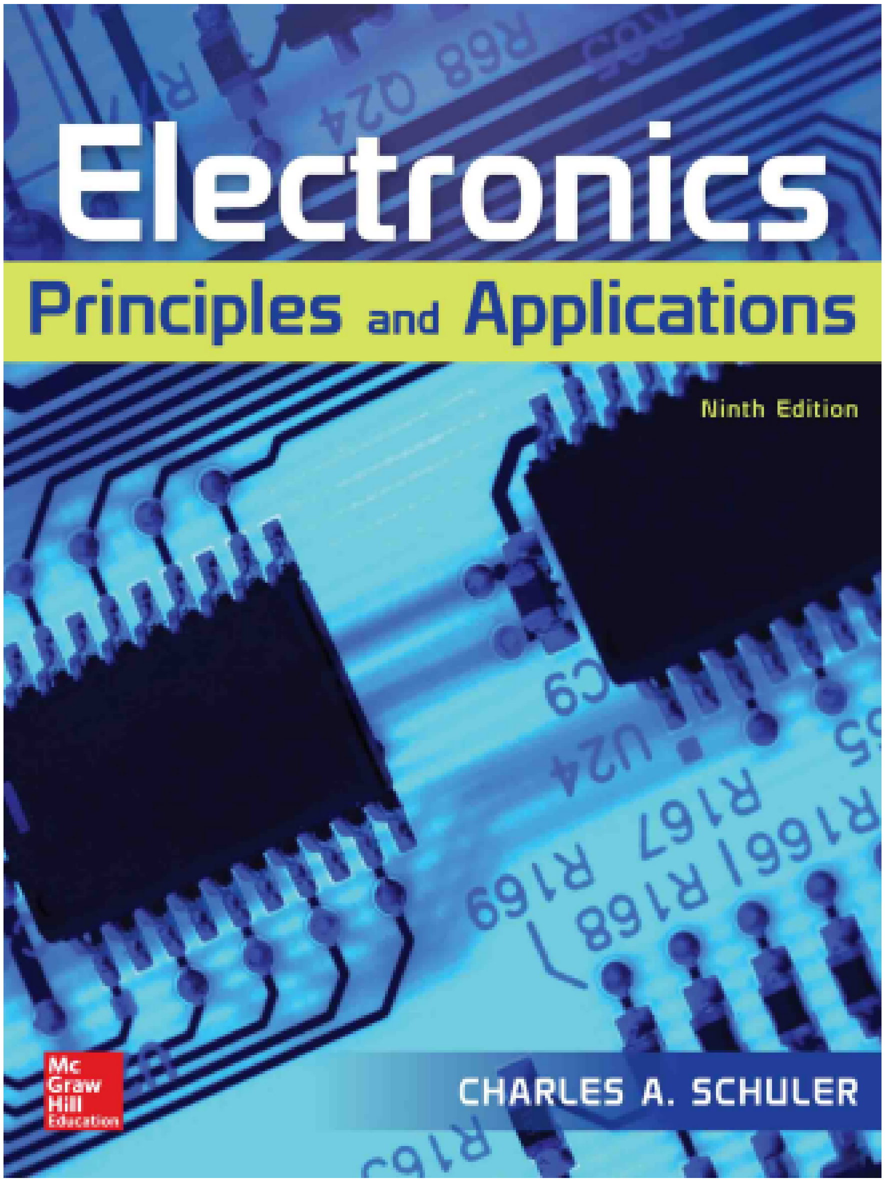


**Ninth Edition**

# Electronics

## Principles & Applications

# Charles A. Schuler

ELECTRONICS: PRINCIPLES AND APPLICATIONS, NINTH EDITION

Published by McGraw-Hill Education, 2 Penn Plaza, New York, NY 10121. 

This book is printed on acid-free paper.

1 2 3 4 5 6 7 8 9 LWI 21 20 19 18

ISBN 978-0-07-337383-6
MHID 0-07-337383-4

Senior Portfolio Manager: *Thomas Scaife, PhD*
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Cover Image: ©*Ingram Publishing/SuperStock*
Compositor: *MPS Limited*



**Library of Congress Cataloging-in-Publication Data**

Schuler, Charles A., author.
Electronics : principles & applications / Charles A. Schuler.
Ninth edition. | New York, NY : McGraw-Hill Education, [2018]
LCCN 2017039730| ISBN 9780073373836 (acid-free paper) | ISBN 0073373834 (acid-free paper)
LCSH: Electronics.
LCC TK7816 .S355 2018 | DDC 621.381—dc23
LC record available at https://lccn.loc.gov/2017039730

mheducation.com/highered

# Contents

# Contents

# Editor’s Foreword

The McGraw-Hill Career Education *Trade and Technol ogy list* has been designed to provide entry-level compe tencies in a wide range of occupations in the electrical and electronic fields. It consists of coordinated instructional materials designed especially for the career-oriented stu dent. A textbook, an experiments manual, and an instruc tor productivity center support each major subject area covered. All of these focus on the theory, practices, ap plications, and experiences necessary for those preparing to enter technical careers.

There are two fundamental considerations in the preparation of a text like *Electronics: Principles and Applications:* the needs of the learner and the needs of the employer. This text meets these needs in an expert fashion. The author and editors have drawn upon their broad teaching and technical experiences to accurately interpret and meet the needs of the student. The needs of business and industry have been identified through personal inter views, industry publications, government occupational trend reports, and reports by industry associations. The processes used to produce and refine the series have been ongoing. Technological change is rapid, and the content has been revised to focus on current trends.

Refinements in pedagogy have been defined and imple mented based on classroom testing and feedback from students and instructors using the series. Every effort has been made to offer the best possible learning materials. These include animated PowerPoint presentations, circuit files for simulation, a test generator with correlated test banks, dedicated Web sites for both students and instruc tors, basic instrumentation labs, and other items as well. All of these are well coordinated and have been prepared by the authors.

The widespread acceptance of *Electronics: Principles and Applications* and the positive responses from users confirm the basic soundness in content and design of all of the components as well as their effectiveness as teach

ing and learning tools. Instructors will find the texts and manuals in each of the subject areas logically structured, well paced, and developed around a framework of modern objectives. Students will find the materials to be readable, lucidly illustrated, and interesting. They will also find a generous amount of self-study, review items, and exam

ples to help them determine their own progress.

***Charles A. Schuler, Project***

***Editor***

## Basic Skills in Electricity and Electronics

Charles A. Schuler, Project Editor

***Editions in This Series***

*Electricity: Principles and Applications, Eighth Edition,* Richard J. Fowler
*Electronics: Principles and Applications, Ninth Edition,* Charles A.
Schuler *Digital Electronics: Principles and Applications, Eighth Edition,*
Roger Tokheim



# Preface

*Electronics: Principles and Applications*, 9e, introduces analog devices, circuits, and systems. It also presents various digital techniques that are now commonly used in what was once con sidered the sole domain of analog electronics. It is intended for students who have a basic understanding of Ohm's law; Kirch hoff's laws; power; schematic diagrams; and basic components such as resistors, capacitors, and inductors. The digital material is self-contained and will not pose a problem for those students who have not completed a course in digital electronics. The

only mathematics prerequisite is a command of basic algebra. The major objective of this text is to provide entry-level knowledge and skills for a wide range of occupations in elec tricity and electronics. Its purpose is to assist in the education and preparation of technicians who can effectively diagnose, re pair, verify, install, and upgrade electronic circuits and systems. It also provides a solid and practical foundation in analog elec tronic concepts, device theory, and modern digital solutions for those who may need or want to go on to more advanced study. The ninth edition, like the earlier ones, combines theory and applications in a logical, evenly paced sequence. It is important that a student's first exposure to electronic devices and circuits be based on a smooth integration of theory and practice. This approach helps the student develop an understanding of how devices such as diodes, transistors, and integrated circuits func tion and how they are used in practice. Then the understanding of these functions can be applied to the solution of practical problems such as performance analysis and troubleshooting. This is an extremely practical text. The devices, circuits, and applications are typical of those used in all phases of electron ics. Reference is made to common aids such as parts catalogs, component identification systems, and substitution guides, and real-world troubleshooting techniques are applied whenever ap propriate. The information, theory, and calculations presented are the same as those used by practicing technicians. The for mulas presented are immediately applied in examples that make sense and relate to the kinds of calculations actually made by technical workers.

