

Mn-Zn and Ni-Zn spinel ferrites are used in magnetic recording heads for various types of magnetic tapes. Recording heads are made from polycrystalline Ni-Zn ferrite since the operating frequencies required (100 kHz to 2.5 GHz) are too high for metallic alloy heads because of high eddy-current losses.

Magnetic-core memories based on the 0 and 1 binary logic are used for some types of computers. The magnetic core is useful where loss of power does not cause loss of information. Since magnetic-core memories have no moving parts, they are used when high shock resistance is needed, as in some military uses.

### 15.10.2 Magnetically Hard Ferrites

A group of **hard ferrites** that are used for permanent magnets have the general formula  $MO \cdot 6Fe_2O_3$  and are hexagonal in crystal structure. The most important ferrite of this group is *barium ferrite* ( $BaO \cdot 6Fe_2O_3$ ), which was introduced in the Netherlands by the Philips Company in 1952 under the trade name Ferroxdure. In recent years, the barium ferrites have been replaced to some extent by the strontium ferrites, which have the general formula  $(SrO \cdot 6Fe_2O_3)$  and which have superior magnetic properties compared with the barium ferrites. These ferrites are produced by almost the same method used for the soft ferrites, with most being wet-pressed in a magnetic field to align the easy magnetizing axis of the particles with the applied field.

The hexagonal ferrites are low in cost, low in density, and have a high coercive force, as shown in Fig. 15.24. The high magnetic strengths of these materials is due mainly to their high magnetocrystalline anisotropy. The magnetization of these materials is believed to take place by domain wall nucleation and motion because their grain size is too large for single-domain behavior. Their  $(BH)_{max}$  energy products vary from 14 to 28 kJ/m<sup>3</sup>.

These hard-ferrite ceramic permanent magnets find widespread use in generators, relays, and motors. Electronic applications include magnets for loudspeakers, telephone ringers, and receivers. They are also used for holding devices for door closers, seals, and latches and are used in many toy designs.

## 15.11 SUMMARY

Magnetic materials are important industrial materials used for many engineering designs. Most industrial magnetic materials are *ferro-* or *ferrimagnetic* and show large magnetizations. The most important ferromagnetic materials are based on alloys of Fe, Co, and Ni. More recently some ferromagnetic alloys have been made with some rare earth elements such as Sm. In ferromagnetic materials such as Fe, there exist regions called *magnetic domains* in which atomic magnetic dipole moments are aligned parallel to each other. The magnetic domain structure in a ferromagnetic material is determined by the following energies that are minimized: exchange, magnetostatic, magnetocrystalline anisotropy, domain wall, and magnetostrictive energies. When the ferromagnetic domains in a sample are at random orientations, the sample is in a demagnetized state. When a magnetic field is applied to a ferromagnetic material sample, the domains in the sample are aligned; the material becomes magnetized and remains magnetized to some extent when the field is removed. The magnetization behavior of a ferromagnetic material is recorded by a magnetic

induction versus an applied field graph called a *hysteresis loop*. When a demagnetized ferromagnetic material is magnetized by an applied field  $H$ , its magnetic induction  $B$  eventually reaches a saturation level called the *saturation induction*  $B_s$ . When the applied field is removed, the magnetic induction decreases to a value called the *remanent induction*  $B_r$ . The demagnetizing field required to reduce the magnetic induction of a magnetized ferromagnetic sample to zero is called the *coercive force*  $H_c$ .

A *soft magnetic material* is one that is easily magnetized and demagnetized. Important magnetic properties of a soft magnetic material are high permeability, high saturation induction, and low coercive force. When a soft ferromagnetic material is repeatedly magnetized and demagnetized, *hysteresis* and *eddy-current* energy losses occur. Examples of soft ferromagnetic materials include Fe-3 to 4% Si alloys used in motors and power transformers and generators and Ni-20 to 50% Fe alloys used primarily for high-sensitivity communications equipment.

A *hard magnetic material* is one that is difficult to magnetize and which remains magnetized to a great extent after the magnetizing field is removed. Important properties of a hard magnetic material are high coercive force and high saturation induction. The power of a hard magnetic material is measured by its maximum energy product, which is the maximum value of the product of  $B$  and  $H$  in the demagnetizing quadrant of its  $B$ - $H$  hysteresis loop. Examples of hard magnetic materials are the alnicos, which are used as permanent magnets for many electrical applications, and some rare earth alloys that are based on  $\text{SmCo}_5$  and  $\text{Sm}(\text{Co}, \text{Cu})_{7.5}$  compositions. The rare earth alloys are used for small motors and other applications requiring an extremely high energy-product magnetic material.

The *ferrites*, which are ceramic compounds, are another type of industrially important magnetic material. These materials are ferrimagnetic due to a net magnetic moment produced by their ionic structure. Most magnetically soft ferrites have the basic composition  $\text{MO} \cdot \text{Fe}_2\text{O}_3$ , where  $M$  is a divalent ion such as  $\text{Fe}^{2+}$ ,  $\text{Mn}^{2+}$ , and  $\text{Ni}^{2+}$ . These materials have the *inverse spinel structure* and are used for low-signal, memory-core, audiovisual, and recording-head applications, as examples. Since these materials are insulators, they can be used for high-frequency applications where eddy currents are a problem with alternating fields. Magnetically hard ferrites with the general formula  $\text{MO} \cdot 6\text{Fe}_2\text{O}_3$ , where  $M$  is usually a Ba or Sr ion, are used for applications requiring low-cost, low-density permanent magnetic materials. These materials are used for loudspeakers, telephone ringers and receivers, and for holding devices for doors, seals, and latches.

## 15.12 DEFINITIONS

### Sec. 15.2

**Ferromagnetic material:** one that is capable of being highly magnetized. Elemental iron, cobalt, and nickel are ferromagnetic materials.

**Magnetic field  $H$ :** the magnetic field produced by an external applied magnetic field or the magnetic field produced by a current passing through a conducting wire or coil of wire (solenoid).

**Magnetization  $M$ :** a measure of the increase in magnetic flux due to the insertion of a given material into a magnetic field of strength  $H$ . In SI units, the magnetization is equal to the permeability of a vacuum ( $\mu_0$ ) times the magnetization, or  $\mu_0 M$ . ( $\mu_0 = 4\pi \times 10^{-4} \text{ T} \cdot \text{m/A}$ .)

**Magnetic induction  $B$ :** the sum of the applied field  $H$  and the magnetization  $M$  due to the insertion of a given material into the applied field. In SI units,  $B = \mu_0(H + M)$ .

**Magnetic permeability  $\mu$ :** the ratio of the magnetic induction  $B$  to the applied magnetic field  $H$  for a material;  $\mu = B/H$ .

