1.3 Six Materials That Changed Your World

The most obvious question to be addressed by the engineering student entering an introductory course on materials is, "What materials are available to me?" Various classification systems are possible for the wide-ranging answer to this question. In this book, we distinguish six categories that encompass the materials available to practicing engineers: metals, ceramics, glasses, polymers, composites, and semiconductors. We will introduce each of these categories with a single example.

STEEL BRIDGES—INTRODUCING METALS

If there is a "typical" material associated in the public's mind with modern engineering practice, it is structural *steel.* This versatile construction material has several properties that we consider **metallic**: First, it is strong and can be readily formed into practical shapes. Second, its extensive, permanent deformability, or **ductility**, is an important asset in permitting small amounts of yielding to sudden and severe loads. For example, many Californians have been able to observe moderate earthquake activity that leaves windows of glass, which is relatively **brittle** (i.e., lacking in ductility), cracked, while steel-support framing still functions normally. Third, a freshly cut steel surface has a characteristic metallic luster; and fourth, a steel bar shares a fundamental characteristic with other metals: It is a good conductor of electrical current.

Among the most familiar uses of structural steel are bridges, and one of the most famous and beautiful examples is the Golden Gate Bridge connecting San Francisco, California with Marin County to the north (Figure 1.2). The opening on May 27, 1937, allowed 200,000 local residents to stroll across the impressive new structure. The following day, a ribbon cutting ceremony inaugurated automobile traffic that has continued to be an important part of the fabric of life in the San Francisco Bay area for more than 75 years. For many years, the Golden Gate held the title of "longest suspension bridge" in the world (2,737 meters). Although new bridge technologies have provided newer holders of that title, the Golden Gate is still, in the words of a local historian, a "symphony in steel."

FIGURE 1.2 *The Golden Gate Bridge north of San Francisco, California, is one of the most famous and most beautiful examples of a steel bridge. (© LOOK Die Bildagentur der Fotografen GmbH / Alamy.)*

Steel bridges continue to provide a combination of function and beauty with the Sundial Bridge in Redding, California being a stunning example (Figure 1.3). The Redding Bridge is a 66-meter pedestrian walkway designed by the famous Spanish architect Santiago Calatrava. It connects a walking trail system with the Turtle Bay Exploration Park. New bridges like this one are not merely serving as sculptural art projects. The aging infrastructure, including many bridges built as long as a century ago, also provides a challenge to engineers and the requirement for both maintenance and replacement of these important structures.

In Chapter 2, the nature of metals will be defined and placed in perspective relative to the other categories. It is useful to consider the extent of metallic behavior in the currently known range of chemical elements. Figure 1.4 highlights the chemical elements in the periodic table that are inherently metallic. This is a large family indeed. The shaded elements are the bases of the various engineering alloys, including the irons and steels (from Fe), aluminum alloys (Al), magnesium alloys (Mg), titanium alloys (Ti), nickel alloys (Ni), zinc alloys (Zn), and copper alloys (Cu) [including the brasses (Cu, Zn)].

LUCALOX LAMPS—INTRODUCING CERAMICS

Aluminum (Al) is a common metal, but aluminum *oxide*, a compound of aluminum and oxygen such as Al_2O_3, is typical of a fundamentally different family of engineering materials, **ceramics**. Aluminum oxide has two principal advantages over metallic aluminum. First, Al_2O_3 is chemically stable in a wide

FIGURE 1.3 *The Sundial Bridge in Redding, California is a modern masterpiece of bridge design.*

I A	II A	III B	IV B	V B	VI B	VII B	VIII	VIII	VIII	I B	II B	III A	IV A	V A	VI A	VII A	0
1 H																	2 He
3 Li	4 Be											5 B	6 C	7 N	8 O	9 F	10 Ne
11 Na	12 Mg											13 Al	14 Si	15 P	16 S	17 Cl	18 Ar
19 K	20 Ca	21 Sc	22 Ti	23 V	24 Cr	25 Mn	26 Fe	27 Co	28 Ni	29 Cu	30 Zn	31 Ga	32 Ge	33 As	34 Se	35 Br	36 Kr
37 Rb	38 Sr	39 Y	40 Zr	41 Nb	42 Mo	43 Tc	44 Ru	45 Rh	46 Pd	47 Ag	48 Cd	49 In	50 Sn	51 Sb	52 Te	53 I	54 Xe
55 Cs	56 Ba	57 La	72 Hf	73 Ta	74 W	75 Re	76 Os	77 Ir	78 Pt	79 Au	80 Hg	81 Tl	82 Pb	83 Bi	84 Po	85 At	86 Rn
87 Fr	88 Ra	89 Ac	104 Rf	105 Db	106 Sg												

