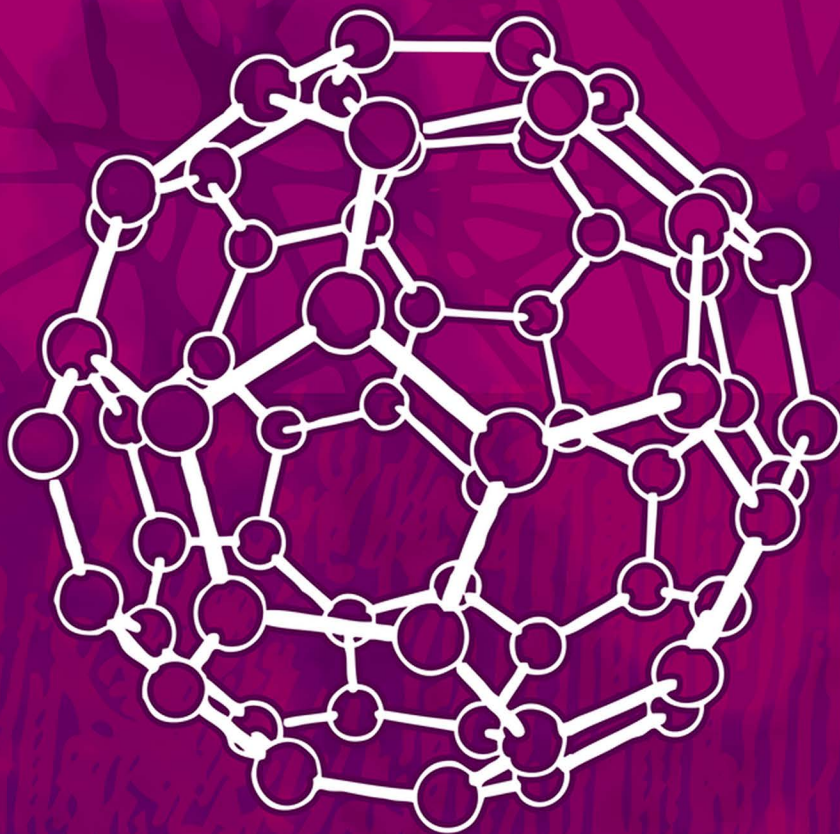


Elementary Materials Science

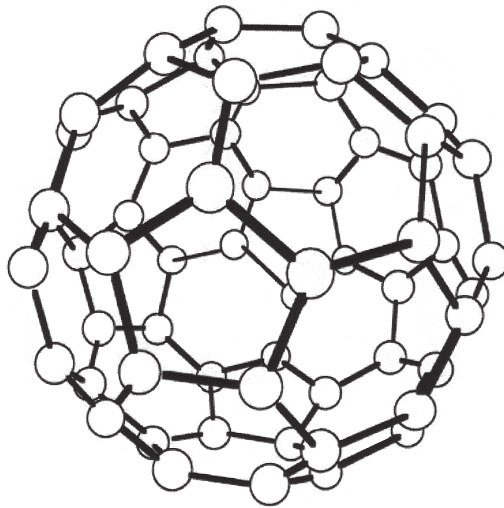
William F. Hosford



ASM
INTERNATIONAL

Elementary Materials Science

William F. Hosford



ASM International®
Materials Park, Ohio 44073-0002
www.asminternational.org

Copyright © 2013
by
ASM International®
All rights reserved

No part of this book may be reproduced, stored in a retrieval system, or transmitted, in any form or by any means, electronic, mechanical, photocopying, recording, or otherwise, without the written permission of the copyright owner.

First printing, August 2013

Great care is taken in the compilation and production of this book, but it should be made clear that NO WARRANTIES, EXPRESS OR IMPLIED, INCLUDING, WITHOUT LIMITATION, WARRANTIES OF MERCHANTABILITY OR FITNESS FOR A PARTICULAR PURPOSE, ARE GIVEN IN CONNECTION WITH THIS PUBLICATION. Although this information is believed to be accurate by ASM, ASM cannot guarantee that favorable results will be obtained from the use of this publication alone. This publication is intended for use by persons having technical skill, at their sole discretion and risk. Since the conditions of product or material use are outside of ASM's control, ASM assumes no liability or obligation in connection with any use of this information. No claim of any kind, whether as to products or information in this publication, and whether or not based on negligence, shall be greater in amount than the purchase price of this product or publication in respect of which damages are claimed. THE REMEDY HEREBY PROVIDED SHALL BE THE EXCLUSIVE AND SOLE REMEDY OF BUYER, AND IN NO EVENT SHALL EITHER PARTY BE LIABLE FOR SPECIAL, INDIRECT OR CONSEQUENTIAL DAMAGES WHETHER OR NOT CAUSED BY OR RESULTING FROM THE NEGLIGENCE OF SUCH PARTY. As with any material, evaluation of the material under end-use conditions prior to specification is essential. Therefore, specific testing under actual conditions is recommended.

Nothing contained in this book shall be construed as a grant of any right of manufacture, sale, use, or reproduction, in connection with any method, process, apparatus, product, composition, or system, whether or not covered by letters patent, copyright, or trademark, and nothing contained in this book shall be construed as a defense against any alleged infringement of letters patent, copyright, or trademark, or as a defense against liability for such infringement.

