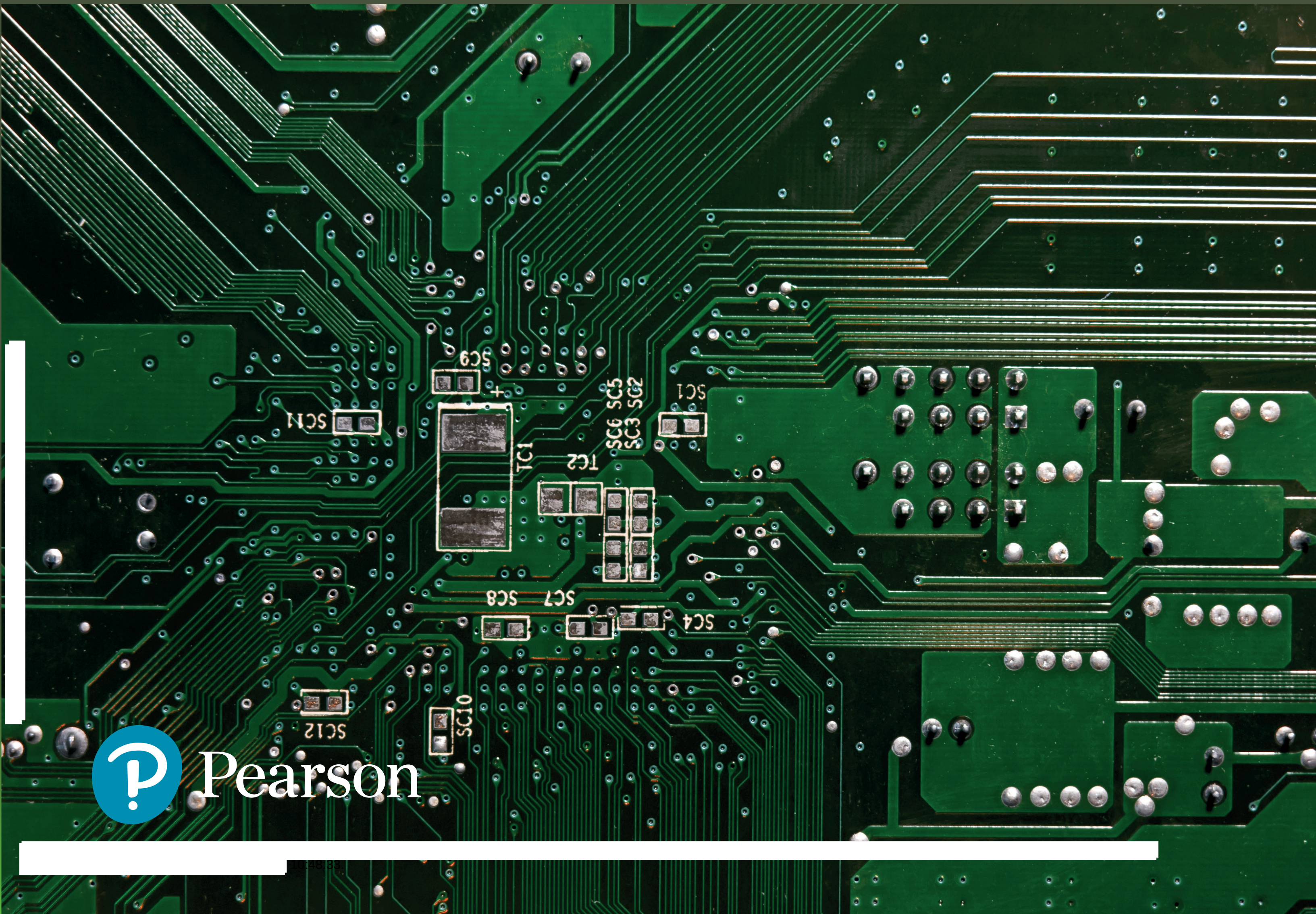
GLOBAL
EDITION

Electronic Devices

Conventional Current Version

TENTH EDITION

Thomas L. Floyd



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ELECTRONIC DEVICES

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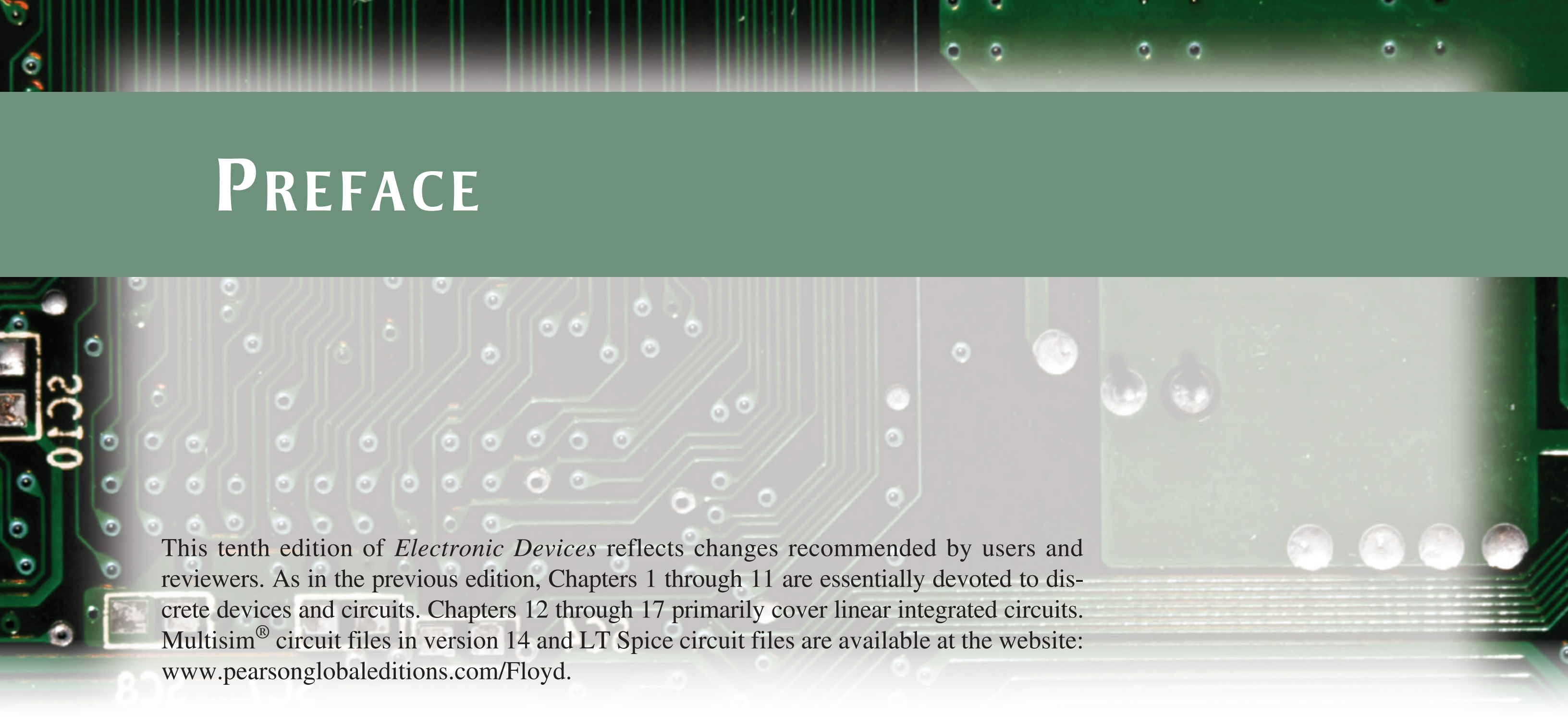


PREFACE

This tenth edition of *Electronic Devices* reflects changes recommended by users and reviewers. As in the previous edition, Chapters 1 through 11 are essentially devoted to discrete devices and circuits. Chapters 12 through 17 primarily cover linear integrated circuits. Multisim® circuit files in version 14 and LT Spice circuit files are available at the website: www.pearsonglobaleditions.com/Floyd.

New Features

- LT Spice circuit simulation.
- Mutlisim files upgraded to Version 14 and new files added.
- Several new examples.
- Expanded coverage of FETs including JFET limiting parameters, FINFET, UMOSFET, Current source biasing, Cascode dual-gate MOSFET, and tunneling MOSFET.
- Expanded coverage of thyristors including SSRs using SCRs, motor speed control.
- Expanded coverage of switching circuits including interfacing with logic circuits.
- Expanded PLL coverage.
- Many new problems.

Standard Features

- Full-color format.
- Chapter openers include a chapter outline, chapter objectives, introduction, key terms list, Device Application preview, and website reference.
- Introduction and objectives for each section within a chapter.
- Large selection of worked-out examples set off in a graphic box. Each example has a related problem for which the answer can be found at: www.pearsonglobaleditions.com/Floyd
- Multisim® circuit files for selected examples, troubleshooting, and selected problems are on the companion website.
- LT Spice circuit files for selected examples and problems are on the companion website.
- Section checkup questions are at the end of each section within a chapter. Answers can be found at: www.pearsonglobaleditions.com/Floyd.
- Troubleshooting sections in many chapters.

- A Device Application is at the end of most chapters.
- A Programmable Analog Technology feature is at the end of selected chapters.
- A sectionalized chapter summary, key term glossary, and formula list at the end of each chapter.
- True/false quiz, circuit-action quiz, self-test, and categorized problem set with basic and advanced problems at the end of each chapter.
- Appendix with answers to odd-numbered problems, glossary, and index are at the end of the book.
- Updated PowerPoint® slides, developed by Dave Buchla, are available online. These innovative, interactive slides are coordinated with each text chapter and are an excellent tool to supplement classroom presentations.
- A laboratory manual by Dave Buchla and Steve Wetterling coordinated with this textbook is available in print.

Student Resources

Digital Resources (*www.pearsonglobaleditions.com/Floyd*) This section offers students an online study guide that they can check for conceptual understanding of key topics. Also included on the website are tutorials for Multisim® and LT Spice. Answers to Section Checkups, Related Problems for Examples, True/False Quizzes, Circuit-Action Quizzes, and Self-Tests are found on this website.

Circut Simulation (*www.pearsonglobaleditions.com/Floyd*) These online files include simulation circuits in Multisim® 14 and LT Spice for selected examples, troubleshooting sections, and selected problems in the text. These circuits were created for use with Multisim® or LT Spice software. These circuit simulation programs are widely regarded as excellent for classroom and laboratory learning. However, no part of your textbook is dependent upon the Multisim® or LT Spice software or provided files.

Instructor Resources

To access supplementary materials online, instructors need to request an instructor access code. Go to www.pearsonglobaleditions.com/Floyd to register for an instructor access code. Within 48 hours of registering, you will receive a confirming e-mail including an instructor access code. Once you have received your code, locate your text in the online catalog and click on the Instructor Resources button on the left side of the catalog product page. Select a supplement, and a login page will appear. Once you have logged in, you can access instructor material for all Pearson textbooks. If you have any difficulties accessing the site or downloading a supplement, please contact Customer Service at: http://support.pearson.com/getsupport

Online Instructor's Resource Manual Includes solutions to chapter problems, Device Application results, summary of Multisim® and LT Spice circuit files, and a test item file. Solutions to the lab manual are also included.