58 Ce	59 Pr	60 Nd	61 Pm	62 Sm	63 Eu	64 Gd	65 Tb	66 Dy	67 Ho	68 Er	69 Tm	70 Yb	71 Lu
90 Th	91 Pa	92 U	93 Np	94 Pu	95 Am	96 Cm	97 Bk	98 Cf	99 Es	100 Fm	101 Md	102 No	103 Lw

FIGURE 1.4 *Periodic table of the elements. Those elements that are inherently metallic in nature are shown in color.*

variety of severe environments, whereas metallic aluminum would be oxidized (a term discussed further in Chapter 15). In fact, a common reaction product in the chemical degradation of aluminum is the more chemically stable oxide. Second, the ceramic Al_2O_3 has a significantly higher melting point (2020°C) than does the metallic Al (660°C), which makes Al_2O_3 a popular **refractory** (i.e., a

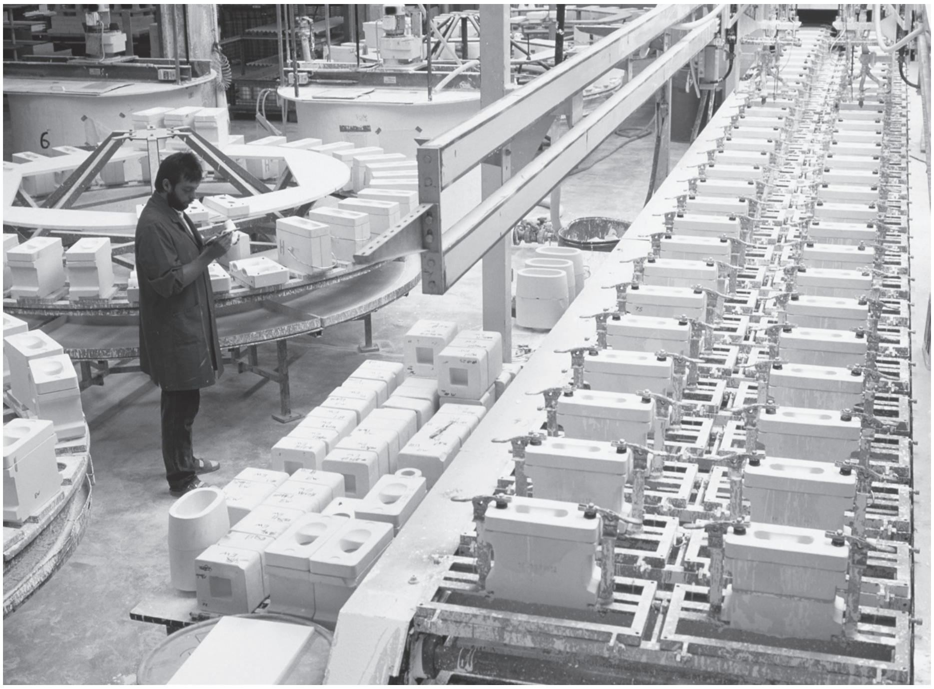


FIGURE 1.5 *A technician observes the production of chemically stable and high-temperature resistant oxide ceramics. Such materials have a wide range of applications in modern industry. (Maximilian Stock Ltd / Photo Researchers, Inc.)*

high-temperature-resistant material of wide use in industrial furnace construction). The production of such oxide ceramics for modern industry is shown in Figure 1.5.

With its superior chemical and temperature-resistant properties, why isn't Al_2O_3 used for applications such as automotive engines in place of metallic aluminum? The answer to this question lies in the most limiting property of ceramics—brittleness. Aluminum and other metals have high ductility, a desirable property that permits them to undergo relatively severe impact loading without fracture, whereas aluminum oxide and other ceramics lack this property. Thus, ceramics are eliminated from many structural applications because they are brittle.