Comments, criticisms, and suggestions are invited, and should be forwarded to ASM International.

Prepared under the direction of the ASM International Technical Book Committee (2012–2013), Bradley J. Diak, Chair.

ASM International staff who worked on this project include Scott Henry, Senior Manager, Content Development and Publishing; Karen Marken, Senior Managing Editor; Amy Nolan, Content Developer; Sue Sellers, Editorial Assistant; Madrid Tramble, Manager of Production; and Diane Whitelaw, Production Coordinator.

Library of Congress Control Number: 2013931785

ISBN-13: 978-1-62708-002-6

ISBN-10: 0-62708-002-3

SAN: 204-7586

ASM International®
Materials Park, OH 44073-0002

www.asminternational.org

Printed in the United States of America

Contents

CHAPTER 1	
Chemistry Basics.	1
Elements	1
Fundamental Particles	2
Bonding	2
Crystal Structures	4
Amorphous (Noncrystalline) Materials	9
Exercises	10
CHAPTER 2	
Phase Relations	11
Phases	11
Solid Solutions	11
Phase Diagrams	12
Freezing	16
Segregation during Freezing	17
Metal Glasses	19
Exercises	21
CHAPTER 3	
Mechanical Behavior	23
Stress and Strain	23
Elasticity	23
Plastic Deformation	25
Ductility	28
Hardness	28
Creep	29
Fatigue	29
Fracture	30
Exercises	34

CHAPTER 4	
Electrical Behavior	37
Conduction	37
Metallic Conduction	37
Ionic Conduction	40
Energy Bands	40
Intrinsic Semiconduction	41
Extrinsic Semiconduction	42
III-V Compound Semiconductors	44
<i>p-n</i> Rectifiers	45
Light Emitting Diodes	46
Transistors	46
Polar Compounds	47
Piezoelectric Behavior	47
Thermal Conductivity	49
Exercise	49
CHAPTER 5	
Magnetic Behavior	51
Ferromagnetism	51
Magnetostatic Circuits	52
Domain Boundaries	54
Soft versus Hard Magnetic Materials	54
Soft Magnetic Materials	55
Hard Magnetic Materials	56
Exercise	57
CHAPTER 6	
Nonferrous Metals	59
Cold Work	60
Annealing	60
Copper	63
Aluminum	63
Magnesium	65
Titanium	65
Zinc	66
Lead and Tin	66
Exercises	67
CHAPTER 7	
Iron and Steel	69
Steels	69
Hardening	71
Tempering	74
Low-Carbon Steels	76

Stainless Steels	76
Cast Irons.	77
Exercises	78
CHAPTER 8	
Ceramics	81
Crystalline Ceramics	81
Glasses	82
Pottery	88
Hydration Reactions	91
Carbon	93
Exercise	98
CHAPTER 9	
Polymers.	99
Thermoplastics	100
Thermosetting Polymers	100
Degree of Polymerization and Molecular Weight	103
Branching	103
Cross-linking and Stereoisomerism	104
Copolymers.	105
Molecular Configuration	105
Glass Transition	106
Additives	106
Degradation	107
Properties and Uses of Polymers	109
Stretching of a Thermoplastic	112
Exercises	113
CHAPTER 10	
Composites	115
Fiber-Reinforced Composites	115
Volume Fraction of Fibers	117
Fiber Length	118
Particulate Composites	120
Lamellar Composites	120
Exercise	120
CHAPTER 11	
Wood	121
Structure of Wood	121
Dimensional Changes with Moisture.	122
Anisotropy of Properties	124
Plywood	125
Paper and Cardboard	125
Exercises	126

CHAPTER 12	
Corrosion	129
Corrosion in Water Solutions	129
Passivation	132
Corrosion Control	134
Stress Corrosion	135
Rust	136
Direct Oxidation	136
Exercise	138
CHAPTER 13	
Forming and Shaping	139
Liquid to Solid Processing	139
Bulk Forming of Solid Metals	140
Hot Working versus Cold Working	140
Sheet Forming	141
Polymer Processing	142
Powder Processing	144
Modern Manufacturing Techniques	146
CHAPTER 14	
Recycling	149
Metals	149
Plastics	150
Rubber	151
Glass and Paper	151
APPENDIX I	
Greek Alphabet	153
APPENDIX II	
SI Unit System	155
APPENDIX III	
Conversions and Constants	157
APPENDIX IV	
Properties of Elements	159
APPENDIX V	
Properties of Materials.	161
APPENDIX VI	
Unit Abbreviations.	163
Index	165

Preface

This textbook, which covers the subject of materials science with very few equations, is designed for students who are interested in materials science. It is assumed they already have had a course in chemistry. A prior course in physics is not necessary, and the use of mathematics is limited to algebra. This text also will be useful to nontechnical professionals in the materials industry.

The book first introduces materials science through the discussion of the elements, bonding, crystal structures, and amorphous (noncrystalline) materials; then presents the properties of phase relations, mechanical behavior, electrical behavior, and magnetic behavior. There is one chapter each devoted to the following materials: nonferrous metals, ferrous metals, ceramics, polymers, composites, and wood. To round out this important basic volume on a growing interdisciplinary scientific field are chapters on corrosion, forming and shaping, and recycling. There are 14 chapters. Chapters 3 to 7, and 9 will likely require more time to cover than chapters 1, 2, 8, 10, and 12. Chapters 11, 13, and 14 can be covered in less time than the others. Chapters end with a Note of Interest and Exercises—all pertaining to the chapters' topics of discussion. The Notes of Interest engage readers with fascinating bits of information about notable people, events, and developments; the Exercises allow students to explore the world of materials in a pragmatic, hands-on manner.

