

4

Physical Properties of Materials

Chapter Contents

4.1 Volumetric and Melting Properties

- 4.1.1 Density
- 4.1.2 Thermal Expansion
- 4.1.3 Melting Characteristics

4.2 Thermal Properties

- 4.2.1 Specific Heat and Thermal Conductivity
- 4.2.2 Thermal Properties in Manufacturing

4.3 Mass Diffusion

4.4 Electrical Properties

- 4.4.1 Resistivity and Conductivity
- 4.4.2 Classes of Materials by Electrical Properties

4.5 Electrochemical Processes

Physical properties, as the term is used here, defines the behavior of materials in response to physical forces other than mechanical. They include volumetric, thermal, electrical, and electrochemical properties. Components in a product must do more than simply withstand mechanical stresses. They must conduct electricity (or prevent its conduction), allow heat to be transferred (or allow it to escape), transmit light (or block its transmission), and satisfy myriad other functions.

Physical properties are important in manufacturing because they often influence the performance of the process. For example, thermal properties of the work material in machining determine the cutting temperature, which affects how long the tool can be used before it fails. In microelectronics, electrical properties of silicon and the way in which these properties can be altered by various chemical and physical processes comprise the basis of semiconductor manufacturing.

This chapter covers the physical properties that are most important in manufacturing—properties that are encountered in subsequent chapters of the book. They are divided into major categories such as volumetric, thermal, electrical, and so on. Also, as in the previous chapter on mechanical properties, the importance of these properties in manufacturing is discussed.

4.1 Volumetric and Melting Properties

These properties are related to the volume of solids and how they are affected by temperature. The properties include density, thermal expansion, and melting point. They are explained in the following, and typical values for selected engineering materials are presented in Table 4.1.

TABLE • 4.1 Volumetric properties in U.S. customary units for selected engineering materials.

Material	Density, r		Coefficient of Thermal Expansion, α		Melting Point, T_m	
	g/cm ³	lb/in ³	8C ²¹ 3 10 ²⁶	8F ²¹ 3 10 ²⁶	8C	8F
Metals						
Aluminum	2.70	0.098	24	13.3	660	1220
Copper	8.97	0.324	17	9.4	1083	1981
Iron	7.87	0.284	12.1	6.7	1539	2802
Lead	11.35	0.410	29	16.1	327	621
Magnesium	1.74	0.063	26	14.4	650	1202
Nickel	8.92	0.322	13.3	7.4	1455	2651
Steel	7.87	0.284	12	6.7	^a	^a
Tin	7.31	0.264	23	12.7	232	449
Titanium	4.51	0.163	8.6	4.7	1668	3034
Tungsten	19.30	0.697	4.0	2.2	3410	6170
Zinc	7.15	0.258	40	22.2	420	787
Ceramics and Silicon						
Glass	2.5	0.090	1.8–9.0	1.0–5.0	^b	^b
Alumina	3.8	0.137	9.0	5.0	NA	NA
Silica	2.66	0.096	NA	NA	^b	^b
Silicon	2.33	0.085	2.6	1.4	1414	2577
Polymers						
Phenol resins	1.3	0.047	60	33	^c	^c
Nylon	1.16	0.042	100	55	^b	^b
Teflon	2.2	0.079	100	55	^b	^b
Natural rubber	1.2	0.043	80	45	^b	^b
Polyethylene (low density)	0.92	0.033	180	100	^b	^b
Polystyrene	1.05	0.038	60	33	^b	^b

Compiled from, [2], [3], [4], and other sources.

^aMelting characteristics of steel depend on composition.

^bSoftens at elevated temperatures and does not have a well-defined melting point.

^cChemically degrades at high temperatures. NA = not available; value of property for this material could not be obtained.

4.1.1 DENSITY

In engineering, the density of a material is its weight per unit volume. Its symbol is r , and typical units are g/cm³ (lb/in³). The density of an element is determined by its atomic number and other factors such as atomic radius and atomic packing. The term **specific gravity** expresses the density of a material relative to the density of water and is therefore a ratio with no units.

Density is an important consideration in the selection of a material for a given application, but it is generally not the only property of interest. Strength is also important, and the two properties are often related in a **strength-to-weight ratio**, which is the tensile strength of the material divided by its density. The ratio is useful in comparing materials for structural applications in aircraft, automobiles, and other products in which weight and energy are of concern.

