**To the many students I've had the privilege of teaching over the years who have contributed in many ways to the broad field of electrical engineering, and to future students who will contribute in ways we cannot now imagine.**

# ABOUT THE AUTHOR

**Donald A. Neamen** is a professor emeritus in the Department of Electrical and Computer Engineering at the University of New Mexico where he taught for more than 25 years. He received his Ph.D. from the University of New Mexico and then became an electronics engineer at the Solid State Sciences Laboratory at Hanscom Air Force Base. In 1976, he joined the faculty in the ECE department at the University of New Mexico, where he specialized in teaching semiconductor physics and devices courses and electronic circuits courses. He is still a part-time instructor in the department.

In 1980, Professor Neamen received the Outstanding Teacher Award for the University of New Mexico. In 1983 and 1985, he was recognized as Outstanding Teacher in the College of Engineering by Tau Beta Pi. In 1990, and each year from 1994 through 2001, he received the Faculty Recognition Award, presented by graduating ECE students. He was also honored with the Teaching Excellence Award in the College of Engineering in 1994.

In addition to his teaching, Professor Neamen served as Associate Chair of the ECE department for several years and has also worked in industry with Martin Marietta, Sandia National Laboratories, and Raytheon Company. He has published many papers and is the author of *Electronic Circuit Analysis and Design,* Second Edition and *Semiconductor Physics and Devices: Basic Principles,* Third Edition.

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# PREFACE

## PHILOSOPHY AND GOALS

The purpose of this text is to provide a basis for understanding the characteristics, operation, and limitations of semiconductor devices. In order to gain this understanding, it is essential to have a thorough knowledge of the physics of the semiconductor material. The goal of this book is to bring together the fundamental physics of the semiconductor material and the semiconductor device physics.

Since the objective of this text is to provide an introduction to the theory of semiconductor devices, there is a great deal of advanced theory that is not considered. This material is found in more advanced texts. There are occasions in the text where equations and relationships are simply stated with no or very little derivation. Again, the details are found in more advanced texts. However, the author feels that there is enough mathematics included to provide a good foundation for the basic understanding of semiconductor devices in this first course.

## PREREQUISITES

This text is intended for junior and senior undergraduates in electrical engineering. The prerequisites for understanding the material are college mathematics, up to and including differential equations, and college physics, including an introduction to modern physics and electrostatics. Prior completion of an introductory course in electronic circuits is helpful, but not essential.

## ORDER OF PRESENTATION

Each instructor has a personal preference for the order in which the course material is presented. The order of presentation of topics in this text is somewhat different compared to many semiconductor textbooks. Chapters 1–4 cover the basic physics of the semiconductor material and contain topics normally covered initially in any semiconductor device course. Chapter 5 discusses the electrostatics of the pn and Schottky junctions. This material is necessary and sufficient for the understanding of the MOS transistor presented in Chapters 6 and 7. There are two reasons for discussing the MOS transistor at this point. First, since the MOS transistor is fundamental to integrated circuits, this material is presented early enough in the course so that it doesn't get "short changed," as it might when covered at the end of a course. Second, since a "real" semiconductor device is discussed fairly early in the course, the reader may have more motivation to continue studying this course material.

After the MOS transistor is presented, the nonequilibrium characteristics of the semiconductor material is presented in Chapter 8 and then the forward-biased pn junction and Schottky diodes are discussed in Chapter 9. The bipolar transistor is presented in Chapter 10. Chapter 11 covers additional devices such as junction field-effect transistors and thyristors. Finally, optical devices are discussed in Chapter 12.

One possible disadvantage to this order of presentation is that the discussion of the pn junction is "interrupted." However, the author feels that a "just-in-time" approach is justified. Some discussion of the pn junction is necessary before presenting the MOS transistor. However, if the entire discussion of the pn junction, including the discussion of nonequilibrium excess carriers, took place before the MOS transistor, then much of the knowledge gained of forward-biased pn junctions would be lost by the reader by the time the bipolar transistor is discussed.