A significant achievement in materials technology is the development of transparent ceramics, which has made possible new products and substantial improvements in others (e.g., commercial lighting). To make traditionally opaque ceramics, such as aluminum oxide (Al_2O_3), into optically transparent materials required a fundamental change in manufacturing technology. Commercial ceramics are frequently produced by heating crystalline powders to high temperatures until a relatively strong and dense product results. Traditional ceramics made in this way contained a substantial amount of residual porosity (see also the Feature Box, "Structure Leads to Properties"), corresponding to the open space between the original powder particles prior to high-temperature processing. A significant reduction in porosity resulted from a relatively simple invention* that involved adding a small amount of impurity (0.1 wt % MgO), which caused the high-temperature densification process for the Al_2O_3 powder to go to completion.

*R. L. Coble, U.S. Patent 3,026,210, March 20, 1962.

FIGURE 1.6 *These high-temperature sodium vapor street lamps are made possible by use of a translucent* Al_2O_3 *cylinder for containing the sodium vapor. (David Nunuk / Photo Researchers, Inc.)*

I A	II A	III B	IV B	V B	VI B	VII B	VIII	VIII	VIII	I B	II B	III A	IV A	V A	VI A	VII A	0
1 H																	2 He
3 Li	4 Be											5 B	6 C	7 N	8 O	9 F	10 Ne
11 Na	12 Mg											13 Al	14 Si	15 P	16 S	17 Cl	18 Ar
19 K	20 Ca	21 Sc	22 Ti	23 V	24 Cr	25 Mn	26 Fe	27 Co	28 Ni	29 Cu	30 Zn	31 Ga	32 Ge	33 As	34 Se	35 Br	36 Kr
37 Rb	38 Sr	39 Y	40 Zr	41 Nb	42 Mo	43 Tc	44 Ru	45 Rh	46 Pd	47 Ag	48 Cd	49 In	50 Sn	51 Sb	52 Te	53 I	54 Xe
55 Cs	56 Ba	57 La	72 Hf	73 Ta	74 W	75 Re	76 Os	77 Ir	78 Pt	79 Au	80 Hg	81 Tl	82 Pb	83 Bi	84 Po	85 At	86 Rn
87 Fr	88 Ra	89 Ac	104 Rf	105 Db	106 Sg												

58 Ce	59 Pr	60 Nd	61 Pm	62 Sm	63 Eu	64 Gd	65 Tb	66 Dy	67 Ho	68 Er	69 Tm	70 Yb	71 Lu
90 Th	91 Pa	92 U	93 Np	94 Pu	95 Am	96 Cm	97 Bk	98 Cf	99 Es	100 Fm	101 Md	102 No	103 Lw

FIGURE 1.7 *Periodic table with ceramic compounds indicated by a combination of one or more metallic elements (in light color) with one or more nonmetallic elements (in dark color). Note that elements silicon* (Si) *and germanium* (Ge) *are included with the metals in this figure but were not included in the periodic table shown in Figure 1.4. They are included here because, in elemental form,* Si *and* Ge *behave as semiconductors (Figure 1.16). Elemental tin* (Sn) *can be either a metal or a semiconductor, depending on its crystalline structure.*

Cylinders of translucent Al_2O_3 became the heart of the design of high-temperature (1000°C) sodium vapor lamps, which provide substantially higher illumination than do conventional lightbulbs (100 lumens/W compared to 15 lumens/W). Commercial sodium vapor lamps are shown in Figure 1.6.

Aluminum oxide is typical of the traditional ceramics, with magnesium oxide (MgO) and **silica** (SiO_2) being other good examples. In addition, SiO_2 is the basis of a large and complex family of **silicates**, which includes clays and claylike minerals. Silicon nitride (Si_3N_4) is an important nonoxide ceramic used in a variety of structural applications. The vast majority of commercially important ceramics are chemical compounds made up of at least one metallic element (see Figure 1.4) and one of five **nonmetallic** elements (C, N, O, P, or S). Figure 1.7 illustrates the various metals (in light color) and the five key nonmetals (in dark color) that can be combined to form an enormous range of ceramic materials. Bear in mind that many commercial ceramics include compounds and solutions of many more than two elements, just as commercial metal alloys are composed of many elements.