CHAPTER 1

Chemistry Basics

MATERIALS are so important to civilization that the terms *stone age*, *bronze age*, and *iron age* have been used to describe periods of history. Perhaps the present day will be called the *silicon age*. Without steel, modern inventions such as the automobile, the bicycle, and railroads would be impossible. Without aluminum, there would be no airplanes. Without silicon, there would be no electronic devices like computers, digital cameras, or cell phones.

Advancements in materials have been responsible for most of today's prosperity. Two centuries ago the most important materials were wood and clay. Glass and steel, wrought iron, copper, silver, and pewter were available, but were very expensive. There were no plastics, processed aluminum, modern rubber, and semiconductors. In the mid 1800's advances in steelmaking made the production of steel much less expensive. The technique for economically producing aluminum was developed in the late 1800's. The first plastics appeared in the early 1900's, but only a few were available until the mid 1900's. The development of semiconductors in the last half of the twentieth century made possible the wide variety of electronic products in common use today.

Elements

Before delving into a discussion of materials, it will be helpful to take a look at the particles that materials are composed of, and the chemistry and forces at work behind them. An overview of chemistry is, in fact, necessary to arrive at an understanding of why and how materials have the characteristics they do.

The periodic table of the elements (Fig. 1.1) allows one to quickly see which chemical elements are similar to others. The elements are arranged in order of increasing atomic number.

The table includes periods (typically horizontal) and groups (typically vertical). Elements in groups share some similar properties.

2 / Elementary Materials Science

H 1 1.008	metals ← → nonmetals																He 2 4.003	
Li 3 6.94	Be 4 9.01											B 5 10.81	C 6 12.01	N 7 14.01	O 8 16.00	F 9 19.00	Ne 10 20.18	
Na 11 22.99	Mg 12 24.31											Al 13 26.98	Si 14 28.09	P 15 30.97	S 16 32.06	Cl 17 35.45	Ar 18 39.95	
K 19 39.10	Ca 20 40.08	Sc 21 44.96	Ti 22 47.90	V 23 50.94	Cr 24 52.00	Mn 25 54.94	Fe 26 55.85	Co 27 58.93	Ni 28 58.71	Cu 29 63.54	Zn 30 65.37	Ga 31 69.72	Ge 32 72.59	As 33 74.92	Se 34 78.96	Br 35 79.91	Kr 36 83.80	
Rb 37 85.47	Sr 38 87.62	Y 39 88.91	Zr 40 91.22	Nb 41 92.91	Mo 42 95.94	Tc 43 99	Ru 44 101.1	Rh 45 102.9	Pd 46 106.4	Ag 47 107.9	Cd 48 112.4	In 49 114.8	Sn 50 118.7	Sb 51 121.7	Te 52 127.6	I 53 126.9	Xe 54 131.3	
Ca 55 132.9	Ba 56 137.3	La 57-71 178.5	Hf 72 178.5	Ta 73 180.9	W 74 183.8	Re 75 186.2	Os 76 190.2	Re 77 192.2	Pt 78 195.1	Au 79 197.0	Hg 80 200.6	Tl 81 204.4	Pb 82 207.2	Bi 83 209.0	Po 84 210	At 85 210	Rn 86 222	
Fr 87 223	Ra 88 226	Ac 89-103																
			Ce 58	Pr 59	Nd 60	Pm 61	Sm 62	Eu 63	Gd 64	Tb 65	Dy 66	Ho 67	Er 68	Tm 69	Yb 70	Lu 71		
			Th 90	Pa 91	U 92	Np 93	Pu 94	Am 95	Cm 96	Bk 97	Cf 98	Es 99	Fm 100	Md 101	No 102	Lw 103		

Fig. 1.1 The periodic table of the elements. The atomic numbers are in the upper right corners and the atomic wts (in amu) at the bottom.

Fundamental Particles

All solid materials are composed of atoms, ions, or molecules. *Atoms* are the basic unit of chemical elements. *Ions* are simply atoms or groups of atoms that have lost or gained one or more electrons and carry an electric charge. *Molecules* are groups of atoms chemically bonded to each other.

Bonding

The study of materials requires an understanding of the forces that hold atoms together as solids. There are four types of bonds: metallic, ionic, covalent, and van der Waals. In metallic bonding, individual atoms lose their valence electrons, which forms a negatively charged “electron gas.” This electron gas holds together the positively charged atoms. In ionic solids there is a transfer of valence electrons. Cations (metallic ions) have lost valence electrons and become positively charged, while anions (nonmetal ions) are atoms that have accepted extra electrons and become negatively charged. Electrostatic attraction bonds anions to cations. Figures 1.2(a) and (b) illustrate metallic and ionic bonding, respectively. In covalent bonding (Fig. 1.2c), valence electrons are shared so that outer shells can be complete. For example, if a carbon atom with four valence electrons shares one electron with each of four neighboring carbon atoms, each carbon atom will have eight outer electrons. Often bonding between atoms is partially ionic and partially covalent in character. Van der Waals (Fig. 1.2d) bonding

is much weaker than metallic, ionic, and covalent bonding. It arises from the electrostatic attraction of molecules. Asymmetric molecules are likely to have dipole moments (meaning the ends have different charges), and bonding results from the attraction between the dipoles. Even symmetric molecules and atoms have statistical dipoles, which results in even weaker bonding. Hydrogen atoms covalently bonded in water molecules create strong dipoles. The term *hydrogen bonding* refers to van der Waals bonding resulting from these dipoles. Figure 1.3 illustrates this schematically.