4.1.2 THERMAL EXPANSION

The density of a material is a function of temperature. The general relationship is that density decreases with increasing temperature. Put another way, the volume per

unit weight increases with temperature. Thermal expansion is the name given to this effect that temperature has on density. It is usually expressed as the **coefficient of thermal expansion**, which measures the change in length per degree of temperature, as mm/mm/°C (in/in/°F). It is a length ratio rather than a volume ratio because this is easier to measure and apply. It is consistent with the usual design situation in which dimensional changes are of greater interest than volumetric changes. The change in length corresponding to a given temperature change is given by:

$$L_2 - L_1 = \alpha L_1 (T_2 - T_1) \quad (4.1)$$

where α = coefficient of thermal expansion, °C⁻¹(°F⁻¹); and L_1 and L_2 are lengths, mm (in), corresponding, respectively, to temperatures T_1 and T_2 , °C (°F).

Values of coefficient of thermal expansion given in Table 4.1 suggest that it has a linear relationship with temperature. This is only an approximation. Not only is length affected by temperature, but the thermal expansion coefficient itself is also affected. For some materials it increases with temperature; for other materials it decreases. These changes are usually not significant enough to be of much concern, and values like those in the table are quite useful in design calculations for the range of temperatures contemplated in service. Changes in the coefficient are more substantial when the metal undergoes a phase transformation, such as from solid to liquid, or from one crystal structure to another.

In manufacturing operations, thermal expansion is put to good use in shrink fit and expansion fit assemblies (Section 31.3), in which a part is heated to increase its size or cooled to decrease its size to permit insertion into some other part. When the part returns to ambient temperature, a tightly fitted assembly is obtained. Thermal expansion can be a problem in heat treatment (Chapter 26) and welding (Section 29.6) because of thermal stresses that develop in the material during these processes.

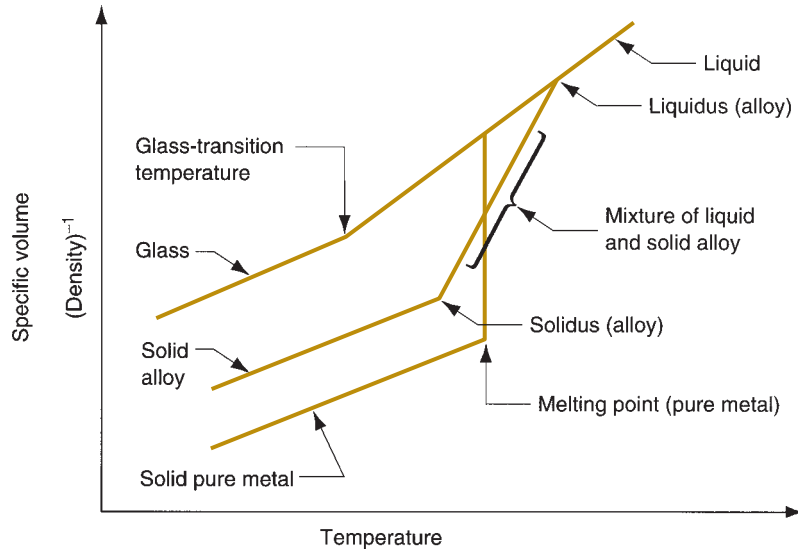
4.1.3 MELTING CHARACTERISTICS

For a pure element, the **melting point** T_m is the temperature at which the material transforms from solid to liquid state. The reverse transformation, from liquid to solid, occurs at the same temperature and is called the **freezing point**. For crystalline elements, such as metals, the melting and freezing temperatures are the same. A certain amount of heat energy, called the **heat of fusion**, is required at this temperature to accomplish the transformation from solid to liquid.

Melting of a metal element at a specific temperature assumes equilibrium conditions. Exceptions occur in nature; for example, when a molten metal is cooled, it may remain in the liquid state below its freezing point if nucleation of crystals does not initiate immediately. When this happens, the liquid is said to be **supercooled**.