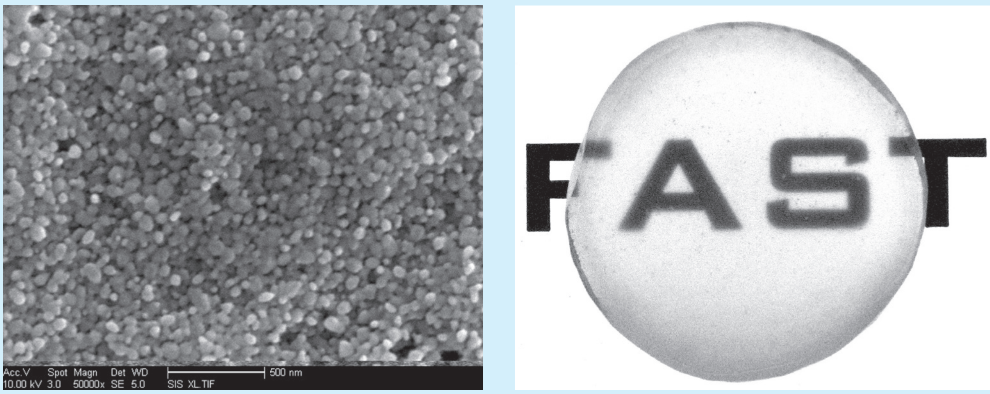
THE MATERIAL WORLD

Structure Leads to Properties

To understand the properties or observable characteristics of engineering materials, it is necessary to understand their structure. Virtually every major property of the six materials' categories outlined in this chapter will be shown to result directly from mechanisms occurring on a small scale (usually either the atomic or the microscopic level).

The dramatic effect that fine-scale structure has on large-scale properties is well illustrated by the development of transparent ceramics, just discussed in the introduction to ceramic materials. The microscopic-scale residual porosity in a traditional aluminum oxide leads to loss of visible light transmission (i.e., a loss in transparency) by providing a light-scattering mechanism. Each Al_2O_3—air interface at a pore surface is a source of light refraction (change of direction). Only about 0.3% porosity can cause Al_2O_3 to be translucent (capable of transmitting a diffuse image), and 3% porosity can cause the material to be completely opaque. The elimination of porosity provided by the Lucalox patent (adding 0.1 wt % MgO) produced a pore-free microstructure and a nearly transparent material with an important additional property—excellent resistance to chemical attack by high-temperature sodium vapor.

The example of translucent ceramics shows a typical and important demonstration of how properties of engineering materials follow directly from structure. Throughout this book, we shall be alert to the continuous demonstration of this interrelationship for all the materials of importance to engineers. A contemporary example is given in the images below, a microstructure and the resulting translucent disc of hydroxyapatite ceramic developed for biomedical applications. By using the Field-Assisted Sintering Technique (FAST) as highlighted in the Feature Box in Chapter 10, researchers were able to produce a material with minimal porosity (note the densely packed nano-scale grain structure in part a) and the resulting ability to transmit a visual image (part b). The effect of porosity on light transmission is discussed further in Chapter 14 (e.g., Figures 14.8 and 14.9), and the importance of hydroxyapatite in orthopedic prostheses is discussed further in Chapter 15.



(a) (b)

(Courtesy of T. B. Tien and J. R. Groza, University of California, Davis.)

OPTICAL FIBERS—INTRODUCING GLASSES

The metals and ceramics just introduced have a similar structural feature on the atomic scale: They are **crystalline**, which means that their constituent atoms are stacked together in a regular, repeating pattern. A distinction between metallic- and ceramic-type materials is that, by fairly simple processing techniques, many ceramics can be made in a **noncrystalline** form (i.e., their atoms are stacked in irregular, random patterns), which is illustrated in Figure 1.8. The general term for noncrystalline solids with compositions comparable to those of crystalline ceramics is **glass** (Figure 1.9). Most common glasses are silicates; ordinary window glass is approximately 72% silica (SiO_2) by weight, with the balance of the material

