

## MATERIALS OF IMPORTANCE

### Piezoelectric Ceramics

A few ceramic materials (as well as some polymers) exhibit the unusual phenomenon of piezoelectricity<sup>1</sup>—electric polarization<sup>2</sup> (i.e., an electric field or voltage) is induced in the ceramic crystal when a mechanical strain (dimensional change) is imposed on it. The inverse piezoelectric effect is also displayed by this group of materials; that is, a mechanical strain results from the imposition of an electrical field.

Piezoelectric materials may be utilized as transducers between electrical and mechanical energies. One of the early uses of piezoelectric ceramics was in sonar, wherein underwater objects (e.g., submarines) are detected and their positions determined using an ultrasonic emitting and receiving system. A piezoelectric crystal is caused to oscillate by an electrical signal, which produces high-frequency mechanical vibrations that are transmitted through the water. Upon encounter-

<sup>1</sup> The piezoelectric phenomenon is described in more detail in Section 18.25.

<sup>2</sup> Electric polarization (explained in Sections 18.19 and 18.20) is the alignment of electric dipoles (Section 2.7) in a common direction, which gives rise to an electric field that is oriented in this same direction.

ing an object, these signals are reflected back, and another piezoelectric material receives this reflected vibrational energy, which it then converts back into an electrical signal. Distance from the ultrasonic source and reflecting body is determined from the elapsed time between sending and receiving events.

More recently, the utilization of piezoelectric devices has grown dramatically as a consequence of increases in automatization and consumer attraction to modern sophisticated gadgets. Applications that employ piezoelectric devices are found in the automotive, computer, commercial/consumer, and medical sectors. Some of these applications are as follows: automotive—wheel balances, seat belt buzzers, tread-wear indicators, keyless door entry, and airbag sensors; computer—microactuators for hard disks and notebook transformers; commercial/consumer—ink-jet printing heads, strain gauges, ultrasonic welders, and smoke detectors; medical—insulin pumps, ultrasonic therapy, and ultrasonic cataract-removal devices.

Commonly used piezoelectric ceramics include barium titanate ( $\text{BaTiO}_3$ ), lead titanate ( $\text{PbTiO}_3$ ), lead zirconate–titanate (PZT) [ $\text{Pb}(\text{Zr},\text{Ti})\text{O}_3$ ], and potassium niobate ( $\text{KNbO}_3$ ).

the hybrid bearings, because the coefficient of friction of  $\text{Si}_3\text{N}_4$  is approximately 30% that of steel; this leads to an increase in grease life. In addition, lower lubrication levels are required than for the all-steel bearings. Ceramic materials are inherently more corrosion resistant than metal alloys; thus, the silicon nitride balls may be used in more corrosive environments and at higher operating temperatures. Finally, because  $\text{Si}_3\text{N}_4$  is an electrical insulator (bearing steels are much more electrically conductive), the ceramic bearings are immune to arcing damage.

Some of the applications that employ these hybrid bearings include inline skates, bicycles, electric motors, machine tool spindles, precision medical hand tools (e.g., high-speed dental drills and surgical saws), and textile, food processing, and chemical equipment.

It should also be mentioned that all-ceramic bearings (having both ceramic races and balls) are now being utilized on a limited basis in applications where a high degree of corrosion resistance is required.

A significant research effort has gone into the development of this silicon nitride bearing material. Some of the challenges that were encountered are as follows: processing/fabrication techniques to yield a pore-free material, fabrication of spherical pieces that require a minimum of machining, and a polishing/lapping technique to produce a smoother surface finish than steel balls.

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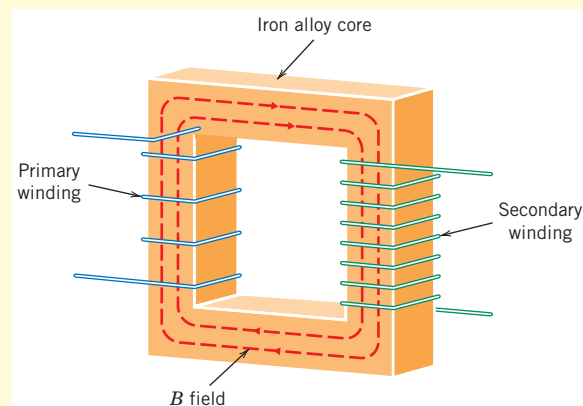
### An Iron-Silicon Alloy That is Used in Transformer Cores