There are other variations in the melting process—differences in the way melting occurs in different materials. For example, unlike pure metals, most metal alloys do not have a single melting point. Instead, melting begins at a certain temperature, called the **solidus**, and continues as the temperature increases until finally converting completely to the liquid state at a temperature called the **liquidus**. Between the two temperatures, the alloy is a mixture of solid and molten metals, the amounts of each being inversely proportional to their relative distances from the liquidus and solidus. Although most alloys behave in this way, exceptions are eutectic alloys that

FIGURE 4.1 Changes in volume per unit weight ($1/\text{density}$) as a function of temperature for a hypothetical pure metal, alloy, and glass; all exhibiting similar thermal expansion and melting characteristics.



melt (and freeze) at a single temperature. These issues are examined in the discussion of phase diagrams in Chapter 6.

Another difference in melting occurs with noncrystalline materials (glasses). In these materials, there is a gradual transition from solid to liquid states. The solid material gradually softens as temperature increases, finally becoming liquid at the melting point. During softening, the material has a consistency of increasing plasticity (increasingly like a fluid) as it gets closer to the melting point.

These differences in melting characteristics among pure metals, alloys, and glass are portrayed in Figure 4.1. The plots show changes in density as a function of temperature for three hypothetical materials: a pure metal, an alloy, and glass. Plotted in the figure is the volumetric change, which is the reciprocal of density.

The importance of melting in manufacturing is obvious. In metal casting (Chapters 10 and 11), the metal is melted and then poured into a mold cavity. Metals with lower melting points are generally easier to cast, but if the melting temperature is too low, the metal loses its applicability as an engineering material. Melting characteristics of polymers are important in plastic molding and other polymer shaping processes (Chapter 13). Sintering of powdered metals and ceramics requires knowledge of melting points. Sintering does not melt the materials, but the temperatures used in the process must approach the melting point to achieve the required bonding of the powders (Chapters 15 and 16).

4.2 Thermal Properties

Much of the previous section is concerned with the effects of temperature on volumetric properties of materials. Certainly, thermal expansion, melting, and heat of fusion are thermal properties because temperature determines the thermal energy level of the atoms, leading to the changes in the materials. The current section examines several additional thermal properties—ones that relate to the storage and flow of heat within a substance. The usual properties of interest are specific heat

TABLE • 4.2 Values of common thermal properties for selected materials. Values are at room temperature, and these values change for different temperatures.

Material	Specific Heat	Thermal Conductivity		Material	Specific Heat	Thermal Conductivity	
	Cal/g °C ^a or Btu/lbm °F	J/s mm °C	Btu/hr in °F		Cal/g °C ^a or Btu/lbm °F	J/s mm °C	Btu/hr in °F
Metals				Ceramics			
Aluminum	0.21	0.22	9.75	Alumina	0.18	0.029	1.4
Cast iron	0.11	0.06	2.7	Concrete	0.2	0.012	0.6
Copper	0.092	0.40	18.7	Polymers			
Iron	0.11	0.072	2.98	Phenolics	0.4	0.00016	0.0077
Lead	0.031	0.033	1.68	Polyethylene	0.5	0.00034	0.016
Magnesium	0.25	0.16	7.58	Teflon	0.25	0.00020	0.0096
Nickel	0.105	0.070	2.88	Natural rubber	0.48	0.00012	0.006
Steel	0.11	0.046	2.20	Other			
Stainless steel ^b	0.11	0.014	0.67	Silicon	0.17	0.149	6.6
Tin	0.054	0.062	3.0	Water (liquid)	1.00	0.0006	0.029
Zinc	0.091	0.112	5.41	Ice	0.46	0.0023	0.11

Compiled from [2], [3], [6], and other sources.

^aSpecific heat has the same numerical value in Btu/lbm-F or Cal/g-C. 1.0 Calorie = 4.186 Joule.

^bAustenitic (18-8) stainless steel.

and thermal conductivity, values of which are compiled for selected materials in Table 4.2.

4.2.1 SPECIFIC HEAT AND THERMAL CONDUCTIVITY

The specific heat C of a material is defined as the quantity of heat energy required to increase the temperature of a unit mass of the material by one degree. Some typical values are listed in Table 4.2. To determine the amount of energy needed to heat a certain weight of a metal in a furnace to a given elevated temperature, the following equation can be used:

$$H = C W (T_2 - T_1) \quad (4.2)$$

where H = amount of heat energy, J (Btu); C = specific heat of the material, J/kg °C (Btu/lb °F); W = its weight, kg (lb); and $(T_2 - T_1)$ = change in temperature, °C (°F).