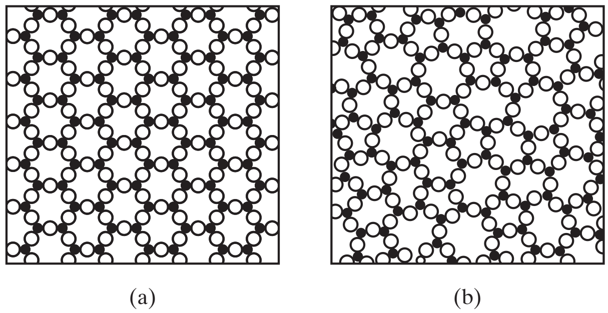


FIGURE 1.8 *Schematic comparison of the atomic-scale structure of (a) a ceramic (crystalline) and (b) a glass (noncrystalline). The open circles represent a nonmetallic atom, and the solid black circles represent a metal atom.*

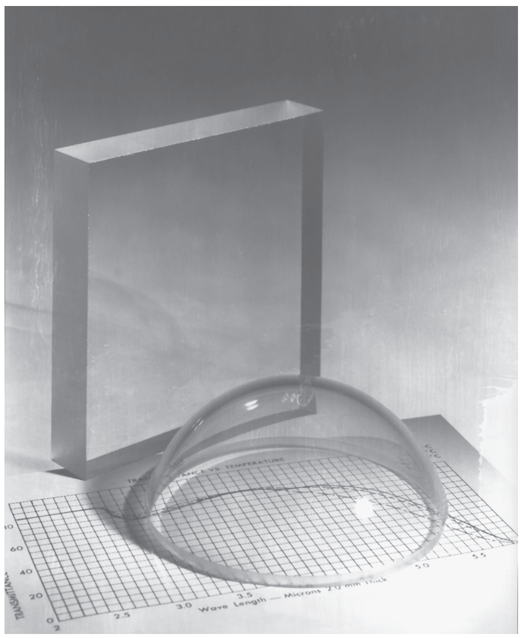


FIGURE 1.9 *Some common silicate glasses for engineering applications. These materials combine the important qualities of transmitting clear visual images and resisting chemically aggressive environments. (Courtesy of Corning Glass Works.)*

being primarily sodium oxide (Na_2O) and calcium oxide (CaO). Glasses share the property of brittleness with crystalline ceramics. Glasses are important engineering materials because of other properties, such as their ability to transmit visible light (as well as ultraviolet and infrared radiation) and chemical inertness.

A major revolution in the field of telecommunications occurred with the transition from traditional metal cable to optical glass fibers (Figure 1.10). Although Alexander Graham Bell had transmitted speech several hundred meters over a beam of light shortly after his invention of the telephone, technology did not permit the practical, large-scale application of this concept for nearly a century. The key to the rebirth of this approach was the invention of the laser in 1960. By 1970, researchers at Corning Glass Works had developed an **optical fiber** with a loss as low as 20 dB/km at a wavelength of 630 nm (within the visible range). By the mid-1980s, silica fibers had been developed with losses as low as 0.2 dB/km at 1.6 μm (in the infrared range). As a result, telephone conversations and any other form of digital data can be transmitted as laser light pulses rather than as the electrical signals used in copper cables. Glass fibers are excellent examples of **photonic materials**, in which signal transmission occurs by photons rather than by the electrons of electronic materials.

Glass-fiber bundles of the type illustrated in Figure 1.10 were put into commercial use by Bell Systems in the mid-1970s. The reduced expense and size, combined with an enormous capacity for data transmission, led to a rapid growth in the construction of optical communication systems. Now, virtually all telecommunications are transmitted in this way. Ten billion digital bits can be transmitted per second along an optical fiber in a contemporary system carrying tens of thousands of telephone calls.

NYLON PARACHUTES—INTRODUCING POLYMERS

A major impact of modern engineering technology on everyday life has been made by the class of materials known as **polymers**. An alternative name for this category is **plastics**, which describes the extensive formability of many polymers

FIGURE 1.10 *The small cable on the right contains 144 glass fibers and can carry more than three times as many telephone conversations as the traditional (and much larger) copper-wire cable on the left. (© Bettmann/CORBIS.)*

FIGURE 1.11 *Miscellaneous internal parts of a parking meter are made of an acetal polymer. Engineered polymers are typically inexpensive and are characterized by ease of formation and adequate structural properties. (Courtesy of the DuPont Company, Engineering Polymers Division.)*

during fabrication. These synthetic, or human-made, materials represent a special branch of organic chemistry. Examples of inexpensive, functional polymer products are readily available to each of us (Figure 1.11). The "mer" in a polymer is a single hydrocarbon molecule such as ethylene (C_2H_4). Polymers are long-chain molecules composed of many mers bonded together. The most common commercial polymer is **polyethylene** $\left(C_2H_4 \right)_n$ where *n* can range from approximately 100 to 1,000. Figure 1.12 shows the relatively limited portion of the periodic table that is associated with commercial polymers. Many important polymers, including polyethylene, are simply compounds of hydrogen and carbon. Others contain oxygen (e.g., acrylics), nitrogen (nylons), fluorine (fluoroplastics), and silicon (silicones).