The following table lists the textbook approach to the order of presentation of topics. Unfortunately, because of time constraints, every topic in every chapter cannot be covered in a one-semester course.

| **Textbook Approach** | |
|---|---|
| Chapter 1 | Crystal structure |
| Chapter 2 | Selected topics from quantum mechanics and theory of solids |
| Chapter 3 | Semiconductor material physics |
| Chapter 4 | Transport phenomena |
| Chapter 5 | Electrostatics of the pn junction |
| Chapter 6 | The MOS transistor |
| Chapter 7 | Selected topics for advanced MOSFETs |
| Chapter 8 | Selected topics from nonequilibrium semiconductor physics |
| Chapter 9 | The pn junction diode |
| Chapter 10 | The bipolar transistor |
| Chapter 11 | Selected topics from other devices |
| Chapter 12 | Selected topics from optical devices |

For those instructors who prefer the classical approach and wish to cover the bipolar transistor before the MOS transistor, the following table lists the order of presentation. The chapters are written so that this order of presentation is very plausible.

| **Classical Approach** | |
|---|---|
| Chapter 1 | Crystal structure |
| Chapter 2 | Selected topics from quantum mechanics and theory of solids |
| Chapter 3 | Semiconductor material physics |
| Chapter 4 | Transport phenomena |
| Chapter 8 | Selected topics from Nonequilibrium semiconductor physics |
| Chapter 5 | Electrostatics of the pn junction |
| Chapter 9 | The pn junction diode |
| Chapter 10 | The bipolar transistor |
| Chapter 6 | The MOS transistor |
| Chapter 7 | Selected topics from advanced MOSFETs |
| Chapter 11 | Selected topics from other devices |
| Chapter 12 | Selected topics from optical devices |

## USE OF THE BOOK

The text is intended for a one-semester course at the junior or senior level. As with most textbooks, there is more material than can be conveniently covered in one semester; this enables each instructor some flexibility in designing the course to his or her own specific needs.

At the end of several chapters, there is a section dealing with fabrication technology. In Chapter 1, this topic deals with the growth of semiconductor materials and the oxidation process. In Chapter 3, this topic deals with the introduction of specific impurities into the semiconductor by either diffusion or ion implantation. In later chapters, this topic deals with the fabrication of specific devices. In each case, the fabrication discussion is relatively short and intended only to give the reader a basic understanding of the fabrication technology. These sections, as well as a few other sections in the text, are denoted by the symbol $\Sigma$ in front of the section heading. The symbol $\Sigma$ shows that reading these sections will aid in the total summation of the understanding of semiconductor devices. However, a basic understanding of semiconductor device physics can be accomplished without studying these sections in detail during this first introductory course.

## FEATURES OF THE BOOK

- *Preview section:* A preview section introduces each chapter. This preview links the chapter to previous chapters and states the chapter's goals, that is, what the reader should gain from the chapter.
- *Historical and Present-Day Insights:* A Historical Insight section relates the chapter material to a few historical events and a Present-Day Insight section relates the chapter material to current research and manufacturing events.
- *Icon:* $\Sigma$, indicates sections that are to be read for understanding to increase the total summation of knowledge of semiconductor devices. However, a detailed study of these sections is not required during this first introductory course.
- *Key terms in the margin:* Key terms are listed in the margin of the text. Quickly finding a key term adjacent to the text in which the material is discussed should aid the student in reviewing the material.
- *Examples:* There are a liberal number of examples given in the text to reinforce the theoretical concepts being developed. These examples contain all the details of the analysis or design, so the reader does not have to fill in missing steps.
- *Exercise problems:* An exercise problem is given after each example. These exercises are similar in scope to the preceding example. The ability to solve these exercise problems should be an indication as to whether the student has mastered the previous material. Answers to these problems are given.
- *Test Your Understanding exercises:* At the end of major sections, additional exercise problems are given. These exercise problems tend to be more comprehensive than the exercise problems given after each example. Answers to these problems are also given.

- *Summary:* A summary section follows the text of each chapter. This section summarizes the overall results derived in the chapter and reviews the basic concepts developed.
- *Checkpoint:* A checkpoint section follows the Summary section. This section states the goals that should have been met and states the abilities the reader should have gained. The Checkpoints will help assess progress before moving to the next chapter.
- *Review questions:* A list of review questions is included at the end of each chapter. These questions serve as a self-test to help the reader determine how well the concepts developed in the chapter have been mastered.
- *End-of-chapter problems:* A substantial number of problems are provided at the end of each chapter, organized according to the subject of each section. An asterisk in front of a problem indicates a more difficult problem. Answers to a selected number are provided in Appendix F.
- *Reading list:* A reading list finishes up each chapter. The references indicated by an asterisk are at a more advanced level compared with this text.
- *Answers to selected problems:* Answers to selected problems are given in Appendix F. Knowing the answer to a problem can aid and reinforce the problem solving.