**Relative permeability  $\mu_r$ :** the ratio of the permeability of a material to the permeability of a vacuum;  $\mu_r = \mu/\mu_0$ .

**Magnetic susceptibility  $\chi_m$ :** the ratio of  $M$  (magnetization) to  $H$  (applied magnetic field);  $\chi_m = M/H$ .

### Sec. 15.3

**Diamagnetism:** a weak, negative, repulsive reaction of a material to an applied magnetic field; a diamagnetic material has a small negative magnetic susceptibility.

**Paramagnetism:** a weak, positive, attractive reaction of a material to an applied magnetic field; a paramagnetic material has a small positive magnetic susceptibility.

**Ferromagnetism:** the creation of a very large magnetization in a material when subjected to an applied magnetic field. After the applied field is removed, the ferromagnetic material retains much of the magnetization.

**Bohr magneton:** the magnetic moment produced in a ferro- or ferrimagnetic material by one unpaired electron without interaction from any others; the Bohr magneton is a fundamental unit. 1 Bohr magneton =  $9.27 \times 10^{-24} \text{ A} \cdot \text{m}^2$ .

**Antiferromagnetism:** a type of magnetism in which magnetic dipoles of atoms are aligned in opposite directions by an applied magnetic field so that there is no net magnetization.

**Ferrimagnetism:** a type of magnetism in which the magnetic dipole moments of different ions of an ionically bonded solid are aligned by a magnetic field in an antiparallel manner so that there is a net magnetic moment.

### Sec. 15.4

**Curie temperature:** the temperature at which a ferromagnetic material when heated completely loses its ferromagnetism and becomes paramagnetic.

### Sec. 15.5

**Magnetic domain:** a region in a ferro- or ferrimagnetic material in which all magnetic dipole moments are aligned.

### Sec. 15.6

**Exchange energy:** the energy associated with the coupling of individual magnetic dipoles into a single magnetic domain. The exchange energy can be positive or negative.

**Magnetostatic energy:** the magnetic potential energy due to the external magnetic field surrounding a sample of a ferromagnetic material.

**Magnetocrystalline anisotropy energy:** the energy required during the magnetization of a ferromagnetic material to rotate the magnetic domains because of crystalline anisotropy. For example, the difference in magnetizing energy between the hard [111] direction of magnetization and the [100] easy direction in Fe is about  $1.4 \times 10^4 \text{ J/m}^3$ .

**Magnetostriction:** the change in length of a ferromagnetic material in the direction of magnetization due to an applied magnetic field.

**Magnetostrictive energy:** the energy due to the mechanical stress caused by magnetostriction in a ferromagnetic material.

**Domain wall energy:** the potential energy associated with the disorder of dipole moments in the wall volume between magnetic domains.

### Sec. 15.7

**Hysteresis loop:** the  $B$  versus  $H$  or  $M$  versus  $H$  graph traced out by the magnetization and demagnetization of a ferro- or ferrimagnetic material.

**Saturation induction  $B_s$ :** the maximum value of induction  $B_s$  or magnetization  $M_s$  for a ferromagnetic material.

**Remanent induction  $B_r$ :** the value of  $B$  or  $M$  in a ferromagnetic material after  $H$  is decreased to zero.

**Coercive force  $H_c$ :** the applied magnetic field required to decrease the magnetic induction of a magnetized ferro- or ferrimagnetic material to zero.

#### Sec. 15.8

**Soft magnetic material:** a magnetic material with a high permeability and low coercive force.

**Hysteresis energy loss:** the work or energy lost in tracing out a  $B$ - $H$  hysteresis loop. Most of the energy lost is expended in moving the domain boundaries during magnetization.

**Eddy-current energy losses:** energy losses in magnetic materials while using alternating fields; the losses are due to induced currents in the material.

**Iron-silicon alloys:** Fe-3 to 4% Si alloys that are soft magnetic materials with high saturation inductions. These alloys are used in motors and low-frequency power transformers and generators.

**Nickel-iron alloys:** high-permeability soft magnetic alloys used for electrical applications where a high sensitivity is required such as for audio and instrument transformers. Two commonly used basic compositions are 50% Ni-50% Fe and 79% Ni-21% Fe.

#### Sec. 15.9

**Hard magnetic material:** a magnetic material with a high coercive force and a high saturation induction.

**Maximum energy product  $(BH)_{\max}$ :** the maximum value of  $B$  times  $H$  in the demagnetization curve of a hard magnetic material. The  $(BH)_{\max}$  value has SI units of J/m<sup>3</sup>.

**Alnico (aluminum-nickel-cobalt) alloys:** a family of permanent magnetic alloys having the basic composition of Al, Ni, and Co, and about 25 to 50 percent Fe. A small amount of Cu and Ti is added to some of these alloys.

**Magnetic anneal:** the heat treatment of a magnetic material in a magnetic field that aligns part of the alloy in the direction of the applied field. For example, the  $\alpha'$  precipitate in alnico 5 alloy is elongated and aligned by this type of heat treatment.

**Rare earth alloys:** a family of permanent magnetic alloys with extremely high energy products.  $\text{SmCo}_5$  and  $\text{Sm}(\text{Co}, \text{Cu})_{7.4}$  are the two most important commercial compositions of these alloys.

**Iron-chromium-cobalt alloys:** a family of permanent magnetic alloys containing about 30% Cr-10 to 23% Co and the balance iron. These alloys have the advantage of being cold-formable at room temperature.

#### Sec. 15.10

**Soft ferrites:** ceramic compounds with the general formula  $\text{MO} \cdot \text{Fe}_2\text{O}_3$ , where M is a divalent ion such as  $\text{Fe}^{2+}$ ,  $\text{Mn}^{2+}$ ,  $\text{Zn}^{2+}$ , or  $\text{Ni}^{2+}$ . These materials are ferrimagnetic and are insulators and so can be used for high-frequency transformer cores.

**Normal spinel structure:** a ceramic compound having the general formula  $\text{MO} \cdot \text{M}_2\text{O}_3$ . The oxygen ions in this compound form an FCC lattice, with the  $\text{M}^{2+}$  ions occupying tetrahedral interstitial sites and the  $\text{M}^{3+}$  ions occupying octahedral sites.

**Inverse spinel structure:** a ceramic compound having the general formula  $\text{MO} \cdot \text{M}_2\text{O}_3$ . The oxygen ions in this compound form an FCC lattice, with the  $\text{M}^{2+}$  ions occupying octahedral sites and the  $\text{M}^{3+}$  ions occupying both octahedral and tetrahedral sites.

