\text{m}$ thick                        | 8500–10,000           | 13,200               |
| Glass, borosilicate (Pyrex), plate                                                | 8.50–17.00            | 18.2                 |
| Glass, soda–lime, plate                                                           | 1.75–2.35             | 2.9                  |
| Glass ceramic (Pyrocera), plate                                                   | 12.25–19.25           | 22.5                 |
| Graphite                                                                          |                       |                      |
| • Powder, synthetic, 99% pure, particle size ~10 $\mu\text{m}$                    | 5.00                  | 7.1                  |
| • Powder, synthetic, 99.7% pure, particle size ~10 $\mu\text{m}$                  | 7.50                  | 10.7                 |
| • Extruded, high purity, fine (<0.75 mm) particle size                            | 6.00–7.00             | 9.3                  |
| • Isostatically pressed parts, high purity, ~20 $\mu\text{m}$ particle size       | 15.00–25.50           | 29                   |
| Silica, fused, plate                                                              | 315–395               | 500                  |
| Silicon                                                                           |                       |                      |
| • Test grade, undoped, 100 mm dia. wafers, ~425 $\mu\text{m}$ thick               | 900–2000              | 2070                 |
| • Prime grade, undoped, 100 mm dia. wafers, ~425 $\mu\text{m}$ thick              | 2075–2525             | 3300                 |
| Silicon carbide                                                                   |                       |                      |
| • $\alpha$ -phase sinterable powder, particle size between 1 and 10 $\mu\text{m}$ | 22.00–58.00           | 57.1                 |
| • $\alpha$ -phase, polishing abrasive                                             | 4.50–21.50            | 18.6                 |
| • $\beta$ -phase sinterable powder, particle size between 1 and 10 $\mu\text{m}$  | 40.00–100.00          | 100                  |
| • $\beta$ -phase, polishing abrasive, 1200 to 400 mesh                            | 8.00–22.00            | 21.4                 |
| • $\alpha$ -phase ball grinding media, 1/4 in. dia., sintered                     | 250.00                | 360                  |
| Silicon nitride                                                                   |                       |                      |
| • Sinterable powder, submicron particle size                                      | 100.00                | 143                  |
| • Balls, unfinished, 0.25 in. to 0.50 in. in diameter, hot isostatic pressed      | 875–1100              | 1400                 |
| • Balls, finished ground, 0.25 in. to 0.50 in. diameter, hot isostatic pressed    | 2000–4000             | 4300                 |
| Zirconia, partially stabilized (3 mol% $\text{Y}_2\text{O}_3$ )                   |                       |                      |
| • Sinterable powder, submicron particle size                                      | 45.00–50.00           | 68                   |
| • Sinterable powder, particle size greater than a micron                          | 22.00–33.00           | 39.3                 |
| • Ball grinding media, 15 mm dia., sintered                                       | 125.00–175.00         | 215                  |