## SUPPLEMENTS

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# CHAPTER

# 1

# The Crystal Structure of Solids

This text deals with the electrical properties and characteristics of semiconductor materials and devices. The electrical properties of solids are therefore of primary interest. Since the semiconductor is in general a single-crystal material and since the electrical properties of a single-crystal material are determined not only by the chemical composition but also by the arrangement of atoms in the solid, a brief study of the crystal structure of solids is warranted. This introductory chapter provides the necessary background in single-crystal materials and crystal growth for a basic understanding of the electrical properties of semiconductor materials and devices.

## 1.0 | PREVIEW

In this chapter, we will

1. List and describe semiconductor materials.
2. Describe three classifications of solids: amorphous, polycrystalline, and single crystal.
3. Describe basic crystal structures, crystal planes, and the diamond structure.
4. Discuss differences in atomic bonding between various solids.
5. Describe various single-crystal imperfections and impurities in solids.
6. Describe processes that are used to create single-crystal semiconductor materials.
7. Describe the formation of an oxide on silicon.

## Historical Insight

Materials have always been an integral part of electrical engineering, from finding good conductors of electricity that can handle hundreds of amperes to finding good insulators that can handle thousands of volts. Dielectric properties of materials are fundamental in the design of capacitors and magnetic properties of materials are fundamental in the design of electromagnets or permanent magnets. Creating high-purity single-crystal semiconductor materials has been crucial to the development of the vast semiconductor industry.

## Present-Day Insight

Materials continue to be a fundamental component of electrical engineering. Creating single-crystal silicon semiconductor wafers that are 12 inches in diameter and, at the other end of the scale, creating layers of different semiconductor materials that are on the order of tens of angstroms thick are continuing topics of research. The properties of high-purity single-crystal materials are fundamental to the design of the vast number of semiconductor devices.

## 1.1 | SEMICONDUCTOR MATERIALS

**Objective: List and describe semiconductor materials.**

Semiconductors are a group of materials having conductivities between those of metals and insulators. One fundamental characteristic of a semiconductor material is that the conductivity can be varied over several orders of magnitude by adding controlled amounts of impurity atoms. The ability to control and change the conductivity of a semiconductor material allows for the design of the vast number of semiconductor devices.

Two general classifications of semiconductors are the elemental semiconductor materials, found in group IV of the periodic table, and the compound semiconductor materials, most of which are formed from special combinations of group III and group V elements. Table 1.1 shows a portion of the periodic table in which the more common semiconductors are found, and Table 1.2 lists a few of the semiconductor materials. (Semiconductors can also be formed from combinations of group II and group VI elements, but in general these will not be considered in this text.)

**Elemental semiconductor**

The elemental materials, those that are composed of single species of atoms, are silicon and germanium. Silicon dominates the semiconductor commercial market. The vast majority of integrated circuits (ICs) are fabricated in silicon, so silicon will be emphasized to a great extent in this text.

**Binary semiconductor**

The two-element, or *binary,* compounds such as gallium arsenide or gallium phosphide are formed by combining one group III and one group V element. Gallium arsenide is one of the more common of the compound semiconductors. It is used to make light-emitting diodes and laser diodes. GaAs is also used in specialized applications in which, for example, very high speed is required.

**Ternary semiconductor**

We can also form a three-element, or *ternary,* compound semiconductor. An example is $Al_xGa_{1-x}As$, in which the subscript $x$ indicates the fraction of the lower atomic number element component. More complex semiconductors can also be formed that provide flexibility when choosing material properties.

**Table 1.1** | A portion of the periodic table showing elements used in semiconductor materials

| Period \ Group | II | III | IV | V | VI |
|---|---|---|---|---|---|
| 2 | | B<br>Boron | C<br>Carbon | N<br>Nitrogen | O<br>Oxygen |
| 3 | | Al<br>Aluminum | Si<br>Silicon | P<br>Phosphorus | S<br>Sulfur |
| 4 | Zn<br>Zinc | Ga<br>Gallium | Ge<br>Germanium | As<br>Arsenic | Se<br>Selenium |
| 5 | Cd<br>Cadmium | In<br>Indium | Sn<br>Tin | Sb<br>Antimony | Te<br>Tellurium |
| 6 | Hg<br>Mercury | | | | |