**Hard ferrites:** ceramic permanent magnetic materials. The most important family of these materials has the basic composition  $\text{MO} \cdot \text{Fe}_2\text{O}_3$ , where M is a barium (Ba) ion or a strontium (Sr) ion. These materials have a hexagonal structure and are low in cost and density.

## 15.13 PROBLEMS

Answers to problems marked with an asterisk are given at the end of the book.

### Knowledge and Comprehension Problems

- 15.1 What elements are strongly ferromagnetic at room temperature?
- 15.2 How can a magnetic field around a magnetized iron bar be revealed?
- 15.3 What are the SI and cgs units for the magnetic field strength  $H$ ?
- 15.4 Define magnetic induction  $B$  and magnetization  $M$ .
- 15.5 What is the relationship between  $B$  and  $H$ ?
- 15.6 What is the permeability of free-space constant  $\mu_0$ ?
- 15.7 What are the SI units for  $B$  and  $M$ ?
- 15.8 Write an equation that relates  $B$ ,  $H$ , and  $M$ , using SI units.
- 15.9 Why is the relation  $B \approx \mu_0 M$  often used in magnetic property calculations?
- 15.10 Define magnetic permeability and relative magnetic permeability.
- 15.11 Is the magnetic permeability of a ferromagnetic material a constant? Explain.
- 15.12 What magnetic permeability quantities are frequently specified?
- 15.13 Define magnetic susceptibility. For what situation is this quantity often used?
- 15.14 Describe two mechanisms involving electrons by which magnetic fields are created.
- 15.15 Define diamagnetism. What is the order of magnitude for the magnetic susceptibility of diamagnetic materials at 20°C?
- 15.16 Define paramagnetism. What is the order of magnitude for the magnetic susceptibility of paramagnetic materials at 20°C?
- 15.17 Define ferromagnetism. Which elements are ferromagnetic?
- 15.18 What causes ferromagnetism in Fe, Co, and Ni?
- 15.19 How many unpaired 3d electrons are there per atom in Cr, Mn, Fe, Co, Ni, and Cu?
- 15.20 What are magnetic domains?
- 15.21 How does a positive exchange energy affect the alignment of magnetic dipoles in ferromagnetic materials?
- 15.22 What is the explanation given for the fact that Fe, Co, and Ni are ferromagnetic and Cr and Mn are not, even though all these elements have unpaired 3d electrons?
- 15.23 Define antiferromagnetism. Which elements show this type of behavior?
- 15.24 Define ferrimagnetism. What are ferrites? Give an example of a ferromagnetic compound.
- 15.25 What is the Curie temperature?
- 15.26 How may the domain structure of a ferromagnetic material be revealed for observation in the optical microscope?
- 15.27 What are the five types of energies that determine the domain structure of a ferromagnetic material?
- 15.28 Define magnetic exchange energy. How can the exchange energy of a ferromagnetic material be minimized with respect to magnetic dipole alignment?
- 15.29 Define magnetostatic energy. How can the magnetostatic energy of a ferromagnetic material sample be minimized?

- 15.30 Define magnetocrystalline anisotropy energy. What are the easy directions of magnetization for (a) Fe and (b) Ni?
- 15.31 Define magnetic domain wall energy. What is the average width in terms of number of atoms for a ferromagnetic domain wall?
- 15.32 What two energies determine the domain wall width? What energy is minimized when the wall is widened? What energy is minimized when the wall is made narrower?
- 15.33 Define magnetostriction and magnetostrictive energy. What is the cause of magnetostriction in ferromagnetic materials?
- 15.34 Define a soft magnetic material and a hard magnetic material.
- 15.35 What type of a hysteresis loop does a soft ferromagnetic material have?
- 15.36 What are eddy currents? How are they created in a ferromagnetic material?
- 15.37 What is the structure of a metallic glass? How are magnetic glass ribbons produced?
- 15.38 What are some special properties of metallic glasses?
- 15.39 What are the advantages of metallic glasses for power transformers? Disadvantages?
- 15.40 What are some engineering advantages of using nickel-iron alloys for electrical applications?
- 15.41 What compositions of Ni-Fe alloys are especially important for electrical applications?
- 15.42 What is the maximum energy product for a hard magnetic material? How is it calculated? What are the SI and cgs units for the energy product?
- 15.43 What elements are included in the alnico magnetic materials?
- 15.44 What two processes are used to produce alnico permanent magnets?
- 15.45 What is the basic structure of an alnico 8 magnetic material?
- 15.46 What is the origin of ferromagnetism in rare earth magnetic alloys?
- 15.47 What are the two main groups of rare earth alloys?
- 15.48 What are some applications for rare earth magnetic alloys?
- 15.49 What fabrication advantage do the Fe-Cr-Co magnetic alloys have for making permanent magnetic alloy parts?
- 15.50 What is a typical chemical composition of an Fe-Cr-Co magnetic alloy?
- 15.51 What is the basic structure of an Fe-Cr-Co magnetic alloy? What is the mechanism for coercivity of the Fe-Cr-Co type magnetic alloys?
- 15.52 For what types of applications are the Fe-Cr-Co alloys particularly suited?
- 15.53 What are the ferrites? How are they produced?
- 15.54 What is the basic composition of the cubic soft ferrites?
- 15.55 Describe the unit cell of the spinel structure  $\text{MgO} \cdot \text{Al}_2\text{O}_3$ , including which ions occupy tetrahedral and octahedral interstitial sites.
- 15.56 Describe the unit cell of the inverse spinel structure, including which ions occupy tetrahedral and octahedral interstitial sites.
- 15.57 What are the compositions of the two most commonly used ferrites? Why are mixtures of ferrites used instead of a single pure ferrite?
- 15.58 What are some industrial applications for soft ferrites?

- 15.59 What is the basic composition of the hexagonal hard ferrites?
- 15.60 What are the advantages of the hard ferrites for industrial use?
- 15.61 What are some applications for hard ferrite magnetic materials?

