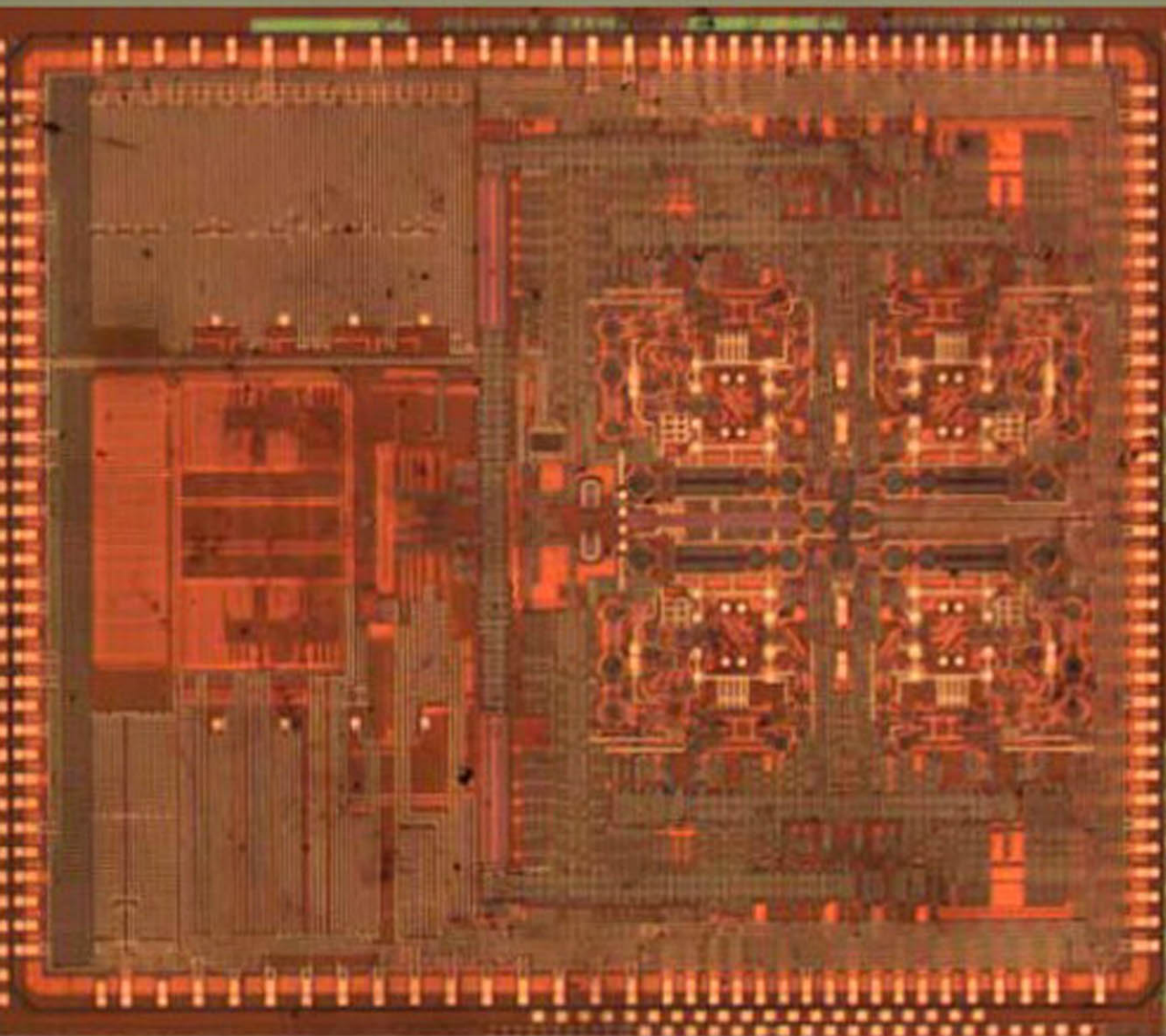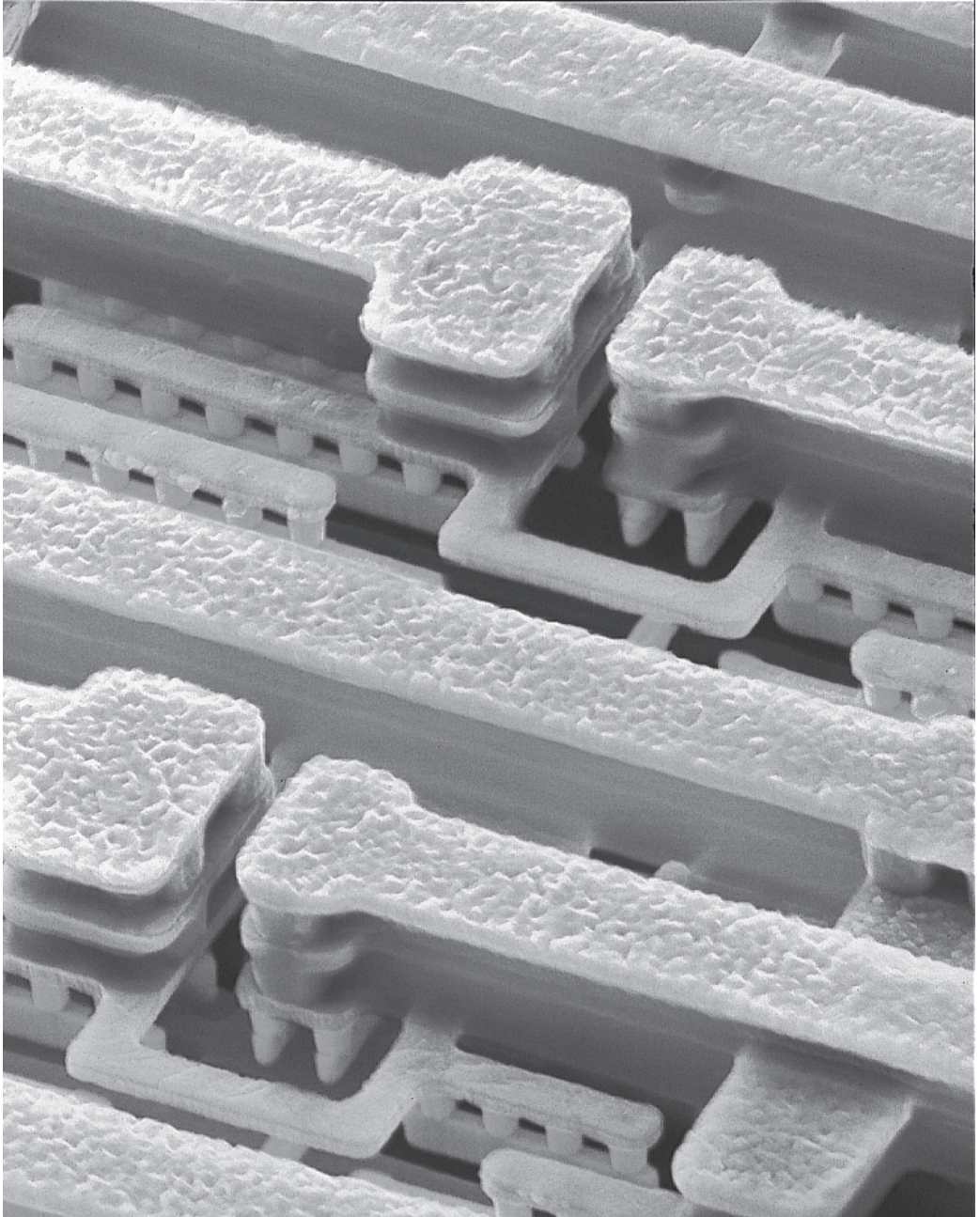# SOLID STATE ELECTRONIC DEVICES