**Table 1.2** | A partial list of semiconductor materials

| **Elemental Semiconductors** | | **IV Compound Semiconductors** | |
|---|---|---|---|
| Si | Silicon | SiC | Silicon carbide |
| Ge | Germanium | SiGe | Silicon germanium |
| **Binary III–V Compounds** | | **Binary II–VI Compounds** | |
| AlAs | Aluminum arsenide | CdS | Cadmium sulfide |
| AlP | Aluminum phosphide | CdTe | Cadmium telluride |
| AlSb | Aluminum antimonide | HgS | Mercury sulfide |
| GaAs | Gallium arsenide | ZnS | Zinc sulfide |
| GaP | Gallium phosphide | ZnTe | Zinc telluride |
| GaSb | Gallium antimonide | | |
| InAs | Indium arsenide | | |
| InP | Indium phosphide | | |
| **Ternary Compounds** | | **Quaternary Compounds** | |
| $Al_xGa_{1-x}As$ | Aluminum gallium arsenide | $Al_xGa_{1-x}As_ySb_{1-y}$ | Aluminum gallium arsenic atimonide |
| $GaAs_{1-x}P_x$ | Gallium arsenic phosphide | $Ga_xIn_{1-x}As_{1-y}P_y$ | Gallium indium arsenic phosphide |

## 1.2 | TYPES OF SOLIDS

**Objective: Describe three classifications of solids: amorphous, polycrystalline, and single crystal.**

In Section 1.1, we simply listed various semiconductor materials. Since semiconductors used in discrete device or IC fabrication are generally single-crystal materials, it is worth while discussing various types of crystalline structures. We will describe the spatial arrangement of atoms in crystals and attempt to visualize the three-dimensional configurations. The arrangement of atoms, as well as the chemical composition, affect the electrical properties of the material.

Amorphous, polycrystalline, and single crystal are the three general types of solids. Each type is characterized by the size of an ordered region within the material.

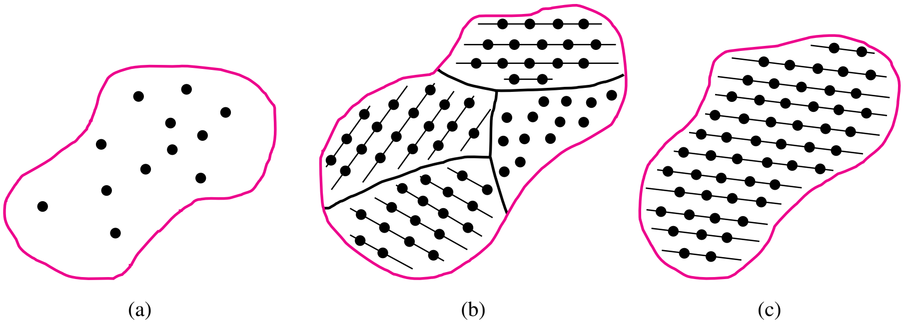

**Figure 1.1** | Two-dimensional schematics of three general types of solids: (a) amorphous, (b) polycrystalline, and (c) single crystal.

An ordered region is a spatial volume in which atoms or molecules have a regular geometric arrangement or periodicity. Amorphous materials have order only within a few atomic or molecular dimensions, while polycrystalline materials have a high degree of order over many atomic or molecular dimensions. These ordered regions, or single-crystal regions, vary in size and orientation with respect to one another. The single-crystal regions are called grains and are separated from one another by grain boundaries. Single-crystal materials, ideally, have a high degree of order, or regular geometric periodicity, throughout the entire volume of the material. The advantage of a single-crystal material is that, in general, its electrical properties are superior to those of a nonsingle-crystal material, since grain boundaries tend to degrade the electrical characteristics. Two-dimensional representations of amorphous, polycrystalline, and single-crystal materials are shown in Figure 1.1.

## 1.3 | SPACE LATTICES

**Objective: Describe basic crystal structures, crystal planes, and the diamond structure.**

Our primary concern will be the single crystal with its regular geometric periodicity in the atomic arrangement. A representative unit, or group of atoms, is repeated at regular intervals in each of the three dimensions to form the single crystal. The periodic arrangement of atoms in the crystal is called the *lattice*.

**Lattice**

### 1.3.1 Primitive and Unit Cell

**Lattice point**

We can represent a particular atomic array by a dot that is called a *lattice point*. Figure 1.2 shows part of an infinite two-dimensional array of lattice points. The simplest means of repeating an atomic array is by translation. Each lattice point in Figure 1.2 can be translated a distance $a_1$ in one direction and a distance $b_1$ in a second noncolinear direction to generate the two-dimensional lattice. A third noncolinear translation will produce the three-dimensional lattice. The translation directions need not be perpendicular.