### Application and Analysis Problems

- \*15.62 Calculate a theoretical value for the saturation magnetization and saturation induction for nickel, assuming all unpaired  $3d$  electrons contribute to the magnetization. (Ni is FCC and  $a = 0.352$  nm.)
- 15.63 Calculate a theoretical value for the saturation magnetization of pure cobalt metal assuming all unpaired  $3d$  electrons contribute to the magnetization. (Co is HCP with  $a = 0.25071$  nm and  $c = 0.40686$  nm.)
- 15.64 Calculate a theoretical value for the saturation magnetization of pure gadolinium below  $16^\circ\text{C}$  assuming all seven unpaired  $4f$  electrons contribute to the magnetization. (Gd is HCP with  $a = 0.364$  nm and  $c = 0.578$  nm.)
- \*15.65 Cobalt has a saturation magnetization of  $1.42 \times 10^6$  A/m. What is its average magnetic moment in Bohr magnetons per atom?
- 15.66 Nickel has an average of 0.604 Bohr magnetons/atom. What is its saturation induction?
- 15.67 Gadolinium at very low temperatures has an average of 7.1 Bohr magnetons/atom. What is its saturation magnetization?
- 15.68 What effect does increasing temperature above 0 K have on the alignment of magnetic dipoles in ferromagnetic materials?
- 15.69 How can a ferromagnetic material be demagnetized? What is the arrangement of the magnetic domains in a demagnetized ferromagnetic material?
- 15.70 When a demagnetized ferromagnetic material is slowly magnetized by an applied magnetic field, what changes occur first in domain structure?
- 15.71 After domain growth due to magnetization of a ferromagnetic material by an applied field has finished, what change in domain structure occurs with a further substantial increase in the applied field?
- 15.72 What changes in domain structure occur in a ferromagnetic material when the applied field that magnetized a sample to saturation is removed?
- 15.73 What are domains of closure? How are magnetostrictive stresses created by domains of closure?
- 15.74 How does the domain size affect the magnetostrictive energy of a magnetized ferromagnetic material sample?
- 15.75 How does domain size affect the amount of domain wall energy in a sample?
- 15.76 Draw a hysteresis  $B$ - $H$  loop for a ferromagnetic material and indicate on it (a) the saturation induction  $B_s$ , (b) the remanent induction  $B_r$ , and (c) the coercive force  $H_c$ .
- 15.77 Describe what happens to the magnetic induction when a ferromagnetic material is magnetized, demagnetized, and remagnetized by an applied magnetic field.
- 15.78 What happens to the magnetic domains of a ferromagnetic material sample during magnetization and demagnetization?

- 15.79 What are desirable magnetic properties for a soft magnetic material?
- 15.80 What are hysteresis energy losses? What factors affect hysteresis losses?
- 15.81 How does the AC frequency affect the hysteresis losses of soft ferromagnetic materials? Explain.
- 15.82 How can eddy currents be reduced in metallic magnetic transformer cores?
- 15.83 Why does the addition of 3 to 4 percent silicon to iron reduce transformer-core energy losses?
- 15.84 What disadvantages are there to the addition of silicon to iron for transformer-core materials?
- 15.85 Why does a laminated structure increase the electrical efficiency of a power transformer?
- 15.86 Why does grain-oriented iron-silicon transformer sheet steel increase the efficiency of a transformer core?
- 15.87 Why are magnetic metallic glasses so easily magnetized and demagnetized?
- 15.88 Calculate the weight percent of the elements in the metallic glass with the atomic percent composition  $\text{Fe}_{78}\text{B}_{13}\text{Si}_9$ .
- 15.89 How does ordering in an Ni-Fe alloy affect the magnetic properties of a 78.5% Ni–21.5% Fe alloy? How can ordering be prevented?
- 15.90 How does magnetic annealing increase the magnetic properties of a 65% Ni–35% Fe alloy?
- 15.91 What are important magnetic properties for a hard magnetic material?
- 15.92 Estimate the maximum energy product for the  $\text{SmCo}_5$  rare earth hard magnetic alloy (curve 2) of Fig. 15.24.
- \*15.93 Estimate the maximum energy product for the alnico 5 alloy (curve 4) of Fig. 16.24.
- 15.94 Approximately how much energy in kilojoules per cubic meter would be required to demagnetize a fully magnetized  $2\text{ cm}^3$  block of alnico 8 alloy?
- 15.95 How does precipitation in a magnetic field affect the shape of the precipitates in an alnico 8 alloy? How does the shape of the precipitates affect the coercivity of this material?
- 15.96 How do the maximum energy products of the alnicos compare with those of the rare earth magnetic alloys?
- 15.97 What is believed to be the basic mechanism of coercivity for the  $\text{SmCo}_5$  magnetic alloys?
- 15.98 How does plastic deformation before the final aging treatment affect the shape of the precipitated particles and the coercivity of the Fe-Cr-Co magnetic alloys?
- 15.99 What is the net magnetic moment per molecule for each of the following ferrites: (a)  $\text{FeO} \cdot \text{Fe}_2\text{O}_3$ , (b)  $\text{NiO} \cdot \text{Fe}_2\text{O}_3$ , and (c)  $\text{MnO} \cdot \text{Fe}_2\text{O}_3$ ?
- \*15.100 Calculate the theoretical saturation magnetization in amperes per meter and saturation induction in teslas for the ferrite  $\text{NiO} \cdot \text{Fe}_2\text{O}_3$  ( $a = 0.834\text{ nm}$  for  $\text{NiO} \cdot \text{Fe}_2\text{O}_3$ ).
- 15.101 Why is a high electrical resistivity necessary for a magnetic material that is to be used for a transformer core operating at a high frequency?
- 15.102 Why are magnetic core memories particularly useful for high-shock-resistance applications?

### Synthesis and Evaluation Problems

- 15.103 Investigate what types of magnets are used in a magnetic resonance imaging (MRI) system. What are their respective strengths? Compare them to the Earth's magnetic field.
- 15.104 Investigate the role of the magnet(s) in a magnetic resonance imaging (MRI) system.
- 15.105 Magnetic resonance imaging (MRI) system operators always make sure not to carry any metallic objects when they enter the room that houses the MRI—even when the machine is not operating. Why?
- 15.106 Identify those subjects that cannot be imaged using a magnetic resonance imaging (MRI). Explain your answer.