Seventh Edition

Ben G. Streetman　　Sanjay K. Banerjee

Solid State Electronic Devices

Multilevel copper metallization of a complementary metal oxide semiconductor (CMOS) chip. This scanning electron micrograph (scale: 1 cm = 3.5 microns) of a CMOS integrated circuit shows six levels of copper metallization that are used to carry electrical signals on the chip. The inter-metal dielectric insulators have been chemically etched away here to reveal the copper interconnects. (Photograph courtesy of IBM.)

Solid State Electronic Devices

BEN G. STREETMAN AND SANJAY KUMAR BANERJEE

Microelectronics Research Center
Department of Electrical and Computer Engineering
The University of Texas at Austin

Vice President and Editorial Director, ECS: *Marcia J. Horton*	Cover Designer: *John Christiana*
Senior Editor: *Andrew Gilfillan*	Composition: *Jouve India*
Executive Marketing Manager: *Tim Galligan*	Full-Service Project Management: *Shylaja Gattupalli/*
Marketing Assistant: *Jon Bryant*	*Jouve India*
Permissions Project Manager: *Karen Sanatar*	Printer/Binder: *Edwards Brothers Malloy*
Senior Managing Editor: *Scott Disanno*	Cover Printer: *Lehigh-Phoenix*
Production Project Manager: *Greg Dulles*	Typeface: *10/12 Times Ten LT Std Roman*
Operations Specialist: *Linda Sager*	

About the Cover: THZ radio chip courtesy of Texas Instruments. Photograph provided by Dr. Robert Doering.

PEARSON

CONTENTS

This page intentionally left blank

PREFACE

This book is an introduction to semiconductor devices for undergraduate electrical engineers, other interested students, and practicing engineers and scientists whose understanding of modern electronics needs updating. The book is organized to bring students with a background in sophomore physics to a level of understanding that will allow them to read much of the current literature on new devices and applications.

An undergraduate course in electronic devices has two basic purposes: (1) to provide students with a sound understanding of existing devices, so that their studies of electronic circuits and systems will be meaningful and (2) to develop the basic tools with which they can later learn about newly developed devices and applications. Perhaps the second of these objectives is the more important in the long run; it is clear that engineers and scientists who deal with electronics will continually be called upon to learn about new devices and processes in the future. For this reason, we have tried to incorporate the basics of semiconductor materials and conduction processes in solids, which arise repeatedly in the literature when new devices are explained. Some of these concepts are often omitted in introductory courses, with the view that they are unnecessary for understanding the fundamentals of junctions and transistors. We believe this view neglects the important goal of equipping students for the task of understanding a new device by reading the current literature. Therefore, in this text most of the commonly used semiconductor terms and concepts are introduced and related to a broad range of devices.