Since the three-dimensional lattice is a periodic repetition of a group of atoms, we do not need to consider the entire lattice, but only a fundamental unit that is being

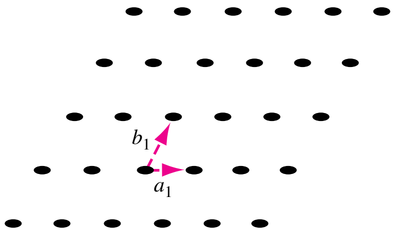

**Figure 1.2** | Two-dimensional representation of a single-crystal lattice.

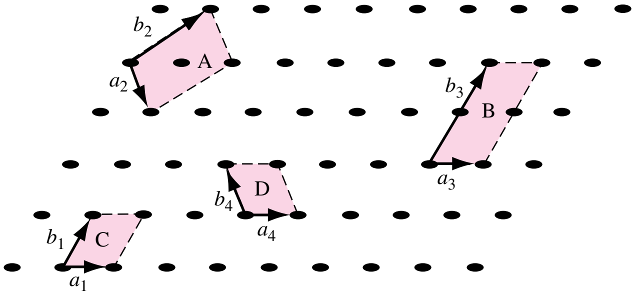

**Figure 1.3** | Two-dimensional representation of a single-crystal lattice showing various possible unit cells.

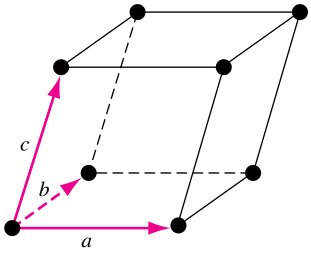

**Figure 1.4** | A generalized primitive unit cell.

repeated. A *unit cell* is a small volume of the crystal that can be used to reproduce the entire crystal. A unit cell is not a unique entity. Figure 1.3 shows several possible unit cells in a two-dimensional lattice.

**Unit cell**

The unit cell A can be translated in directions $a_2$ and $b_2$, the unit cell B can be translated in directions $a_3$ and $b_3$, and the entire two-dimensional lattice can be constructed by the translations of either of these unit cells. The unit cells C and D in Figure 1.3 can also be used to construct the entire lattice by using the appropriate translations. This discussion of two-dimensional unit cells can easily be extended to three dimensions to describe a real single-crystal material.

**Primitive cell**

A *primitive cell* is the smallest unit cell that can be repeated to form the lattice. In many cases, it is more convenient to use a unit cell that is not a primitive cell. Unit cells may be chosen that have orthogonal sides, for example, whereas the sides of a primitive cell may be nonorthogonal.

A generalized three-dimensional unit cell is shown in Figure 1.4. The relationship between this cell and the lattice is characterized by three vectors $\bar{a}$, $\bar{b}$, and $\bar{c}$, which need not be perpendicular and which may or may not be equal in length. Every equivalent lattice point in the three-dimensional crystal can be found using the vector

$$\bar{r} = p\bar{a} + q\bar{b} + s\bar{c} \tag{1.1}$$

where $p$, $q$, and $s$ are integers. Since the location of the origin is arbitrary, we will let $p$, $q$, and $s$ be positive integers for simplicity.

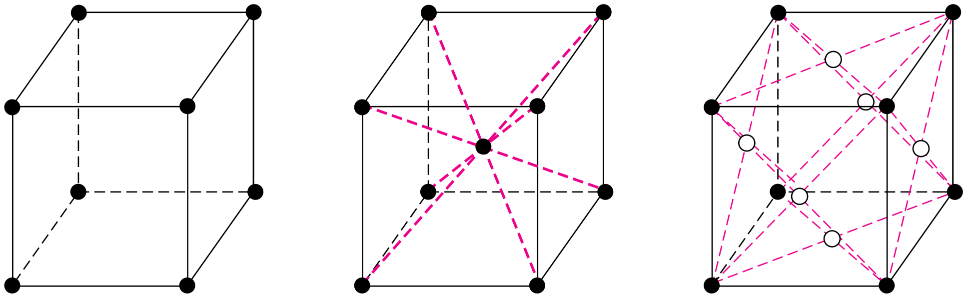
(a) (b) (c)