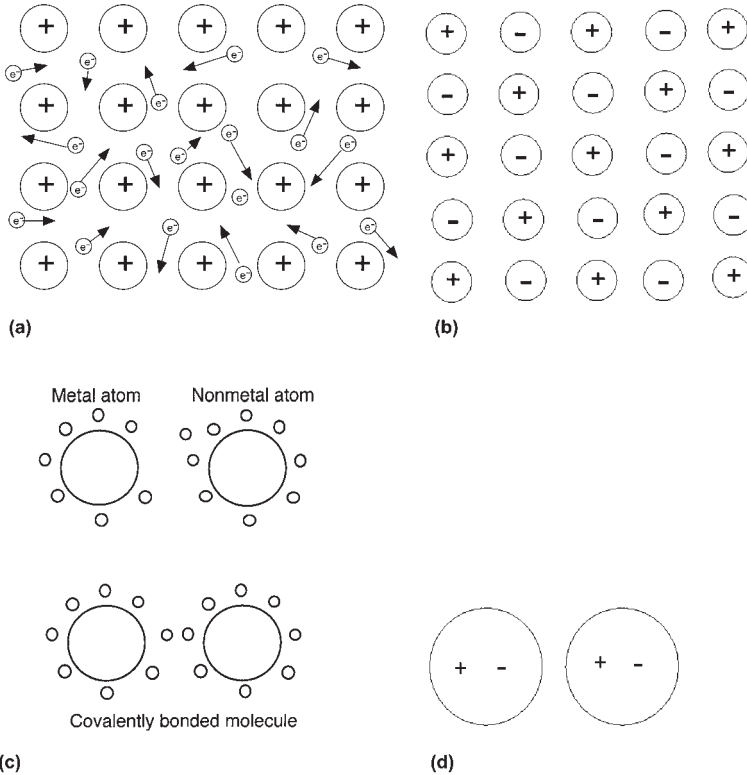


Fig. 1.2 (a) Metallic bonding results from attraction of positive atoms to electron gas. (b) Ionic bonding results from mutual attraction of anions and cations. (c) Covalent bonding involves sharing of electrons to complete outer shells. (d) Van der Waals bonds are the result of statistical dipoles.

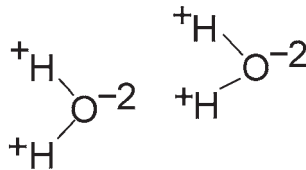


Fig. 1.3 Hydrogen bond between adjacent water molecules resulting from the dipole of the hydrogen atom

Table 1.1 Bond strengths

Bond type	Energy (kJ/mol)
Van der Waals	0.0–10
Hydrogen	10–40
Ionic	50–1000
Covalent	200–1000
Metallic	50–1000

Source: Ref 1.1

Table 1.1 gives the approximate ranges of the strengths of the different types of bonds.

It is useful to think of atoms and ions as hard spheres. In solids and liquids, these hard spheres are in contact with each other.

Crystal Structures

Solids can be classified into those that are crystalline and those that are not. A *crystal structure* is one that repeats itself over long distances. Most solids are crystal structures, or crystalline. The atoms, ions, or molecules are arranged in repeating three-dimensional patterns or lattices. The smallest characteristic piece of the repeating pattern is called the *unit cell*. In metal, crystal atoms are in contact with each other. Most crystal structures are either the densest way of packing spheres or almost the densest. Most metals crystallize in one of three crystal structures.

Face-Centered Cubic Crystal Structure

One of these is called *face-centered cubic* (fcc) because the unit cell (Fig. 1.4) is cubic with an atom on each corner of a cube and one in the center of each face.

The atoms on each corner of the unit cell are shared with eight other unit cells, so the number of corner atoms is (8 corners) (1/8 atom per corner) = 1 corner atom. There are six faces, and atoms in the centers of each face are shared with one other unit cell, so there are (6 face-centering atoms) (1/2 atom per face) = 3 face-centering atoms. Thus there are four atoms in the unit cell. In an fcc crystal, each atom has 12 nearest neighbors. The face-centered cubic structure is one of the most densely ways of packing spheres. Atoms are arranged in close-packed hexagonal planes as shown in Fig. 1.5. These planes are stacked so that the atoms in one plane are nested into the valleys of the planes below. There are two sets of valleys. In the face-centered cubic structure, the planes are stacked so that the third plane is not directly over the first. Aluminum, copper, nickel, lead, gold, silver, platinum, as well as iron at elevated temperatures, crystallize in a face-centered cubic crystal structure.