WHAT IS NEW IN THIS EDITION

- updated discussion of MOS devices, both in the underlying theory of ballistic FETs as well as discussion of advanced MOSFETs such as FinFETs, strained Si devices, metal gate/ high-k devices, III-V high channel mobility devices
- updated treatment of optoelectronic devices, including high bandgap nitride semiconductors and quantum cascade lasers
- brand new section on nanoelectronics to introduce students to exciting concepts such as 2D materials including graphene and topological insulators, 1D nanowires and nanotubes, and 0D quantum dots;
- discussion of spintronics, and novel resistive and phase change memories
- about 100 new problems, and current references which extend concepts in the text.

READING LISTS   As a further aid in developing techniques for independent study, the reading list at the end of each chapter includes a few articles which students can read comfortably as they study this book. We do not expect that students will read all articles recommended in the reading lists; nevertheless, some exposure to periodicals is useful in laying the foundation for a career of constant updating and self-education. We have also added a summary of the key concepts at the end of each chapter.

PROBLEMS   One of the keys to success in understanding this material is to work problems that exercise the concepts. The problems at the end of each chapter are designed to facilitate learning the material. Very few are simple "plug-in" problems. Instead, they are chosen to reinforce or extend the material presented in the chapter. In addition, we have added "self quiz" problems that test the conceptual understanding on the part of the students.

UNITS   In keeping with the goals described above, examples and problems are stated in terms of units commonly used in the semiconductor literature. The basic system of units is rationalized MKS, although cm is often used as a convenient unit of length. Similarly, electron volts (eV) are often used rather than joules (J) to measure the energy of electrons. Units for various quantities are given in Appendices I and II.

PRESENTATION   In presenting this material at the undergraduate level, one must anticipate a few instances which call for a phrase such as "It can be shown . . ." This is always disappointing; on the other hand, the alternative is to delay study of solid state devices until the graduate level, where statistical mechanics, quantum theory, and other advanced background can be freely invoked. Such a delay would result in a more elegant treatment of certain subjects, but it would prevent undergraduate students from enjoying the study of some very exciting devices.

     The discussion includes both silicon and compound semiconductors, to reflect the continuing growth in importance for compounds in optoelectronic and high-speed device applications. Topics such as heterojunctions, lattice-matching using ternary and quaternary alloys, variation of band gap with alloy composition, and properties of quantum wells add to the breadth of the discussion. Not to be outdone by the compounds, silicon-based devices have continued their dramatic record of advancement. The discussion of FET structures and Si integrated circuits reflects these advancements. Our objective is not to cover all the latest devices, which can only be done in the journal and conference literature. Instead, we have chosen devices to discuss which are broadly illustrative of important principles.

The first four chapters of the book provide background on the nature of semiconductors and conduction processes in solids (Chapters 3, 4). Included is a brief introduction to quantum concepts (Chapter 2) for those students who do not already have this background from other courses. Chapter 5 describes the p-n junction and some of its applications. Chapters 6 and 7 deal with the principles of transistor operation. Chapter 8 covers optoelectronics, and Chapter 9 discusses integrated circuits. Chapter 10 applies the theory of junctions and conduction processes to microwave and power devices. A completely new section on nanoelectronics has been added. All of the devices covered are important in today's electronics; furthermore, learning about these devices should be an enjoyable and rewarding experience. We hope this book provides that kind of experience for its readers.

ABOUT THE AUTHORS

Ben G. Streetman is Dean Emeritus of the Cockrell School of Engineering at The University of Texas at Austin. He is an Emeritus Professor of Electrical and Computer Engineering, where he held the Dula D. Cockrell Centennial Chair. He was the founding Director of the Microelectronics Research Center (1984–1996) and served as Dean of Engineering from 1996 to 2008. His teaching and research interests involve semiconductor materials and devices. After receiving a Ph.D. from The University of Texas at Austin (1966) he was on the faculty (1966–1982) of the University of Illinois at Urbana-Champaign. He returned to The University of Texas at Austin in 1982. His honors include the Education Medal of the Institute of Electrical and Electronics Engineers (IEEE), the Frederick Emmons Terman Medal of the American Society for Engineering Education (ASEE), and the Heinrich Welker Medal from the International Conference on Compound Semiconductors. He is a member of the National Academy of Engineering and the American Academy of Arts and Sciences. He is a Fellow of the IEEE and the Electrochemical Society. He has been honored as a Distinguished Alumnus of The University of Texas at Austin and as a Distinguished Graduate of the UT College of Engineering. He has received the General Dynamics Award for Excellence in Engineering Teaching, and was honored by the Parents' Association as a Teaching Fellow for outstanding teaching of undergraduates. He has served on numerous panels and committees in industry and government, and several corporate boards. He has published more than 290 articles in the technical literature. Thirty-four students of Electrical Engineering, Materials Science, and Physics have received their Ph.D.s under his direction.