The 16 chapters progress from an introduction to the broad field of electronics through solid-state theory, transistors, and the concepts of gain, amplifiers, oscillators, electronic commu nications and data transfer, integrated circuits, control circuitry, regulated power supplies, and digital signal processing. As an example of the practicality of the text, an entire chapter is de voted to troubleshooting circuits and systems. In other chapters, entire sections are devoted to this vital topic. Since the last edi tion, the electronics industry has continued its march toward more digital and mixed-signal applications to replace what used to be purely analog functions. The distinction between analog and digital continues to blur. This is the only text of its kind that addresses this issue.

## New to this Edition

This edition updates devices and equipment. For example, more emphasis is placed on digital meter readings and less on analog displays. It also portrays up-to-date test equipment. Lastly, de vices that are no longer available have been eliminated. Perhaps the most significant change is the emphasis on ther mal issues and power devices. As technicians ply their craft, they will likely deal with devices such as power transistors. This is because power devices have a higher failure rate and the replacement of power devices is often more cost-effective than the replacement of other parts. One entirely new section is devoted to power transistors and another to troubleshooting thermal issues.

More information about topics such as total harmonic dis tortion has been included. Along with that, spectral analysis to measure total harmonic distortion is presented. Measurements that once required very expensive test equipment can now be made using affordable personal computers and software. That is also true with certain radio-frequency measurements that can be made with a PC. This edition covers wireless network troubleshooting and presents more information about digital modulation methods.

Last but not least, there is now more troubleshooting in formation. In addition to using software and PCs, methods of using basic calculations to predict circuit performance are dis cussed. For example, a regulated power supply circuit is ana lyzed to determine normal voltage readings. This is becoming more important as fewer voltage readings and fewer wave forms are supplied with schematics. Technicians are forced to become more self-reliant and better educated about the circuit principles and theory that are covered here. The practicality of this book has always been very strong and has continued to evolve over time.

## Additional Resources

### Online Learning Center

The *Online Learning Center* (OLC) contains a wealth of fea tures, including extra review questions, links to industry sites, chapter study overviews, assignments, the Instructor's Manual, and a MultiSim Primer, all for students. The following is a list of features that can be found on the OLC.



## Student Side of the Online Learning Center

Student PowerPoint presentations
Soldering PowerPoint presentation and .pdf file Circuit interrupter PowerPoint (GFCI and AFCI) Breadboarding PowerPoint presentation
Data sheets in .pdf format
Digital signal processing simulations (4 programs) "Audio Examples" PowerPoint presentation
HP instrumentation simulator
Instrumentation PowerPoint presentations
Circuit files (EWB 5 and Multisim versions 6, 7, 8, and 11) MultiSim Primer (by Patrick Hoppe of Gateway Technical College), which provides a tutorial for new users of the software

## Instructor Side of the Online Learning Center

Instructor's Manual
PowerPoint presentations for classroom use
Electronic test bank questions for each chapter
Parts and equipment lists
Learning Outcomes
Answers to textbook questions:
  Chapter review questions
  Critical thinking questions
Answers and data for lab experiments and assignments Projects

HP instrumentation simulator
Instrumentation PowerPoint presentations (lab 1 to lab 4) Instrumentation lab experiments in .pdf format

Breadboarding PowerPoint presentation
Soldering (.pdf file)
Circuit interrupters (GFCI & AFCI) PowerPoint presentations Circuit simulation files (EWB 5 and MultiSim versions 6, 7, 8, 11, and 14)
Digital Signal Processing simulations (four programs)
"Audio Examples" PowerPoint presentation for Chapter 16 Calculus PowerPoint presentation, with EWB and Multisim circuit files
Data sheets in .pdf format
Statistics .pdf files
Pro Electron Type Numbering .pdf file

Visit the Online Learning Center at www.mhhe.com/schuler9e.

**Experiments Manual**

A correlated Experiments Manual provides a wide array of hands-on labwork, problems, and circuit simulations. Multi Sim files are provided for both the simulation activities and the hands-on activities. These files are located on the Student Side of the Online Learning Center.

## About the Author

Charles A. Schuler received his Ed.D. from Texas A&M Uni versity in 1966, where he was an N.D.E.A. fellow. He has pub lished many articles and seven textbooks on electricity and electronics, almost as many laboratory manuals, and another book that deals with ISO 9000. He taught electronics technol ogy and electrical engineering technology at California Univer sity of Pennsylvania for 30 years. He is currently a full-time writer, as he continues his passion to make the difficult easy to understand.



# Walkthrough

*Electronics: Principles and Applications* takes a concise and practical approach to this fascinating subject. The textbook's easy-to-read style, color illustrations, and basic

# Introduction

math level make it ideal for students who want to learn the essentials of modern electronics and apply them to real job-related situations.

that give the reader an idea of what to expect in derstand some basic functions that take the following pages, and what he or she should place in electronic circuits and systems

## Learning Outcomes

*This chapter will help you to:*

1-1 *Identify* some major events in the history of electronics. [1-1]

1-2 *Classify* circuit operation as digital or analog. [1-2]

1-3 *Name* major analog circuit functions. [1-3] 1-4 *Begin* developing a system viewpoint for troubleshooting. [1-3]

1-5 *Analyze* circuits with both dc and ac sources. [1-4]

Electronics is a recent technology that

has undergone explosive growth. It is widespread and touches all our lives in many ways. This chapter will help you to understand how electronics developed over the years and how it is currently divided

be able to accomplish by the end of the chapter.

and will also help you to build on what

These outcomes are distinctly linked to the

Each chapter starts with ***Learning Outcomes***

chap you have already learned about circuits and

into specialty areas. It will help you to un

1-6 *List* the current trends in components.

ter subsections.

electronics. [1-5]

beginning of electronics. The year 1899 is one possibility. During that year, J. J. Thomson, at the Univer sity of Cambridge in England, discovered the electron. Two important developments at the beginning of the twentieth century made peo ple interested in electronics. The first was in 1901, when Guglielmo Marconi sent a message

***Key Terms****,* noted in the margins, call the reader's attention to key concepts.

## 1-1 A Brief History

It is hard to place an exact date on the

## 1-2 Digital or Analog

The signal going into the circuit is on the left,

across the Atlantic Ocean using *wireless* teleg

Today, electronics is such a huge field that it is

and the signal coming out is on the right. For

raphy. Today we call wireless communication

often necessary to divide it into smaller subfields.

now, think of a signal as some electrical quan

*radio.* The second development came in 1906,

You will hear terms such as medical electronics,

tity, such as voltage, that changes with time.

when Lee De Forest invented the audion vac

instrumentation electronics, automotive elec

digital

The circuit marked *A* is an example of a

uum tube. The term

**Audion**

*audion* related to its first

tronics, avionics, consumer electronics, industrial

device. Digital waveforms are rectangular. The

use, to make sounds ("audio") louder. It was

electronics, and others. One way that electronics

output signal is a rectangular wave; the input

not long before the wireless inventors used the

**Digital**

can be divided is into digital or analog.