# APPENDIX

## Some Properties of Selected Elements

Element	Symbol	Melting point, °C	Density,* g/cm <sup>3</sup>	Atomic radius, nm	Crystal structure† (20°C)	Lattice constants 20°C, nm	
						a	c
Aluminum	Al	660	2.70	0.143	FCC	0.40496	
Antimony	Sb	630	6.70	0.138	Rhombohedral	0.45067	
Arsenic	As	817	5.72	0.125	Rhombohedral‡	0.4131	
Barium	Ba	714	3.5	0.217	BCC‡	0.5019	
Beryllium	Be	1278	1.85	0.113	HCP‡	0.22856	0.35832
Boron	B	2030	2.34	0.097	Orthorhombic		
Bromine	Br	-7.2	3.12	0.119	Orthorhombic		
Cadmium	Cd	321	8.65	0.148	HCP‡	0.29788	0.561667
Calcium	Ca	846	1.55	0.197	FCC‡	0.5582	
Carbon (graphite)	C	3550	2.25	0.077	Hexagonal	0.24612	0.67078
Cesium	Cs	28.7	1.87	0.190	BCC		
Chlorine	Cl	-101	1.9	0.099	Tetragonal		
Chromium	Cr	1875	7.19	0.128	BCC‡	0.28846	
Cobalt	Co	1498	8.85	0.125	HCP‡	0.2506	0.4069
Copper	Cu	1083	8.96	0.128	FCC	0.36147	
Fluorine	F	-220	1.3	0.071			
Gallium	Ga	29.8	5.91	0.135	Orthorhombic		
Germanium	Ge	937	5.32	0.139	Diamond cubic	0.56576	
Gold	Au	1063	19.3	0.144	FCC	0.40788	
Helium	He	-270	...	...	HCP		
Hydrogen	H	-259	...	0.046	Hexagonal		
Indium	In	157	7.31	0.162	FC tetragonal	0.45979	0.49467
Iodine	I	114	4.94	0.136	Orthorhombic		
Iridium	Ir	2454	22.4	0.135	FCC	0.38389	
Iron	Fe	1536	7.87	0.124	BCC‡	0.28664	
Lead	Pb	327	11.34	0.175	FCC	0.49502	
Lithium	Li	180	0.53	0.157	BCC	0.35092	

(continued)

Element	Symbol	Melting point, °C	Density,* g/cm <sup>3</sup>	Atomic radius, nm	Crystal structure† (20°C)	Lattice constants 20°C, nm	
						a	c
Magnesium	Mg	650	1.74	0.160	HCP	0.32094	0.52105
Manganese	Mn	1245	7.43	0.118	Cubic‡	0.89139	
Mercury	Hg	-38.4	14.19	0.155	Rhombohedral		
Molybdenum	Mo	2610	10.2	0.140	BCC	0.31468	
Neon	Ne	-248.7	1.45	0.160	FCC		
Nickel	Ni	1453	8.9	0.125	FCC	0.35236	
Niobium	Nb	2415	8.6	0.143	BCC	0.33007	
Nitrogen	N	-240	1.03	0.071	Hexagonal‡		
Osmium	Os	2700	22.57	0.135	HCP	0.27353	0.43191
Oxygen	O	-218	1.43	0.060	Cubic‡		
Palladium	Pd	1552	12.0	0.137	FCC	0.38907	
Phosphorus (white)	P	44.2	1.83	0.110	Cubic‡		
Platinum	Pt	1769	21.4	0.139	FCC	0.39239	
Potassium	K	63.9	0.86	0.238	BCC	0.5344	
Rhenium	Re	3180	21.0	0.138	HCP	0.27609	0.44583
Rhodium	Rh	1966	12.4	0.134	FCC	0.38044	
Ruthenium	Ru	2500	12.2	0.125	HCP	0.27038	0.42816
Scandium	Sc	1539	2.99	0.160	FCC	0.4541	
Silicon	Si	1410	2.34	0.117	Diamond cubic	0.54282	
Silver	Ag	961	10.5	0.144	FCC	0.40856	
Sodium	Na	97.8	0.97	0.192	BCC	0.42906	
Strontium	Sr	76.8	2.60	0.215	FCC‡	0.6087	
Sulfur (yellow)	S	119	2.07	0.104	Orthorhombic		
Tantalum	Ta	2996	16.6	0.143	BCC	0.33026	
Tin	Sn	232	7.30	0.158	Tetragonal‡	0.58311	0.31817
Titanium	Ti	1668	4.51	0.147	HCP‡	0.29504	0.46833
Tungsten	W	3410	19.3	0.141	BCC	0.31648	
Uranium	U	1132	19.0	0.138	Orthorhombic‡	0.2858	0.4955
Vanadium	V	1900	6.1	0.136	BCC	0.3039	
Zinc	Zn	419.5	7.13	0.137	HCP	0.26649	0.49470
Zirconium	Zr	1852	6.49	0.160	HCP‡	0.32312	0.51477

\*Density of solid at 20°C.

†b = 0.5877 nm.

‡Other crystal structures exist at other temperatures.

# APPENDIX

## Ionic Radii<sup>1</sup> of the Elements

<sup>1</sup>Ionic radii can vary in different crystals due to many factors.

Atomic number	Element (symbol)	Ion	Ionic radius, nm	Atomic number	Element (symbol)	Ion	Ionic radius, nm
1	H	H <sup>+</sup>	0.154	23	V	V <sup>3+</sup>	0.065
2	He					V <sup>4+</sup>	0.061
3	Li	Li <sup>+</sup>	0.078			V <sup>5+</sup>	~0.04
4	Be	Be <sup>2+</sup>	0.034	24	Cr	Cr <sup>3+</sup>	0.064
5	B	B <sup>3+</sup>	0.02			Cr <sup>6+</sup>	0.03–0.04
		<sup>6</sup> C		C <sup>4+</sup>	<0.02		
25	Mn	Mn <sup>2+</sup>	0.091			Mn <sup>3+</sup>	0.070
7	N	N <sup>3+</sup>	0.01–0.02			Mn <sup>4+</sup>	0.052
8	O	O <sup>2-</sup>	0.132	26	Fe	Fe <sup>2+</sup>	0.087
9	F	F <sup>-</sup>	0.133			Fe <sup>3+</sup>	0.067
10	Ne			27	Co	Co <sup>2+</sup>	0.082
11	Na	Na <sup>+</sup>	0.098			Co <sup>3+</sup>	0.065
12	Mg	Mg <sup>2+</sup>	0.078	28	Ni	Ni <sup>2+</sup>	0.078
13	Al	Al <sup>3+</sup>	0.057	29	Cu	Cu <sup>+</sup>	0.096
14	Si	Si <sup>4-</sup>	0.198	30	Zn	Zn <sup>2+</sup>	0.083
		Si <sup>4+</sup>	0.039	31	Ga	Ga <sup>3+</sup>	0.062
15	P	P <sup>5+</sup>	0.03–0.04	32	Ge	Ge <sup>4+</sup>	0.044
16	S	S <sup>2-</sup>	0.174	33	As	As <sup>3+</sup>	0.069
		S <sup>6+</sup>	0.034			As <sup>5+</sup>	~0.04
17	Cl	Cl <sup>-</sup>	0.181	34	Se	Se <sup>2-</sup>	0.191
18	Ar					Se <sup>6+</sup>	0.03–0.04
19	K	K <sup>+</sup>	0.133	35	Br	Br <sup>-</sup>	0.196
20	Ca	Ca <sup>2+</sup>	0.106	36	Kr		
21	Sc	Sc <sup>2+</sup>	0.083	37	Rb	Rb <sup>+</sup>	0.149
22	Ti	Ti <sup>2+</sup>	0.076	38	Sr	Sr <sup>2+</sup>	0.127
		Ti <sup>3+</sup>	0.069				
		Ti <sup>4+</sup>	0.064				