As mentioned earlier in this section, transformer cores require the use of soft magnetic materials, which are easily magnetized and demagnetized (and also have relatively high electrical resistivities). One alloy commonly used for this application is the iron–silicon alloy listed in Table 20.5 (97 wt% Fe–3 wt% Si). Single crystals of this alloy are magnetically anisotropic, as are also single crystals of iron (as explained above). Consequently, energy losses of transformers could be minimized if their cores were fabricated from single crystals such that a [100]-type direction [the direction of easy magnetization (Figure 20.17)] is oriented parallel to the direction of an applied magnetic field; this configuration for a transformer core is represented schematically in Figure 20.20. Unfortunately, single crystals are expensive to prepare, and, thus, this is an economically unpractical situation. A better alternative—one that is used commercially, being more economically attractive—is to fabricate cores from polycrystalline sheets of this alloy that are anisotropic.

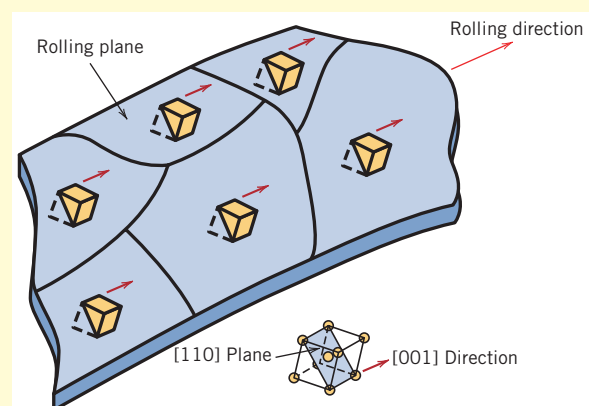
It is often the case that the grains in polycrystalline materials are randomly oriented, with the result that their properties are isotropic (Section 3.15). However, one way of developing anisotropy in

polycrystalline metals is via plastic deformation, for example by rolling (Section 11.4, Figure 11.8*b*); rolling is the technique by which sheet transformer cores are fabricated. A flat sheet that has been rolled is said to have a *rolling* (or *sheet*) *texture*, or there is a preferred crystallographic orientation of the grains. For this type of texture, during the rolling operation, for most of the grains in the sheet, a specific crystallographic plane ( $hkl$ ) becomes aligned parallel (or nearly parallel) to the surface of the sheet, and, in addition a direction  $[uvw]$  in that plane lies parallel (or nearly parallel) to the rolling direction. Thus, a rolling texture is indicated by the plane–direction combination,  $(hkl)[uvw]$ . For body-centered cubic alloys (to include the iron–silicon alloy mentioned above), the rolling texture is  $(110)[001]$ , which is represented schematically in Figure 20.21. Thus, transformer cores of this iron–silicon alloy are fabricated such the direction in which the sheet was rolled (corresponding to a [001]-type direction for most of the grains) is aligned parallel to the direction of the magnetic field application.<sup>3</sup>

The magnetic characteristics of this alloy may be further improved through a series of deformation and heat-treating procedures that produce a  $(100)[001]$  texture.



**Figure 20.20** Schematic diagram of a transformer core, including the direction of  $B$  field that is generated.



**Figure 20.21** Schematic representation of the  $(110)[001]$  rolling texture for body-centered cubic iron.

<sup>3</sup> For body-centered cubic metals and alloys, [100] and [001] directions are equivalent (Section 3.10)—that is, both are directions of easy magnetization.

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### Carbonated Beverage Containers

One common item that presents some interesting material property requirements is the container for carbonated beverages. The material used for this application must satisfy the following constraints: (1) provide a barrier to the passage of carbon dioxide, which is under pressure in the container; (2) be nontoxic, unreactive with the beverage, and, preferably be recyclable; (3) be relatively strong, and capable of surviving a drop from a height of several feet when containing the beverage; (4) be inexpensive and the cost to fabricate the final shape should be relatively low; (5) if optically transparent, retain its optical clarity; and (6) capable of being produced having different colors and/or able to be adorned with decorative labels.

All three of the basic material types—metal (aluminum), ceramic (glass), and polymer (polyester plastic)—are used for carbonated beverage containers (per the chapter-opening photographs for this chapter). All of these materials are nontoxic

and unreactive with beverages. In addition, each material has its pros and cons. For example, the aluminum alloy is relatively strong (but easily dented), is a very good barrier to the diffusion of carbon dioxide, is easily recycled, beverages are cooled rapidly, and labels may be painted onto its surface. On the other hand, the cans are optically opaque, and relatively expensive to produce. Glass is impervious to the passage of carbon dioxide, is a relatively inexpensive material, may be recycled, but it cracks and fractures easily, and glass bottles are relatively heavy. Whereas the plastic is relatively strong, may be made optically transparent, is inexpensive and lightweight, and is recyclable, it is not as impervious to the passage of carbon dioxide as the aluminum and glass. For example, you may have noticed that beverages in aluminum and glass containers retain their carbonization (i.e., “fizz”) for several years, whereas those in two-liter plastic bottles “go flat” within a few months.