*vacuum tube* to improve their equipment. A *digital electronic*

*device* or circuit will wave. Rect **Vacuum tube** voltage levels and
signal is not exactly a rectangular angular waves have only two
Another development in 1906 is worth men
**electronic** of only several devices.
recognize or produce an output are very common in digital
tioning. Greenleaf W. Pickard used the first
**device** digital cir device. The
limited states. For example, most Circuit *B* in Fig. 1-1 is an analog
crystal radio detector. This great improvement
cuits will respond to only two input input and the output are sine waves. The
conditions: output
helped make radio and electronics more popu
**Digital circuit** be called been shifted
low or high. *Digital circuits* may also is larger than the input, and it has
lar. It also suggested the use **Semiconductor**
of *semiconductors*
*binary* since they are based on a number above the zero axis. The most important
system feature
(crystals) as materials with future promise for
**Linear circuit** the new field of radio and is that the output signal is a
with only two digits: 0 and 1. electronics. An *analog circuit* can combination of an in finite number
respond to or produce of voltages. In a *linear circuit,* the
Commercial radio was born in Pittsburgh,
**Analog circuit** states. An input. Though cir
an output for an infinite number of output is an exact replica of the
Pennsylvania, at station KDKA in 1920. This de
analog input or output might vary between 0 cuit *B* is linear, not all analog circuits are
and linear.
velopment marked the beginning of a new era,
digital circuit recognizes inputs ranging from 0 to nonlinear. Circuits *C* through *F* are all digital.
0.4 V as low (binary 0) and those ranging from Note that
2.0 to 5 V as high (binary 1). A digital circuit **1**
does not respond any differently for an input of 2 the outputs are all *rectangular* waves (two levels
V than it does for one at 4 V. Both of these of voltage). Circuit *F* deserves special attention.
voltages are in the high range. Input voltages Its input is a rectangular wave. This could be an
between 0.4 and analog circuit responding to only two voltage

## viii Walkthrough

10 volts (V). Its actual value could be 1.5, 2.8, or
even 7.653 V. In theory, an *infinite* number of volt
ages are possible. On the other hand, the typical
For example, a certain audio amplifier could levels except that something has happened to
have a distorted sound. This amplifier would still the
be in the analog category, but it would be

*-digital (A/D) converter* is a circuit s a binary (only 0s and 1s) output. numbers stored in memory are bi k (a timing circuit) drives the A/D
ample the analog signal on a repeti ure 1-3 shows the analog waveform tail. This waveform is sampled by verter every 20 microseconds (μs).
signal can be achieved. Step size is determined by the number of binary digits (bits) used. The num ber of steps is found by raising 2 to the power of the number of bits. A 5-bit system provides

Antenna Pure direct current

$2^5 = 32$ steps

An 8-bit system would provide

$2^8 = 256$ steps

**A/D converter**

taken. The required sampling rate og
signal is a function of the fre

RFC RFC

$C_1$

Numerous solved ***Example*** prob
[redacted]hroughout the chapters

**EXAMPLE 1-1**

peri od of 0.8 millisecond (ms), forty
at signal. The higher the frequency
An audio compact disk (CD) uses 16 bits

Amplifier

demonstrate the u[redacted] of formulas

$C_2$ $C_3$

the higher the sampling rate. temperature and resistance is positive—that is, Whether a material will insulate de
to represent each sample of the signal. How

$R_L$

Coaxial cable

and the methods used to analyze

to Fig. 1-2. The analog signal can they increase together. many steps or volume levels are possible?

on how the atoms are arranged. Carb Pure alternating current

by sending the binary contents of 65,536 in electronics. Most of the wire used in conductors.
*digital-to-analog (D/A) converter.* elec such a material. Figure 2-3(*a*) shows

**Printed circuit**

nformation is clocked out of mem me Pure alternating current carranged in the diamond structure.

**D/A converter**

rate as the original signal was Copper is the most widely applied con Witcrystal or diamond structure, the
tronics is made from copper. *Printed* vaelectrons cannot move to serve as
Use the appropriate power of 2: $2^{16}$ = ductor electronic circuits. *circuits* use copper foil to act as circuit curre

ure 1-4 shows the output of the D/A
This is easy to solve using a calculator with Copper is a good conductor, and it is easy to riers. Diamonds are insulators. Figure
an $x^y$ key. Press 2, then $x^y$, and then 16 fol

an be seen that the waveform is not lowed by the = key. Direct and alternating current shows carbon arranged in the graphite
me as the original analog signal. It is solder. This makes it very popular. Aluminum is a good conductor, but not ture. Here, the valence electrons are f

Fig. 1-14 Sending power and signal on the same cable.

as good as copper. It is used more in power
transformers and transmission lines than it is
in electronics. Aluminum is less expensive than



move when a voltage is applied. It may odd that both diamonds and graphite are from carbon. One insulates, and the
wires to the roof along with a separate cable for battery from shorting the high-frequency signal
copper, but it is difficult to solder and tends to does not. It is simply a matter of wheth
the television signal. The one coaxial cable can to ground. The inductive reactance of the choke
corrode rapidly when brought into contact with valence electrons are locked into the
serve both needs (power and signal).
other metals. ture. Carbon in graphite form is used to
The battery in Fig. 1-14 powers an amplifier out of the power wiring to the amplifier.
on the left side of Fig. 1-14 keeps the ac signal
lectrons for Silver is the best conductor because it has resistors and electrodes. So far, the dia
located at the opposite end of the coaxial cable.
the least resistance. It is also easy to solder. The structure of carbon has not been used to
pe material. N-type ma as the ground for both the battery and the remote electrical or electronic devices.
The outer conductor of the coaxial cable serves
high cost of silver makes it less widely applied than copper. However, silver-plated conduc
amplifier. The inner conductor of the coaxial cable

## Niels Bohr and the Atom

rial.

tors are sometimes used in critical electronic
serves as the positive connection point for both the
an be manu Chokes are so named because they "choke off" circuits to minimize resistance.
Scientists change the future by
al has very Radio-frequency chokes high-frequency current flow.
battery and the amplifier. improving on the ideas of others.
Gold is a good conductor. It is very stable
(*RFC*s) are used to isolate the signal from the
h this keeps and does not corrode as badly as copper and
Niels Bohr proposed a model
power circuit. *RFC*s are coils wound with copper
a minimum, energy levels (quantum electronic
of atomic structure in 1913 tha liding and moving
gh tempera
wire. They are inductors and

contacts are gold-plated. This makes
in electronic roduces mi s ac the con tacts very reliable.
mechanics) to the
Rutherford

**EXAMPLE 1-4**

for higher frequencies. The opposite of a conductor is called
model of the atom. Bohr also an *insulator.* In an insulator, the
used some of the work of valence electrons
Max

**Insulator**

Planck. re and more o break their

s both a free

. . . that inductive reactance increases with starts at 54 MHz. Determine the minimum

***About Electronics*** add historical depth to

s carriers in tured to be

frequency:

*Source:* Library of Congress

Prints and Photographs Division

$X_L = 2\pi fL$

**Compound**

Assume that the RFCs in Fig. 1-14 are 10 are tightly bound to their parent atoms. They are

μH. The lowest-frequency television channel

***History of Electronics***, ***You May Recall***, and

not free to move, so little or no current flows

when a voltage is applied. Practically all insula inductive reactance for television signals. tors used in electronics are based on compounds.

Compare the minimum choke reactance with

the topics and highlight new and interesting

A *compound* is a combination of two or more the impedance of the coaxial cable, which is

al hole be

[LC-USZ62-112063]

Frequency and reactance are *directly* related in

technologies or facts.

(a) Diamond

different kinds of atoms. Some of the widely

an inductor. As one increases, so does the

other.

72 V.

the thermal rriers. If the ial, then the riers and the

important areas where the compound semi conductors offer advantages are at very high

applied insulating materials include rubber,

$X_L = 2\pi fL = 6.28 \times 54 \times 10^6 \times 10 \times 10$[redacted]

plastic, Mylar, ceramic, Teflon, and polystyrene. = 3.39 kΩ

At direct current ( $f$ = 0 Hz), the induc frequencies (often called microwaves), in pho

tive reactance is zero. The dc power passes

tonics (the production, sensing, control, and

through the chokes with no loss. As frequency

transmission of light), and in hostile environ

increases, so does the inductive reactance. In

The reactance of the chokes is almost 50 times the cable impedance. This means the chokes effectively isolate the cable signal from the battery and from the power circuit

carriers.

creases the roduces mi

ing minority

ments such as extreme cold and

high radiation.

**Materials Used for Dopants,**

**Semiconductors, and**

Fig. 1-14 the inductive reactance of the choke

of the amplifier.

t on the way

The following is a partial

list of compound

**Microwave Devices**

silicon be ade from it. *compound* semiconductors:

· Gallium arsenide · Indium phosphide

on the right side of the figure prevents the

ortant. They e and indus at are better three most

material is

**Compound**

- It is theoretically possible to make semiconductor devices

**Semiconductors**

from crystalline carbon.