The volumetric heat storage capacity of a material is often of interest. This is simply density multiplied by specific heat ρC . Thus, **volumetric specific heat** is the heat energy required to raise the temperature of a unit volume of material by one degree, J/mm³ °C (Btu/in³ °F).

Conduction is a fundamental heat-transfer process. It involves transfer of thermal energy within a material from molecule to molecule by purely thermal motions; no transfer of mass occurs. The thermal conductivity of a substance is therefore its capability to transfer heat through itself by this physical mechanism. It is measured by the **coefficient of thermal conductivity** k , which has typical units of J/s mm °C (Btu/in hr °F). The coefficient of thermal conductivity is generally high in metals, low in ceramics and plastics.

The ratio of thermal conductivity to volumetric specific heat is frequently encountered in heat transfer analysis. It is called the *thermal diffusivity* K and is determined as

$$K = \frac{k}{rC} \quad (4.3)$$

Thermal diffusivity is used to calculate cutting temperatures in machining (Section 20.5.1).

4.2.2 THERMAL PROPERTIES IN MANUFACTURING

Thermal properties play an important role in manufacturing because heat generation is common in so many processes. In some operations heat is the energy that accomplishes the process; in others heat is generated as a consequence of the process.

Specific heat is of interest for several reasons. In processes that require heating of the material (e.g., casting, heat treating, and hot metal forming), specific heat determines the amount of heat energy needed to raise the temperature to a desired level, according to Equation (4.2).

In many processes carried out at ambient temperature, the mechanical energy to perform the operation is converted to heat, which raises the temperature of the work part. This is common in machining and cold forming of metals. The temperature rise is a function of the metal's specific heat. Coolants are often used in machining to reduce these temperatures, and here the fluid's heat capacity is critical. Water is almost always employed as the base for these fluids because of its high heat-carrying capacity.

Thermal conductivity functions to dissipate heat in manufacturing processes, sometimes beneficially, sometimes not. In mechanical processes such as metal forming and machining, much of the power required to operate the process is converted to heat. The ability of the work material and tooling to conduct heat away from its source is highly desirable in these processes.

On the other hand, high thermal conductivity of the work metal is undesirable in fusion welding processes such as arc welding. In these operations, the heat input must be concentrated at the joint location so that the metal can be melted. For example, copper is generally difficult to weld because its high thermal conductivity allows heat to be conducted from the energy source into the work too rapidly, inhibiting heat buildup for melting at the joint.

4.3 Mass Diffusion

In addition to heat transfer in a material, there is also mass transfer. *Mass diffusion* involves movement of atoms or molecules within a material or across a boundary between two materials in contact. It is perhaps more appealing to one's intuition that such a phenomenon occurs in liquids and gases, but it also occurs in solids. It occurs in pure metals, in alloys, and between materials that share a common interface. Because of thermal agitation of the atoms in a material (solid, liquid, or gas), atoms are continuously moving about. In liquids and gases, where the level of thermal agitation is high, it is a free-roaming movement. In solids (metals in particular), the atomic motion is facilitated by vacancies and other imperfections in the crystal structure.

Diffusion can be illustrated by the series of sketches in Figure 4.2 for the case of two metals suddenly brought into intimate contact with each other. At the start, both