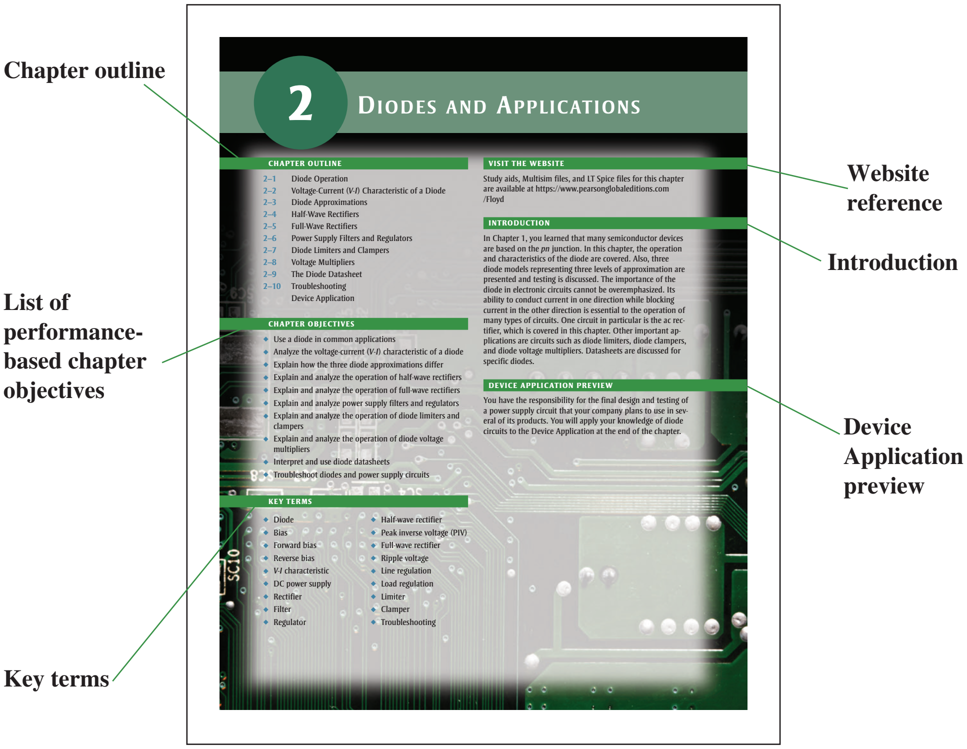
Online Course Support If your program is offering your electronics course in a distance learning format, please contact your local Pearson sales representative for a list of product solutions.

Online PowerPoint® Slides This innovative, interactive PowerPoint slide presentation for each chapter in the book provides an effective supplement to classroom lectures.

Online TestGen This is a test bank of over 800 questions.

Chapter Features

Chapter Opener Each chapter begins with an opening page, as shown in Figure P–1. The chapter opener includes a chapter introduction, a list of chapter sections, chapter objectives, key terms, a Device Application preview, and a website reference for associated study aids.



2 DIODES AND APPLICATIONS

CHAPTER OUTLINE

2–1 Diode Operation
2–2 Voltage-Current (*V-I*) Characteristic of a Diode
2–3 Diode Approximations
2–4 Half-Wave Rectifiers
2–5 Full-Wave Rectifiers
2–6 Power Supply Filters and Regulators
2–7 Diode Limiters and Clampers
2–8 Voltage Multipliers
2–9 The Diode Datasheet
2–10 Troubleshooting
Device Application

CHAPTER OBJECTIVES

- Use a diode in common applications
- Analyze the voltage-current (*V-I*) characteristic of a diode
- Explain how the three diode approximations differ
- Explain and analyze the operation of half-wave rectifiers
- Explain and analyze the operation of full-wave rectifiers
- Explain and analyze power supply filters and regulators
- Explain and analyze the operation of diode limiters and clampers
- Explain and analyze the operation of diode voltage multipliers
- Interpret and use diode datasheets
- Troubleshoot diodes and power supply circuits

KEY TERMS

- Diode
- Bias
- Forward bias
- Reverse bias
- *V-I* characteristic
- DC power supply
- Rectifier
- Filter
- Regulator
- Half-wave rectifier
- Peak inverse voltage (PIV)
- Full-wave rectifier
- Ripple voltage
- Line regulation
- Load regulation
- Limiter
- Clamper
- Troubleshooting

VISIT THE WEBSITE

Study aids, Multisim files, and LT Spice files for this chapter are available at https://www.pearsonglobaleditions.com/Floyd

INTRODUCTION

In Chapter 1, you learned that many semiconductor devices are based on the *pn* junction. In this chapter, the operation and characteristics of the diode are covered. Also, three diode models representing three levels of approximation are presented and testing is discussed. The importance of the diode in electronic circuits cannot be overemphasized. Its ability to conduct current in one direction while blocking current in the other direction is essential to the operation of many types of circuits. One circuit in particular is the ac rectifier, which is covered in this chapter. Other important applications are circuits such as diode limiters, diode clampers, and diode voltage multipliers. Datasheets are discussed for specific diodes.

DEVICE APPLICATION PREVIEW

You have the responsibility for the final design and testing of a power supply circuit that your company plans to use in several of its products. You will apply your knowledge of diode circuits to the Device Application at the end of the chapter.

▲ FIGURE P–1

A typical chapter opener.

Section Opener Each section in a chapter begins with a brief introduction and section objectives. An example is shown in Figure P–2.

Section Checkup Each section in a chapter ends with a list of questions that focus on the main concepts presented in the section. This feature is also illustrated in Figure P–2. The answers to the Section Checkups can be found at: www.pearsonglobaleditions.com/Floyd.

Troubleshooting Sections Many chapters include a troubleshooting section that relates to the topics covered in the chapter and that illustrates troubleshooting procedures and techniques. The Troubleshooting section also provides Multisim® Troubleshooting exercises.

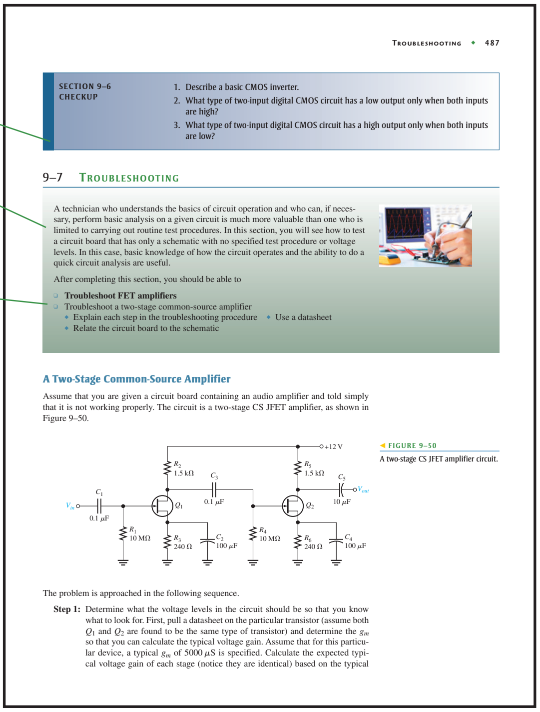
FIGURE P–2

A typical section opener and section review.

Section checkup ends each section.

Introductory paragraph begins each section.

Performance-based section objectives



TROUBLESHOOTING ◆ 487

SECTION 9–6 CHECKUP

1. Describe a basic CMOS inverter.
2. What type of two-input digital CMOS circuit has a low output only when both inputs are high?
3. What type of two-input digital CMOS circuit has a high output only when both inputs are low?

9–7 TROUBLESHOOTING

A technician who understands the basics of circuit operation and who can, if necessary, perform basic analysis on a given circuit is much more valuable than one who is limited to carrying out routine test procedures. In this section, you will see how to test a circuit board that has only a schematic with no specified test procedure or voltage levels. In this case, basic knowledge of how the circuit operates and the ability to do a quick circuit analysis are useful.

After completing this section, you should be able to

- **Troubleshoot FET amplifiers**
- Troubleshoot a two-stage common-source amplifier
  - Explain each step in the troubleshooting procedure
  - Use a datasheet
  - Relate the circuit board to the schematic

A Two-Stage Common-Source Amplifier

Assume that you are given a circuit board containing an audio amplifier and told simply that it is not working properly. The circuit is a two-stage CS JFET amplifier, as shown in Figure 9–50.

FIGURE 9–50

A two-stage CS JFET amplifier circuit.

The problem is approached in the following sequence.

Step 1: Determine what the voltage levels in the circuit should be so that you know what to look for. First, pull a datasheet on the particular transistor (assume both Q_1 and Q_2 are found to be the same type of transistor) and determine the g_m so that you can calculate the typical voltage gain. Assume that for this particular device, a typical g_m of 5000 μS is specified. Calculate the expected typical voltage gain of each stage (notice they are identical) based on the typical

Worked Examples, Related Problems, and Circuit Simulation Exercises Numerous worked-out examples throughout each chapter illustrate and clarify basic concepts or specific procedures. Each example ends with a Related Problem that reinforces or expands on the example by requiring the student to work through a problem similar to the example. Selected examples feature a Multisim® or LT Spice exercise keyed to a file on the companion website that contains the circuit illustrated in the example. A typical example with a Related Problem and a Multisim® or LT Spice exercise are shown in Figure P–3. Answers to Related Problems can be found at: www.pearsonglobaleditions.com/Floyd.

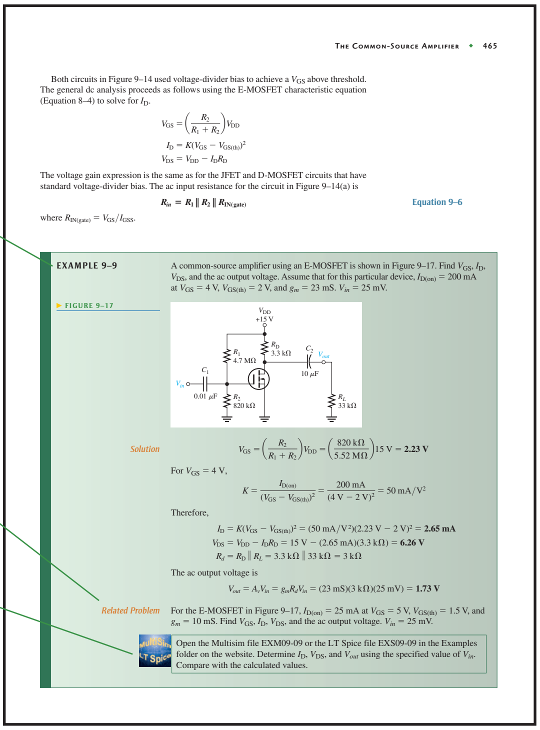
FIGURE P–3

A typical example with a related problem and Multisim®/LT Spice exercise.

Examples are set off from text.

Each example contains a related problem relevant to the example.

Selected examples include a Multisim®/LT Spice exercise coordinated with the circuit simulation files on the website.