(continued)

Atomic number	Element (symbol)	Ion	Ionic radius, nm	Atomic number	Element (symbol)	Ion	Ionic radius, nm
39	Y	Y <sup>3+</sup>	0.106	66	Dy	Dy <sup>3+</sup>	0.107
40	Zr	Zr <sup>4+</sup>	0.087	67	Ho	Ho <sup>3+</sup>	0.105
41	Nb	Nb <sup>4+</sup>	0.069	68	Er	Er <sup>3+</sup>	0.104
		Nb <sup>5+</sup>	0.069	69	Tm	Tm <sup>3+</sup>	0.104
42	Mo	Mo <sup>4+</sup>	0.068	70	Yb	Yb <sup>3+</sup>	0.100
		Mo <sup>6+</sup>	0.065	71	Lu	Lu <sup>3+</sup>	0.099
44	Ru	Ru <sup>4+</sup>	0.065	72	Hf	Hf <sup>4+</sup>	0.084
45	Rh	Rh <sup>3+</sup>	0.068	73	Ta	Ta <sup>5+</sup>	0.068
		Rh <sup>4+</sup>	0.065	74	W	W <sup>4+</sup>	0.068
46	Pd	Pd <sup>2+</sup>	0.050			W <sup>6+</sup>	0.065
47	Ag	Ag <sup>+</sup>	0.113	75	Re	Re <sup>4+</sup>	0.072
48	Cd	Cd <sup>2+</sup>	0.103	76	Os	Os <sup>4+</sup>	0.067
49	In	In <sup>3+</sup>	0.092	77	Ir	Ir <sup>4+</sup>	0.066
50	Sn	Sn <sup>4+</sup>	0.215	78	Pt	Pt <sup>4+</sup>	0.052
		Sn <sup>4+</sup>	0.074			Pt <sup>4+</sup>	0.055
51	Sb	Sb <sup>3+</sup>	0.090	79	Au	Au <sup>+</sup>	0.137
52	Te	Te <sup>2-</sup>	0.211	80	Hg	Hg <sup>2+</sup>	0.112
		Te <sup>4+</sup>	0.089	81	Tl	Tl <sup>+</sup>	0.149
53	I	I <sup>-</sup>	0.220			Tl <sup>3+</sup>	0.106
		I <sup>5+</sup>	0.094	82	Pb	Pb <sup>4-</sup>	0.215
54	Xe					Pb <sup>2+</sup>	0.132
55	Cs	Cs <sup>+</sup>	0.165			Pb <sup>4+</sup>	0.084
56	Ba	Ba <sup>2+</sup>	0.143			Bi <sup>3+</sup>	0.120
57	La	La <sup>3+</sup>	0.122	83	Bi		
58	Ce	Ce <sup>3+</sup>	0.118	84	Po		
		Ce <sup>4+</sup>	0.102	85	At		
59	Pr	Pr <sup>3+</sup>	0.116	86	Rn		
		Pr <sup>4+</sup>	0.100	87	Fr		
60	Nd	Nd <sup>3+</sup>	0.115	88	Ra	Ra <sup>+</sup>	0.152
61	Pm	Pm <sup>3+</sup>	0.106	89	Ac		
62	Sm	Sm <sup>3+</sup>	0.113	90	Th	Th <sup>4+</sup>	0.110
63	Eu	Eu <sup>3+</sup>	0.113	91	Pa		
64	Gd	Gd <sup>3+</sup>	0.111	92	U	U <sup>4+</sup>	0.105
65	Tb	Tb <sup>3+</sup>	0.109				
		Tb <sup>4+</sup>	0.089				

\*Ionic radii can vary in different crystals due to many factors.

Source: C. J. Smithells (ed.), "Metals Reference Book," 5th ed., Butterworth, 1976.

# ANSWERS TO SELECTED PROBLEMS

## Chapter 2

- 2.29  $2.07 \times 10^{14}$  soccer balls  
 2.30 (a) 5.67 gr (b) 8.3 wt % Ni (c) 91.7 wt % Cu  
 2.32 (a) 10.81 amu (b) 10.81 gr (c) match  
 2.34  $\text{MgAl}_2$   
 2.37 (a) 72 photons (b) less photons of higher energy blue light  
 2.42 (a) 3.02 eV (b)  $7.3 \times 10^{14}$  Hz (c) 410 nm  
 2.45  $\ell = 0$  ( $m_\ell = 0$ );  $\ell = 1$  ( $m_\ell = -1, 0, +1$ ),  
 $\ell = 2$  ( $m_\ell = -2, -1, 0, +1, +2$ ),  $\ell = 3$   
 $(m_\ell = -3, -2, -1, 0, +1, +2, +3)$   
 2.49 (a)  $n = 2$ ,  $\ell = 0$ ,  $m_\ell = 0$ ,  $m_s = +1/2$   
 (b)  $n = 3$ ,  $\ell = 1$ ,  $m_\ell = +1$ ,  $m_s = +1/2$   
 (c)  $n = 3$ ,  $\ell = 1$ ,  $m_\ell = 0$ ,  $m_s = -1/2$   
 2.61 (a) LiCl ( $\text{Li}^+$  has a smaller radius than  $\text{Cs}^+$  thus stronger bond)  
 (b) RbCl  
 (c) MgO ( $\text{Mg}^{++}$  is doubly charged)  
 (d) MgO ( $\text{Mg}^{++}$  radius is smaller)  
 2.62 (a)  $\Delta H^\circ = -910$  kJ (b) as solid NaF is formed, energy is released  
 2.68 InP is more ionic (8.6%) versus CdTe (6.1%)  
 2.70 (a) Ni, Cr, Fe (b) these are the primary constituents of stainless steel  
 2.73 Na atoms have stronger metallic bonds because the radius is smaller in comparison to K  
 2.74 Be has twice as many valence electrons as Li thus the bonds between Be atoms are stronger.  
 2.79 The bonds between Al and O or mostly ionic a much stronger bond than those between Al mostly metallic.  
 2.87 So the hot tungsten wire won't react (burn up) with impurity gasses inside the bulb