Sanjay Kumar Banerjee is the Cockrell Chair Professor of Electrical and Computer Engineering, and Director of the Microelectronics Research Center at The University of Texas at Austin. He received his B.Tech. from the Indian Institute of Technology, Kharagpur, and his M.S. and Ph.D. from the University of Illinois at Urbana-Champaign in 1979, 1981, and 1983, respectively, in electrical engineering. He worked at TI from 1983–1987 on the world's first 4Megabit DRAM, for which he was a co-recipient of an ISSCC Best Paper Award. He has more than 900 archival refereed publications and conference papers, 30 U.S. patents, and has supervised over 50 Ph.D. students. His honors include the NSF Presidential Young Investigator Award (1988), the Texas Atomic Energy Centennial Fellowship (1990–1997), Cullen Professorship (1997–2001), and the Hocott Research Award from the University of Texas. He has received the ECS Callinan Award (2003), Industrial R&D 100 Award (2004), Distinguished Alumnus Award, IIT (2005), IEEE Millennium Medal (2000) and IEEE Andrew S. Grove Award (2014). He is a Fellow of IEEE, APS and AAAS. He is interested in beyond-CMOS nanoelectronic transistors based on 2D materials and spintronics, fabrication and modeling of advanced MOSFETs, and solar cells.

Solid State Electronic Devices

This page intentionally left blank

Chapter 1

Crystal Properties and Growth of Semiconductors

OBJECTIVES

1. Describe what a semiconductor is
2. Perform simple calculations about crystals
3. Understand what is involved in bulk Czochralski and thin-film epitaxial crystal growth
4. Learn about crystal defects

In studying solid state electronic devices we are interested primarily in the electrical behavior of solids. However, we shall see in later chapters that the transport of charge through a metal or a semiconductor depends not only on the properties of the electron but also on the arrangement of atoms in the solid. In this chapter we shall discuss some of the physical properties of semiconductors compared with other solids, the atomic arrangements of various materials, and some methods of growing semiconductor crystals. Topics such as crystal structure and crystal growth technology are often the subjects of books rather than introductory chapters; thus we shall consider only a few of the more important and fundamental ideas that form the basis for understanding electronic properties of semiconductors and device fabrication.

1.1 SEMICONDUCTOR MATERIALS

Semiconductors are a group of materials having electrical conductivities intermediate between metals and insulators. It is significant that the conductivity of these materials can be varied over orders of magnitude by changes in temperature, optical excitation, and impurity content. This variability of electrical properties makes the semiconductor materials natural choices for electronic device investigations.

Semiconductor materials are found in column IV and neighboring columns of the periodic table (Table 1–1). The column IV semiconductors, silicon and germanium, are called *elemental* semiconductors because they are composed of single species of atoms. In addition to the elemental materials, compounds of column III and column V atoms, as well as certain combinations from II and VI, and from IV, make up the *compound* semiconductors.

As Table 1–1 indicates, there are numerous semiconductor materials. As we shall see, the wide variety of electronic and optical properties of these semiconductors provides the device engineer with great flexibility in the design of electronic and optoelectronic functions. The elemental semiconductor Ge was widely used in the early days of semiconductor development for transistors and diodes. Silicon is now used for the majority of rectifiers, transistors, and integrated circuits (ICs). However, the compounds are widely used in high-speed devices and devices requiring the emission or absorption of light. The two-element (*binary*) III–V compounds such as GaN, GaP, and GaAs are common in light-emitting diodes (LEDs). As discussed in Section 1.2.4, three-element (*ternary*) compounds such as GaAsP and four-element (*quaternary*) compounds such as InGaAsP can be grown to provide added flexibility in choosing materials properties.

Fluorescent materials such as those used in television screens usually are II–VI compound semiconductors such as ZnS. Light detectors are commonly made with InSb, CdSe, or other compounds such as PbTe and HgCdTe. Si and Ge are also widely used as infrared and nuclear radiation detectors. Light-emitting diodes are made using GaN and other III–V compounds. Semiconductor lasers are made using GaAs, AlGaAs, and other ternary and quaternary compounds.

One of the most important characteristics of a semiconductor, which distinguishes it from metals and insulators, is its *energy band gap*. This property, which we will discuss in detail in Chapter 3, determines among other things the wavelengths of light that can be absorbed or emitted by the semiconductor. For example, the band gap of GaAs is about 1.43 electron volts (eV), which

Table 1–1 Common semiconductor materials: (a) the portion of the periodic table where semiconductors occur; (b) elemental and compound semiconductors.

(a)	II	III	IV	V	VI
		B	C	N	
		Al	Si	P	S
	Zn	Ga	Ge	As	Se
	Cd	In		Sb	Te

(b)	Elemental	IV compounds	Binary III–V compounds	Binary II–VI compounds
	Si	SiC	AlP	ZnS
	Ge	SiGe	AlAs	ZnSe
			AlSb	ZnTe
			GaN	CdS
			GaP	CdSe
			GaAs	CdTe
			GaSb	
			InP	
			InAs	
			InSb	

corresponds to light wavelengths in the near infrared. In contrast, GaP has a band gap of about 2.3 eV, corresponding to wavelengths in the green portion of the spectrum.[1] The band gap E_g for various semiconductor materials is listed along with other properties in Appendix III. As a result of the wide variety of semiconductor band gaps, LEDs and lasers can be constructed with wavelengths over a broad range of the infrared and visible portions of the spectrum.