**Figure 1.5** | Three lattice types: (a) simple cubic, (b) body-centered cubic, and (c) face-centered cubic.

## 1.3.2 Basic Crystal Structures

**Simple cubic**
**Body-centered cubic**
**Face-centered cubic**

Before we discuss semiconductor crystals, let us consider the characteristics of three basic cubic structures. Figure 1.5 shows the simple cubic, body-centered cubic, and face-centered cubic structures. For these simple structures, we can choose unit cells such that the general vectors $\bar{a}$, $\bar{b}$, and $\bar{c}$ are perpendicular to each other and the lengths are equal. The *simple cubic* (sc) structure has an atom located at each corner; the *body-centered cubic* (bcc) structure has an additional atom at the center of the cube; and the *face-centered cubic* (fcc) structure has an additional atom at the center of each face plane.

By knowing the crystal structure of a material and its lattice dimensions, we can determine several characteristics of the crystal. For example, we can determine the volume density of atoms.

### EXAMPLE 1.1

**OBJECTIVE**

Determine the volume density of atoms in a crystal.

Consider a single-crystal material that is a face-centered cubic with a lattice constant $a_0 = 5\text{Å} = 5 \times 10^{-8}$ cm. Each corner atom is shared by eight unit cells that meet at the corner, so each corner atom effectively contributes one-eighth of its volume to each unit cell. The eight corner atoms then contribute an equivalent of one atom to the unit cell. Each face atom is shared by two unit cells that meet at each side, so each face atom effectively contributes one-half of its volume to each unit cell. The six face atoms then contribute an equivalent of three atoms to the unit cell. Each unit cell of a face-centered cubic then effectively contains four atoms.

■ **Solution**

The volume density of atoms is then found by dividing the number of unit cell atoms by the unit cell volume, or

$$\text{Volume density} = \frac{4 \text{ atoms}}{a_0^3} = \frac{4}{(5 \times 10^{-8})^3}$$

or

$$\text{Volume density} = 3.2 \times 10^{22} \text{ atoms per cm}^3$$

**Comment**

This value of the volume density of atoms in a crystal represents the order of magnitude of density for most materials. The actual density is a function of the crystal type and crystal structure since the packing density—number of atoms per unit cell—depends on crystal structure.

**Exercise Problem**

**EX1.1** The lattice constant of a body-centered cubic structure is $a_0 = 4.75$Å. Determine the volume density of atoms. (Ans. $1.87 \times 10^{22}$ cm$^{-3}$)

### 1.3.3 Crystal Planes and Miller Indices

Since real crystals are not infinitely large, they eventually terminate at a surface. Semiconductor devices are fabricated at or near a surface, so the surface properties may influence the device characteristics. We would like to be able to describe these surfaces in terms of the lattice. Surfaces, or planes through the crystal, can be described by first considering the intercepts of the plane along the $\bar{a}$, $\bar{b}$, and $\bar{c}$ axes used to describe the lattice.

Figure 1.6 shows a general plane intercepting the $\bar{a}$, $\bar{b}$, and $\bar{c}$ axes at points $pa$, $qb$, and $sc$, where $p$, $q$, and $s$ are integers. To describe the plane, we write the reciprocals of the intercepts as

$$\left(\frac{1}{p}, \frac{1}{q}, \frac{1}{s}\right) \tag{1.2}$$

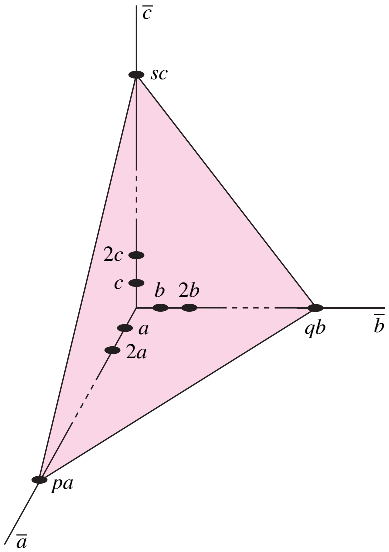

**Figure 1.6** | General lattice plane intercepting the $\bar{a}$, $\bar{b}$, and $\bar{c}$ axes at $p$, $q$, and $s$, respectively.

Multiplying by the lowest common denominator, we obtain a set of numbers such as ($hkl$). The plane is then referred to as the ($hkl$) plane. The parameters $h$, $k$, and $l$ are referred to as the Miller indices.