- Crystal radio receivers were an early application of semiconductors.

- Gallium arsenide (GaAs) works better than silicon in microwave devices because it allows faster movement of electrons.

- Materials other than boron and arsenic are used as dopants.

*is true*

· Mercury cadmium telluride

· Silicon carbide

· Cadmium sulphide

· Cadmium telluride

onductor l is about ilicon atoms. heated, one can expect the number of minority carriers to increase.

32. As P-type semiconductor material is heated, the number of majority carriers

**22 Chapter 2** Semiconductors

**Walkthrough**

**ix**

(b) Graphite

Fig. 2-3 Structures of diamond and graphite.

Introduction **Chapter 1 13**

31. As P-type semiconductor

All critical facts and principles are reviewed in the ***Summary and Review*** section at the end of each chapter.

# Chapter 1 Summary and

# Review Chapter 1 Summary and Review

1. Electronics is a relatively young field. Its history began in the twentieth century.
2. Electronic circuits can be classified as digital or analog.
10. The number of output levels from a D/A

converter

is equal to 2 raised to the power of the number of bits used.

11. Digital signal processing uses computers to enhance

1. Electronics is a relatively young field. Its history 3. The number of states or voltage levels is limited in

began in the twentieth century.

a digital circuit (usually to two).

2. Electronic circuits can be classified as digital or 4. An analog circuit has an infinite number of voltage

analog.

levels.

3. The number of states or voltage levels is limited in 5. In a linear circuit, the output signal is a replica of

a digital circuit (usually to two).

the input.

4. An analog circuit has an infinite number of voltage 6. All linear circuits are analog, but not all analog

levels.

circuits are linear. Some analog circuits distort

5. In a linear circuit, the output signal is a replica of signals.

the input.

7. Analog signals can be converted to a digital format

6. All linear circuits are analog, but not all analog with an A/D converter.

circuits are linear. Some analog circuits distort 8. Digital-to-analog converters are used to produce a

signals.

simulated analog output from a digital system.

7. Analog signals can be converted to a digital

format

10. The number of output levels from a D/A converter signals.

is equal to 2 raised to the power of the number of 12. Block diagrams give an overview of electronic

bits used.

system operation.

11. Digital signal processing uses computers to enhance 13. Schematic diagrams show individual part wiring

signals.

and are usually required for component-level

12. Block diagrams give an overview of electronic troubleshooting.

system operation.

14. Troubleshooting begins at the system level.

13. Schematic diagrams show individual part wiring 15. Alternating current and direct current signals are

and are usually required for component-level

often combined in electronic circuits.

troubleshooting.

16. Capacitors can be used to couple ac signals, to block

14. Troubleshooting begins at the system level. direct current, or to bypass alternating current.

15. Alternating current and direct current signals are 17. *SMT* is replacing insertion technology.

often combined in electronic circuits.

16. Capacitors can be used to couple ac signals, to block

All of the important chapter formulas are summarized at the end of each

9. The quality of a digital representation of an

direct current, or to bypass alternating current.

analog with an A/D converter.

chapter in ***Related Formulas***. ***Chapter Review Questions*** are found at

signal is determined by the sampling rate and produce a

the 8. Digital-to-analog converters are used to 17. *SMT* is replacing insertion technology.

the end of each chapter; and separate, more challenging ***Chapter Review*** number of bits used.

simulated analog output from a digital system.

***Problems*** sections are available in appropriate chapters.

9. The quality of a digital representation of an analog

signal is determined by the sampling rate and the number of bits used.

Number of levels in a binary system:
levels = $2^n$ Capacitive reactance: $X_C$ =
_____ 1

$2\pi fC$
Inductive reactance: $X_L = 2\pi fL$

levels = $2^n$
Inductive reactance: $X_L = 2\pi fL$
Capacitive reactance: $X_C = \dfrac{1}{2\pi fC}$

Number of levels in a binary system:

*Determine whether each statement is true or false.*

1-1. Most digital circuits can output only two states, high and low. (1-2)
*Determine whether each statement is true or false.*
1-2. Digital circuit outputs are usually sine waves. (1-2)
1-1. Most digital circuits can output only two states,
1-3. The output of a linear circuit is an exact replica
high and low. (1-2)
of the input. (1-2)
1-2. Digital circuit outputs are usually sine waves.
1-4. Linear circuits are classified as analog. (1-2)
(1-2)
1-5. All analog circuits are linear. (1-2)
1-3. The output of a linear circuit is an exact replica
of the input. (1-2)
1-4. Linear circuits are classified as analog. (1-2)
1-5. All analog circuits are linear. (1-2)



18 Chapter 1 Introduction

1-6. The output of a 4-bit D/A converter can produce

**Walkthrough**

128 different voltage levels. (1-2)
1-7. An attenuator is an electronic circuit used to make signals stronger. (1-3)
1-6. The output of a 4-bit D/A converter can produce 1-8. Block diagrams are best for component-level
128 different voltage levels. (1-2)
troubleshooting. (1-3)
1-7. An attenuator is an electronic circuit used to 1-9. In Fig. 1-8, if the signal at point 4 is faulty, then
make signals stronger. (1-3)
the signal at point 3 must also be faulty. (1-3)
1-8. Block diagrams are best for component-level 1-10. Refer to Fig. 1-8. The power supply should be
troubleshooting. (1-3)
checked first. (1-3)
1-9. In Fig. 1-8, if the signal at point 4 is faulty, then the signal at point 3 must also be faulty. (1-3) 1-10. Refer to Fig. 1-8. The power supply should be checked first. (1-3)

**x**

1 · ·

1-1. Functions now accomplished by using electron ics may be accomplished in different ways in the future. Can you think of any examples?

1-3. What could go wrong with capacitor $C_2$ in Fig. 1-10, and how would the fault affect the waveform at Node D?

Finally, each chapter ends with ***Critical Thinking***

1-2. Can you describe a simple system that uses only

1-4. What could go wrong with capacitor $C_2$ in

***Questions*** and ***Answers to Self-Tests****.*

9. T
10. F

1. T 2. T 3. F 4. T
two wires but will selectively signal two differ ent people?

7. T
8. F

13. F 14. F 15. T 16. F
Fig. 1-13, and how would the fault affect the waveform at Node D?

19. capacitors
20. bypass
21. coupling (dc block)
22. F

5. F 6. T

11. F 12. T V, 0 V
17. −7.5 V 18. 12.5 23. T 24. F

1-11. Refer to Fig. 1-10. Capacitor $C_2$ would be called a bypass capacitor. (1-4)

1-12. Node C in Fig. 1-10 has no dc component since $C_1$ blocks direct current. (1-4)

1-13. In Fig. 1-11, Node D is the only waveform with dc and ac components. (1-4)

1-14. Refer to Fig. 1-14. The reactance of the coils is high for dc signals. (1-4)

1-1. Functions now accomplished by using electron ics may be accomplished in different ways in the future. Can you think of any examples?

1-2. Can you describe a simple system that uses only two wires but will selectively signal two differ

Contrast between an LED light source and

ent people?

incandescent lamps. The LEDs are much

more efficient and will be replacing the older incandescent types.

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1-3. What could go wrong with capacitor $C_2$ in Fig. 1-10, and how would the fault affect the waveform at Node D?

1-4. What could go wrong with capacitor $C_2$ in Fig. 1-13, and how would the fault affect the waveform at Node D?

7. T
13. F
19. capacitors

1. T



2. T 3. F 4. T 5. F 6. T
8. F 9. T 10. F 11. F 12. T
14. F
15. T
16. F
17. −7.5 V
18. 12.5 V, 0 V

LED light source and incandescent lamps. The LEDs are much more efficient and will be replacing the older incandescent types.

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20. bypass
21. coupling (dc block) 22. F
23. T
24. F

**Walkthrough**



Contrast between an

# Acknowledgments

Where does one begin? This book is part of a series that started with a research project. Many people contributed to that effort . . . both in education and in industry. Their dedication and diligence helped launch what has become a very successful series. Then, there are all those instructors and students who have given sage and thoughtful advice over the years. And there are those gifted and hardwork ing folks at McGraw-Hill. Finally, there is my family, who indulge my passion and encourage my efforts.