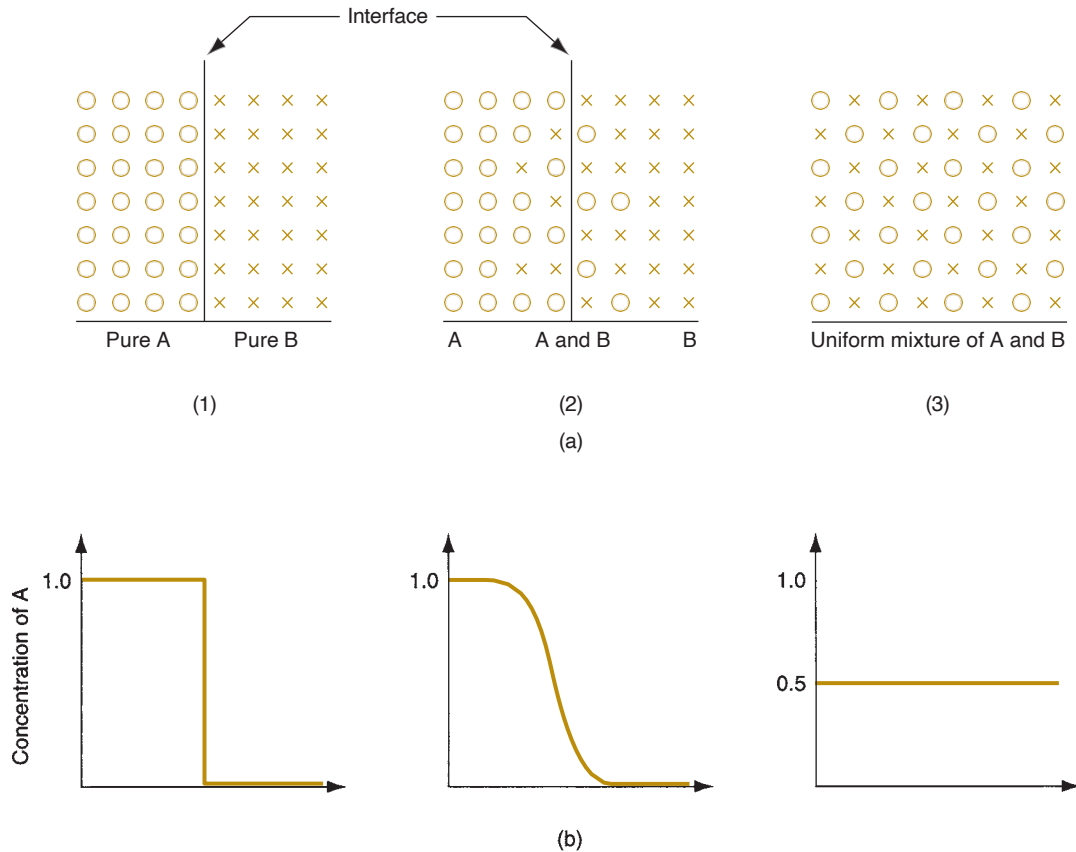


FIGURE 4.2 Mass diffusion: (a) model of atoms in two solid blocks in contact: (1) at the start when two pieces are brought together, they each have their individual compositions; (2) after some time, an exchange of atoms has occurred; and (3) eventually, a condition of uniform concentration occurs. The concentration gradient dc/dx for metal A is plotted in (b) of the figure.

metals have their own atomic structure; but with time there is an exchange of atoms, not only across the boundary, but within the separate pieces. Given enough time, the assembly of two pieces will finally reach a uniform composition throughout.

Temperature is an important factor in diffusion. At higher temperatures, thermal agitation is greater and the atoms can move about more freely. Another factor is the concentration gradient dc/dx , which indicates the concentration of the two types of atoms in a direction of interest defined by x . The concentration gradient is plotted in Figure 4.2(b) to correspond to the instantaneous distribution of atoms in the assembly. The relationship often used to describe mass diffusion is **Fick's first law**:

$$dm = -D \left(\frac{dc}{dx} \right) A dt \quad (4.4)$$

where dm = small amount of material transferred, D = diffusion coefficient of the metal, which increases rapidly with temperature, dc/dx = concentration gradient, A = area of the boundary, and dt represents a small time increment. An alternative expression of Equation (4.4) gives the mass diffusion rate:

$$\frac{dm}{dt} = -D \left(\frac{dc}{dx} \right) A \quad (4.5)$$

Although these equations are difficult to use in calculations because of the problem of assessing D , they are helpful in understanding diffusion and the variables on which D depends.

Mass diffusion is used in several processes. A number of surface-hardening treatments are based on diffusion (Section 26.4), including carburizing and nitriding. Among the welding processes, diffusion welding (Section 29.5.2) is used to join two components by pressing them together and allowing diffusion to occur across the boundary to create a permanent bond. Diffusion is also used in electronics manufacturing to alter the surface chemistry of a semiconductor chip in microscopic localized regions to create circuit details (Section 33.4.3).

4.4 Electrical Properties

Engineering materials exhibit a great variation in their capacity to conduct electricity. This section defines the physical properties by which this capacity is measured.