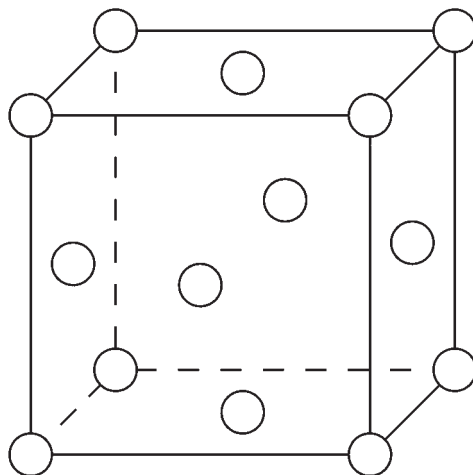


Fig. 1.4 The unit cell of a face-centered cubic structure

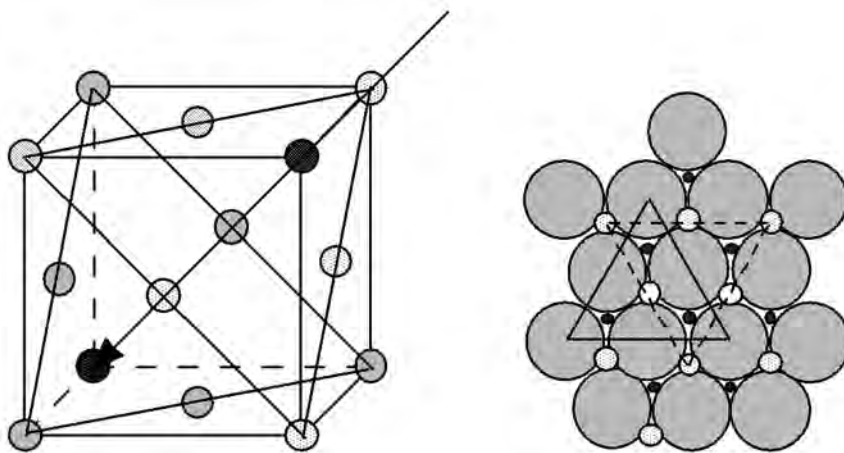


Fig. 1.5 Close packed planes in the face-centered cubic structure

Body-Centered Cubic Crystal Structure

Another common crystal structure of metals is called *body-centered cubic* (bcc) because the unit cell is cubic with an atom on each corner of a cube and one in the middle of the cube (Fig. 1.6). Each of the eight corner atoms is shared by eight unit cells so there are two atoms per unit cell (one corner atom and one body-centering atom). Among the metals having a body-centered cubic crystal structure are chromium, tantalum, vanadium, niobium, tungsten, molybdenum, iron at room temperature, and both titanium and zirconium at elevated temperatures.

Hexagonal Close Packed Crystal Structure

The third common crystal structure of metals is called *hexagonal close packed* (hcp) because the basic structure is a hexagonal prism (Fig. 1.7). The prism is composed of three layers of atoms, each arranged in a hexagonal pattern with an atom in the center of the hexagon. Only three

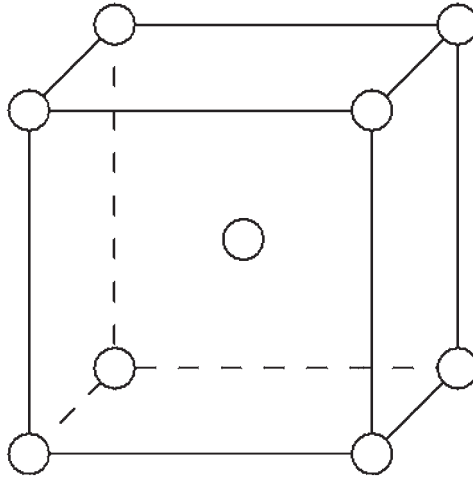


Fig. 1.6 The unit cell of the body-centered cubic structure

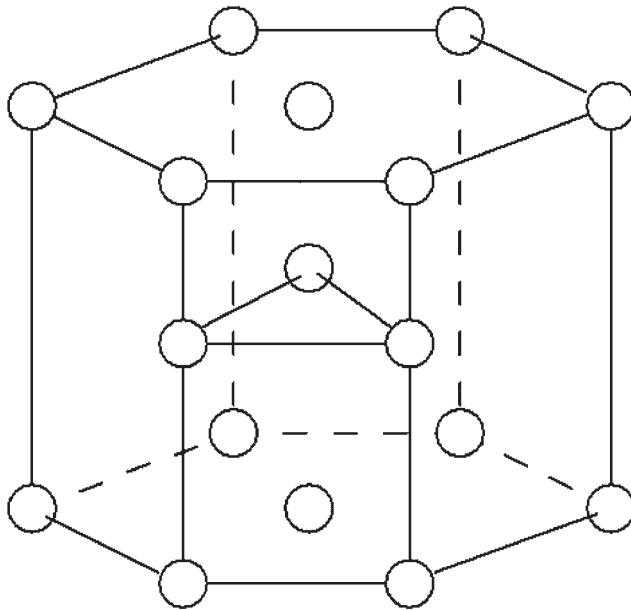


Fig. 1.7 The basic hexagonal cell of the hexagonal close packed structure

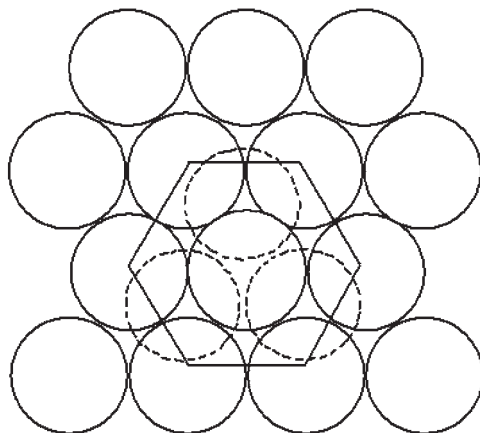


Fig. 1.8 Stacking of close packed planes in the hexagonal close packed structure

atoms of the middle plane are in the basic cell. There are two atoms in the top and bottom that are shared by two prisms, and 12 corner atoms shared by six prisms, so there are a total of $3 + 1 + 2 = 6$ atoms per prism. The structure consists of stacked hexagonal planes, as shown from above, in Fig. 1.8.