### Composites

A composite is composed of two (or more) individual materials, which come from the categories discussed above—viz., metals, ceramics, and polymers. The design goal of a composite is to achieve a combination of properties that is not displayed by any single material, and also to incorporate the best characteristics of each of the component materials. A large number of composite types exist that are represented by different combinations of metals, ceramics, and polymers. Furthermore, some naturally-occurring materials are also considered to be composites—for example, wood and bone. However, most of those we consider in our discussions are synthetic (or man-made) composites.

One of the most common and familiar composites is fiberglass, in which small glass fibers are embedded within a polymeric material (normally an epoxy or polyester).<sup>4</sup> The glass fibers are relatively strong and stiff (but also brittle), whereas the polymer is ductile (but also weak and flexible). Thus, the resulting fiberglass is relatively stiff, strong, (Figures 1.4 and 1.5) flexible, and ductile. In addition, it has a low density (Figure 1.3).

Another of these technologically important materials is the “carbon fiber-reinforced polymer” (or “CFRP”) composite—carbon fibers that are embedded within a polymer. These materials are stiffer and stronger than the glass fiber-reinforced materials (Figures 1.4 and 1.5), yet they are more expensive. The CFRP composites

<sup>4</sup> Fiberglass is sometimes also termed a “glass fiber-reinforced polymer” composite, abbreviated “GFRP.”

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### Water (Its Volume Expansion Upon Freezing)

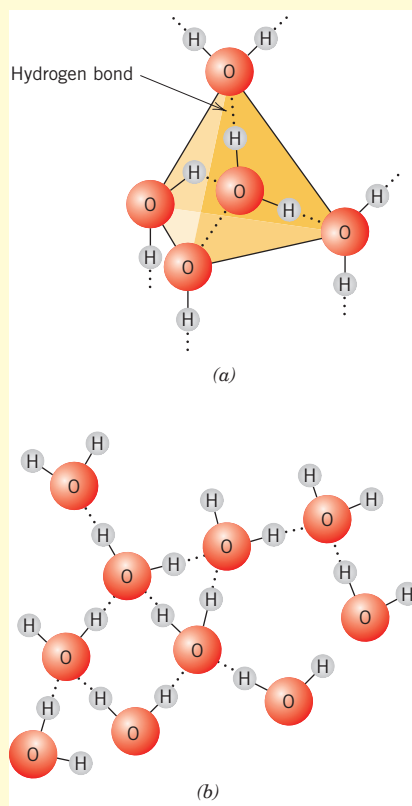
Upon freezing (i.e., transforming from a liquid to a solid upon cooling), most substances experience an increase in density (or, correspondingly, a decrease in volume). One exception is water, which exhibits the anomalous and familiar expansion upon freezing—approximately 9 volume percent expansion. This behavior may be explained on the basis of hydrogen bonding. Each  $\text{H}_2\text{O}$  molecule has two hydrogen atoms that can bond to oxygen atoms; in addition, its single O atom can bond to two hydrogen atoms of other  $\text{H}_2\text{O}$  molecules. Thus, for solid ice, each water molecule participates in four hydrogen bonds as shown in the three-dimensional schematic of Figure 2.16*a*; here hydrogen bonds are denoted by dashed lines, and each water molecule has 4 nearest-neighbor molecules. This is a relatively open structure—i.e., the molecules are not closely packed together—and, as a result, the

density is comparatively low. Upon melting, this structure is partially destroyed, such that the water molecules become more closely packed together (Figure 2.16*b*)—at room temperature the average number of nearest-neighbor water molecules has increased to approximately 4.5; this leads to an increase in density.

Consequences of this anomalous freezing phenomenon are familiar. This phenomenon explains why icebergs float, why, in cold climates, it is necessary to add antifreeze to an automobile's cooling system (to keep the engine block from cracking), and why freeze-thaw cycles break up the pavement in streets and cause potholes to form.



A watering can that ruptured along a side panel-bottom panel seam. Water that was left in the can during a cold late-autumn night expanded as it froze and caused the rupture. (Photography by S. Tanner.)