THE COMMON-SOURCE AMPLIFIER ◆ 465

Both circuits in Figure 9–14 used voltage-divider bias to achieve a V_{GS} above threshold. The general dc analysis proceeds as follows using the E-MOSFET characteristic equation (Equation 8–4) to solve for I_D.

$$V_{GS} = \left(\frac{R_2}{R_1 + R_2}\right)V_{DD}$$
$$I_D = K(V_{GS} - V_{GS(th)})^2$$
$$V_{DS} = V_{DD} - I_D R_D$$

The voltage gain expression is the same as for the JFET and D-MOSFET circuits that have standard voltage-divider bias. The ac input resistance for the circuit in Figure 9–14(a) is

$$\boldsymbol{R_{in} = R_1 \parallel R_2 \parallel R_{IN(gate)}}$$ Equation 9–6

where $R_{IN(gate)} = V_{GS}/I_{GSS}$.

EXAMPLE 9–9

A common-source amplifier using an E-MOSFET is shown in Figure 9–17. Find V_{GS}, I_D, V_{DS}, and the ac output voltage. Assume that for this particular device, $I_{D(on)} = 200$ mA at $V_{GS} = 4$ V, $V_{GS(th)} = 2$ V, and $g_m = 23$ mS. $V_{in} = 25$ mV.

FIGURE 9–17

Solution

$$V_{GS} = \left(\frac{R_2}{R_1 + R_2}\right)V_{DD} = \left(\frac{820\ \text{k}\Omega}{5.52\ \text{M}\Omega}\right)15\ \text{V} = \mathbf{2.23\ V}$$

For $V_{GS} = 4$ V,

$$K = \frac{I_{D(on)}}{(V_{GS} - V_{GS(th)})^2} = \frac{200\ \text{mA}}{(4\ \text{V} - 2\ \text{V})^2} = 50\ \text{mA/V}^2$$

Therefore,

$$I_D = K(V_{GS} - V_{GS(th)})^2 = (50\ \text{mA/V}^2)(2.23\ \text{V} - 2\ \text{V})^2 = \mathbf{2.65\ mA}$$
$$V_{DS} = V_{DD} - I_D R_D = 15\ \text{V} - (2.65\ \text{mA})(3.3\ \text{k}\Omega) = \mathbf{6.26\ V}$$
$$R_d = R_D \parallel R_L = 3.3\ \text{k}\Omega \parallel 33\ \text{k}\Omega = 3\ \text{k}\Omega$$

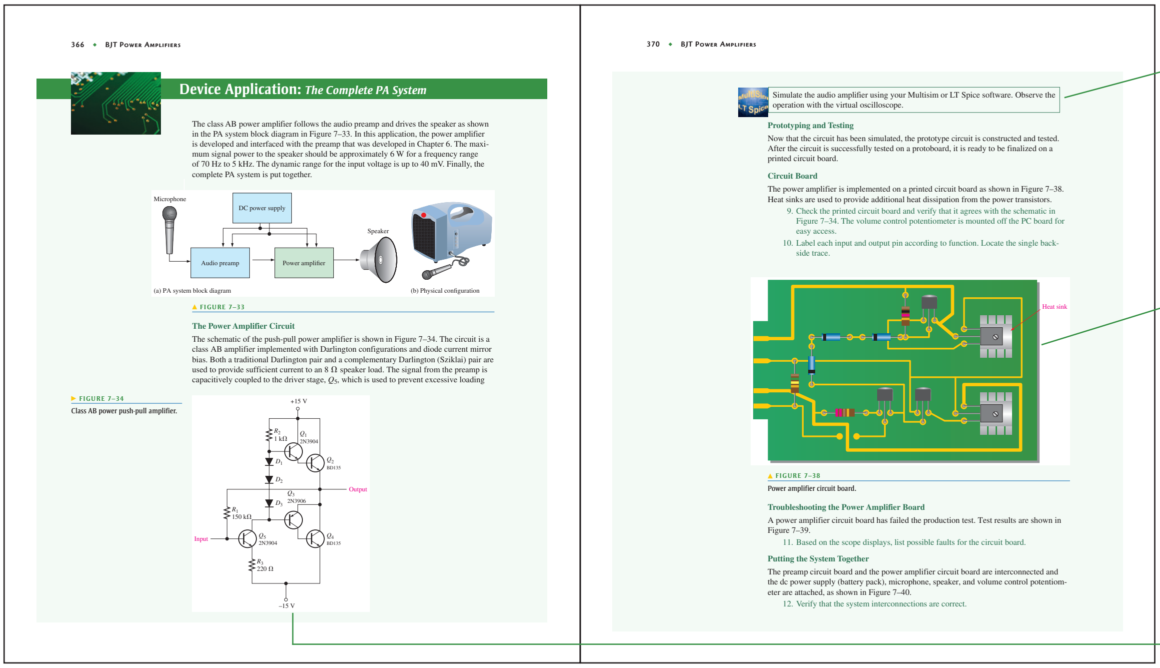
The ac output voltage is

$$V_{out} = A_v V_{in} = g_m R_d V_{in} = (23\ \text{mS})(3\ \text{k}\Omega)(25\ \text{mV}) = \mathbf{1.73\ V}$$

Related Problem For the E-MOSFET in Figure 9–17, $I_{D(on)} = 25$ mA at $V_{GS} = 5$ V, $V_{GS(th)} = 1.5$ V, and $g_m = 10$ mS. Find V_{GS}, I_D, V_{DS}, and the ac output voltage. $V_{in} = 25$ mV.

Open the Multisim file EXM09-09 or the LT Spice file EXS09-09 in the Examples folder on the website. Determine I_D, V_{DS}, and V_{out} using the specified value of V_{in}. Compare with the calculated values.

Device Application This feature follows the last section in most chapters and is identified by a special graphic design. A practical application of devices or circuits covered in the chapter is presented. The student learns how the specific device or circuit is used and is taken through the steps of design specification, simulation, prototyping, circuit board implementation, and testing. A typical Device Application is shown in Figure P–4. Device Applications are optional. Results are provided in the Online Instructor's Resource Manual.



366 ◆ BJT Power Amplifiers

Device Application: ***The Complete PA System***

The class AB power amplifier follows the audio preamp and drives the speaker as shown in the PA system block diagram in Figure 7–33. In this application, the power amplifier is developed and interfaced with the preamp that was developed in Chapter 6. The maximum signal power to the speaker should be approximately 6 W for a frequency range of 70 Hz to 5 kHz. The dynamic range for the input voltage is up to 40 mV. Finally, the complete PA system is put together.

(a) PA system block diagram (b) Physical configuration

▲ FIGURE 7–33

The Power Amplifier Circuit

The schematic of the push-pull power amplifier is shown in Figure 7–34. The circuit is a class AB amplifier implemented with Darlington configurations and diode current mirror bias. Both a traditional Darlington pair and a complementary Darlington (Sziklai) pair are used to provide sufficient current to an 8 Ω speaker load. The signal from the preamp is capacitively coupled to the driver stage, Q_5, which is used to prevent excessive loading

▶ FIGURE 7–34

Class AB power push-pull amplifier.

370 ◆ BJT Power Amplifiers

Simulate the audio amplifier using your Multisim or LT Spice software. Observe the operation with the virtual oscilloscope.

Prototyping and Testing

Now that the circuit has been simulated, the prototype circuit is constructed and tested. After the circuit is successfully tested on a protoboard, it is ready to be finalized on a printed circuit board.

Circuit Board

The power amplifier is implemented on a printed circuit board as shown in Figure 7–38. Heat sinks are used to provide additional heat dissipation from the power transistors.

9. Check the printed circuit board and verify that it agrees with the schematic in Figure 7–34. The volume control potentiometer is mounted off the PC board for easy access.
10. Label each input and output pin according to function. Locate the single backside trace.

▲ FIGURE 7–38

Power amplifier circuit board.

Troubleshooting the Power Amplifier Board

A power amplifier circuit board has failed the production test. Test results are shown in Figure 7–39.

11. Based on the scope displays, list possible faults for the circuit board.

Putting the System Together

The preamp circuit board and the power amplifier circuit board are interconnected and the dc power supply (battery pack), microphone, speaker, and volume control potentiometer are attached, as shown in Figure 7–40.

12. Verify that the system interconnections are correct.

Multisim®/ LT Spice Activity

Printed circuit board

Simulations are provided for most Device Application circuits.

▲ FIGURE P–4

Portion of a typical Device Application section.

Chapter End Matter The following pedagogical features are found at the end of most chapters:

- Summary
- Key Term Glossary
- Key Formulas
- True/False Quiz
- Circuit-Action Quiz
- Self-Test
- Basic Problems
- Advanced Problems
- Datasheet Problems (selected chapters)
- Device Application Problems (many chapters)
- Multisim® Troubleshooting Problems (most chapters)

Suggestions for Using This Textbook

As mentioned, this book covers discrete devices and circuits in Chapters 1 through 11 and linear integrated circuits in Chapters 12 through 17.

Option 1 (two terms) Chapters 1 through 11 can be covered in the first term. Depending on individual preferences and program emphasis, selective coverage may be necessary. Chapters 12 through 17 can be covered in the second term. Again, selective coverage may be necessary.

Option 2 (one term) By omitting certain topics and by maintaining a rigorous schedule, this book can be used in one-term courses. For example, a course covering only discrete devices and circuits would use Chapters 1 through 11 with, perhaps, some selectivity.

Similarly, a course requiring only linear integrated circuit coverage would use Chapters 12 through 17. Another approach is a very selective coverage of discrete devices and circuits topics followed by a limited coverage of integrated circuits (only op-amps, for example). Also, elements such as the Multisim® and LT Spice exercises, and Device Application can be omitted or selectively used.

To the Student

When studying a particular chapter, study one section until you understand it and only then move on to the next one. Read each section and study the related illustrations carefully; think about the material; work through each example step-by-step, work its Related Problem and check the answer; then answer each question in the Section Checkup, and check your answers. Don’t expect each concept to be completely clear after a single reading; you may have to read the material two or even three times. Once you think that you understand the material, review the chapter summary, key formula list, and key term definitions at the end of the chapter. Take the true/false quiz, the circuit-action quiz, and the self-test. Finally, work the assigned problems at the end of the chapter. Working through these problems is perhaps the most important way to check and reinforce your comprehension of the chapter. By working problems, you acquire an additional level of insight and understanding and develop logical thinking that reading or classroom lectures alone do not provide.

Generally, you cannot fully understand a concept or procedure by simply watching or listening to someone else. Only hard work and critical thinking will produce the results you expect and deserve.

Acknowledgments

Many capable people have contributed to the tenth edition of *Electronic Devices.* It has been thoroughly reviewed and checked for both content and accuracy. Those at Pearson who have contributed greatly to this project throughout the many phases of development and production include Faraz Sharique Ali and Rex Davidson. Thanks to Jyotsna Ojha at Cenveo for her management of the art and text programs. Dave Buchla contributed extensively to the content of the book, helping to make this edition the best one yet. Gary Snyder created the circuit files for the Multisim® and LT Spice features in this edition. I wish to express my appreciation to those already mentioned as well as the reviewers who provided many valuable suggestions and constructive criticism that greatly influenced this edition. These reviewers are David Beach, Indiana State University; Mahmoud Chitsazzadeh, Community College of Allegheny County; Wang Ng, Sacramento City College; Almasy Edward, Pennsylvania College of Technology; and Moser Randall, Pennsylvania College of Technology.