The electronic and optical properties of semiconductor materials are strongly affected by impurities, which may be added in precisely controlled amounts. Such impurities are used to vary the conductivities of semiconductors over wide ranges and even to alter the nature of the conduction processes from conduction by negative charge carriers to positive charge carriers. For example, an impurity concentration of one part per million can change a sample of Si from a poor conductor to a good conductor of electric current. This process of controlled addition of impurities, called *doping*, will be discussed in detail in subsequent chapters.

To investigate these useful properties of semiconductors, it is necessary to understand the atomic arrangements in the materials. Obviously, if slight alterations in purity of the original material can produce such dramatic changes in electrical properties, then the nature and specific arrangement of atoms in each semiconductor must be of critical importance. Therefore, we begin our study of semiconductors with a brief introduction to crystal structure.

In this section we discuss the arrangements of atoms in various solids. We shall distinguish between single crystals and other forms of materials and then investigate the periodicity of crystal lattices. Certain important crystallographic terms will be defined and illustrated in reference to crystals having a basic cubic structure. These definitions will allow us to refer to certain planes and directions within a lattice. Finally, we shall investigate the diamond lattice; this structure, with some variations, is typical of most of the semiconductor materials used in electronic devices.

1.2
CRYSTAL LATTICES

1.2.1 Periodic Structures

A crystalline solid is distinguished by the fact that the atoms making up the crystal are arranged in a periodic fashion. That is, there is some basic arrangement of atoms that is repeated throughout the entire solid. Thus the crystal appears exactly the same at one point as it does at a series of other equivalent points, once the basic periodicity is discovered. However, not all solids are crystals (Fig. 1–1); some have no periodic structure at all (*amorphous* solids), and others are composed of many small regions of single-crystal material (*polycrystalline* solids). The high-resolution micrograph shown in Fig. 6–33 illustrates the periodic array of atoms in the single-crystal silicon of a transistor channel compared with the amorphous SiO_2 (glass) of the oxide layer.

---

[1] The conversion between the energy E of a photon of light (eV) and its wavelength λ (μm) is $\lambda = 1.24/E$. For GaAs, $\lambda = 1.24/1.43 = 0.87$ μm.

(a) Crystalline   (b) Amorphous   (c) Polycrystalline
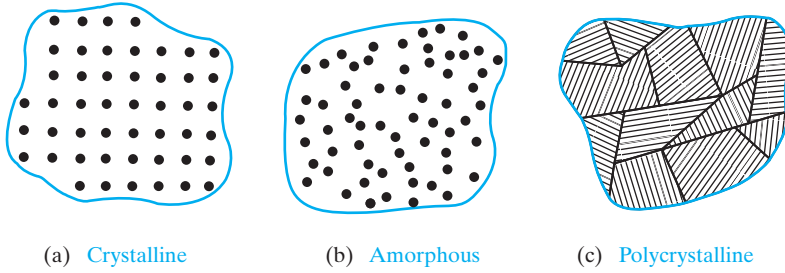
Figure 1–1
Three types of solids, classified according to atomic arrangement: (a) crystalline and (b) amorphous materials are illustrated by microscopic views of the atoms, whereas (c) polycrystalline structure is illustrated by a more macroscopic view of adjacent single-crystalline regions, such as (a).

The periodicity in a crystal is defined in terms of a symmetric array of points in space called the *lattice*. We can add atoms at each lattice point in an arrangement called a *basis,* which can be one atom or a group of atoms having the same spatial arrangement, to get a *crystal*. In every case, the lattice contains a volume or *cell* that represents the entire lattice and is regularly repeated throughout the crystal. As an example of such a lattice, Fig. 1–2 shows a two-dimensional arrangement of atoms called a rhombic lattice, with a *primitive* cell ODEF, which is the smallest such cell. Notice that we can define vectors **a** and **b** such that if the primitive cell is translated by integral multiples of these vectors, a new primitive cell identical to the original is found (e.g., O'D'E'F'). These vectors, **a** and **b** (and **c** if the lattice is three dimensional), are called the *primitive vectors* for the lattice. Points within the lattice are indistinguishable if the vector between the points is