**Miller indices**

## EXAMPLE 1.2

### OBJECTIVE

Describe the plane shown in Figure 1.7.

The lattice points in Figure 1.7 are shown along the $\bar{a}$, $\bar{b}$, and $\bar{c}$ axes only.

### ■ Solution

From Equation (1.1), the intercepts of the plane correspond to $p = 2$, $q = 3$, and $s = 2$. Write the reciprocals of the intercepts, from Equation (1.2), as

$$\left(\frac{1}{2}, \frac{1}{3}, \frac{1}{2}\right)$$

Now multiply by the lowest common denominator, which in this case is 6, to obtain (3, 2, 3). The plane in Figure 1.7 is then referred to as the (323) plane. The integers are referred to as the Miller indices. We will refer to a general plane as the ($hkl$) plane.

### ■ Comment

We can show that the same three Miller indices are obtained for any plane that is parallel to the one shown in Figure 1.7. Any parallel plane is entirely equivalent to any other.

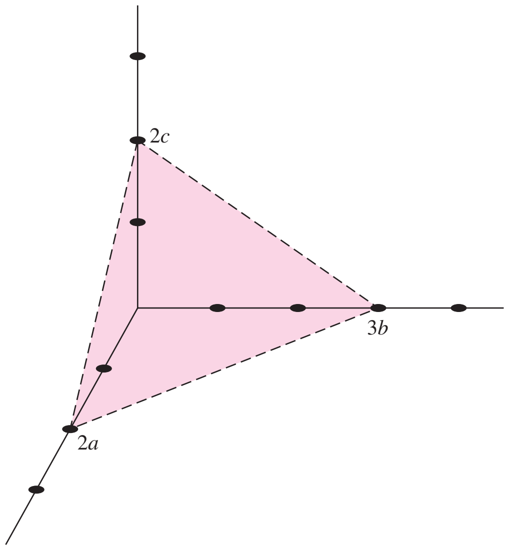

**Figure 1.7** | A crystal-lattice plane for Example 1.2.

**Exercise Problem**

**EX1.2** A plane in a simple cubic crystal is described as a (132) plane. (*a*) What are the intercepts on the $\bar{a}$, $\bar{b}$, and $\bar{c}$ axes. (*b*) Sketch the plane. [Ans. (*a*) $p = 6$, $q = 2$, $s = 3$]

Three planes that are commonly considered in a cubic crystal are shown shaded in Figure 1.8. The plane in Figure 1.8a is parallel to the $\bar{b}$ and $\bar{c}$ axes so the intercepts are given as $p = 1$, $q = \infty$, and $s = \infty$. Taking the reciprocal, we obtain the Miller indices as (1, 0, 0), so the plane shown in Figure 1.8a is referred to as the (100) plane. Again, any plane parallel to the one shown in Figure 1.8a and separated by an integral number of lattice constants is equivalent and is referred to as the (100) plane. One advantage to taking the reciprocal of the intercepts to obtain the Miller indices is that the use of infinity is avoided when describing a plane that is parallel to an axis. If we were to describe a plane passing through the origin of our system, we would obtain infinity as one or more of the Miller indices after taking the reciprocal of the intercepts. However, the location of the origin of our system is entirely arbitrary and so, by translating the origin to another equivalent lattice point, we can avoid the use of infinity in the set of Miller indices.

For the simple cubic structure, the body-centered cubic, and the face-centered cubic, there is a high degree of symmetry. The axes can be rotated by 90° in each of the three dimensions and each lattice point can again be described by Equation (1.1) as

$$\bar{r} = p\bar{a} + q\bar{b} + s\bar{c} \tag{1.1}$$

Each face plane of the cubic structure shown in Figure 1.8a is entirely equivalent. These planes are grouped together and are referred to as the {100} set of planes.