Nylon is an especially familiar example. Polyhexamethylene adipamide, or nylon, is a member of the family of synthetic polymers known as polyamides invented in 1935 at the DuPont Company. Nylon was the first commercially successful polymer and was initially used as bristles in toothbrushes (1938) followed by the highly popular use as an alternative to silk stockings (1940). Developed as a synthetic alternative to silk, nylon became the focus of an intensive effort during the early stages of World War II to replace the diminishing supply of Asian silk for parachutes and other military supplies. At the beginning of World War II, the fiber industry was dominated by the natural materials cotton and wool. By the end, synthetic fibers accounted for 25% of the market share. A contemporary example of a nylon parachute is shown in Figure 1.13. Today, nylon remains a popular fiber material, but it is also widely used in solid form for applications such as gears and bearings.

As the descriptive title implies, *plastics* commonly share with metals the desirable mechanical property of ductility. Unlike brittle ceramics, polymers are frequently lightweight, low-cost alternatives to metals in structural design applications. The nature of chemical bonding in polymeric materials will be explored in Chapter 2. Important bonding-related properties include lower strength

I A	II A	III B	IV B	V B	VI B	VII B	VIII	VIII	VIII	I B	II B	III A	IV A	V A	VI A	VII A	0
1 H																	2 He
3 Li	4 Be											5 B	6 C	7 N	8 O	9 F	10 Ne
11 Na	12 Mg											13 Al	14 Si	15 P	16 S	17 Cl	18 Ar
19 K	20 Ca	21 Sc	22 Ti	23 V	24 Cr	25 Mn	26 Fe	27 Co	28 Ni	29 Cu	30 Zn	31 Ga	32 Ge	33 As	34 Se	35 Br	36 Kr
37 Rb	38 Sr	39 Y	40 Zr	41 Nb	42 Mo	43 Tc	44 Ru	45 Rh	46 Pd	47 Ag	48 Cd	49 In	50 Sn	51 Sb	52 Te	53 I	54 Xe
55 Cs	56 Ba	57 La	72 Hf	73 Ta	74 W	75 Re	76 Os	77 Ir	78 Pt	79 Au	80 Hg	81 Tl	82 Pb	83 Bi	84 Po	85 At	86 Rn
87 Fr	88 Ra	89 Ac	104 Rf	105 Db	106 Sg												

58 Ce	59 Pr	60 Nd	61 Pm	62 Sm	63 Eu	64 Gd	65 Tb	66 Dy	67 Ho	68 Er	69 Tm	70 Yb	71 Lu
90 Th	91 Pa	92 U	93 Np	94 Pu	95 Am	96 Cm	97 Bk	98 Cf	99 Es	100 Fm	101 Md	102 No	103 Lw

FIGURE 1.12 *Periodic table with the elements associated with commercial polymers in color.*

FIGURE 1.13 *Since its development during World War II, nylon fabric remains the most popular material of choice for parachute designs. (Courtesy of Stringer/Agence France Presse/Getty Images.)*

compared with metals and lower melting point and higher chemical reactivity compared with ceramics and glasses. In spite of their limitations, polymers are highly versatile and useful materials. Substantial progress has been made in recent decades in the development of engineering polymers with sufficiently high strength and stiffness to permit substitution for traditional structural metals.