Tom Floyd

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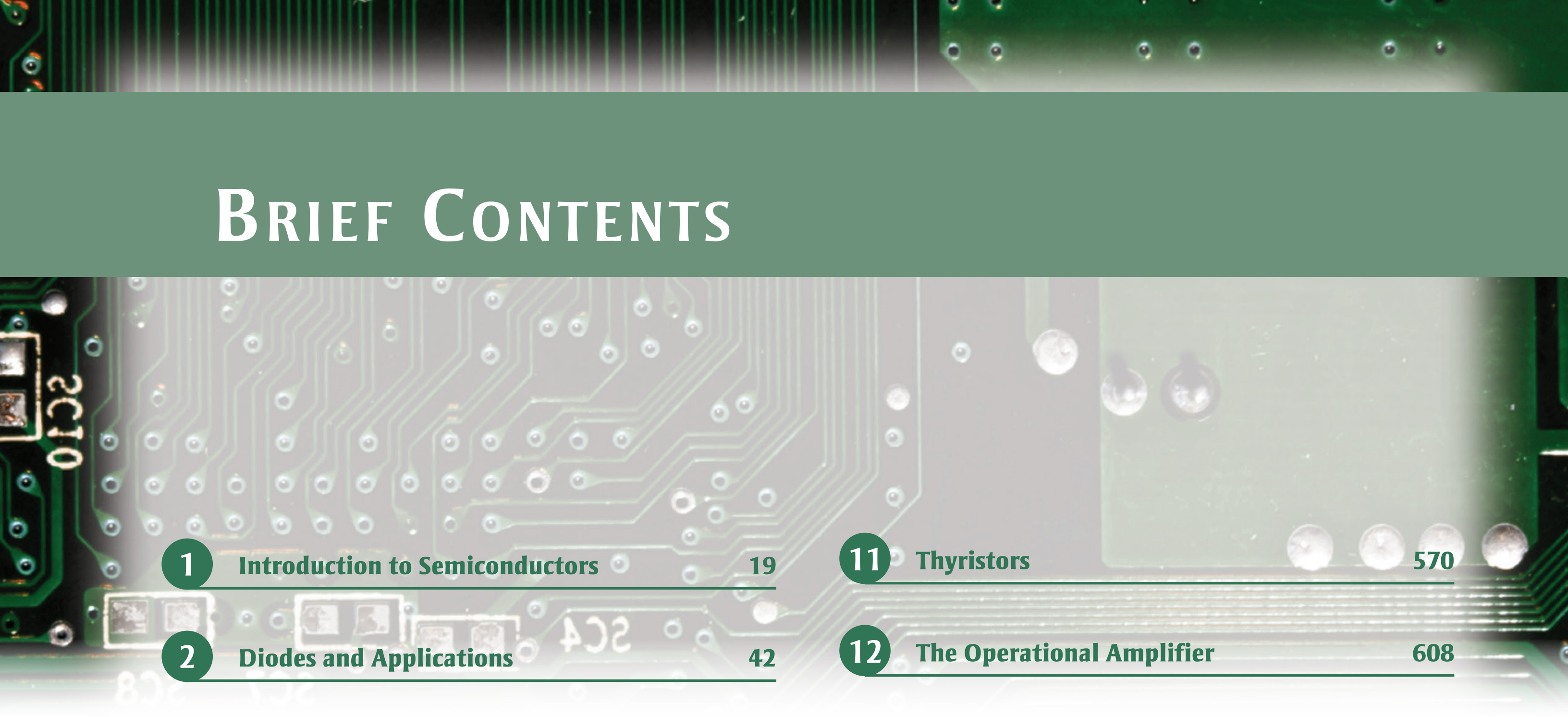
BRIEF CONTENTS



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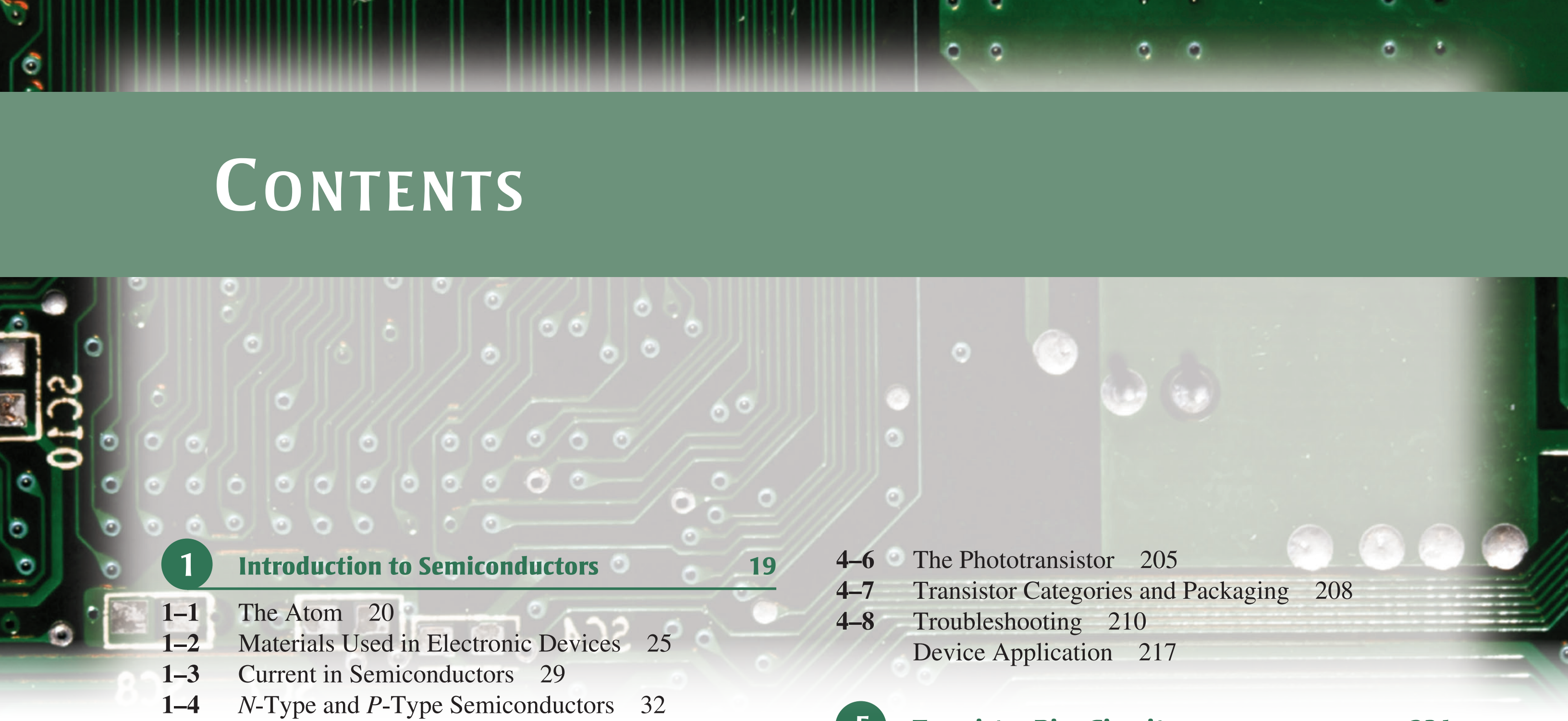

CONTENTS

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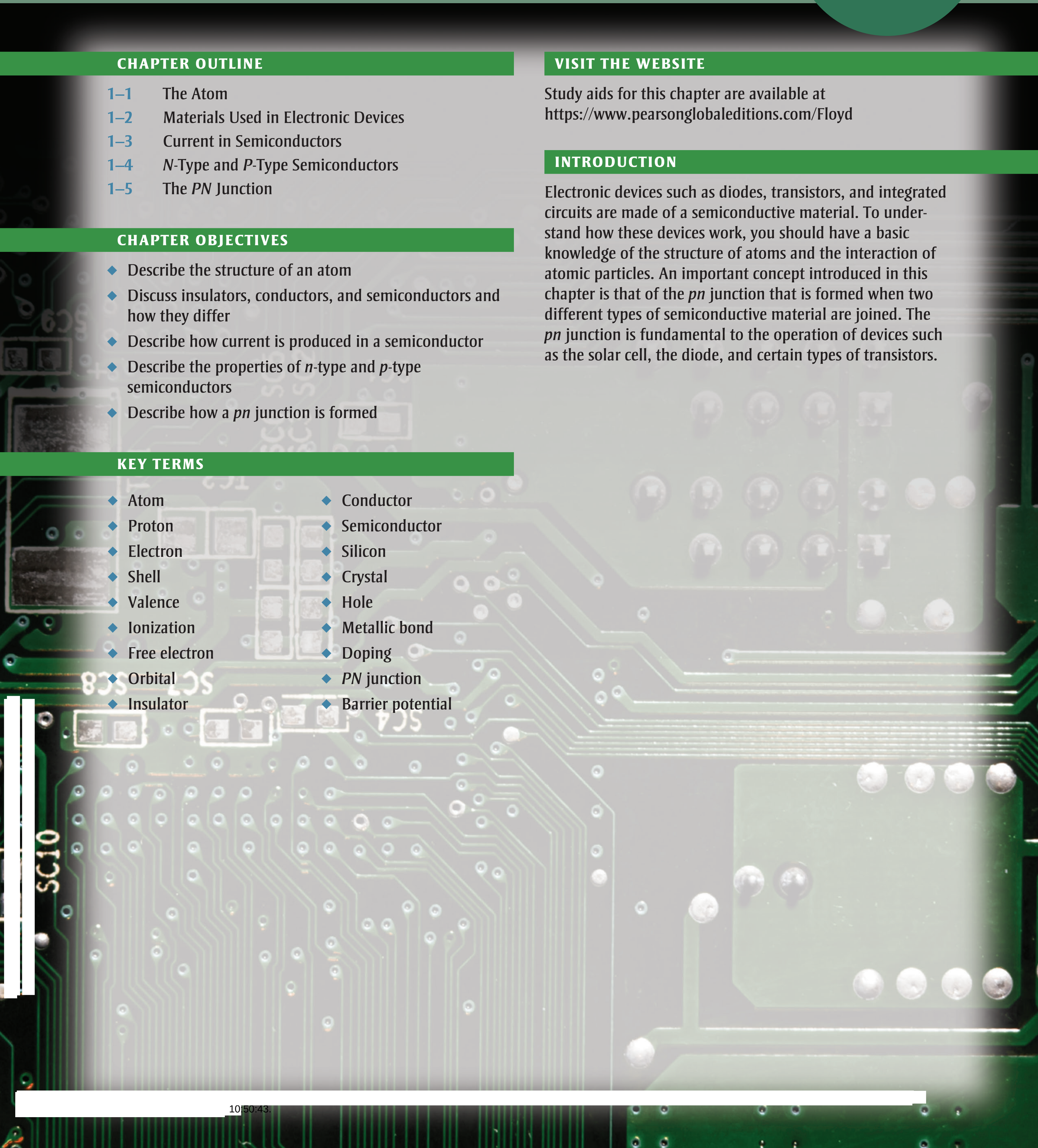
INTRODUCTION TO SEMICONDUCTORS

1



CHAPTER OUTLINE

CHAPTER OBJECTIVES

- Describe the structure of an atom
- Discuss insulators, conductors, and semiconductors and how they differ
- Describe how current is produced in a semiconductor
- Describe the properties of *n*-type and *p*-type semiconductors
- Describe how a *pn* junction is formed

KEY TERMS

- Atom
- Proton
- Electron
- Shell
- Valence
- Ionization
- Free electron
- Orbital
- Insulator
- Conductor
- Semiconductor
- Silicon
- Crystal
- Hole
- Metallic bond
- Doping
- *PN* junction
- Barrier potential

VISIT THE WEBSITE

Study aids for this chapter are available at https://www.pearsonglobaleditions.com/Floyd

INTRODUCTION

Electronic devices such as diodes, transistors, and integrated circuits are made of a semiconductive material. To understand how these devices work, you should have a basic knowledge of the structure of atoms and the interaction of atomic particles. An important concept introduced in this chapter is that of the *pn* junction that is formed when two different types of semiconductive material are joined. The *pn* junction is fundamental to the operation of devices such as the solar cell, the diode, and certain types of transistors.