# Safety

Electric and electronic circuits can be dangerous. Safe practices are necessary to prevent electrical shock, fires, explosions, mechanical damage, and injuries resulting from the improper use of tools.

Perhaps the greatest hazard is electrical shock. A current through the human body in excess of 10 milliam peres can paralyze the victim and make it impossible to let go of a "live" conductor or component. Ten milliamperes is a rather small amount of current flow: It is only *ten one-thousandths* of an ampere. An ordinary flashlight can provide more than 100 times that amount of current!

Flashlight cells and batteries are safe to handle because the resistance of human skin is normally high enough to keep the current flow very small. For example, touch ing an ordinary 1.5-V cell produces a current flow in the microampere range (a microampere is one one-millionth of an ampere). This amount of current is too small to be noticed.

High voltage, on the other hand, can force enough cur rent through the skin to produce a shock. If the current approaches 100 milliamperes or more, the shock can be fatal. Thus, the danger of shock increases with voltage. Those who work with high voltage must be properly trained and equipped.

When human skin is moist or cut, its resistance to the flow of electricity can drop drastically. When this hap pens, even moderate voltages may cause a serious shock. Experienced technicians know this, and they also know that so-called low-voltage equipment may have a high voltage section or two. In other words, they do not practice two methods of working with circuits: one for high volt age and one for low voltage. They follow safe procedures at all times. They do not assume protective devices are working. They do not assume a circuit is off even though the switch is in the OFF position. They know the switch could be defective.

Even a low-voltage, high-current-capacity system like an automotive electrical system can be quite dangerous. Short-circuiting such a system with a ring or metal watch band can cause very severe burns—especially when the ring or band welds to the points being shorted.

As your knowledge and experience grow, you will learn many specific safe procedures for dealing with electricity and electronics. In the meantime,

1. Always follow procedures.
2. Use service manuals as often as possible. They often contain specific safety information. Read, and com ply with, all appropriate material safety data sheets. 3. Investigate before you act.
4. When in doubt, *do not act*. Ask your instructor or supervisor.

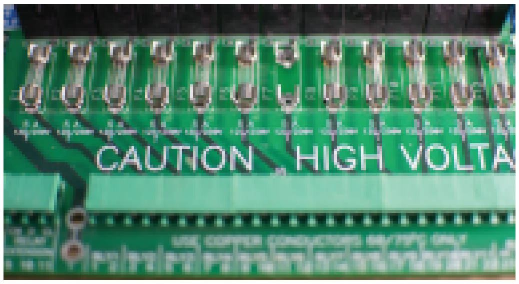
## General Safety Rules for Electricity and Electronics

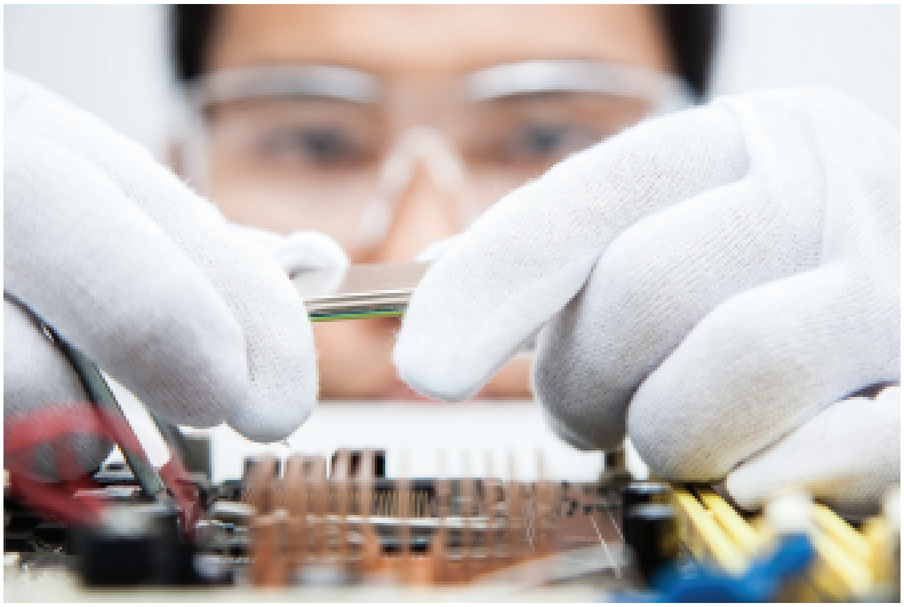
Safe practices will protect you and your fellow workers. Study the following rules. Discuss them with others, and ask your instructor about any you do not understand.

1. Do not work when you are tired or taking medicine that makes you drowsy.
2. Do not work in poor light.
3. Do not work in damp areas or with wet shoes or clothing.
4. Use approved tools, equipment, and protective devices.
5. Avoid wearing rings, bracelets, and similar metal items when working around exposed electric circuits.
6. Never assume that a circuit is off. Double-check it with an instrument that you are sure is operational.
7. Some situations require a "buddy system" to guarantee that power will not be turned on while a technician is still working on a circuit.
8. Never tamper with or try to override safety devices such as an interlock (a type of switch that automati cally removes power when a door is opened or a panel removed).
9. Keep tools and test equipment clean and in good working condition. Replace insulated probes and leads at the first sign of deterioration.

10. Some devices, such as capacitors, can store a *lethal* charge. They may store this charge for long periods of time. You must be certain these devices are dis charged before working around them.
11. Do not remove grounds, and do not use adaptors that defeat the equipment ground.
12. Use only an approved fire extinguisher for electrical and electronic equipment. Water can conduct electricity and may severely damage equipment. Carbon dioxide ($CO_2$) or halogenated-type extinguishers are usually preferred. Foam-type extinguishers may also be desired in *some* cases. Commercial fire extinguishers are rated for the type of fires for which they are effective. Use only those rated for the proper working conditions.
13. Follow directions when using solvents and other chemicals. They may be toxic or flammable, or they may damage certain materials such as plastics. Always read and follow the appropriate material safety data sheets.
14. A few materials used in electronic equipment are toxic. Examples include tantalum capacitors and be ryllium oxide transistor cases. These devices should not be crushed or abraded, and you should wash your hands thoroughly after handling them. Other materials (such as heat shrink tubing) may produce irritating fumes if overheated. Always read and follow the appropriate material safety data sheets.
15. Certain circuit components affect the safe perfor mance of equipment and systems. Use only exact or approved replacement parts.
16. Use protective clothing and safety glasses when handling high-vacuum devices such as picture tubes and cathode-ray tubes.
17. Don’t work on equipment before you know proper pro cedures and are aware of any potential safety hazards. 18. Many accidents have been caused by people rush ing and cutting corners. Take the time required to protect yourself and others. Running, horseplay, and practical jokes are strictly forbidden in shops and laboratories.
19. Never look directly into light-emitting diodes or fiber-optic cables. Some light sources, although invisible, can cause serious eye damage.
20. Lithium batteries can explode and start fires. They must be used only as intended and only with ap proved chargers. Lead-acid batteries produce hydro gen gas, which can explode. They too must be used and charged properly.

Circuits and equipment must be treated with respect. Learn how they work and the proper way of working on them. Always practice safety: your health and life depend on it.



Electronics workers use specialized safety knowledge.







# Introduction

## Learning Outcomes

*This chapter will help you to:*

1-1 *Identify* some major events in the history of electronics. [1-1]

1-2 *Classify* circuit operation as digital or analog. [1-2]

1-3 *Name* major analog circuit functions. [1-3]

1-4 *Begin* developing a system viewpoint for troubleshooting. [1-3]

1-5 *Analyze* circuits with both dc and ac sources. [1-4]

1-6 *List* the current trends in electronics. [1-5]

Electronics is a recent technology that has undergone explosive growth. It is widespread and touches all our lives in many ways. This chapter will help you to understand how electronics developed over the years and how it is currently divided into specialty areas. It will help you to understand some basic functions that take place in electronic circuits and systems and will also help you to build on what you have already learned about circuits and components.