KEVLAR®–REINFORCED TIRES—INTRODUCING COMPOSITES

The structural engineering materials we have discussed so far—metals, ceramics/glasses, and polymers—contain various elements and compounds that can be classified by their chemical bonding. Metals are associated with metallic bonding, ceramics/glasses with ionic bonding, and polymers with covalent bonding. Such classifications are described further in Chapter 2. Another important set of materials is made up of some combinations of individual materials from the previous categories. This fourth group is **composites**, and an excellent example is **fiberglass**. This composite of glass fibers embedded in a polymer matrix is commonplace (Figure 1.14). Characteristic of good composites, fiberglass has the best properties of each component, producing a product that is superior to either of the components separately. The high strength of the small-diameter glass fibers is combined with the ductility of the polymer matrix to produce a strong material capable of withstanding the normal loading required of a structural material. There is no need to illustrate a region of the periodic table as characteristic of composites, since they involve virtually the entire table except for the noble gases (column 0), equivalent to an overlay of the periodic table coverage for metals, ceramics, and polymers combined.

Kevlar fiber reinforcements provide significant advances over traditional glass fibers for **polymer–matrix composites**. Kevlar is a DuPont trade name for

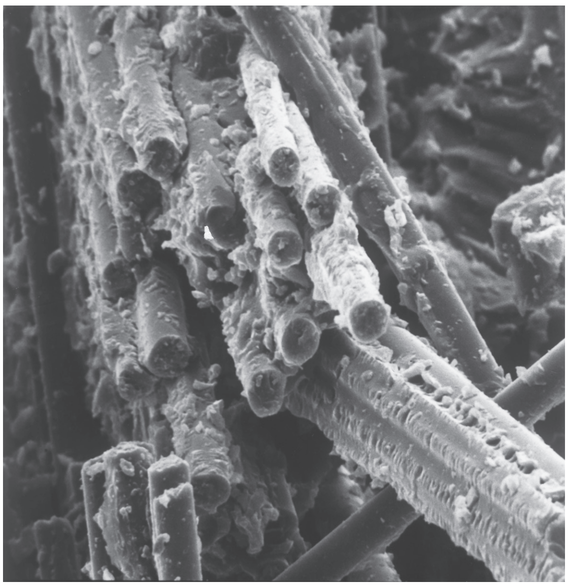


FIGURE 1.14 *Example of a fiberglass composite composed of microscopic-scale reinforcing glass fibers in a polymer matrix. (Courtesy of Owens-Corning Fiberglas Corporation.)*

FIGURE 1.15 *Kevlar reinforcement is a popular application in modern high-performance tires. In this case, an automobile is subjected to aquaplaning at a test track. (© Culture-images GmbH / Alamy.)*

poly *p*-phenyleneterephthalamide (PPD-T), a para-aramid. Substantial progress has been made in developing new polymer matrices, such as polyetherether-ketone (PEEK) and polyphenylene sulfide (PPS). These materials have the advantages of increased toughness and recyclability. Kevlar-reinforced polymers are used in pressure vessels, and Kevlar reinforcement is widely used in tires (Figure 1.15). Kevlar was developed in 1965 and has been used commercially since the early 1970s. It is especially popular for demanding applications given that its strength-to-weight ratio is five times that of structural steel. The modern automobile tire is an especially good example.

SILICON CHIPS—INTRODUCING SEMICONDUCTORS

Although polymers are highly visible engineering materials that have had a major impact on contemporary society, semiconductors are relatively invisible but have had a comparable social impact. Technology has clearly revolutionized society, but solid-state electronics has revolutionized technology itself. A relatively small group of elements and compounds has an important electrical property, *semiconduction,* in which they are neither good electrical conductors nor good electrical insulators. Instead, their ability to conduct electricity is intermediate. These materials are called **semiconductors**, and in general they do not fit into any of the structural materials categories based on atomic bonding. As discussed earlier, metals are inherently good electrical conductors. Ceramics and polymers (nonmetals) are generally poor conductors, but good insulators. An important section of the periodic table is shown in dark color in Figure 1.16 These three