1–1 THE ATOM

All matter is composed of atoms; all atoms consist of electrons, protons, and neutrons except normal hydrogen, which does not have a neutron. Each element in the periodic table has a unique atomic structure, and all atoms for a given element have the same number of protons. At first, the atom was thought to be a tiny indivisible sphere. Later it was shown that the atom was not a single particle but was made up of a small, dense nucleus around which electrons orbit at great distances from the nucleus, similar to the way planets orbit the sun. Niels Bohr proposed that the electrons in an atom circle the nucleus in different obits, similar to the way planets orbit the sun in our solar system. The Bohr model is often referred to as the planetary model. Another view of the atom called the *quantum model* is considered a more accurate representation, but it is difficult to visualize. For most practical purposes in electronics, the Bohr model suffices and is commonly used because it is easy to visualize.

After completing this section, you should be able to

- ☐ **Describe the structure of an atom**
  - ◆ Discuss the Bohr model of an atom
  - ◆ Define *electron, proton, neutron,* and *nucleus*
- ☐ Define *atomic number*
- ☐ Discuss electron shells and orbits
  - ◆ Explain energy levels
- ☐ Define *valence electron*
- ☐ Discuss ionization
  - ◆ Define *free electron* and *ion*
- ☐ Discuss the basic concept of the quantum model of the atom

The Bohr Model

An **atom*** is the smallest particle of an element that retains the characteristics of that element. Each of the known 118 elements has atoms that are different from the atoms of all other elements. This gives each element a unique atomic structure. According to the classical Bohr model, atoms have a planetary type of structure that consists of a central nucleus surrounded by orbiting electrons, as illustrated in Figure 1–1. The **nucleus** consists of positively charged particles called **protons** and uncharged particles called **neutrons.** The basic particles of negative charge are called **electrons**.

Each type of atom has a certain number of electrons and protons that distinguishes it from the atoms of all other elements. For example, the simplest atom is that of hydrogen, which has one proton and one electron, as shown in Figure 1–2(a). As another example, the helium atom, shown in Figure 1–2(b), has two protons and two neutrons in the nucleus and two electrons orbiting the nucleus.

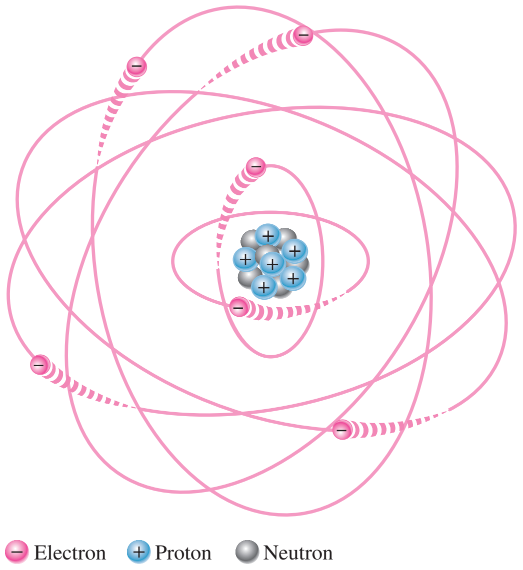
HISTORY NOTE

Niels Henrik David Bohr (October 7, 1885–November 18, 1962) was a Danish physicist, who made important contributions to understanding the structure of the atom and quantum mechanics by postulating the "planetary" model of the atom. He received the Nobel Prize in physics in 1922. Bohr drew upon the work or collaborated with scientists such as Dalton, Thomson, and Rutherford, among others and has been described as one of the most influential physicists of the 20th century.

Atomic Number

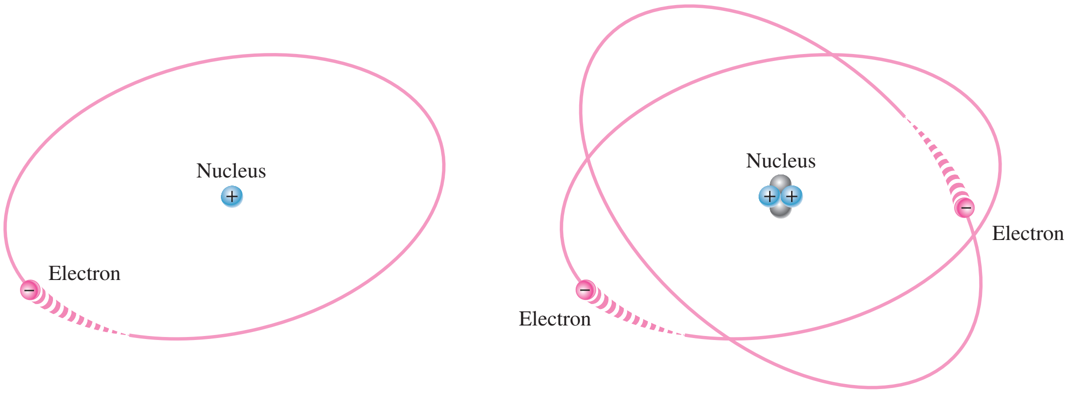
All elements are arranged in the periodic table of the elements in order according to their atomic number. The **atomic number** equals the number of protons in the nucleus, which is the same as the number of electrons in an electrically balanced (neutral) atom. For example, hydrogen has an atomic number of 1 and helium has an atomic number of 2. In their normal (or neutral) state, all atoms of a given element have the same number of electrons as protons; the positive charges cancel the negative charges, and the atom has a net charge of zero.

***All bold terms are in the end-of-book glossary. The bold terms in color are key terms and are also defined at the end of the chapter.**



▲ **FIGURE 1–1**

The Bohr model of an atom showing electrons in orbits around the nucleus, which consists of protons and neutrons. The “tails” on the electrons indicate motion.



(a) Hydrogen atom

(b) Helium atom

▲ **FIGURE 1–2**

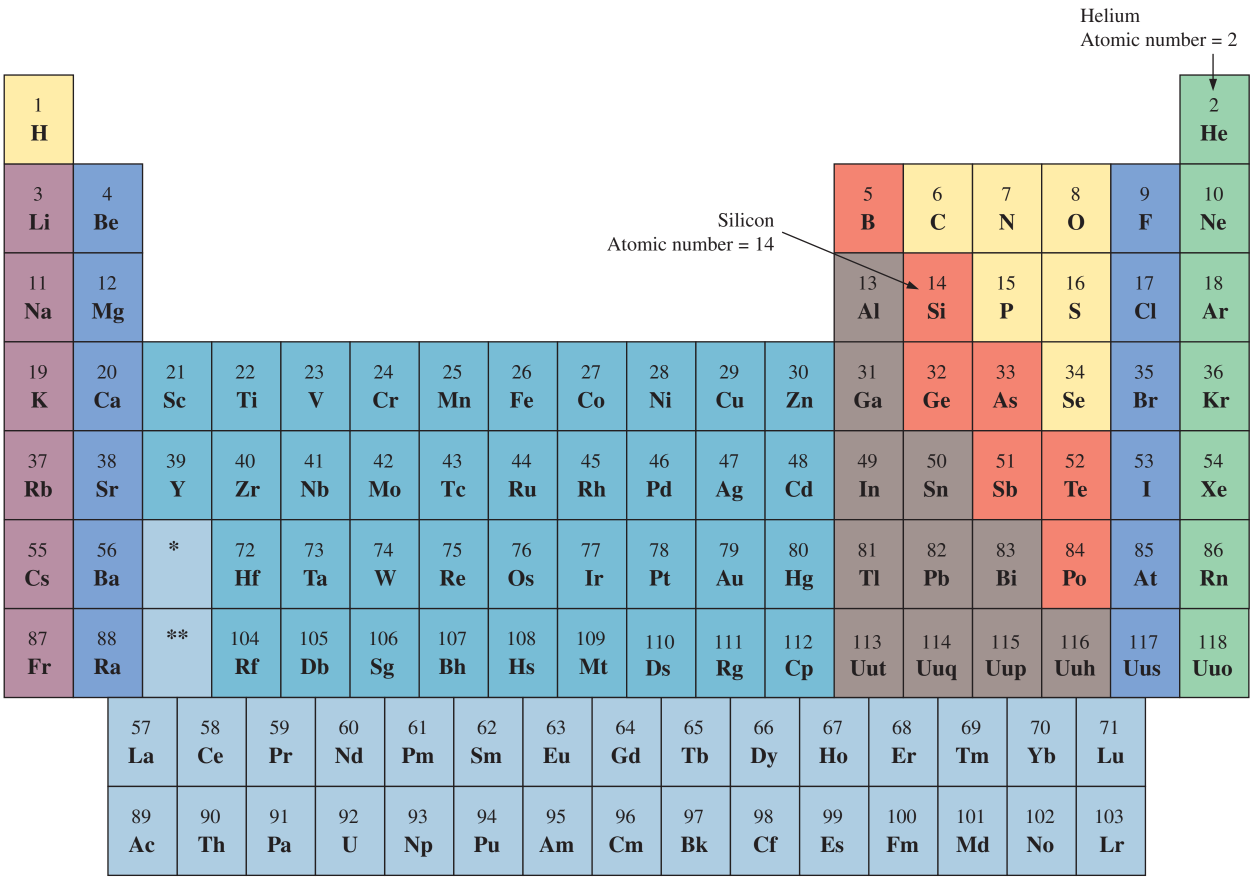
Two simple atoms, hydrogen and helium.

Atomic numbers of all the elements are shown on the periodic table of the elements in Figure 1–3.