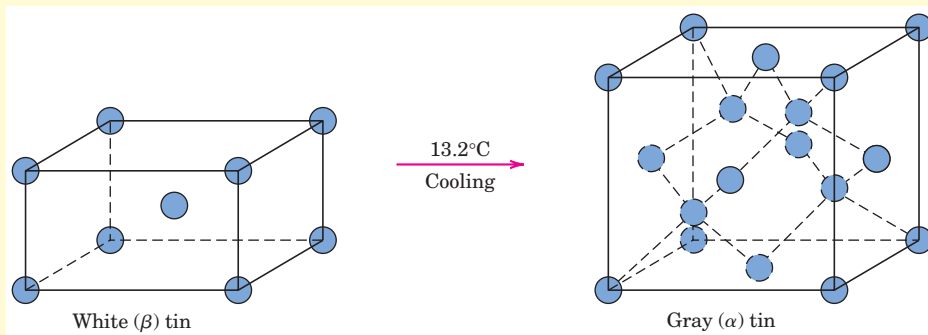
**Figure 2.16** The arrangement of water ( $\text{H}_2\text{O}$ ) molecules in (a) solid ice, and (b) liquid water.

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### Tin (Its Allotropic Transformation)

Another common metal that experiences an allotropic change is tin. White (or  $\beta$ ) tin, having a body-centered tetragonal crystal structure at room temperature, transforms, at  $13.2^{\circ}\text{C}$  ( $55.8^{\circ}\text{F}$ ),

to gray (or  $\alpha$ ) tin, which has a crystal structure similar to diamond (i.e., the diamond cubic crystal structure); this transformation is represented schematically as follows:



The rate at which this change takes place is extremely slow; however, the lower the temperature (below  $13.2^{\circ}\text{C}$ ) the faster the rate. Accompanying this white tin-to-gray tin transformation is an increase in volume (27 percent), and, accordingly, a decrease in density (from  $7.30\text{ g/cm}^3$  to  $5.77\text{ g/cm}^3$ ). Consequently, this volume expansion results in the disintegration of the white tin metal into a coarse powder of the gray allotrope. For normal subambient temperatures, there is no need to worry about this disintegration process for tin products, due to the very slow rate at which the transformation occurs.

This white-to-gray-tin transition produced some rather dramatic results in 1850 in Russia. The winter that year was particularly cold, and record low temperatures persisted for extended periods of time. The uniforms of some Russian soldiers had tin buttons, many of which crumbled due to these extreme cold conditions, as did also many of the tin church organ pipes. This problem came to be known as the “tin disease.”



Specimen of white tin (left). Another specimen disintegrated upon transforming to gray tin (right) after it was cooled to and held at a temperature below  $13.2^{\circ}\text{C}$  for an extended period of time.

(Photograph courtesy of Professor Bill Plumbridge, Department of Materials Engineering, The Open University, Milton Keynes, England.)

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### Catalysts (and Surface Defects)

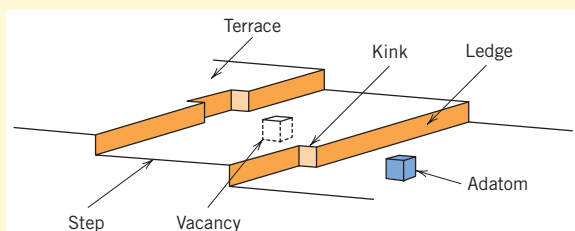
A *catalyst* is a substance that speeds up the rate of a chemical reaction without participating in the reaction itself (i.e., it is not consumed). One type of catalyst exists as a solid; reactant molecules in a gas or liquid phase are adsorbed<sup>5</sup> onto the catalytic surface, at which point some type of interaction occurs that promotes an increase in their chemical reactivity rate.

Adsorption sites on a catalyst are normally surface defects associated with planes of atoms; an interatomic/intermolecular bond is formed between a defect site and an adsorbed molecular species. Several types of surface defects, represented schematically in Figure 4.10, include ledges, kinks, terraces, vacancies, and individual adatoms (i.e., atoms adsorbed on the surface).