| <i>Material/Condition</i>                       | <i>Cost (\$US/kg)</i> | <i>Relative Cost</i> |
|-------------------------------------------------|-----------------------|----------------------|
| <b>POLYMERS</b>                                 |                       |                      |
| Butadiene-acrylonitrile (nitrile) rubber        |                       |                      |
| • Raw and unprocessed                           | 2.90                  | 4.1                  |
| • Extruded sheet (1/4 to 1/8 in. thick)         | 9.90–10.50            | 14.6                 |
| • Calendered sheet (1/4 to 1/8 in. thick)       | 8.40                  | 12.0                 |
| Styrene-butadiene (SBR) rubber                  |                       |                      |
| • Raw and unprocessed                           | 1.20                  | 1.7                  |
| • Extruded sheet (1/4 to 1/8 in. thick)         | 7.60–12.20            | 14.1                 |
| • Calendered sheet (1/4 to 1/8 in. thick)       | 6.80                  | 9.7                  |
| Silicone rubber                                 |                       |                      |
| • Raw and unprocessed                           | 5.50                  | 7.9                  |
| • Extruded sheet (1/4 to 1/8 in. thick)         | 12.60–26.20           | 27.7                 |
| • Calendered sheet (1/4 to 1/8 in. thick)       | 31.50–38.50           | 50.0                 |
| Epoxy resin, raw form                           | 3.00–4.00             | 5.0                  |
| Nylon 6,6                                       |                       |                      |
| • Raw form                                      | 4.40–6.00             | 7.4                  |
| • Extruded                                      | 9.40                  | 13.4                 |
| Phenolic resin, raw form                        | 6.50–12.00            | 13.2                 |
| Polybutylene terephthalate (PBT)                |                       |                      |
| • Raw form                                      | 4.00                  | 5.7                  |
| • Sheet                                         | 9.75                  | 13.9                 |
| Polycarbonate (PC)                              |                       |                      |
| • Raw form                                      | 4.85–5.30             | 7.3                  |
| • Sheet                                         | 7.00–10.00            | 12.1                 |
| Polyester (thermoset), raw form                 | 1.50–4.40             | 4.2                  |
| Polyetheretherketone (PEEK), raw form           | 90.00–110.00          | 143                  |
| Polyethylene                                    |                       |                      |
| • Low density (LDPE), raw form                  | 1.20–1.35             | 1.8                  |
| • High density (HDPE), raw form                 | 1.00–1.70             | 1.9                  |
| • Ultrahigh molecular weight (UHMWPE), raw form | 3.00–8.50             | 8.2                  |
| Polyethylene terephthalate (PET)                |                       |                      |
| • Raw form                                      | 1.90–2.10             | 2.9                  |
| • Sheet                                         | 3.30–7.70             | 7.9                  |
| Polymethyl methacrylate (PMMA)                  |                       |                      |
| • Raw form                                      | 2.40                  | 3.4                  |
| • Calendered sheet                              | 4.20                  | 6.0                  |
| • Cell cast                                     | 5.85                  | 8.4                  |
| Polypropylene (PP), raw form                    | 0.85–1.65             | 1.8                  |
| Polystyrene (PS), raw form                      | 1.00–1.10             | 1.5                  |
| Polytetrafluoroethylene (PTFE)                  |                       |                      |
| • Raw form                                      | 20.00–26.50           | 33.2                 |
| • Sheet                                         | 38.00                 | 54                   |
| Polyvinyl chloride (PVC), raw form              | 1.40–2.80             | 3.0                  |
| <b>FIBER MATERIALS</b>                          |                       |                      |
| Aramid (Kevlar 49), continuous                  | 31.00                 | 44.3                 |
| Carbon (PAN precursor), continuous              |                       |                      |
| • Standard modulus                              | 31.50–41.50           | 52.1                 |
| • Intermediate modulus                          | 70.00–105.00          | 125                  |
| • High modulus                                  | 175.00–225.00         | 285                  |
| E glass, continuous                             | 1.90–3.30             | 3.7                  |

| <i>Material/Condition</i>                          | <i>Cost (\$US/kg)</i> | <i>Relative Cost</i> |
|----------------------------------------------------|-----------------------|----------------------|
| <b>COMPOSITE MATERIALS</b>                         |                       |                      |
| Aramid (Kevlar 49) continuous-fiber, epoxy prepreg | 55.00–62.00           | 84                   |
| Carbon continuous-fiber, epoxy prepreg             |                       |                      |
| • Standard modulus                                 | 40.00–60.00           | 71                   |
| • Intermediate modulus                             | 100.00–130.00         | 164                  |
| • High modulus                                     | 200.00–275.00         | 340                  |
| E-glass continuous-fiber, epoxy prepreg            | 22.00                 | 31.4                 |
| Woods                                              |                       |                      |
| Douglas fir                                        | 0.54–0.60             | 0.8                  |
| Red oak                                            | 2.55–3.35             | 4.2                  |



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