Electrons and Shells

Energy Levels Electrons orbit the nucleus of an atom at certain distances from the nucleus. Electrons near the nucleus have less energy than those in more distant orbits. Only discrete (separate and distinct) values of electron energies exist within atomic structures. Therefore, electrons must orbit only at discrete distances from the nucleus.

Each discrete distance (**orbit**) from the nucleus corresponds to a certain energy level. In an atom, the orbits are grouped into energy levels known as **shells**. A given atom has a fixed number of shells. Each shell has a fixed maximum number of electrons. The shells (energy levels) are designated 1, 2, 3, and so on, with 1 being closest to the nucleus. The Bohr model of the silicon atom is shown in Figure 1–4. Notice that there are 14 electrons surrounding the nucleus with exactly 14 protons, and usually 14 neutrons in the nucleus.



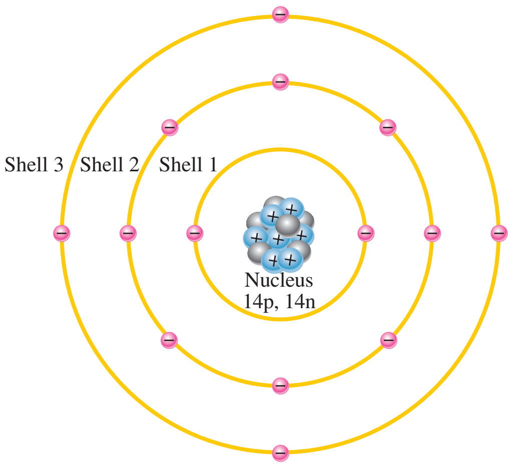
1 H																	2 He
3 Li	4 Be											5 B	6 C	7 N	8 O	9 F	10 Ne
11 Na	12 Mg											13 Al	14 Si	15 P	16 S	17 Cl	18 Ar
19 K	20 Ca	21 Sc	22 Ti	23 V	24 Cr	25 Mn	26 Fe	27 Co	28 Ni	29 Cu	30 Zn	31 Ga	32 Ge	33 As	34 Se	35 Br	36 Kr
37 Rb	38 Sr	39 Y	40 Zr	41 Nb	42 Mo	43 Tc	44 Ru	45 Rh	46 Pd	47 Ag	48 Cd	49 In	50 Sn	51 Sb	52 Te	53 I	54 Xe
55 Cs	56 Ba	*	72 Hf	73 Ta	74 W	75 Re	76 Os	77 Ir	78 Pt	79 Au	80 Hg	81 Tl	82 Pb	83 Bi	84 Po	85 At	86 Rn
87 Fr	88 Ra	**	104 Rf	105 Db	106 Sg	107 Bh	108 Hs	109 Mt	110 Ds	111 Rg	112 Cp	113 Uut	114 Uuq	115 Uup	116 Uuh	117 Uus	118 Uuo
		57 La	58 Ce	59 Pr	60 Nd	61 Pm	62 Sm	63 Eu	64 Gd	65 Tb	66 Dy	67 Ho	68 Er	69 Tm	70 Yb	71 Lu	
		89 Ac	90 Th	91 Pa	92 U	93 Np	94 Pu	95 Am	96 Cm	97 Bk	98 Cf	99 Es	100 Fm	101 Md	102 No	103 Lr	

▲ FIGURE 1–3

The periodic table of the elements. Some tables also show atomic mass.

▶ FIGURE 1–4

Illustration of the Bohr model of the silicon atom.



The Maximum Number of Electrons in Each Shell The maximum number of electrons (N_e) that can exist in each shell of an atom is a fact of nature and can be calculated by the formula,

Equation 1–1

$$N_e = 2n^2$$

where n is the number of the shell. The maximum number of electrons that can exist in the innermost shell (shell 1) is

$$N_e = 2n^2 = 2(1)^2 = 2$$

The maximum number of electrons that can exist in shell 2 is

$$N_e = 2n^2 = 2(2)^2 = 2(4) = 8$$

The maximum number of electrons that can exist in shell 3 is

$$N_e = 2n^2 = 2(3)^2 = 2(9) = 18$$

The maximum number of electrons that can exist in shell 4 is

$$N_e = 2n^2 = 2(4)^2 = 2(16) = 32$$

Valence Electrons

Electrons that are in orbits farther from the nucleus have higher energy and are less tightly bound to the atom than those closer to the nucleus. This is because the force of attraction between the positively charged nucleus and the negatively charged electron decreases with increasing distance from the nucleus. Electrons with the highest energy exist in the outermost shell of an atom and are relatively loosely bound to the atom. This outermost shell is known as the **valence** shell, and electrons in this shell are called *valence electrons.* These valence electrons contribute to chemical reactions and bonding within the structure of a material and determine its electrical properties. When a valence electron gains sufficient energy from an external source, it can break free from its atom. This is the basis for conduction in materials.

Ionization

When an atom absorbs energy, the valence electrons can easily jump to higher energy shells. If a valence electron acquires a sufficient amount of energy, called *ionization energy,* it can actually escape from the outer shell and the atom's influence. The departure of a valence electron leaves a previously neutral atom with an excess of positive charge (more protons than electrons). The process of losing a valence electron is known as **ionization**, and the resulting positively charged atom is called a *positive ion.* For example, the chemical symbol for hydrogen is H. When a neutral hydrogen atom loses its valence electron and becomes a positive ion, it is designated H^+. The escaped valence electron is called a **free electron**.

The reverse process can occur in certain atoms when a free electron collides with the atom and is captured, releasing energy. The atom that has acquired the extra electron is called a *negative ion*. The ionization process is not restricted to single atoms. In many chemical reactions, a group of atoms that are bonded together can lose or acquire one or more electrons.

For some nonmetallic materials such as chlorine, a free electron can be captured by the neutral atom, forming a negative ion. In the case of chlorine, the ion is more stable than the neutral atom because it has a filled outer shell. The chlorine ion is designated as Cl^-.

The Quantum Model

Although the Bohr model of an atom is widely used because of its simplicity and ease of visualization, it is not a complete model. The quantum model is considered to be more accurate. The quantum model is a statistical model and very difficult to understand or visualize. Like the Bohr model, the quantum model has a nucleus of protons and neutrons surrounded by electrons. Unlike the Bohr model, the electrons in the quantum model do not exist in precise circular orbits as particles. Three important principles underlie the quantum model: the wave-particle duality principle, the uncertainty principle, and the superposition principle.

- *Wave-particle duality.* Just as light can be thought of as exhibiting both a wave and a particle **(photon),** electrons are thought to exhibit a wave-particle duality. The velocity of an orbiting electron is related to its wavelength, which interferes with neighboring electron wavelengths by amplifying or canceling each other.
- *Uncertainly principle.* As you know, a wave is characterized by peaks and valleys; therefore, electrons acting as waves cannot be precisely identified in terms of their position. According to a principle ascribed to Heisenberg, it is impossible to determine simultaneously both the position and velocity of an electron with any degree

FYI

Atoms are extremely small and cannot be seen even with the strongest optical microscopes; however, a scanning tunneling microscope can detect a single atom. The nucleus is so small and the electrons orbit at such distances that the atom is mostly empty space. To put it in perspective, if the proton in a hydrogen atom were the size of a golf ball, the electron orbit would be approximately one mile away.

Protons and neutrons are approximately the same mass. The mass of an electron is 1/1836 of a proton. Within protons and neutrons there are even smaller particles called quarks. Quarks are the subject of intense study by particle physicists as they help explain the existence of more than 100 subatomic particles.

of accuracy or certainty. The result of this principle produces a concept of the atom with *probability clouds,* which are mathematical descriptions of where electrons in an atom are most likely to be located.

- *Superposition.* A principle of quantum theory that describes a challenging concept about the behavior of matter and forces at the subatomic level. Basically, the principle states that although the state of any object is unknown, it is actually in all possible states simultaneously as long as an observation is not attempted. An analogy known as Schrodinger's cat is often used to illustrate in an oversimplified way quantum superposition. The analogy goes as follows: A living cat is placed in a metal box with a vial of hydrocyanic acid and a very small amount of a radioactive substance. Should even a single atom of the radioactive substance decay during a test period, a relay mechanism will be activated and will cause a hammer to break the vial and kill the cat. An observer cannot know whether or not this sequence has occurred. According to quantum theory, the cat exists in a superposition of both the alive and dead states simultaneously.

In the quantum model, each shell or energy level consists of up to four subshells called **orbitals**, which are designated *s*, *p*, *d*, and *f*. Orbital *s* can hold a maximum of two electrons, orbital *p* can hold six electrons, orbital *d* can hold 10 electrons, and orbital *f* can hold 14 electrons. Each atom can be described by an electron configuration table that shows the shells or energy levels, the orbitals, and the number of electrons in each orbital. For example, the electron configuration table for the nitrogen atom is given in Table 1–1. The first full-size number is the shell or energy level, the letter is the orbital, and the exponent is the number of electrons in the orbital.

▶ **TABLE 1–1**

Electron configuration table for nitrogen.

NOTATION	EXPLANATION
$1s^2$	2 electrons in shell 1, orbital *s*
$2s^2$ $2p^3$	5 electrons in shell 2: 2 in orbital *s*, 3 in orbital *p*

Atomic orbitals do not resemble a discrete circular path for the electron as depicted in Bohr's planetary model. In the quantum picture, each shell in the Bohr model is a three-dimensional space surrounding the atom that represents the mean (average) energy of the electron cloud. The term **electron cloud** (probability cloud) is used to describe the area around an atom's nucleus where an electron will probably be found.

EXAMPLE 1–1

Using the atomic number from the periodic table in Figure 1–3, describe a silicon (Si) atom using an electron configuration table.

Solution The atomic number of silicon is 14. This means that there are 14 protons in the nucleus. Since there is always the same number of electrons as protons in a neutral atom, there are also 14 electrons. As you know, there can be up to two electrons in shell 1, eight in shell 2, and eighteen in shell 3. Therefore, in silicon there are two electrons in shell 1, eight electrons in shell 2, and four electrons in shell 3 for a total of 14 electrons. The electron configuration table for silicon is shown in Table 1–2.

▶ **TABLE 1–2**

NOTATION	EXPLANATION
$1s^2$	2 electrons in shell 1, orbital *s*
$2s^2$ $2p^6$	8 electrons in shell 2: 2 in orbital *s*, 6 in orbital *p*
$3s^2$ $3p^2$	4 electrons in shell 3: 2 in orbital *s*, 2 in orbital *p*

*Related Problem** Develop an electron configuration table for the germanium (Ge) atom in the periodic table.

*** Answers can be found at www.pearsonglobaleditions.com/Floyd.**

In a three-dimensional representation of the quantum model of an atom, the *s*-orbitals are shaped like spheres with the nucleus in the center. For energy level 1, the sphere is a single sphere, but for energy levels 2 or more, each single *s*-orbital is composed of nested spherical shells. A *p*-orbital for shell 2 has the form of two ellipsoidal lobes with a point of tangency at the nucleus (sometimes referred to as a dumbbell shape.) The three *p*-orbitals in each energy level are oriented at right angles to each other. One is oriented on the *x*-axis, one on the *y*-axis, and one on the *z*-axis. For example, a view of the quantum model of a sodium atom (Na) that has 11 electrons as shown in Figure 1–5. The three axes are shown to give you a 3-D perspective.