Among the metals that crystallize in the hexagonal close packed structure are beryllium, magnesium, zinc, cadmium, and both titanium and zirconium at room temperature.

Diamond Cubic Crystal Structure

Aside from the three crystal structures (fcc, bcc, hcp), certain elements, including carbon, silicon, and germanium, crystallize in another crystal structure, the diamond cubic crystal structure, which has a repeating pattern of eight atoms.

The periodic table (Fig. 1.9) shows that elements with the same crystal structure are clustered together.

Sodium Chloride Crystal Structure

There are many different crystal structures of compounds. Figure 1.10 shows the structure of sodium chloride. The chlorine ions are arranged in a face-centered cubic arrangement, with the sodium ions occupying the locations where they are in contact with four chlorine ions. This structure also can be thought of as a face-centered cubic arrangement and the sodium ions with chlorine ions occupying the locations where they are in contact with four sodium ions.

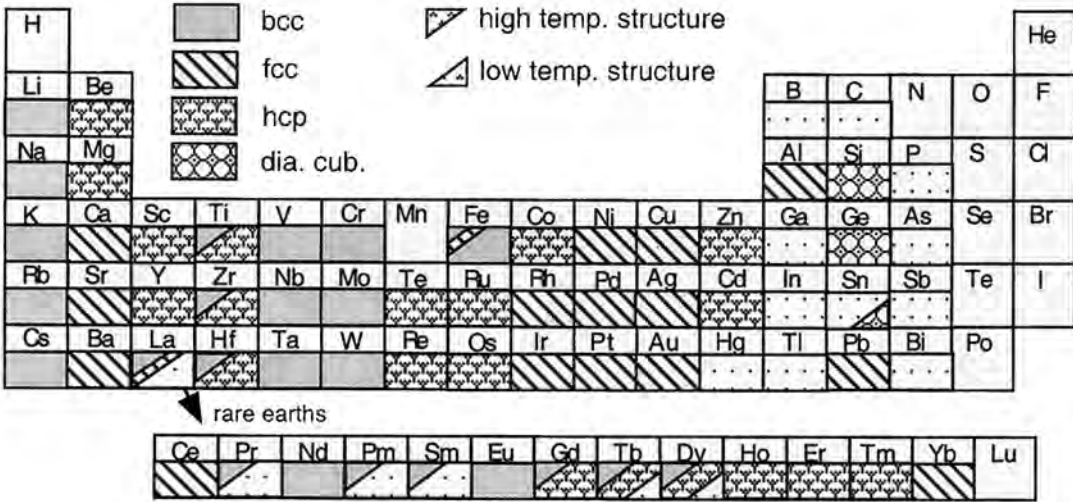


Fig. 1.9 The periodic table. Note that neighboring elements share similar crystal structures. Source: Ref 1.1

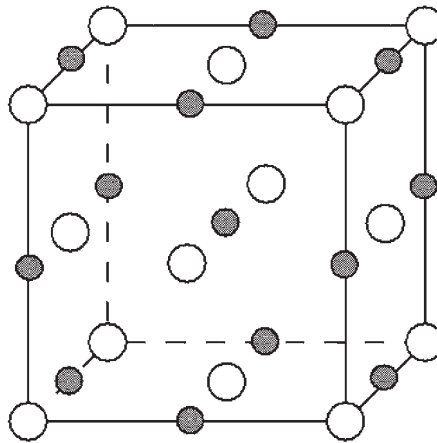


Fig. 1.10 The structure of sodium chloride

Other compounds that crystallize with the sodium chloride structure include:

barium oxide (BaO)
 barium selenide (BaSe)
 barium sulfide (BaS)
 barium telluride (BaTe)
 cadmium oxide (CdO)

calcium oxide (CaO)
 calcium sulfide (CaS)
 cobalt oxide (CoO)
 ferrous oxide (FeO)
 lead sulfide (PbS)

lithium bromide (LiBr)	potassium hydride (KH)
lithium chloride (LiCl)	potassium iodide (KI)
lithium fluoride (LiF)	silver bromide (AgBr)
lithium hydride (LiH)	silver chloride (AgCl)
lithium iodide (LiI)	sodium iodide (NaI)
magnesium oxide (MgO)	tantalum carbide (TaC)
magnesium sulfide (MgS)	tantalum oxide (TaO)
manganese oxide (MnO)	titanium carbide (TiC)
manganese sulfide (MnS)	titanium nitride (TiN)
nickel oxide (NiO)	titanium oxide (TiO)
potassium bromide (KBr)	vanadium carbide (VC)
potassium chloride (KCl)	zirconium carbide (ZrC)
potassium fluoride (KF)	zirconium oxide (ZrO)

There are many other crystal structures of compounds. In all compounds, the anions and cations are in contact. In almost every case, the structure is the one that maximizes the density of the packing of spheres of different sizes.