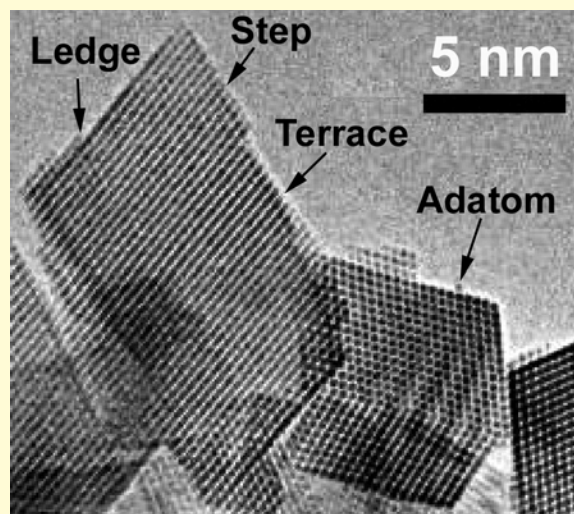
One important use of catalysts is in catalytic converters on automobiles, which reduce the emission of exhaust gas pollutants such as carbon monoxide (CO), nitrogen oxides (NO<sub>x</sub>, where *x* is variable), and unburned hydrocarbons. Air is introduced into the exhaust emissions from the automobile engine; this mixture of gases then passes over the catalyst, which adsorbs on its surface molecules of CO, NO<sub>x</sub>, and O<sub>2</sub>. The NO<sub>x</sub> dissociates into N and O atoms, whereas the O<sub>2</sub> dissociates into its atomic species. Pairs of nitrogen atoms combine to form N<sub>2</sub> molecules, and carbon

monoxide is oxidized to form carbon dioxide (CO<sub>2</sub>). Furthermore, any unburned hydrocarbons are also oxidized to CO<sub>2</sub> and H<sub>2</sub>O.

One of the materials used as a catalyst in this application is (Ce<sub>0.5</sub>Zr<sub>0.5</sub>)O<sub>2</sub>. Figure 4.11 is a high-resolution transmission electron micrograph, which shows several single crystals of this material. Individual atoms are resolved in this micrograph as well as some of the defects presented in Figure 4.10. These surface defects act as adsorption sites for the atomic and molecular species noted in the previous paragraph. Consequently, dissociation, combination, and oxidation reactions involving these species are facilitated, such that the content of pollutant species (CO, NO<sub>x</sub>, and unburned hydrocarbons) in the exhaust gas stream is reduced significantly.



**Figure 4.10** Schematic representations of surface defects that are potential adsorption sites for catalysis. Individual atom sites are represented as cubes. (From BOUDART, MICHEL, *KINETICS OF HETEROGENEOUS CATALYTIC REACTIONS*. © 1984 Princeton University Press. Reprinted by permission of Princeton University Press.)



**Figure 4.11** High-resolution transmission electron micrograph that shows single crystals of (Ce<sub>0.5</sub>Zr<sub>0.5</sub>)O<sub>2</sub>; this material is used in catalytic converters for automobiles. Surface defects represented schematically in Figure 4.10 are noted on the crystals. [From W. J. Stark, L. Mädler, M. Maciejewski, S. E. Pratsinis, A. Baiker, "Flame-Synthesis of Nanocrystalline Ceria/Zirconia: Effect of Carrier Liquid," *Chem. Comm.*, 588–589 (2003). Reproduced by permission of The Royal Society of Chemistry.]

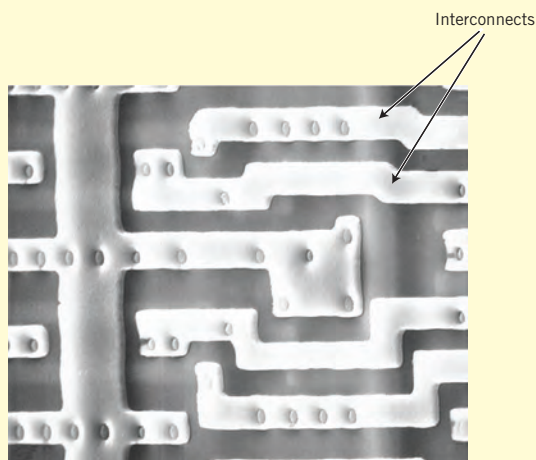
<sup>5</sup> *Adsorption* is the adhesion of molecules of a gas or liquid to a solid surface. It should not be confused with *absorption* which is the assimilation of molecules into a solid or liquid.

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### Aluminum for Integrated Circuit Interconnects

The heart of all computers and other electronic devices is the *integrated circuit* (or *IC*).<sup>4</sup> Each integrated circuit chip is a thin square wafer having dimensions on the order of 6 mm by 6 mm by 0.4 mm; furthermore, literally millions of interconnected electronic components and circuits are embedded in one of the chip faces. The base material for ICs is silicon, to which has been added very specific and extremely minute and controlled concentrations of impurities that are confined to very small and localized regions. For some ICs, the impurities are added using high-temperature diffusion heat treatments.