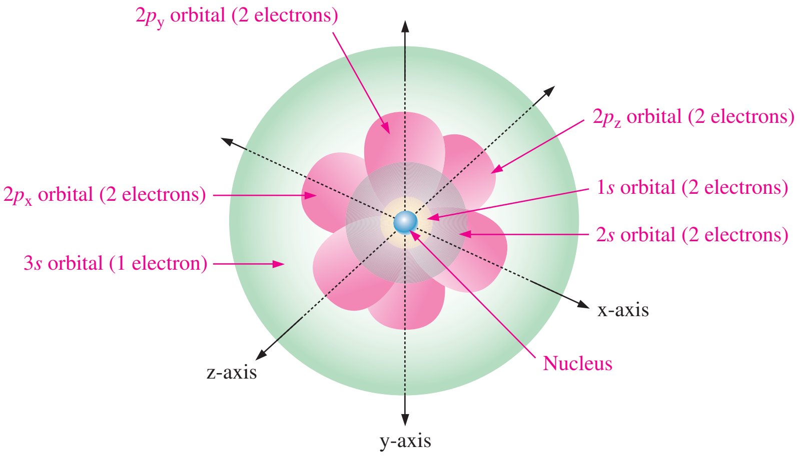


FIGURE 1–5

Three-dimensional quantum model of the sodium atom, showing the orbitals and number of electrons in each orbital.

SECTION 1–1 CHECKUP

Answers can be found at www.pearsonglobaleditions.com/Floyd.

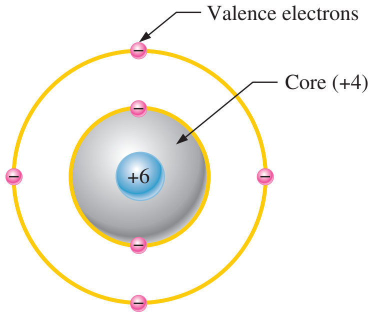
1. Describe the Bohr model of the atom.
2. Define *electron*.
3. What is the nucleus of an atom composed of? Define each component.
4. Define *atomic number*.
5. Discuss electron shells and orbits and their energy levels.
6. What is a valence electron?
7. What is a free electron?
8. Discuss the difference between positive and negative ionization.
9. Name three principles that distinguish the quantum model.

1–2 MATERIALS USED IN ELECTRONIC DEVICES

In terms of their electrical properties, materials can be classified into three groups: conductors, semiconductors, and insulators. When atoms combine to form a solid, crystalline material, they arrange themselves in a symmetrical pattern. The atoms within a semiconductor crystal structure are held together by covalent bonds, which are created by the interaction of the valence electrons of the atoms. Silicon is a crystalline material.

After completing this section, you should be able to

- ☐ **Discuss insulators, conductors, and semiconductors and how they differ**
  - ◆ Define the *core* of an atom ◆ Describe the carbon atom ◆ Name two types each of semiconductors, conductors, and insulators
- ☐ Explain the band gap
  - ◆ Define *valence band* and *conduction band* ◆ Compare a semiconductor atom to a conductor atom
- ☐ Discuss silicon and gemanium atoms
- ☐ Explain covalent bonds
  - ◆ Define *crystal*



▲ FIGURE 1–6

Diagram of a carbon atom.

Insulators, Conductors, and Semiconductors

All materials are made up of atoms. These atoms contribute to the electrical properties of a material, including its ability to conduct electrical current.

For purposes of discussing electrical properties, an atom can be represented by the valence shell and a **core** that consists of all the inner shells and the nucleus. This concept is illustrated in Figure 1–6 for a carbon atom. Carbon is used in some types of electrical resistors. Notice that the carbon atom has four electrons in the valence shell and two electrons in the inner shell. The nucleus consists of six protons and six neutrons, so the +6 indicates the positive charge of the six protons. The core has a net charge of +4 (+6 for the nucleus and −2 for the two inner-shell electrons).

Insulators An **insulator** is a material that does not conduct electrical current under normal conditions. Most good insulators are compounds rather than single-element materials and have very high resistivities. Valence electrons are tightly bound to the atoms; therefore, there are very few free electrons in an insulator. Examples of insulators are rubber, plastics, glass, mica, and quartz.

Conductors A **conductor** is a material that easily conducts electrical current. Most metals are good conductors. The best conductors are single-element materials, such as copper (Cu), silver (Ag), gold (Au), and aluminum (Al), which are characterized by atoms with only one valence electron very loosely bound to the atom. These loosely bound valence electrons can become free electrons with the addition of a small amount of energy to free them from the atom. Therefore, in a conductive material the free electrons are available to carry current.

Semiconductors A **semiconductor** is a material that is between conductors and insulators in its ability to conduct electrical current. A semiconductor in its pure (intrinsic) state is neither a good conductor nor a good insulator. Single-element semiconductors are antimony (Sb), arsenic (As), astatine (At), boron (B), polonium (Po), tellurium (Te), silicon (Si), and germanium (Ge). Compound semiconductors such as gallium arsenide, indium phosphide, gallium nitride, silicon carbide, and silicon germanium are also commonly used. The single-element semiconductors are characterized by atoms with four valence electrons. Silicon is the most commonly used semiconductor.

Band Gap

In solid materials, interactions between atoms "smear" the valence shell into a band of energy levels called the *valence band*. Valence electrons are confined to that band. When an electron acquires enough additional energy, it can leave the valence shell, become a *free electron,* and exist in what is known as the *conduction band.*

The difference in energy between the valence band and the conduction band is called an *energy gap* or **band gap.** This is the amount of energy that a valence electron must have in order to jump from the valence band to the conduction band. Once in the conduction band, the electron is free to move throughout the material and is not tied to any given atom.

Figure 1–7 shows energy diagrams for insulators, semiconductors, and conductors. The energy gap or band gap is the difference between two energy levels and electrons are "not allowed" in this energy gap based on quantum theory. Although an electron may not exist in this region, it can "jump" across it under certain conditions. For insulators, the gap can be crossed only when breakdown conditions occur—as when a very high voltage is applied across the material. The band gap is illustrated in Figure 1–7(a) for insulators. In semiconductors the band gap is smaller, allowing an electron in the valence band to jump into the conduction band if it absorbs a photon. The band gap depends on the semiconductor material. This is illustrated in Figure 1–7(b). In conductors, the conduction band and valence band overlap, so there is no gap, as shown in Figure 1–7(c). This means that electrons in the valence band move freely into the conduction band, so there are always electrons available as free electrons.

FYI

Next to silicon, the second most common semiconductive material is gallium arsenide, GaAs. This is a crystalline compound, not an element. Its properties can be controlled by varying the relative amount of gallium and arsenic.

GaAs has the advantage of making semiconductor devices that respond very quickly to electrical signals. It is widely used in high-frequency applications and in light-emitting diodes and solar cells.

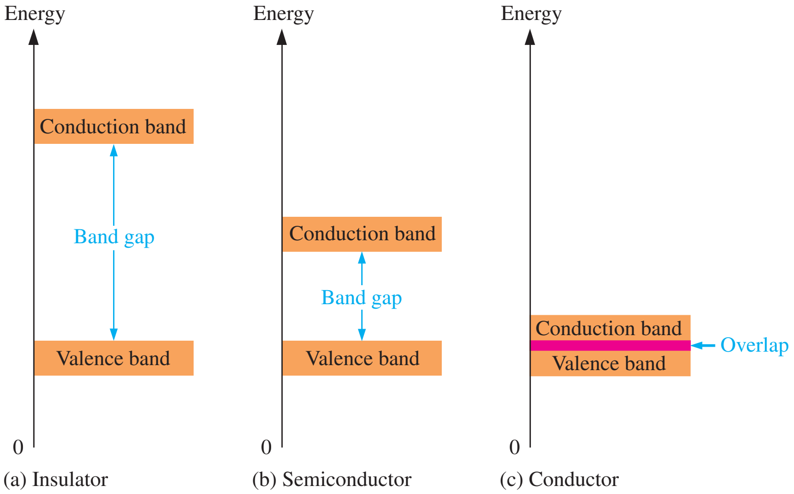
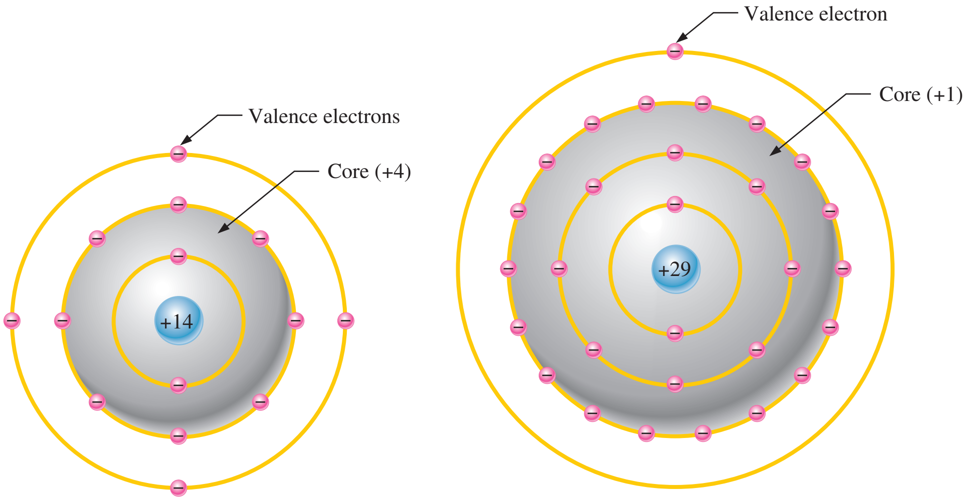


FIGURE 1–7

Energy diagrams for the three types of materials.

Comparison of a Semiconductor Atom to a Conductor Atom

Silicon is a semiconductor and copper is a conductor. Bohr diagrams of the silicon atom and the copper atom are shown in Figure 1–8. Notice that the core of the silicon atom has a net charge of +4 (14 protons – 10 electrons) and the core of the copper atom has a net charge of +1 (29 protons – 28 electrons). Recall that the core includes everything except the valence electrons.


(a) Silicon atom

(b) Copper atom

FIGURE 1–8

Bohr diagrams of the silicon and copper atoms.