4.4.1 RESISTIVITY AND CONDUCTIVITY

The flow of electrical current involves movement of **charge carriers**—infinitesimally small particles possessing an electrical charge. In solids, these charge carriers are electrons. In a liquid solution, charge carriers are positive and negative ions. The movement of charge carriers is driven by the presence of an electric voltage and resisted by the inherent characteristics of the material, such as atomic structure and bonding between atoms and molecules. This is the familiar relationship defined by Ohm's law:

$$I = \frac{E}{R} \quad (4.6)$$

where I = current, A; E = voltage, V; and R = electrical resistance, Ω . The resistance in a uniform section of material (e.g., a wire) depends on its length L , cross-sectional area A , and the resistivity of the material r ; thus,

$$R = r \frac{L}{A} \quad \text{or} \quad r = R \frac{A}{L} \quad (4.7)$$

where resistivity has units of $\Omega\text{-m}^2/\text{m}$ or $\Omega\text{-m}$ ($\Omega\text{-in}$). **Resistivity** is the basic property that defines a material's capability to resist current flow. Table 4.3 lists values of resistivity for selected materials. Resistivity is not a constant; instead it varies, as do so many other properties, with temperature. For metals, it increases with temperature.

It is often more convenient to consider a material as conducting electrical current rather than resisting its flow. The **conductivity** of a material is simply the reciprocal of resistivity:

$$\text{Electrical conductivity} = \frac{1}{r} \quad (4.8)$$

where conductivity has units of $(\Omega\text{-m})^{-1}$ ($(\Omega\text{-in})^{-1}$).

4.4.2 CLASSES OF MATERIALS BY ELECTRICAL PROPERTIES

Metals are the best **conductors** of electricity, because of their metallic bonding. They have the lowest resistivity (Table 4.3). Most ceramics and polymers, whose electrons are tightly bound by covalent and/or ionic bonding, are poor conductors. Many of these materials are used as **insulators** because they possess high resistivities.

TABLE • 4.3 Resistivity of selected materials.

Material	Resistivity		Material	Resistivity	
	V-m	V-in		V-m	V-in
Conductors	10^{-6} – 10^{-8}	10^{-4} – 10^{-7}	Conductors, continued		
Aluminum	2.8×10^{-8}	1.1×10^{-6}	Steel, low C	17.0×10^{-8}	6.7×10^{-6}
Aluminum alloys	4.0×10^{-8a}	1.6×10^{-6a}	Steel, stainless	70.0×10^{-8a}	27.6×10^{-6}
Cast iron	65.0×10^{-8a}	25.6×10^{-6a}	Tin	11.5×10^{-8}	4.5×10^{-6}
Copper	1.7×10^{-8}	0.67×10^{-6}	Zinc	6.0×10^{-8}	2.4×10^{-6}
Gold	2.4×10^{-8}	0.95×10^{-6}	Carbon	5000×10^{-8b}	2000×10^{-6b}
Iron	9.5×10^{-8}	3.7×10^{-6}	Semiconductors	10^1 – 10^5	10^2 – 10^7
Lead	20.6×10^{-8}	8.1×10^{-6}	Silicon	1.0×10^3	0.4×10^5
Magnesium	4.5×10^{-8}	1.8×10^{-6}	Insulators	10^{12} – 10^{15}	10^{13} – 10^{17}
Nickel	6.8×10^{-8}	2.7×10^{-6}	Natural rubber	1.0×10^{12b}	0.4×10^{14b}
Silver	1.6×10^{-8}	0.63×10^{-6}	Polyethylene	100×10^{12b}	40×10^{14b}

Compiled from various standard sources.

^aValue varies with alloy composition.

^bValue is approximate.

An insulator is sometimes referred to as a dielectric, because the term *dielectric* means nonconductor of direct current. It is a material that can be placed between two electrodes without conducting current between them. However, if the voltage is high enough, the current will suddenly pass through the material, for example, in the form of an arc. The *dielectric strength* of an insulating material, then, is the electrical potential required to break down the insulator per unit thickness. Appropriate units are volts/m (volts/in).

In addition to conductors and insulators (or dielectrics), there are also superconductors and semiconductors. A *superconductor* is a material that exhibits zero resistivity. It is a phenomenon that has been observed in certain materials at low temperatures approaching absolute zero. We might expect the existence of this phenomenon, due to the significant effect that temperature has on resistivity. That these superconducting materials exist is of great scientific interest. If materials could be developed that exhibit this property at more normal temperatures, there would be significant practical implications in power transmission, electronic switching speeds, and magnetic field applications.