$$\mathbf{r} = p\mathbf{a} + q\mathbf{b} + s\mathbf{c} \qquad (1–1)$$

where *p, q,* and *s* are integers. The primitive cell shown has lattice points *only* at the corners of the cell. The primitive cell is not unique, but it must cover
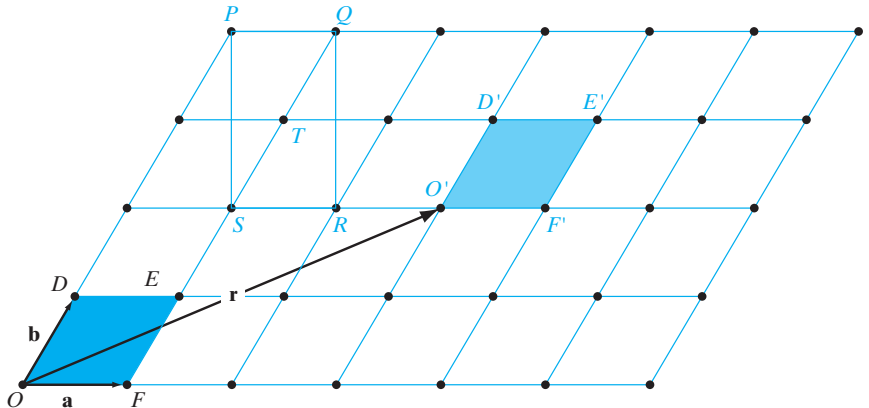
Figure 1–2
A two-dimensional lattice showing translation of a unit cell by r = 3a + 2b.

the entire volume of the crystal (without missing or extra bits) by translations by integer numbers of primitive vectors, and it can have *only* one lattice point per cell. The convention is to choose the smallest primitive vectors. Note that, in the primitive cell shown in Fig. 1–2, the lattice points at the corners are shared with adjacent cells; thus, the *effective* number of lattice points belonging to the primitive cell is unity. Since there are many different ways of placing atoms in a volume, the distances and orientation between atoms can take many forms, leading to different lattice and crystal structures. It is important to remember that the *symmetry* determines the lattice, not the magnitudes of the distances between the lattice points.

In many lattices, however, the primitive cell is not the most convenient to work with. For example, in Fig. 1–2, we see that the rhombic arrangement of the lattice points is such that it can also be considered to be rectangular (PQRS) with a lattice point in the center at T (a so-called *centered rectangular* lattice). (Note that this is not true of all rhombic lattices!) Clearly, it is simpler to deal with a rectangle rather than a rhombus. So, in this case we can choose to work with a larger rectangular *unit* cell, PQRS, rather than the smallest primitive cell, ODEF. A unit cell allows lattice points not only at the corners but also at the face center (and body center in 3-D) if necessary. It is sometimes used instead of the primitive cell if it can represent the symmetry of the lattice better (in this example "centered rectangular" two-dimensional lattice). It replicates the lattice by integer translations of *basis* vectors.

The importance of the unit cell lies in the fact that we can analyze the crystal as a whole by investigating a representative volume. For example, from the unit cell we can find the distances between nearest atoms and next nearest atoms for calculation of the forces holding the lattice together; we can look at the fraction of the unit cell volume filled by atoms and relate the density of the solid to the atomic arrangement. But even more important for our interest in electronic devices, the properties of the periodic crystal lattice determine the allowed energies of electrons that participate in the conduction process. Thus the lattice determines not only the mechanical properties of the crystal but also its electrical properties.

1.2.2   Cubic Lattices

The simplest three-dimensional lattice is one in which the unit cell is a cubic volume, such as the three cells shown in Fig. 1–3. The *simple cubic* structure (abbreviated *sc*) has an atom located at each corner of the unit cell. The

Simple cubic   Body-centered cubic   Face-centered cubic
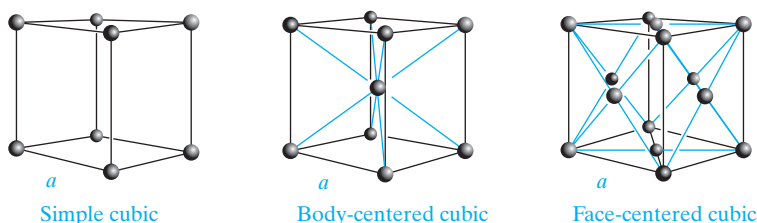
Figure 1–3
Unit cells for three types of cubic lattice structures.

Figure 1–4
Packing of hard
spheres in an fcc
lattice.
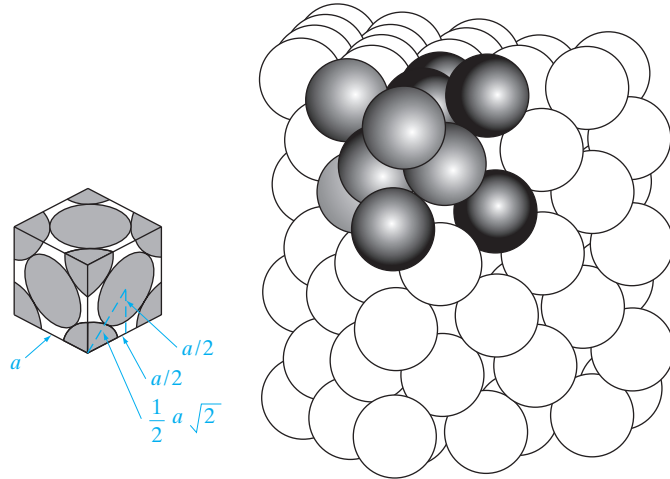
body-centered cubic (*bcc*) lattice has an additional atom at the center of the cube, and the *face-centered cubic* (*fcc*) unit cell has atoms at the eight corners and centered on the six faces. All three structures have different primitive cells, but the same cubic unit cell. We will generally work with unit cells.