One important step in the IC fabrication process is the deposition of very thin and narrow conducting circuit paths to facilitate the passage of current from one device to another; these paths are called “interconnects,” and several are shown in Figure 5.9, a scanning electron micrograph of an IC chip. Of course the material to be used for interconnects must have a high electrical conductivity—a metal, since, of all materials, metals have the highest conductivities. Table 5.3 cites values for silver, copper, gold, and aluminum, the most conductive metals.



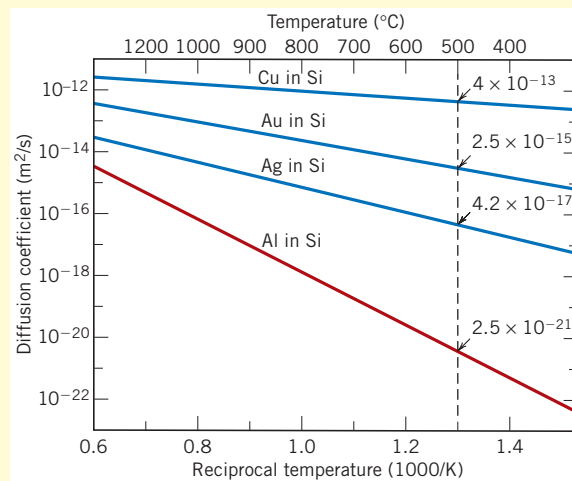
**Figure 5.9** Scanning electron micrograph of an integrated circuit chip, on which is noted aluminum interconnect regions. Approximately 2000 $\times$ . (Photograph courtesy of National Semiconductor Corporation.)

**Table 5.3** Room-Temperature Electrical Conductivity Values for Silver, Copper, Gold, and Aluminum (the Four Most Conductive Metals)

<i>Metal</i>	<i>Electrical Conductivity</i> [(ohm-meters) <sup>-1</sup> ]
Silver	$6.8 \times 10^7$
Copper	$6.0 \times 10^7$
Gold	$4.3 \times 10^7$
Aluminum	$3.8 \times 10^7$

On the basis of these conductivities, and discounting material cost, Ag is the metal of choice, followed by Cu, Au, and Al.

Once these interconnects have been deposited, it is still necessary to subject the IC chip to other heat treatments, which may run as high as 500°C. If, during these treatments, there is significant diffusion of the interconnect metal into the silicon, the electrical functionality of the IC will be destroyed. Thus, since the extent of diffusion is dependent on the magnitude of the diffusion coefficient, it is necessary to select an interconnect metal that has a small value of  $D$  in silicon. Figure 5.10



**Figure 5.10** Logarithm of  $D$ -versus- $1/T$  (K) curves (lines) for the diffusion of copper, gold, silver, and aluminum in silicon. Also noted are  $D$  values at 500°C.

<sup>4</sup> Integrated circuits, their components and materials, are discussed in Section 18.15 and Sections 22.15 through 22.20.

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### Lead-Free Solders

**S**olders are metal alloys that are used to bond or join two or more components (usually other metal alloys). They are used extensively in the electronics industry to physically hold assemblies together; furthermore, they must allow expansion and contraction of the various components, must transmit electrical signals, and also dissipate any heat that is generated. The bonding action is accomplished by melting the solder material, allowing it to flow among and make contact with the components to be joined (which do not melt), and, finally, upon solidification, forming a physical bond with all of these components.

In the past, the vast majority of solders have been lead-tin alloys. These materials are reliable, inexpensive, and have relatively low melting temperatures. The most common lead-tin solder has a composition of 63 wt% Sn–37 wt% Pb. According to the lead-tin phase diagram, Figure 9.8, this composition is near the eutectic and has melting temperature of about 183°C, the lowest temperature possible with the existence of a liquid phase (at equilibrium) for the lead-tin system. It follows that this alloy is often called a “eutectic lead-tin solder.”

Unfortunately, lead is a mildly toxic metal, and there is serious concern about the environmental impact of discarded lead-containing products that can leach into groundwater from landfills or pollute the air if incinerated. Consequently, in some countries legislation has been enacted that bans the use of lead-containing solders. This has forced the development of lead-free solders that, among other things, must have relatively low melting temperatures (or temperature ranges). Some of these are ternary alloys (i.e., composed of three metals), to include tin-silver-copper and tin-silver-bismuth solders. The compositions of several lead-free solders are listed in Table 9.1.