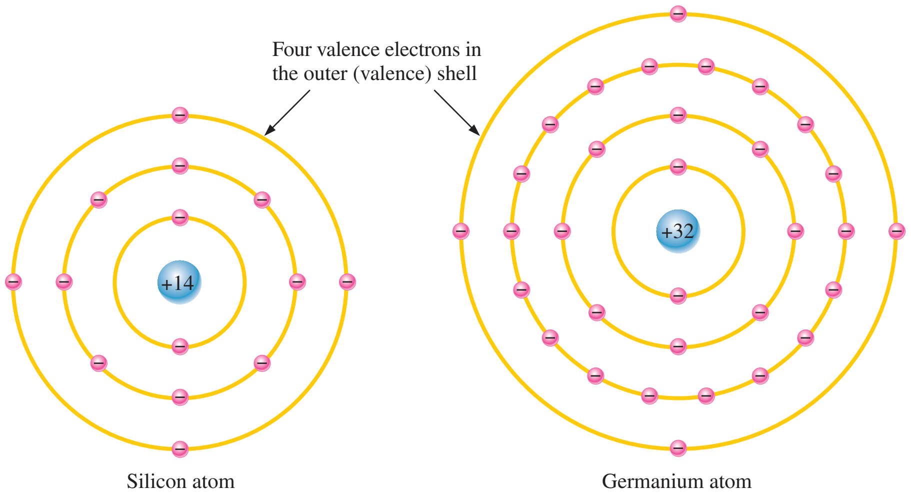
The valence electron in the copper atom "feels" an attractive force of +1 compared to a valence electron in the silicon atom which "feels" an attractive force of +4. Therefore, there is more force trying to hold a valence electron to the atom in silicon than in copper. The copper's valence electron is in the fourth shell, which is a greater distance from its nucleus than the silicon's valence electron in the third shell. Recall that, electrons farthest from the nucleus have the most energy. The valence electron in copper has more energy than the valence electron in silicon. This means that it is easier for valence electrons in copper to acquire enough additional energy to escape from their atoms and become free electrons than it is in silicon. In fact, large numbers of valence electrons in copper already have sufficient energy to be free electrons at normal room temperature.

Silicon and Germanium

The atomic structures of silicon and germanium are compared in Figure 1–9. **Silicon** is used in diodes, transistors, integrated circuits, and other semiconductor devices. Notice that both silicon and **germanium** have the characteristic four valence electrons.

▶ FIGURE 1–9

Diagrams of the silicon and germanium atoms.

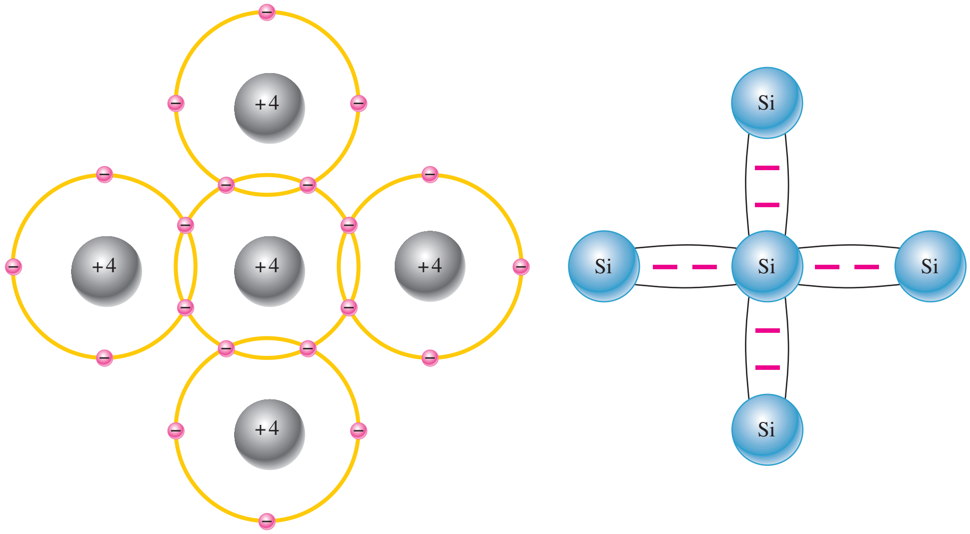


The valence electrons in germanium are in the fourth shell while those in silicon are in the third shell, closer to the nucleus. This means that the germanium valence electrons are at higher energy levels than those in silicon and, therefore, require a smaller amount of additional energy to escape from the atom. This property makes germanium more unstable at high temperatures and results in excessive reverse current. This is why silicon is a more widely used semiconductive material.

Covalent Bonds Figure 1–10 shows how each silicon atom positions itself with four adjacent silicon atoms to form a silicon **crystal**, which is a three-dimensional symmetrical arrangement of atoms. A silicon (Si) atom with its four valence electrons shares an electron with each of its four neighbors. This effectively creates eight shared valence electrons for each atom and produces a state of chemical stability. Also, this sharing of valence electrons produces a strong **covalent bond** that hold the atoms together; each valence electron is attracted equally by the two adjacent atoms which share it. Covalent bonding in an intrinsic silicon crystal is shown in Figure 1–11. An **intrinsic** crystal is one that has no impurities. Covalent bonding for germanium is similar because it also has four valence electrons.

▶ FIGURE 1–10

Illustration of covalent bonds in silicon.



(a) The center silicon atom shares an electron with each of the four surrounding silicon atoms, creating a covalent bond with each. The surrounding atoms are in turn bonded to other atoms, and so on.

(b) Bonding diagram. The red negative signs represent the shared valence electrons.

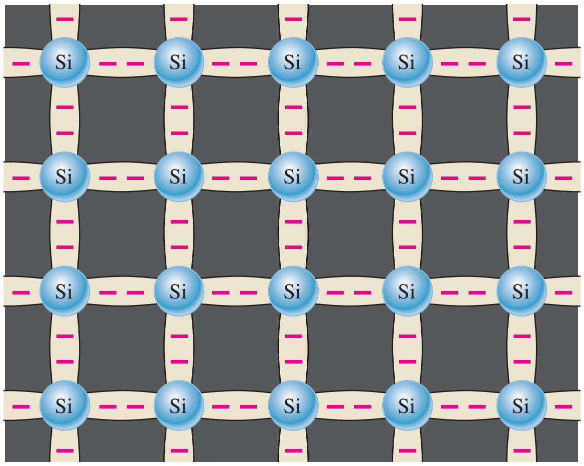


FIGURE 1–11

Covalent bonds in a silicon crystal.

SECTION 1–2 CHECKUP

1. What is the basic difference between conductors and insulators?
2. How do semiconductors differ from conductors and insulators?
3. How many valence electrons does a conductor such as copper have?
4. How many valence electrons does a semiconductor have?
5. Name three of the best conductive materials.
6. What is the most widely used semiconductive material?
7. Why does a semiconductor have fewer free electrons than a conductor?
8. How are covalent bonds formed?
9. What is meant by the term *intrinsic*?
10. What is a crystal?

1–3 CURRENT IN SEMICONDUCTORS

The way a material conducts electrical current is important in understanding how electronic devices operate. You can't really understand the operation of a device such as a diode or transistor without knowing something about current in semiconductors.

After completing this section, you should be able to

- ❑ **Describe how current is produced in a semiconductor**
- ❑ Discuss conduction electrons and holes
  - ◆ Explain an electron-hole pair ◆ Discuss recombination
- ❑ Explain electron and hole current

As you have learned, the electrons in a solid can exist only within prescribed energy bands. Each shell corresponds to a certain energy band and is separated from adjacent shells by band gaps, in which no electrons can exist. Figure 1–12 shows the energy band diagram for the atoms in a pure silicon crystal at its lowest energy level. There are no electrons shown in the conduction band, a condition that occurs *only* at a temperature of absolute 0 Kelvin.

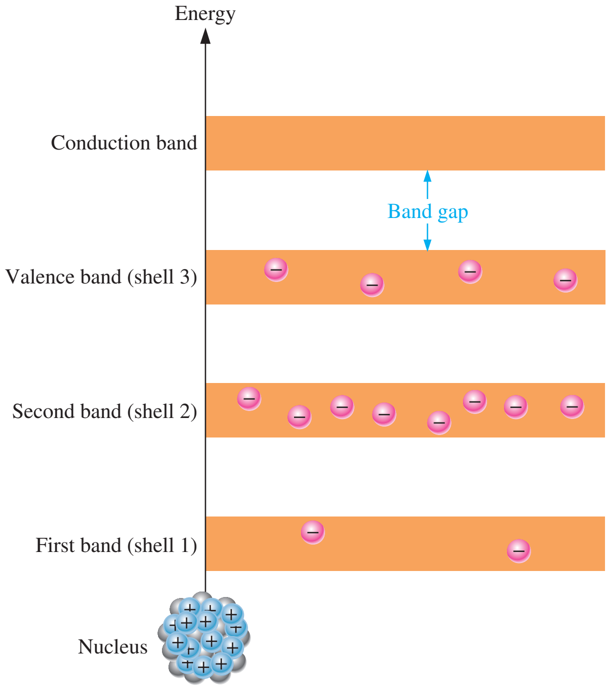
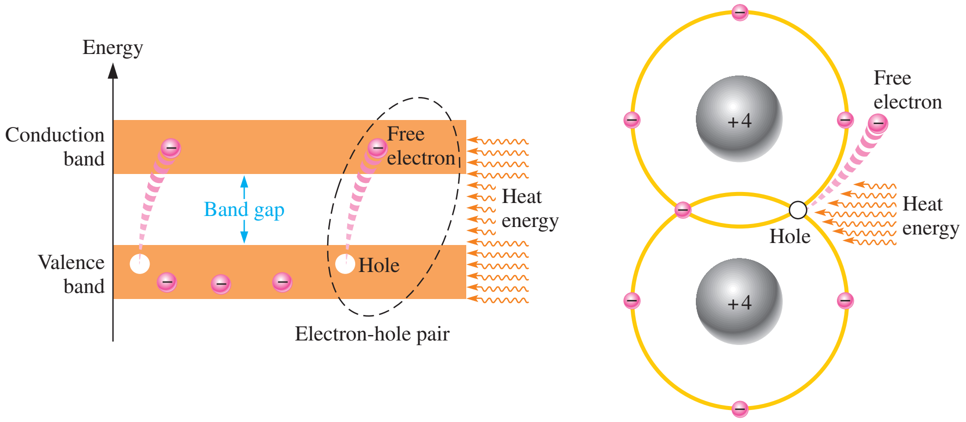


FIGURE 1–12

Energy band diagram for an atom in a pure (intrinsic) silicon crystal at it lowest energy state. There are no electrons in the conduction band at a temperature of 0 K.

Conduction Electrons and Holes

An intrinsic (pure) silicon crystal at room temperature has sufficient heat (thermal) energy for some valence electrons to jump the gap from the valence band into the conduction band, becoming free electrons. Free electrons are also called **conduction electrons.** This is illustrated in the energy diagram of Figure 1–13(a) and in the bonding diagram of Figure 1–13(b).



(a) Energy diagram for the outer two bands

(b) Bonding diagram

FIGURE 1–13

Creation of electron-hole pairs in a silicon crystal. Electrons in the conduction band are free electrons.

When an electron jumps to the conduction band, a vacancy is left in the valence band within the crystal. This vacancy is called a **hole**. For every electron raised to the conduction band by external energy, there is one hole left in the valence band, creating what is called an **electron-hole pair. Recombination** occurs when a conduction-band electron loses energy and falls back into a hole in the valence band.

To summarize, a piece of intrinsic silicon at room temperature has, at any instant, a number of conduction-band (free) electrons that are unattached to any atom and are essentially drifting randomly throughout the material. There is also an equal number of holes in the valence band created when these electrons jump into the conduction band. This is illustrated in Figure 1–14.