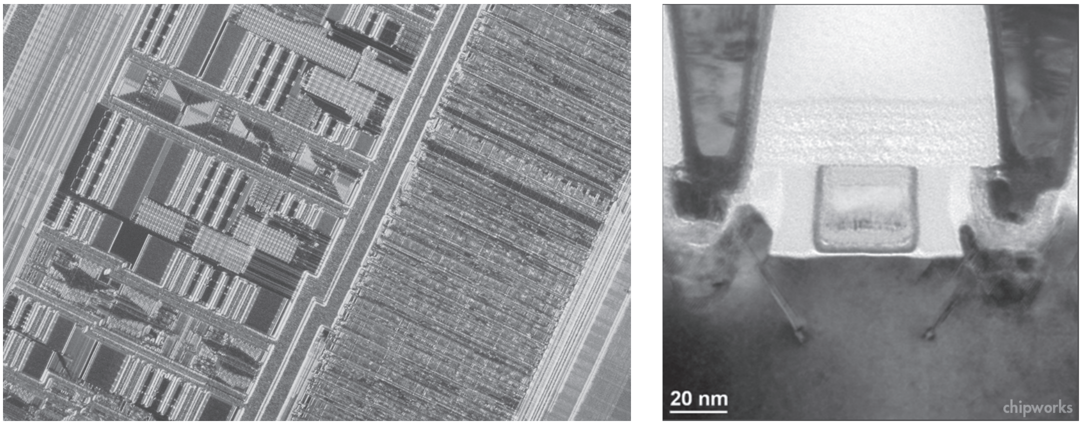
I A	II A	III B	IV B	V B	VI B	VII B	VIII	VIII	VIII	I B	II B	III A	IV A	V A	VI A	VII A	0
1 H																	2 He
3 Li	4 Be											5 B	6 C	7 N	8 O	9 F	10 Ne
11 Na	12 Mg											13 Al	14 Si	15 P	16 S	17 Cl	18 Ar
19 K	20 Ca	21 Sc	22 Ti	23 V	24 Cr	25 Mn	26 Fe	27 Co	28 Ni	29 Cu	30 Zn	31 Ga	32 Ge	33 As	34 Se	35 Br	36 Kr
37 Rb	38 Sr	39 Y	40 Zr	41 Nb	42 Mo	43 Tc	44 Ru	45 Rh	46 Pd	47 Ag	48 Cd	49 In	50 Sn	51 Sb	52 Te	53 I	54 Xe
55 Cs	56 Ba	57 La	72 Hf	73 Ta	74 W	75 Re	76 Os	77 Ir	78 Pt	79 Au	80 Hg	81 Tl	82 Pb	83 Bi	84 Po	85 At	86 Rn
87 Fr	88 Ra	89 Ac	104 Rf	105 Db	106 Sg												

58 Ce	59 Pr	60 Nd	61 Pm	62 Sm	63 Eu	64 Gd	65 Tb	66 Dy	67 Ho	68 Er	69 Tm	70 Yb	71 Lu
90 Th	91 Pa	92 U	93 Np	94 Pu	95 Am	96 Cm	97 Bk	98 Cf	99 Es	100 Fm	101 Md	102 No	103 Lw

FIGURE 1.16 *Periodic table with the elemental semiconductors in dark color and those elements that form semiconducting compounds in light color. The semiconducting compounds are composed of pairs of elements from columns III and V (e.g.,* GaAs*) or from columns II and VI (e.g.,* CdS*).*

semiconducting elements (Si, Ge, and Sn) from column IV A serve as a kind of boundary between metallic and nonmetallic elements. Silicon (Si) and germanium (Ge), widely used elemental semiconductors, are excellent examples of this class of materials. Precise control of chemical purity allows precise control of electronic properties. As techniques have been developed to produce variations in chemical purity over small regions, sophisticated electronic circuitry has been produced in exceptionally small areas (Figure 1.17). Such **microcircuitry** is the basis of the current revolution in technology.

The elements shaded in light color in Figure 1.16 form compounds that are semiconducting. Examples include gallium arsenide (GaAs), which is used as a high-temperature rectifier and a laser material, and cadmium sulfide (CdS), which is used as a relatively low-cost solar cell for conversion of solar energy to useful electrical energy. The various compounds formed by these elements show similarities to many of the ceramic compounds.



(a) (b)

FIGURE 1.17 *(a) Typical microcircuit containing a complex array of semiconducting regions. (Courtesy of Michael W. Davidson / Science Source.) (b) A microscopic cross section of a single circuit element in (a). The rectangular shape in the middle of the micrograph is a metal component approximately 32 nm wide. (Micrograph courtesy of Chipworks.)*

References

At the end of each chapter, a short list of selected references will be cited to indicate some primary sources of related information for the student who wishes to do outside reading. For Chapter 1, the references are some of the general textbooks in the field of materials science and engineering.

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