## 1-1 A Brief History

It is hard to place an exact date on the beginning of electronics. The year 1899 is one possibility. During that year, J. J. Thomson, at the Univer sity of Cambridge in England, discovered the electron. Two important developments at the beginning of the 20th century made people in terested in electronics. The first was in 1901, when Guglielmo Marconi sent a message across the Atlantic Ocean using *wireless* telegraphy. Today we call wireless communication *radio.* The second development came in 1906, when Lee De Forest invented the audion vacuum tube. The term *audion* related to its first use, to make sounds ("audio") louder. It was not long before the wireless inventors used the *vacuum tube* to improve their equipment.

Another development in 1906 is worth men tioning. Greenleaf W. Pickard used the first crystal radio detector. This great improvement helped make radio and electronics more popu lar. It also suggested the use of *semiconductors* (crystals) as materials with future promise for the new field of radio and electronics.

Commercial radio was born in Pittsburgh, Pennsylvania, at station KDKA in 1920. This de velopment marked the beginning of a new era,

**Vacuum tube Semiconductor**

**Audion**



with electronic devices appearing in the average home. By 1937 more than half the homes in the United States had a radio. Commercial televi sion began around 1946. In 1947 several hundred thousand home radio receivers were manufac tured and sold. Complex television receivers and complicated electronic devices made technicians wish for something better than vacuum tubes. The first vacuum tube computer project was funded by the U.S. government, and the research began in 1943. Three years later, the ENIAC was formally dedicated at the Moore School of Electrical Engineering of the University of Pennsylvania on February 15, 1946. It was the world's first electronic digital computer:

· Size: 30 ft × 50 ft
· Weight: 30 tons
· Vacuum tubes: 17,468
· Resistors: 70,000
· Capacitors: 10,000
· Relays: 1,500
· Switches: 6,000
· Power: 150,000 W
· Cost: $486,000 (about $5 million today) · Reliability: 7 minutes mean time be tween failures (MTBF)

A group of students at the Moore School parti cipated in the fiftieth-year anniversary celebra tion of the ENIAC by developing an equivalent complementary metal oxide semiconductor (CMOS) chip:

· Size: 7.44 mm × 5.29 mm

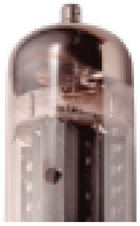
· Package: 132 pin pin grid array (PGA) · Transistors: 174,569

· Cost: several dollars (estimated, per unit, if put into production)

· Power: approximately 1 W

· Reliability: 50 years (estimated)

Scientists had known for a long time that many of the jobs done by vacuum tubes could be done more efficiently by semiconducting



The vacuum tube, the transistor, and then the integrated circuit. The evolution of electronics can be compared with the evolution of life.

(top left): ©Dimitry Sladkov/123RF



crystals, but they could not make crystals pure enough to do the job. The breakthrough came in 1947. Three scientists working with Bell Laboratories made the first working transis
tor. This was such a major contribution to sci ence and technology that the three men—John Bardeen, Walter H. Brattain, and William B. Shockley—were awarded the Nobel Prize. Around the same time (1948) Claude Shan non, also then at Bell Laboratories, published a paper on communicating in binary code. His work formed the basis for the digital commu nications revolution, from cell phones to the Internet. Shannon was also the first to apply Boolean algebra to telephone switching net works when he worked at the Massachusetts Institute of Technology in 1940. Shannon's work forms much of the basis for what we now enjoy in both telecommunications and computing. Improvements in transistors came rapidly, and now they have all but completely replaced the vacuum tube. *Solid state* has become a house hold term. Many people believe that the transis tor is one of the greatest developments ever. Solid-state circuits were small, efficient, and more reliable. But the scientists and en gineers still were not satisfied. Work done by Jack Kilby of Texas Instruments led to the de velopment of the *integrated circuit* in 1958. Robert Noyce, working at Fairchild, developed a similar project. The two men shared a Nobel Prize in Physics for inventing the integrated circuit. Integrated circuits are complex combinations of several kinds of devices on a common base, called a *substrate,* or in a tiny piece of silicon. They offer low cost, high performance, good ef
ficiency, small size, and better reliability than an equivalent circuit built from separate parts. The complexity of some integrated circuits

*Determine whether each statement is true or false.*

1. Electronics is a young technology that began in the 20th century.
2. The early histories of radio and electron ics are closely linked.

allows a single chip of silicon only 0.64 centime ter (cm) [0.25 inch (in.)] square to replace huge pieces of equipment. Although the chip can hold thousands of transistors, it still has diodes, resis tors, and capacitors too!
In 1971 Intel Corporation in California announced one of the most sophisticated of all integrated circuits—the microprocessor. A *microprocessor* is most of the circuitry of a computer reduced to a single integrated circuit. Microprocessors, some containing the equiva
lent of billions of transistors, have provided billions of dollars worth of growth for the elec tronics industry and have opened up entire new areas of applications.
The Intel 4004 contained 2,300 transistors, and today a Xeon processor has more than 6 billion. The 4004 had features as small as 10 micrometers (μm), and today the feature size is shrinking toward 10 nanometers (nm).
In 1977 the cellular telephone system entered its testing phase. Since then, the system has ex perienced immense growth. Its overwhelming success has fostered the development of new technology, such as digital communications and linear integrated circuits for communications.
In 1982, Texas Instruments offered a single chip digital signal processor (DSP). This made it prac tical to apply DSP to many new product designs. The growth has continued ever since, and DSP is now one of the most rapidly expanding segments of the semiconductor industry.
The integrated circuit is producing an elec tronics explosion. Now electronics is being ap plied in more ways than ever before. At one time radio was almost its only application. Today electronics makes a major contribution to our society and to every field of human endeavor. It affects us in ways we may not be aware of. We are living in the electronic age.

**circuit**

3. Transistors were invented before vacuum tubes.
4. A modern integrated circuit can contain thousands of transistors.
5. A microprocessor is a small circuit used to replace radio receivers.

**Substrate**

**Solid state**

**Integrated**

**Microprocessor**



**Linear circuit Analog circuit**

**Digital electronic device**

**Digital circuit**

DSP

## 1-2 Digital or Analog

Today, electronics is such a huge field that it is often necessary to divide it into smaller subfields. You will hear terms such as medical electronics, instrumentation electronics, automotive elec tronics, avionics, consumer electronics, industrial electronics, and others. One way that electronics can be divided is into digital or analog.

A *digital electronic device* or circuit will recognize or produce an output of only several limited states. For example, most digital cir cuits will respond to only two input conditions: low or high. *Digital circuits* may also be called *binary* since they are based on a number system with only two digits: 0 and 1.

An *analog circuit* can respond to or produce an output for an infinite number of states. An analog input or output might vary between 0 and 10 volts (V). Its actual value could be 1.5, 2.8, or even 7.653 V. In theory, an *infinite* number of volt ages are possible. On the other hand, the typical digital circuit recognizes inputs ranging from 0 to 0.4 V as low (binary 0) and those ranging from 2.0 to 5 V as high (binary 1). A digital circuit does not respond any differently for an input of 2 V than it does for one at 4 V. Both of these voltages are in the high range. Input voltages between 0.4 and 2.0 V are not allowed in digital systems because they cause an output that is unpredictable.

For a long time, almost all electronic devices and circuits operated in the analog fashion. This seemed to be the most obvious way to do a partic ular job. After all, most of the things that we mea sure are analog in nature. Your height, weight, and the speed at which you travel in a car are all analog quantities. Your voice is analog. It contains an infinite number of levels and frequencies. So, if you wanted a circuit to amplify your voice, you would probably think of using an analog circuit.

Telephone switching and computer circuits forced engineers to explore digital electronics. They needed circuits and devices to make logi cal decisions based on certain input conditions. They needed highly reliable circuits that would always operate the same way. By limiting the number of conditions or states in which the cir cuits must operate, they could be made more re liable. An infinite number of states—the analog circuit—was not what they needed.

Figure 1-1 gives examples of circuit behavior to help you identify digital or analog operation.