Of course, melting temperatures (or temperature ranges) are important in the development and selection of these new solder alloys, information that is available from phase diagrams. For example, the tin-bismuth phase diagram is presented in Figure 9.10. Here it may be noted that a eutectic

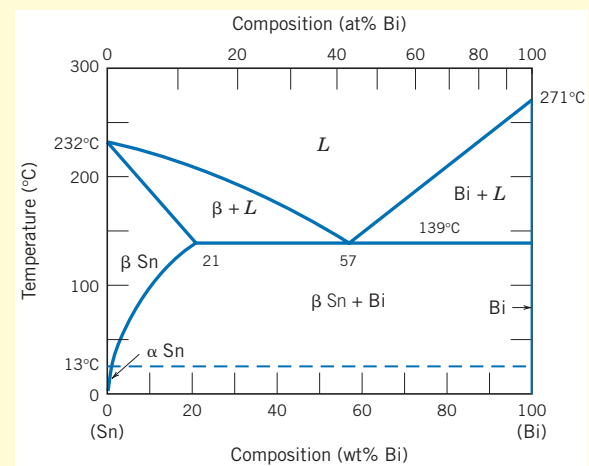
**Table 9.1** Compositions, Solidus Temperatures, and Liquidus Temperatures for Five Lead-Free Solders

Composition (wt%)	Solidus Temperature (°C)	Liquidus Temperature (°C)
52 In/48 Sn*	118	118
57 Bi/43 Sn*	139	139
91.8 Sn/3.4 Ag/ 4.8 Bi	211	213
95.5 Sn/3.8 Ag/ 0.7 Cu*	217	217
99.3 Sn/0.7 Cu*	227	227

\*The compositions of these alloys are eutectic compositions; therefore, their solidus and liquidus temperatures are identical.

**Source:** Adapted from E. Bastow, “Solder Families and How They Work,” *Advanced Materials & Processes*, Vol. 161, No. 12, M. W. Hunt (Editor-in-chief), ASM International, 2003, p. 28. Reprinted by permission of ASM International, Materials Park, OH.

exists at 57 wt% Bi and 139°C, which are indeed the composition and melting temperature of the Bi–Sn solder in Table 9.1



**Figure 9.10** The tin-bismuth phase diagram. [Adapted from *ASM Handbook*, Vol. 3, *Alloy Phase Diagrams*, H. Baker (Editor), ASM International, 1992, p. 2.106. Reprinted by permission of ASM International, Materials Park, OH.]

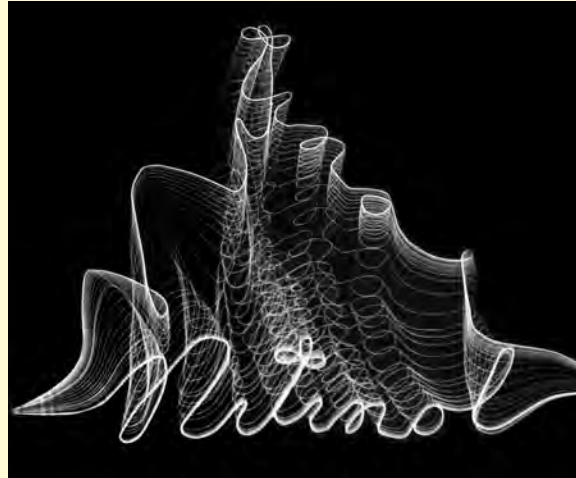


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### Shape-Memory Alloys

A relatively new group of metals that exhibit an interesting (and practical) phenomenon are the *shape-memory alloys* (or *SMA*s). One of these materials, after having been deformed, has the ability to return to its pre-deformed size and shape upon being subjected to an appropriate heat treatment—that is, the material “remembers” its previous size/shape. Deformation normally is carried out at a relatively low temperature, whereas, shape memory occurs upon heating.<sup>5</sup> Materials that have been found to be capable of recovering significant amounts of deformation (i.e., strain) are nickel–titanium alloys (Nitinol,<sup>6</sup> is their trade-name), and some copper-base alloys (viz. Cu–Zn–Al and Cu–Al–Ni alloys).