As atoms are packed into the lattice in any of these arrangements, the distances between neighboring atoms will be determined by a balance between the forces that attract them together and other forces that hold them apart. We shall discuss the nature of these forces for particular solids in Section 3.1.1. For now, we can calculate the maximum fraction of the lattice volume that can be filled with atoms by approximating the atoms as hard spheres. For example, Fig. 1–4 illustrates the packing of spheres in a fcc cell of side *a,* such that the nearest neighbors touch. The dimension *a* for a cubic unit cell is called the *lattice constant*. For the fcc lattice the nearest neighbor distance is one-half the diagonal of a face, or $\frac{1}{2}(a\sqrt{2})$. Therefore, for the atom centered on the face to just touch the atoms at each corner of the face, the radius of the sphere must be one-half the nearest neighbor distance, or $\frac{1}{4}(a\sqrt{2})$.

EXAMPLE 1–1   Find the fraction of the fcc unit cell volume filled with hard spheres.

SOLUTION

$$\text{Nearest atom separation} = \frac{5\sqrt{2}}{2}\,\text{Å} = 3.54\,\text{Å}$$

$$\text{Tetrahedral radius} = 1.77\,\text{Å}$$

$$\text{Volume of each atom} = 23.14\,\text{Å}^3$$

$$\text{Number of atoms per cube } 6\cdot\frac{1}{2} + 8\cdot\frac{1}{8} = 4 \text{ atoms}$$

$$\text{Packing fraction } \frac{23.1\,\text{Å}^3\cdot 4}{(5\,\text{Å})^3} = 0.74 = 74\%$$

1.2.3 Planes and Directions

In discussing crystals it is very helpful to be able to refer to planes and direc-
tions within the lattice. The notation system generally adopted uses a set of
three integers to describe the position of a plane or the direction of a vector
within the lattice. We first set up an *xyz* coordinate system with the origin at
any lattice point (it does not matter which one because they are all equiva-
lent!), and the axes are lined up with the edges of the cubic unit cell. The
three integers describing a particular plane are found in the following way:

1. Find the intercepts of the plane with the crystal axes and express
   these intercepts as integral multiples of the basis vectors (the plane
   can be moved in and out from the origin, retaining its orientation,
   until such an integral intercept is discovered on each axis).

2. Take the reciprocals of the three integers found in step 1 and reduce
   these to the smallest set of integers *h, k,* and *l,* which have the same
   relationship to each other as the three reciprocals.

3. Label the plane (*hkl*).

The plane illustrated in Fig. 1–5 has intercepts at 2**a**, 4**b**, and 1**c** along the
three crystal axes. Taking the reciprocals of these intercepts, we get $\frac{1}{2}$,
$\frac{1}{4}$, and 1. These three fractions have the same relationship to each other
as the integers 2, 1, and 4 (obtained by multiplying each fraction by 4).
Thus the plane can be referred to as a (214) plane. The only exception is
if the intercept is a fraction of the lattice constant *a*. In that case, we do
not reduce it to the lowest set of integers. For example, in Fig. 1–3, planes
parallel to the cube faces, but going through the body center atoms in the
bcc lattice, would be (200) and not (100).
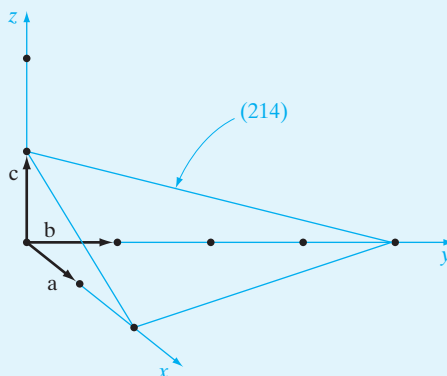
EXAMPLE 1–2

Figure 1–5
A (214) crystal
plane.

The three integers *h, k,* and *l* are called the *Miller indices*; these three
numbers define a set of parallel planes in the lattice. One advantage of taking
the reciprocals of the intercepts is avoidance of infinities in the notation. One

intercept is infinity for a plane parallel to an axis; however, the reciprocal of such an intercept is taken as zero. If a plane contains one of the axes, it is parallel to that axis and has a zero reciprocal intercept. If a plane passes through the origin, it can be translated to a parallel position for calculation of the Miller indices. If an intercept occurs on the negative branch of an axis, the minus sign is placed above the Miller index for convenience, such as ($h\overline{k}l$).

From a crystallographic point of view, many planes in a lattice are equivalent; that is, a plane with given Miller indices can be shifted about in the lattice simply by choice of the position and orientation of the unit cell. The indices of such equivalent planes are enclosed in braces { } instead of parentheses. For example, in the cubic lattice of Fig. 1–6, all the cube faces are crystallographically equivalent in that the unit cell can be rotated in various directions and still appear the same. The six equivalent faces are collectively designated as {100}.