Amorphous (Noncrystalline) Materials

Noncrystalline solids are said to be *amorphous*. An amorphous material has a structure like that of a liquid. Atoms, ions, or molecules are in contact with each other as in a crystal. Often there is short-range order, so that each atom, ion, or molecule has nearly the same surroundings as others, but there is no repeating pattern over long distances. Glass and most plastics are amorphous. In silicate glasses, silicon atoms are surrounded by four oxygen atoms forming tetrahedra. Oxygen atoms are shared by two tetrahedra as sketched in Fig. 1.11.

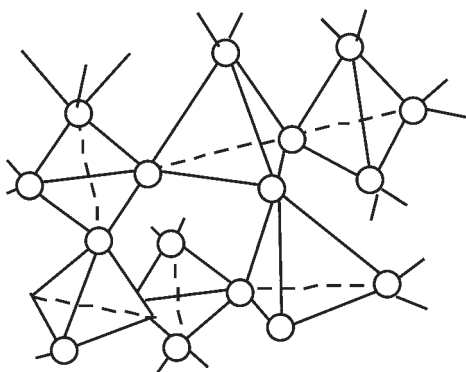


Fig. 1.11 Structure of a silicate glass consists of tetrahedra with silicon atoms in the centers and oxygen atoms on the corners. Source: Ref 1.2

NOTE OF INTEREST

The seven metals known to antiquity are iron, copper, silver, tin, gold, mercury, and lead. Those that occurred in the native (metallic) state are gold, silver, copper, and mercury. Metallic iron in the form of meteorites also was probably known early. Tin and lead are not found in a native state, but they probably were first reduced accidentally in a fire. The first metallic material to be used for tools or weapons likely was bronze, an alloy of copper and tin.

Exercises

1. Forming hexagonal close packed and face-centered cubic crystal structures

Construct four rafts of balls arranged in hexagonal patterns with at least 10 balls in each raft. Then stack the rafts in different patterns. Try to stack them so they form a hexagonal close packed crystal; restack them so they form a face-centered cubic crystal.

If the third raft is placed directly over the first raft, the result is hexagonal close packing. If it is not, but the fourth raft is placed directly over the first raft, the result is face-centered cubic.

2. Comparing fcc and bcc crystal structures

Construct a face-centered cubic unit cell and a body-centered cubic unit cell. Then compare the sizes of the largest holes in each. Which would accommodate a small carbon atom more easily? Next, try to see which has the larger passages between holes. Which would allow the motion of small atoms more easily?

The face-centered cubic cell has the larger hole which allows it to have the greater solubility for carbon. However, the body-centered cubic cell has larger passages between holes so the rates of diffusion in the body-centered cubic lattice are greater.

Chapter 1: Chemistry Basics

References

1.1 W.F. Hosford, *Physical Metallurgy*, 2nd ed., CRC Press, 2010 doi: [10.1201/b15858](https://doi.org/10.1201/b15858)

1.2 W.F. Hosford, *Materials for Engineers*, Cambridge U. Press, 2008 doi:
[10.1017/CBO9780511810732](https://doi.org/10.1017/CBO9780511810732)

Selected References

• R.A. Flinn and P.T. Trojan, *Engineering Materials and their Applications*, 4th ed. Houghton Mifflin, 1990.

Chapter 2: Phase Relations

References

2.1 W.F. Hosford, *Physical Metallurgy*, 2nd ed., CRC Press, 2010 doi: [10.1201/b15858](https://doi.org/10.1201/b15858)

2.2 D.S. Clark and W.R. Varney, *Physical Metallurgy for Engineers* 2nd ed., Van Nostrand Reinhold, 1962

2.3 *Metals Handbook*, Vol. 8, 8th ed., ASM International, 1973

2.4 K.A. Jackson, *Solidification*, ASM International, 1971

Chapter 3: Mechanical Behavior

References

- 3.1 W.F. Hosford, *Mechanical Behavior of Materials*, 2nd ed. Cambridge University Press, 2010
- 3.2 W.F. Hosford in *Tensile Testing*, ASM International, 1992
- 3.3 H.W. Hayden, W.G. Moffatt and J. Wulff, *Structure and Properties of Materials, Vol. III Mechanical Behavior*, Wiley, 1965.
- 3.4 R.W. Vanderbeck and M. Gensamer, *Welding J. Res. Suppl.* p. 37s–48s, January 1950
- 3.5 E. Parker, *Brittle Fracture of Engineering Structures*, Wiley, 1957
- 3.6 C.F. Tipper, *The Brittle Fracture Story*, Cambridge University Press, 1963

Chapter 4: Electrical Behavior

References

- 4.1 W.F. Hosford, *Materials for Engineers*, Cambridge U. Press, 2008. doi: [10.1017/CBO9780511810732](https://doi.org/10.1017/CBO9780511810732)
- 4.2 L.H. Van Vlack, *Elements of Materials Science*, 6th ed., Addison-Wesley, 1989.
- 4.3 W.F. Hosford, *Physical Metallurgy*, CRC, 2005.
- 4.4 A. Wert and R.M. Thompson, *Physics of Solids*, McGraw-Hill, 1970