A shape memory alloy is polymorphic (Section 3.6)—that is, it may have two crystal structures (or phases), and the shape-memory effect involves phase transformations between them. One phase (termed an austenite phase) has a body-centered cubic structure that exists at elevated temperatures; its structure is represented schematically by the inset shown at stage 1 of Figure 10.37. Upon cooling, the austenite transforms spontaneously to a martensite phase, which is similar to the martensitic transformation for the iron–carbon system (Section 10.5)—that is, it is diffusionless, involves an orderly shift of large groups of atoms, occurs very rapidly, and the degree of transformation is dependent on temperature; temperatures at which the transformation begins and ends are indicated by “ $M_s$ ” and “ $M_f$ ” labels on the left vertical axis of Figure 10.37. In addition, this martensite is heavily twinned,<sup>7</sup> as represented schematically by the stage 2 inset, Figure 10.37. Under the influence of an applied stress, deformation of martensite (i.e., the passage from stage 2 to stage 3, Figure 10.37) occurs by the migration of twin boundaries—some twinned regions grow while others shrink; this deformed martensitic



structure is represented by the stage 3 inset. Furthermore, when the stress is removed, the deformed shape is retained at this temperature. And, finally, upon subsequent heating to the initial temperature, the material reverts back to (i.e., “remembers”) its original size and shape (stage 4). This stage 3–stage 4 process is accompanied by a phase transformation from the deformed martensite to the original high-temperature austenite phase. For these shape memory alloys, the martensite-to-austenite transformation occurs over a temperature range, between temperatures denoted by “ $A_s$ ” (austenite start) and “ $A_f$ ” (austenite finish) labels on the right vertical axis of

<sup>5</sup> Alloys that demonstrate this phenomenon only upon heating are said to have a *one-way* shape memory. Some of these materials experience size/shape changes on both heating and cooling; these are termed *two-way* shape memory alloys. In this discussion, we discuss the mechanism for only the one-way shape-memory.

<sup>6</sup> “Nitinol” is really an acronym for *nickel-titanium Naval Ordnance Laboratory*, where this alloy was discovered.

<sup>7</sup> The phenomenon of twinning is described in Section 7.7.

## MATERIALS OF INTEREST

### Metal Alloys Used for Euro Coins

On January 1st, 2002 the euro became the single legal currency in twelve European countries; since that date, several other nations have also joined the European monetary union, and have adopted the euro as their official currency. Euro coins are minted in eight different denominations: 2 and 1 euros, as well as 50, 20, 10, 5, 2, and 1 cent euros. Each coin has a common design on one face, whereas the reverse face design is one of several chosen by the monetary union countries. Several of these coins are shown in the photograph of Figure 11.6.

In deciding which metal alloys to use for these coins, a number of issues were considered; most of them centered on material properties.

- The ability to distinguish a coin of one denomination from that of another denomination is important. This may be accomplished by having coins of different sizes, different colors, and different shapes. With regard to color, alloys must be chosen that retain their distinctive colors, which means that they do not easily tarnish in the air and other commonly encountered environments.
- Security is an important issue—that is, producing coins that are difficult to counterfeit. Most vending machines use electrical conductivity to identify coins, to prevent false coins from being used. This means that each coin must have its own unique “electronic signature,” which depends on its alloy composition.
- The alloys chosen must be “coinable” or easy to mint—that is, sufficiently soft and ductile to allow design reliefs to be stamped into the coin surfaces.
- Also, the alloys must be wear resistant (i.e., hard and strong) for long-term use, and so that the reliefs stamped into the coin surfaces are retained. Of course, strain-hardening (Section 7.10) occurs during the stamping operation which enhances hardness.
- High degrees of corrosion resistance in common environments are required for the alloys selected, to ensure minimal material losses over the lifetimes of the coins.
- It is highly desirable to use alloys of a base metal (or metals) that retains (retain) its (their) intrinsic value(s).
- Alloy recyclability is another requirement for the alloy(s) used.
- The alloy(s) from which the coins are made should also provide for human health—that is, have antibacterial characteristics so undesirable microorganisms will not grow on their surfaces.

Copper was selected as the base metal for all euro coins, inasmuch as it and its alloys satisfy the above criteria. Several different copper alloys and alloy combinations are used for the eight different coins. These are as follows:

- 2 euro coin: This coin is termed “bimetallic”—it consists of an outer ring and an inner disk. For the outer ring, a 75Cu–25Ni alloy is used, which has a silver color. The inner disk is composed of a three-layer structure—high-purity nickel that is clad on both sides with a nickel brass alloy (75Cu–20Zn–5Ni); this alloy has a gold color.
- 1 euro coin: This coin is also bimetallic, whereas the alloys used for its outer ring and inner disk are reversed from those for the 2 euro.
- 50, 20, and 10 euro cent pieces: These coins are made of a “Nordic Gold” alloy—89Cu–5Al–5Zn–1Sn.
- 5, 2, and 1 euro cent pieces: Copper-plated steels are used for these coins.



**Figure 11.6** Photograph showing 1 euro, 2 euro, 20 cent euro, and 50 cent euro coins. (Photograph courtesy of Outokumpu Copper.)