A direction in a lattice is expressed as a set of three integers with the same relationship as the components of a vector in that direction. The three vector components are expressed in multiples of the basis vectors, and the three integers are reduced to their smallest values while retaining the relationship among them. For example, the body diagonal in the cubic lattice (Fig. 1–7a) is composed of the components 1**a,** 1**b,** and 1**c**; therefore, this diagonal is the [111] direction. (Brackets are used for direction indices.) As in the case of planes, many directions in a lattice are equivalent, depending only on the arbitrary choice of orientation for the axes. Such equivalent direction indices are placed in angular brackets ⟨ ⟩. For example, the crystal axes in the cubic lattice [100], [010], and [001] are all equivalent and are called ⟨100⟩ directions (Fig. 1–7b).

Figure 1–6
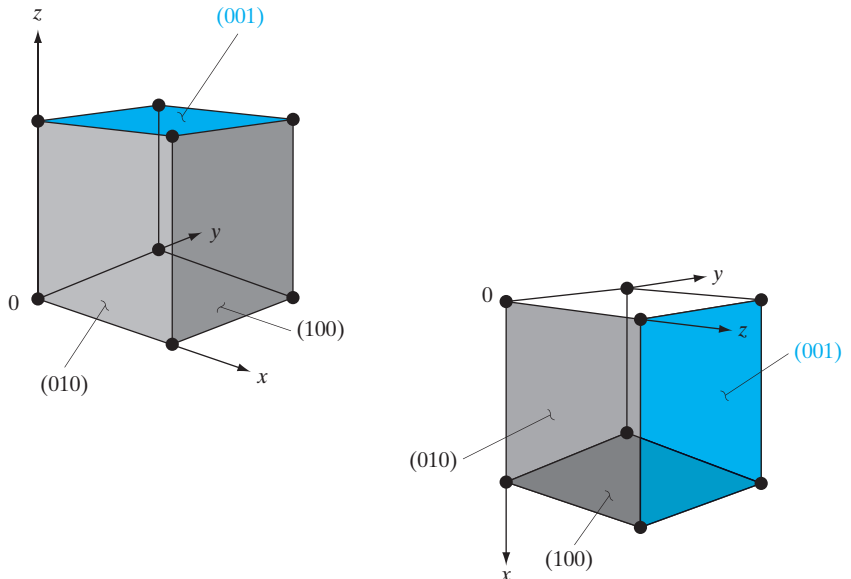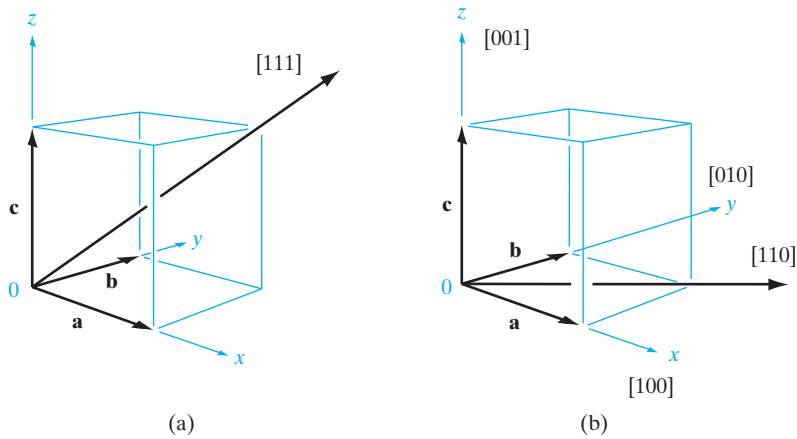Equivalence of the cube faces ({100} planes) by rotation of the unit cell within the cubic lattice.

(a) (b)

Two useful relationships in terms of Miller indices describe the distance between planes and angles between directions. The distance d between two adjacent planes labeled (hkl) is given in terms of the lattice constant, a, as

$$d = a/(h^2 + k^2 + l^2)^{1/2} \qquad (1\text{–}2a)$$

The angle θ between two different Miller index directions is given by

$$\cos\theta = \{h_1 h_2 + k_1 k_2 + l_1 l_2\}\{(h_1^2 + k_1^2 + l_1^2)^{1/2}(h_2^2 + k_2^2 + l_2^2)^{1/2}\} \quad (1\text{–}2b)$$

Comparing Figs. 1–6 and 1–7, we notice that in cubic lattices a direction $[hkl]$ is perpendicular to the plane (hkl). This is convenient in analyzing lattices with cubic unit cells, but it should be remembered that it is not necessarily true in noncubic systems.

1.2.4 The Diamond Lattice

The basic crystal structure for many important semiconductors is the fcc lattice with a basis of two atoms, giving rise to the *diamond* structure, characteristic of Si, Ge, and C in the diamond form. In many compound semiconductors, atoms are arranged in a basic diamond structure, but are different on alternating sites. This is called a *zinc blende* structure and is typical of the III–V compounds. One of the simplest ways of stating the construction of the diamond structure is the following:

> The diamond structure can be thought of as an fcc lattice with an extra atom placed at $\mathbf{a}/4 + \mathbf{b}/4 + \mathbf{c}/4$ from each of the fcc atoms.

Figure 1–8a illustrates the construction of a diamond lattice from an fcc unit cell. We notice that when the vectors are drawn with components one-fourth of the cube edge in each direction, only four additional points within the same unit cell are reached. Vectors drawn from any of the other fcc atoms simply determine corresponding points in adjacent unit cells. This method of