Semiconductors have already proven their practical worth. Their applications range from mainframe computers to household appliances and automotive engine controllers. As one would guess, a *semiconductor* is a material whose resistivity lies between insulators and conductors. The typical range is shown in Table 4.3. The most commonly used semiconductor material today is silicon (Section 7.5.2), largely because of its abundance in nature, relative low cost, and ease of processing. What makes semiconductors unique is the capacity to significantly alter conductivities in their surface chemistries in microscopic areas to fabricate integrated circuits (Chapter 33).

Electrical properties play an important role in various manufacturing processes. Some of the nontraditional processes use electrical energy to remove material. Electric discharge machining (Section 25.3.1) uses the heat generated by electrical energy in the form of sparks to remove material from metals. Most of the important

welding processes use electrical energy to melt the joint metal. Finally, the capacity to alter electrical properties of semiconductor materials is the basis for microelectronics manufacturing.

4.5 Electrochemical Processes

Electrochemistry is a field of science concerned with the relationship between electricity and chemical changes, and with the conversion of electrical and chemical energy.

In a water solution, the molecules of an acid, base, or salt are dissociated into positively and negatively charged ions. These ions are the charge carriers in the solution—they allow electric current to be conducted, playing the same role that electrons play in metallic conduction. The ionized solution is called an **electrolyte**; and electrolytic conduction requires that current enter and leave the solution at **electrodes**. The positive electrode is called the **anode**, and the negative electrode is the **cathode**. The whole arrangement is called an **electrolytic cell**. At each electrode, some chemical reaction occurs, such as the deposition or dissolution of material, or the decomposition of gas from the solution. **Electrolysis** is the name given to these chemical changes occurring in the solution.

Consider a specific case of electrolysis: decomposition of water, illustrated in Figure 4.3. To accelerate the process, dilute sulfuric acid (H_2SO_4) is used as the electrolyte, and platinum and carbon (both chemically inert) are used as electrodes. The electrolyte dissociates in the ions H^+ and SO_4^{2-} . The H^+ ions are attracted to the negatively charged cathode; upon reaching it they acquire an electron and combine into molecules of hydrogen gas:



The SO_4^{2-} ions are attracted to the anode, transferring electrons to it to form additional sulfuric acid and liberate oxygen:



The product H_2SO_4 is dissociated into ions of H^+ and SO_4^{2-} again and so the process continues.

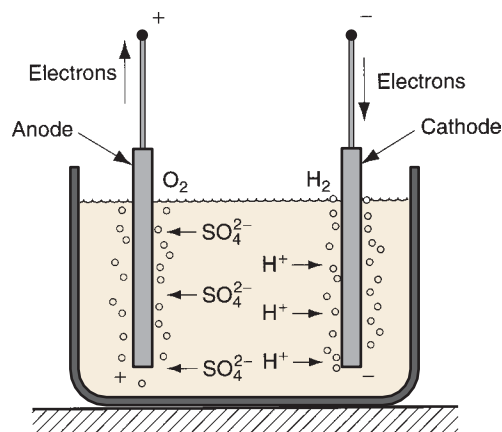


FIGURE 4.3 Example of electrolysis: decomposition of water.

In addition to the production of hydrogen and oxygen gases, as illustrated by the example, electrolysis is also used in several other industrial processes. Two examples are (1) **electroplating** (Section 27.3.1), an operation that adds a thin coating of one metal (e.g., chromium) to the surface of a second metal (e.g., steel) for decorative or other purposes; and (2) **electrochemical machining** (Section 25.2), a process in which material is removed from the surface of a metal part. Both these operations rely on electrolysis to either add or remove material from the surface of a metal part. In electroplating, the work part is set up in the electrolytic circuit as the cathode, so that the positive ions of the coating metal are attracted to the negatively charged part. In electrochemical machining, the work part is the anode, and a tool with the desired shape is the cathode. The action of electrolysis in this setup is to remove metal from the part surface in regions determined by the shape of the tool as it slowly feeds into the work.

The two physical laws that determine the amount of material deposited or removed from a metallic surface were first stated by the British scientist Michael Faraday:

1. The mass of a substance liberated in an electrolytic cell is proportional to the quantity of electricity passing through the cell.
2. When the same quantity of electricity is passed through different electrolytic cells, the masses of the substances liberated are proportional to their chemical equivalents.