The signal going into the circuit is on the left, and the signal coming out is on the right. For now, think of a signal as some electrical quan tity, such as voltage, that changes with time. The circuit marked *A* is an example of a digital device. Digital waveforms are rectangular. The output signal is a rectangular wave; the input signal is not exactly a rectangular wave. Rect angular waves have only two voltage levels and are very common in digital devices.

Circuit *B* in Fig. 1-1 is an analog device. The input and the output are sine waves. The output is larger than the input, and it has been shifted above the zero axis. The most important feature is that the output signal is a combination of an in finite number of voltages. In a *linear circuit,* the output is an exact replica of the input. Though cir cuit *B* is linear, not all analog circuits are linear. For example, a certain audio amplifier could have a distorted sound. This amplifier would still be in the analog category, but it would be nonlinear.

Circuits *C* through *F* are all digital. Note that the outputs are all *rectangular* waves (two levels of voltage). Circuit *F* deserves special attention. Its input is a rectangular wave. This could be an analog circuit responding to only two voltage levels except that something has happened to the signal, which did not occur in any of the other examples. The output frequency is different from the input frequency. Digital circuits that accomplish this are called *counters*, or *dividers.*

It is now common to convert analog signals to a digital format that can be stored in com puter memory, on magnetic or optical disks, or on magnetic tape. Digital storage has advan tages. Everyone who has heard music played from a digital disk knows that it is usually noise free. Digital recordings do not deteriorate with use as analog recordings do.

Another advantage of converting analog signals to digital is that computers can then be used to enhance the signals. Computers are dig ital machines. They are powerful, high-speed number crunchers. A computer can do various things to signals such as eliminate noise and distortion, correct for frequency and phase er rors, and identify signal patterns. This area of electronics is known as digital signal process ing (DSP). DSP is used in medical electronics to enhance scanned images of the human body, in audio to remove noise from old recordings, and in many other ways. DSP is covered in Chap. 16.



Circuit C Circuit D

0 0 0 0 0 0 Circuit A Circuit B 0 0 0 0 0 0

Circuit E Circuit F

High level Low level

1 2 3 4 5 6 1 2 3 4 5 6 **Fig. 1-1** A comparison of digital and analog circuits.

Figure 1-2 shows a system that converts an analog signal to digital and then back to analog. An *analog-to-digital (A/D) converter* is a circuit that produces a binary (only 0s and 1s) output. Note that the numbers stored in memory are bi nary. A clock (a timing circuit) drives the A/D converter to sample the analog signal on a repeti tive basis. Figure 1-3 shows the analog waveform in greater detail. This waveform is sampled

by the A/D converter every 20 microseconds (μs). Thus, over a period of 0.8 millisecond (ms), forty samples are taken. The required sampling rate for any analog signal is a function of the fre quency of that signal. The higher the frequency
of the signal, the higher the sampling rate. Refer back to Fig. 1-2. The analog signal can be recreated by sending the binary contents of mem ory to a *digital-to-analog (D/A) converter.* The binary information is clocked out of memory at the same rate as the original signal was sampled. Figure 1-4 shows the output of the D/A converter. It can be seen that the waveform is not exactly the same as the original analog signal. It is a series
of discrete steps. However, by using more steps, a much closer representation of the original signal can be achieved. Step size is determined by the number of binary digits (bits) used. The number of steps is found by raising 2 to the power of the number of bits. A 5-bit system provides

$2^5 = 32$ steps

An 8-bit system would provide

$2^8 = 256$ steps

**EXAMPLE 1-1**

An audio compact disk (CD) uses 16 bits to represent each sample of the signal. How many steps or volume levels are possible? Use the appropriate power of 2:

$2^{16} = 65{,}536$

This is easy to solve using a calculator with an $x^y$ key. Press 2, then $x^y$, and then 16 fol lowed by the = key.

**A/D converter D/A converter**



input
01100
01001
01001
01000
00111
01000
01011
01110
10000

10001

or storage Clock

D/A

converterFilter

A/D
converter

Analog
signal

Memory

signal
output

Analog

Fig. 1-2 An analog-to-digital-to-analog system.

200

150

200 150

100

0.1 0.2 0.3 0.4 0.5 0.6 0.7 0.8
Milliseconds
100

50

50

0.1 0.2 0.3 0.4 0.5 0.6 0.7 0.8 Milliseconds

Fig. 1-3 An analog waveform. Fig. 1-4 Output of the D/A converter.

Actually, the filter shown in Fig. 1-2 smooths the steps, and the resulting analog output signal would be quite acceptable for many applica tions such as speech.

If enough bits and an adequate sampling rate are used, an analog signal can be converted into an accurate digital equivalent. The signal can be converted back into analog form and may not be distinguishable from the original signal. Or it may be noticeably better if DSP is used.

*Determine whether each statement is true or false.*

6. Electronic circuits can be divided into two categories, digital or analog.
7. An analog circuit can produce an infinite number of output conditions.
8. An analog circuit recognizes only two possible input conditions.

Analog electronics involves techniques and concepts different from those of digital elec tronics. The rest of this book is devoted mainly to analog electronics. Today most electronic technicians must have skills in both analog and digital circuits and systems.

The term *mixed signal* refers to applications or devices that use both analog and digital tech niques. Mixed-signal integrated circuits are covered in Chap. 13.

digital systems.

10. D/A converters are used to convert analog signals to their digital equivalents.

11. The output of a 2-bit D/A converter can produce eight different voltage levels.

9. Rectangular waves are common in



## 1-3 Analog Functions

This section presents an overview of some functions that analog electronic circuits can provide. Complex electronic systems can be broken down into a collection of individual functions. An ability to recognize individual functions, how they interact, and how each contributes to system operation will make sys
tem analysis and troubleshooting easier. Analog circuits perform certain operations. These operations are usually performed on *signals.* Signals are electrical quantities, such as voltages or currents, that have some merit or use. For example, a microphone converts a human voice into a small voltage whose frequency and level change with time. This small voltage is called an *audio signal.* Analog electronic circuits are often named after the function or operation they provide. *Amplification* is the process of making a sig nal larger or stronger, and circuits that do this are called *amplifiers.* Here is a list of the major types of analog electronic circuits.

1. *Adders:* Circuits that add signals together. *Subtractors*, also called *difference amplifiers*, are also available.
2. *Amplifiers:* Circuits that increase signal voltage, current, or power.
3. *Attenuators:* Circuits that decrease signal levels.
4. *Clippers:* Devices that prevent signals from exceeding a fixed amplitude limit or limits. 5. *Comparators:* Devices that compare signal voltage to a reference voltage. Some have one threshold voltage, and others have two. 6. *Controllers:* Devices that regulate signals and load devices. For example, a controller might be used to set and hold the speed of a motor.
7. *Converters:* Devices that change a signal from one form to another (e.g., voltage to-frequency and frequency-to-voltage converters).
8. *Differentiators*: Circuits that respond to rapidly changing events. They may also be called *high-pass filters*.
9. *Demultiplexer:* A device that routes one circuit or device into many or one output path into several.
10. *Detectors:* Devices that remove or recover information from a signal (a radio detector removes voice or music from a radio signal). They are also called *demodulators*.
11. *Dividers:* Devices that arithmetically divide a signal.
12. *Filters:* Devices that remove unwanted frequencies from a signal by allowing only those that are desired to pass through.
13. *Integrator*: A circuit that sums over some time interval.
14. *Inverters*: Devices that convert direct current (dc) to alternating current (ac). 15. *Mixers:* Another name for adders; also, nonlinear circuits that produce the sum and difference frequencies of two input signals. 16. *Modulators*: Devices that allow one signal to control another's amplitude, frequency, or phase.
17. *Multiplexer*: A devices that routes many circuits or devices into one; several signal sources are combined or selected for one output.
18. *Multipliers:* Devices that perform arithmetic multiplication of some signal characteristic. There are frequency and amplitude multipliers.
19. *Oscillators:* Devices that convert dc to ac. 20. *Rectifiers:* Devices that change ac to dc. 21. *Regulators:* Circuits that hold some value, such as voltage or current, constant.
22. *Sensors*: Circuits that convert

some physical characteristic into a voltage or current. 23. *Source*: The origin of a type of energy— voltage, current, or power.
24. *Switches:* Devices that turn signals on or off or change the signal path in an electronic system.
25. *Timers:* Devices that control or measure time.
26. *Trigger:* A circuit that activates at some circuit value and usually produces an output pulse.