We may also consider the planes shown in Figures 1.8b and 1.8c. The intercepts of the plane shown in Figure 1.8b are $p = 1$, $q = 1$, and $s = \infty$. The Miller indices

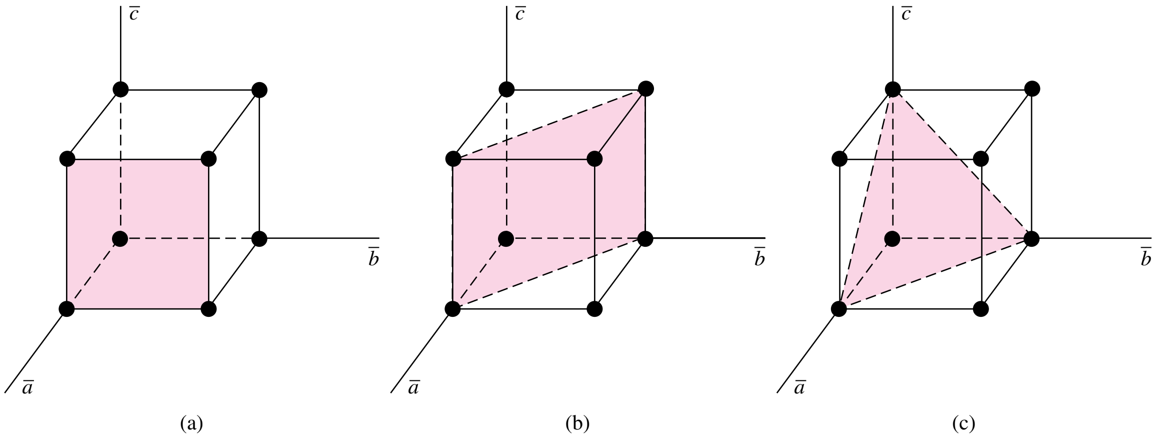

**Figure 1.8** | Three lattice planes in a simple cubic lattice: (a) (100) plane, (b) (110) plane, and (c) (111) plane.

are found by taking the reciprocal of these intercepts and, as a result, this plane is referred to as the (110) plane. In a similar way, the plane shown in Figure 1.8c is referred to as the (111) plane.

One characteristic of a crystal that can be determined is the distance between nearest equivalent parallel planes. Another characteristic is the surface concentration of atoms, number per square centimeter (#/cm$^2$), that are cut by a particular plane. Again, a single-crystal semiconductor is not infinitely large and must terminate at some surface. The surface density of atoms may be important, for example, in determining how another material, such as an insulator, will "fit" on the surface of a semiconductor material.

## EXAMPLE 1.3

### OBJECTIVE

Calculate the surface density of atoms on a particular plane in a crystal.

Consider the face-centered cubic structure and the (110) plane shown in Figure 1.9a. Assume the atoms can be represented as hard spheres with the closest atoms touching each other and that the lattice constant is $a_0 = 4.5$ Å $= 4.5 \times 10^{-8}$ cm. Figure 1.9b shows how the atoms are cut by the (110) plane.

The atom at each corner is shared by four similar equivalent lattice planes, so each corner atom effectively contributes one-fourth of its area to this lattice plane, as indicated in the figure. The four corner atoms then effectively contribute one atom to this lattice plane. The atom on each face plane is shared by two similar equivalent lattice planes, so each face atom effectively contributes one-half of its area to this lattice plane as indicated in the figure. The two face atoms then effectively contribute one atom to this lattice plane. The lattice plane in Figure 1.9b, then, contains two atoms.

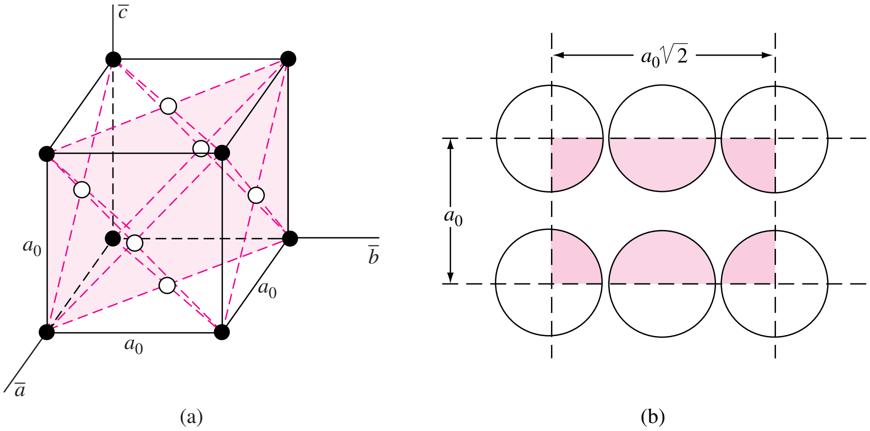

**Figure 1.9** | (a) The (110) plane in a face-centered cubic and (b) the atoms cut by the (110) plane in a face-centered cubic.