Chapter 5: Magnetic Behavior

References

5.1 E.A. Nesbitt, *Ferromagnetic Domains*, Bell Telephone Labs, 1962

5.2 W.F. Hosford, *Physical Metallurgy*, 2nd ed., CRC Press, 2010 doi: [10.1201/b15858](https://doi.org/10.1201/b15858)

Chapter 6: Nonferrous Metals

References

- 6.1 L.H. Van Vlack, *Elements of Materials Science*, 6th ed., Addison-Wesley, 1989
- 6.2 A. Guy and J. Hren, *Elements of Physical Metallurgy*, 3rd ed., Addison-Wesley, 1974
- 6.3 W.C. Leslie, J.T. Michalak, and F.W. Auk, *Iron and its Dilute Solutions*, AIME Conference Series, Interscience, 1963
- 6.4 W.F. Hosford, *Physical Metallurgy*, 2nd ed., CRC Press, 2010 doi: [10.1201/b15858](https://doi.org/10.1201/b15858)
- 6.5 *Metallography, Structures and Phase Diagrams*, Vol 8, *Metals Handbook*, 8th ed., American Society for Metals, 1973

Chapter 7: Iron and Steel

References

7.1 J. Chipman, *Met. Trans.* Vol 3, 1972 doi: [10.17077/0021-065X.1351](https://doi.org/10.17077/0021-065X.1351)

7.2 *Making, Shaping and Treating Steels*, 9th ed., United States Steel Corp, 1971

7.3 *Atlas of Microstructures of Industrial Alloys*, Vol 7, *Metals Handbook*, 8th ed., American Society for Metals, 1972

7.4 W.F. Hosford, *Physical Metallurgy*, CRC, 2005

7.5 L.H. Van Vlack, *Elements of Materials Science*, 5th ed., Addison-Wesley, 1985

7.6 *Metallography, Structures and Phase Diagrams*, Vol 8, *Metals Handbook*, 8th ed., American Society for Metals, 1973

Chapter 8: Ceramics

References

8.1 R.L. Coble and W.D. Kingery, *J. Am. Ceram. Soc.*, Vol 29, 1956

8.2 W.F. Hosford, *Materials for Engineers*, Cambridge U. Press, 2008 doi:
[10.1017/CBO9780511810732](https://doi.org/10.1017/CBO9780511810732)

8.3 *Diderot Pictorial Encyclopedia of Trades and Industries*, Plate 245, 1758

8.4 *Engineering Materials Handbook Volume 4: Ceramics and Glasses*, ASM International, 1991

8.5 H.O. Pierson, *Handbook of Carbon, Graphite, Diamond and Fullerenes*, Knovel, 2001

8.6 H. Kroto, J. Heath, S. O'Brien, R. Curl, and R. Smalley, *Nature*, Vol 318, 1985 doi:
[10.1038/318162a0](https://doi.org/10.1038/318162a0)

Chapter 9: Polymers

References

9.1 W.F. Hosford, *Materials for Engineers*, Cambridge University Press, 2008 doi:
[10.1017/CBO9780511810732](https://doi.org/10.1017/CBO9780511810732)

9.2 W.F. Hosford, *Mechanical Behavior of Materials*, 2nd ed., Cambridge University Press, 2010

9.3 F.W. McClintock and A.S. Argon, *Mechanical Behavior of Materials*, Addison-Wesley, 1966

Chapter 10: Composites

References

10.1 W.F. Hosford, *Mechanical Behavior of Materials*, Cambridge, 2005 doi:
[10.1017/CBO9780511810930](https://doi.org/10.1017/CBO9780511810930)

10.2 *Composites*, Vol 1, *Engineered Materials Handbook*, ASM International, 1987

10.3 T.W. Clyne and P.J. Withers, *An Introduction to Metal Matrix Composites*, Cambridge University Press, 1993 doi: [10.1017/CBO9780511623080](https://doi.org/10.1017/CBO9780511623080)

Chapter 11: Wood

References

11.1 R.B. Hoadley, *Understanding Wood*, The Taunton Press, 1980

11.2 W.F. Hosford, *Materials for Engineers*, Cambridge University Press, 2008 doi:
[10.1017/CBO9780511810732](https://doi.org/10.1017/CBO9780511810732)

Chapter 12: Corrosion

References

12.1 W.F. Hosford. *Physical Metallurgy*, 2nd ed., CRC Press, 2010 doi: [10.1201/b15858](https://doi.org/10.1201/b15858)

12.2 L.H. Van Vlack, *Elements of Materials Science and Engineering*, 3rd ed., Addison-Wesley, 1974

Chapter 13: Forming and Shaping

References

- 13.1 W.F. Hosford, *Materials for Engineers*, Cambridge University Press, 2008 doi:
[10.1017/CBO9780511810732](https://doi.org/10.1017/CBO9780511810732)
- 13.2 W.F. Hosford and R.M. Caddell, *Metal Forming: Mechanics and Metallurgy*, 4th ed.,
Cambridge University Press, 2010
- 13.3 R.M. German, *Powder Metallurgy Science*, Metal Powder Industries Federation, Princeton,
NJ, 1984
- 13.4 http://en.wikipedia.org/wiki/Integrated_circuit, accessed 2007