## Chapter 3

- 3.9 (0, 0, 0), (1, 0, 0), (1, 1, 0), (0, 1, 0),  
 (0, 0, 1), (1, 0, 1), (1, 1, 1), (0, 1, 1)  
 3.29  $0.106 \text{ nm}^3$   
 3.35  $[\bar{1}4\bar{1}]$   
 3.37 [100], [010], [001],  $[\bar{1}00]$ ,  $[0\bar{1}0]$ ,  $[00\bar{1}]$   
 3.42 P3.42a: Plane a ( $0\bar{1}\bar{4}$ ); b ( $\bar{5}\bar{1}\bar{2}0$ );  
 c ( $0\bar{1}3$ ); d (223)  
 P3.42b: Plane a ( $\bar{1}0\bar{3}$ ); b ( $2\bar{2}\bar{3}$ );  
 c ( $\bar{5}\bar{1}\bar{2}0$ ); d ( $1\bar{1}\bar{2}$ )  
 3.48 ( $2\bar{3}\bar{4}$ )  
 3.54 (a) 0.224 nm (b) 0.112 nm (c) 0.100 nm  
 3.56 (a) 0.502 nm (b) 0.217 nm (c) Ba  
 3.58 P3.63a: plane a ( $0\bar{1}10$ ); b ( $01\bar{1}2$ ); c ( $\bar{2}200$ )  
 P3.63b: plane a ( $01\bar{1}0$ ); b ( $1\bar{1}01$ ); c ( $1\bar{1}01$ )  
 3.62 P3.67a:  $[\bar{2}111]$  and  $[11\bar{2}1]$   
 P3.67b:  $[\bar{1}101]$  and  $[10\bar{1}1]$   
 3.66 (a)  $1.20 \times 10^{13}$  atoms/mm<sup>2</sup>  
 (b)  $8.50 \times 10^{12}$  atoms/mm<sup>2</sup>  
 (c)  $1.96 \times 10^{13}$  atoms/mm<sup>2</sup>  
 3.69 (a)  $2.60 \times 10^6$  atoms/mm  
 (b)  $3.68 \times 10^6$  atoms/mm  
 (c)  $1.50 \times 10^6$  atoms/mm<sup>2</sup>  
 3.76 (a) BCC (b) 0.3296 nm (c) Nb  
 3.82  $R^2 + (R \tan 30^\circ)^2 + h^2 = 4R^2$  resulting in  
 $h^2 = 2.667 R^2$  and therefore  $h/R = c/a = 1.633$   
 3.84 (a)  $c = 0.4684$  nm;  $a = 0.2951$  nm  
 (b)  $R = 0.1476$  nm (c) slightly compressed  
 3.89 35.7% increase in volume  
 3.91 (a) a (b) 1.41 a (c)  $(1.73/2)$  a (d) 2.23 a  
 3.96 a and c are not planes because  $(h + k)$  is not equal to  $-i$ .

## Chapter 4

- 4.32  $1.11 \times 10^{-7}$  cm  
 4.38 0.036 nm  
 4.41 10.23  
 4.45  $\sim 0.001$  in  
 4.48 (a) Yes (b) 0.0596 nm  
 4.54 (a) high (b) very high (c) moderate  
 (d) low (e) moderate  
 4.56 (a) 8.94 gr/cm<sup>3</sup> (b) FCC (c)  $4.13 \times 10^{-22}$  g  
 (d) 0.358 nm  
 4.60 decreases by a factor of 4

**Chapter 5**

- 5.11 (a)  $2.77 \times 10^{24}$  vacancies/m<sup>3</sup>  
 (b)  $2.02 \times 10^{-5}$  vacancies/atom
- 5.13  $1.98 \times 10^{14}$  atoms/m<sup>2</sup>.s from B to A
- 5.15 56.6 minutes
- 5.19 5.67 hours

**Chapter 6**

- 6.38 0.0669 cm
- 6.43 engineering  $\epsilon = 0.175$
- 6.49 (a) engineering stress of 125,000 psi and strain of 0.060 (b) true stress of 132,600 psi and strain of 0.0587
- 6.51 (a) 30.6 MPa (b) 0
- 6.55 (a) 148 MPa (b) 414 MPa

- 5.22  $2 \times 10^{-4}$  cm
- 5.25  $0.707 \mu\text{m}$
- 5.33  $6 \times 10^5$  atoms/m<sup>2</sup>.s
- 5.36 (a) 2.2 minutes (b) 70 minutes
- 5.38 268 kJ/mol

- 6.59 (a) 42.8% (b) 80 ksi (c) 7%
- 6.61 (a) 169.3 kJ/mol
- 6.76 (a)  $\epsilon_t = \ln(\epsilon + 1)$  (b)  $\sigma_t = \sigma(\epsilon + 1)$
- 6.77 (a) 0.0015 (b) 0.0015
- 6.86 (a) Metal 2 harder than metal 1 harder than metal 3 (b) tool steel (heat treated)
- 6.91 2.1 MPa

**Chapter 7**

- 7.20 0.015 in
- 7.24 568.0 MPa
- 7.27 (a) 29 ksi (b) 14.5 ksi (c) 10.5 ksi  
 (d) -0.16
- 7.30 149 MPa

- 7.34 1419 hours
- 7.39 (a) 176 joules (b) 125 joules (c) 52 joules
- 7.41 (a) 0.0011 in (b) 0.012 in
- 7.43 (a) either Ti or Steel would be fine (b) Ti for both safety and low weight

**Chapter 8**

- 8.21 (a) wt % liquid is 33.3% and wt % solid 66.7%  
 (b) 100% liquid
- 8.26 (a) alloy is hypereutectic (b) solid solution b containing 19.2% Sn (c) wt % liquid is 77.2% and wt %  $\beta$  22.8% (d) 35.1%  $\alpha$  and 64.8%  $\beta$ .
- 8.30 (a) wt %  $\alpha = 47.4\%$ ; wt % L1 = 52.6%  
 (b) wt %  $\alpha = 72.2\%$ ; wt % L1 = 27.8%  
 (c) wt %  $\alpha = 88.5\%$ ; wt % L2 = 11.5%  
 (d) wt %  $\alpha = 90\%$ ; wt %  $\beta = 10\%$
- 8.34 66.7%
- 8.38 (a) The maximum solid solubility in weight percent of zinc in copper in the solid solution  $\alpha$  is 39%.
- (b) The intermediate phases are  $\beta$ ,  $\gamma$ ,  $\delta$ , and  $\theta$ .
- (c) The three-phase invariant reactions are:
- Peritectic reaction at 903°C, 36.8% Zn  
 $\alpha(32.5\% \text{ Zn}) + L(37.5\% \text{ Zn}) \rightarrow \beta(38.8\% \text{ Zn})$
  - Peritectic reaction at 835°C, 59.8% Zn  
 $\beta(56.5\% \text{ Zn}) + L(59.8\% \text{ Zn}) \rightarrow \gamma(59.8\% \text{ Zn})$

- Peritectic reaction at 700°C, 73% Zn  
 $\gamma(69.8\% \text{ Zn}) + L(80.5\% \text{ Zn}) \rightarrow \delta(73\% \text{ Zn})$
  - Peritectic reaction at 598°C, 78.6% Zn  
 $\delta(76.5\% \text{ Zn}) + L(89\% \text{ Zn}) \rightarrow \theta(78.6\% \text{ Zn})$
  - Peritectic reaction at 424°C, 97.3% Zn  
 $\theta(87.5\% \text{ Zn}) + L(98.3\% \text{ Zn}) \rightarrow \eta(97.3\% \text{ Zn})$
  - Eutectoid reaction at 558°C, 73% Zn  
 $\delta(73\% \text{ Zn}) \rightarrow \gamma(69.8\% \text{ Zn}) + \theta(78.6\% \text{ Zn})$
  - Eutectoid reaction at 250°C, 47% Zn  
 $\beta'(47\% \text{ Zn}) \rightarrow \alpha(37\% \text{ Zn}) + \gamma(59\% \text{ Zn})$
- 8.43 (a) 0, (b) 2, (c) 1, (d) 1, (e) 0
- 8.55 (a) ~65% (b) ~77% (c) the solubility limit curve
- 8.60 (a) salt-water solution to ice + salt-water mixture to ice + salt mixture (b) the salt-water solution will have 5% salt, in the ice + salt-water region, ice will be almost pure and saltwater solution will have from 5% at -4°C to 23% salt at -21°C.

## Chapter 9

9.55 Coarse pearlite

9.58 wt % austenite = 80.8 wt % proeutectoid ferrite = 19.2%

9.65 1.08% C

9.71 (a) proeutectoid cementite 15.3% (b) eutectoid ferrite 74.7% and eutectoid cementite 9.96%

9.74 (a) martensite

(b) tempered martensite, quenching, and tempering process

(c) coarse pearlite

(d) martensite, marquenching process

(e) bainite, austempering

(f) spheroidite

9.75 49 HRC

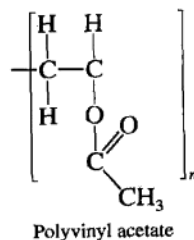
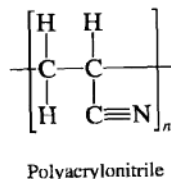
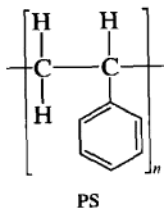
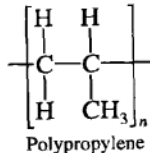
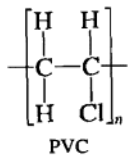
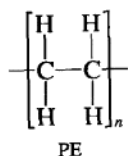
9.80 10°C/s

9.87 ferrite, bainite, martensite, and austenite

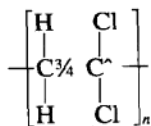
9.91 9.2%

## Chapter 10

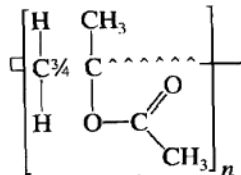
10.13



10.14 (a) Polyvinylidene Chloride



(b) Polymethyl Methacrylate



10.66 14,643 mers

10.70 22,850 g/mol

10.73 0.461

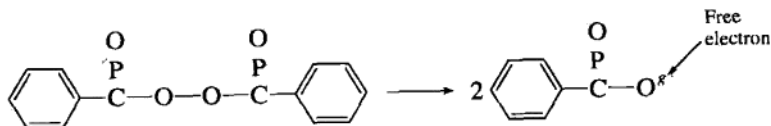
10.76 4.24 g S

10.81 9.83 wt %

10.83 4.0 MPa

10.87 65.95 days

10.91



**Chapter 11****11.64** 0.414**11.66** 4.9 g/cm<sup>3</sup>**11.69** (a) on (111), 12.6 O<sup>2-</sup> ions/nm<sup>2</sup> and on (110) 15.4 O<sup>2-</sup> ions/nm<sup>2</sup> (b) on (111), 8.6 Cl<sup>-</sup> ions/nm<sup>2</sup> on (110) 10.5 Cl<sup>-</sup> ions/nm<sup>2</sup> (the answers are the same for cations)**11.74** 6.32 g/cm<sup>3</sup>**11.75** in [111], 1.07 Ce<sup>4+</sup>/nm and in [110] 2.62 Ce<sup>4+</sup>/nm**11.81** 27% leucite, 36% silica, and 37% mullite**11.91** 236 MPa**11.102** 1009.7 K (736.7°C)**Chapter 12****12.40** 0.414**12.48** 4.9 g/cm<sup>3</sup>**12.63** (a) on (111), 12.6 O<sup>2-</sup> ions/nm<sup>2</sup> and on (110) 15.4 O<sup>2-</sup> ions/nm<sup>2</sup> (b) on (111), 8.6 Cl<sup>-</sup> ions/nm<sup>2</sup> on (110) 10.5 Cl<sup>-</sup> ions/nm<sup>2</sup> (the answers are the same for cations)**12.79** 6.32 g/cm<sup>3</sup>**12.83** 0.396**12.86** 951 MPa**Chapter 13****13.58**  $2.09 \times 10^{-3} \Omega$ **13.62** -146.5 °C**13.70** (a)  $n_n = 7.0 \times 10^{21}$  electrons/m<sup>3</sup>  $p_n = 3.21 \times 10^{10}$  holes/m<sup>3</sup> (b)  $n_i = 6.61 \times 10^{-3} \Omega \cdot m$ **13.75** (a)  $6.17 \times 10^{18}$  electrons/m<sup>3</sup> (b)  $1.24 \times 10^{-4}$ **13.81**  $1.82 \times 10^{-4} (\Omega \cdot m)^{-1}$ **Chapter 14****14.32** 539.7 nm (green visible radiation)**14.35** (a) 3.6% (b) 4.4%**14.38** 0.903**14.44**  $3.79 \times 10^{-2} s$ **14.49** 87.2°**14.51** 3.40 K**Chapter 15****15.62**  $M_s = 1.70 \times 10^6 A/m$   $B_s = 2.14 T$ **15.65** 1.7 Bohr magnetons/atom**15.93**  $M = 2.56 \times 10^5 A/m$ **15.100**  $B_s \sim 0.32 T$

[ G e n e r a l   I n f o r m a t i o n ]

书名 = 材料科学与工程基础      英文版 · 原书第 5 版

作者 = ( 美 ) 史密斯 , ( 美 ) 哈希米著

页数 = 7 8 7

出版社 = 北京市 : 机械工业出版社

出版日期 = 2 0 1 1 . 0 1

S S 号 = 1 2 7 5 6 5 0 8

D X 号 = 0 0 0 0 0 8 0 4 0 1 2 0