**Signals**

A *schematic diagram* shows all the individual parts of a circuit and how they are interconnected. Schematics use standard sym bols to represent circuit components. A *block diagram* shows all the individual functions of a system and how the signals flow through the system. Schematic diagrams are usually required for what is known as *component-level troubleshooting.* A component is a single part, such as a resistor, capacitor, or an integrated circuit. Component-level repair requires the technician to isolate and replace individual parts that are defective.

**Schematic**

**diagram**

**Block diagram Troubleshooting**

Technician inspecting a circuit board.



System-level repair often requires only a block  diagram or a knowledge of the block diagram. The  technician observes symptoms and makes mea surements to determine which function or func tions are improper. Then an entire module, panel, or circuit board is replaced.

Component-level trou bleshooting usually takes longer than system-level  does. Since time is money, it may be economical to replace entire modules or circuit boards.

*Troubleshooting* begins at the system level.  Using a knowledge of circuit functions and the  block diagram, observation of the symptoms,  and measurements, the technician isolates the difficulty to one or more circuit functions. If replacement boards or modules are on hand, one  or more functions can be replaced. However, if  component-level troubleshooting is required,  the technician continues the isolation process  to the component level, often by using a voltme ter and an oscilloscope.

Figure 1-5 shows one block of a block diagram  for you to see the process. Troubleshooting is  often a series of simple yes or no decisions. For example, is the output signal shown in Fig. 1-5  normal? If so, there is no need to troubleshoot  that circuit function. If it is not normal, four  possibilities exist: (1) a power supply problem,  (2) an input signal problem, (3) defective block  (function), or (4) some combination of these  three items. Voltmeters and/or oscilloscopes are generally used to verify the power supply and  the input signal to a block. If the supply and input  signals are normal, then the block can be replaced  or component-level  troubleshooting on  that circuit  function can begin. The following chapters in this  book detail how electronic circuits work and cover  component-level troubleshooting.

Input signal
Output signal Power supply
Electronic
function

**Fig. 1-5** One block of a block diagram.

Figure 1-6 shows a block with only one input  (power) and one output. Assuming the output sig nal is missing or incorrect, the possibilities are:  (1) the power supply is defective, (2) the oscillator  is defective, or (3) both are defective.

Oscillator
Output signal
Power supply

Figure 1-7 shows an amplifier that is con trolled by a separate input. If its output signal  is not correct, the possible causes are: (1) the  power supply is defective, (2) the input signal is  defective, (3) the control input is faulty, (4) the  amplifier has malfunctioned, or (5) some com bination of these four items.

Figure 1-8 illustrates a partial block diagram  for a radio receiver. It shows how signals flow  through the system. A radio signal is ampli fied, detected, attenuated, amplified again, and  then sent to a loudspeaker to produce sound.  Knowing how the signal moves from block to  block enables a technician to work efficiently. For example, if the signal is missing or weak at

Fig. 1-6 A block with only a power

supply input. Control

Controlled
amplifier
Input signal
Output signal Power supply

Fig. 1-7 Amplifier with a control input.



1
Amplifier
Radio signal 2

Detector

point 5, the problem could be caused by a bad signal at point 1, or any of the blocks shown might be defective. The power supply should be checked first, since it affects most of the circuit functions shown. If it checks out good, then the signal can be verified at point 1, then point 2, and so on. A defective stage will quickly be

7 7
Power
supply

3

4

5

Attenuator Amplifier

6

located by this orderly process. If the signal is normal at point 3 but not at point 4, then the attenuator block and/or its control input is bad.

Much of this book is devoted to the circuit details needed for component-level trouble shooting. However, you should remember that troubleshooting begins at the system level. Al ways keep a clear picture in your mind of what the individual circuit function is and how that function can be combined with other functions to accomplish system operation.

Control Loudspeaker Fig. 1-8 Partial

block diagram of a radio receiver.

## 1-4 Circuits with Both DC and AC

The transition from the first electricity course to an electronics course can cause some initial con fusion. One reason for this is that dc and ac circuit concepts are often treated separately in the first

Fig. 1-9 Circuits with dc and ac sources.

*Determine whether each statement is true or false.*

12. Amplifiers make signals larger.
13. If a signal into an amplifier is normal but the output is not, then the amplifier has to be defective.
14. Component-level troubleshooting requires only a block diagram.
15. A schematic diagram shows how

indi vidual parts of a circuit are connected. 16. The first step in troubleshooting is to check individual components for shorts.

series with an ac source. The waveform across the resistor shows

+dc

0 V

course. Later, students are exposed to electronic circuits that have both dc and ac components. This section will make the transition easier.

Figure 1-9 shows examples of circuits con taining both dc and ac components. A battery, a dc source, is connected in

0 V

–dc



**DC component**

**Capacitors block dc component**

that both direct current and alternating current are present. The waveform at the top in Fig. 1-9 shows a sine wave with an average value that is positive. The waveform below this shows a sine wave with a negative average value. The average value in both waveforms is called the *dc component of the waveform,* and it is equal to the battery voltage. Without the batteries, the waveforms would have an average value of 0 V.

Figure 1-10 shows a resistor-capacitor (*RC*) circuit that has both ac and dc sources. This cir cuit is similar to many linear electronic circuits that are energized by dc power supplies, such as batteries, and that often process ac signals. Thus, the waveforms in linear electronic cir cuits often show both ac and dc components.

Figure 1-11 shows the waveforms that occur at the various nodes in Fig. 1-10. A node is a point at which two or more circuit elements (resistors, in ductors, etc.) are connected. These two figures will help you understand some important ideas that you will need in your study of linear electronics.

The waveform for Node A, in Fig. 1-11, shows *pure direct current.* The word "pure" is used be cause there is no ac component. This is the wave form expected from a dc source such as a battery. Since Node A in Fig. 1-10 is the positive terminal of the battery, the dc waveform is no surprise.

Node B, in Fig. 1-11, shows *pure alternat ing current* (there is no dc component). Node B is the ac source terminal in Fig. 1-10, so this waveform is what one would expect it to be.

The other waveforms in Fig. 1-11 require more thought. Starting with Node C, we see a pure ac waveform with about half the amplitude of the ac source. The loss in amplitude is caused by the volt

age drop across $R_3$, discussed later. Node D shows an ac waveform with a 5 V dc component. This dc component is established by $R_1$ and $R_2$ in Fig. 1-10, 10 V

B $R_3$ C

3.3 kΩ

10 $V_{p-p}$

10 kHz

which act as a voltage divider for the 10 V dc battery. Finally, Node E in Fig. 1-11 shows a pure ac waveform. The dc component has been removed by $C_2$ in Fig. 1-10. A dc component is present at Node D but is missing at Node E because *capacitors block or remove the dc component of signals or waveforms.*

. . . that capacitors have infinite reactance (opposition) for direct current and act as open circuits.

The formula for capacitive reactance is $X_C = \frac{1}{2\pi f C}$

As the frequency ( $f$ ) approaches direct current (0 Hz), the reactance approaches infinity. In capacitors, the relationship between frequency and reactance is *inverse.* As one goes down, the other goes up.

**EXAMPLE 1-2**

Determine the reactance of the capacitors in Fig. 1-10 at a frequency of 10 kHz and compare this reactance with the size of the resistors: $X_C = \frac{1}{2\pi f C}$

$$= \frac{1}{6.28 \times 10 \times 10^3 \times 1 \times 10^{-6}}$$

$$= 15.9\ \Omega$$

The reactance 15.9 Ω is low. In fact, we can consider the capacitors to be short circuits at 10 kHz because the resistors in Fig. 1-10 are 10 kΩ, which is much larger.

A

10 kΩ $R_1$

1 μF 1 μF

D E
$C_1$ $C_2$
10 kΩ $R_2$

10 kΩ $R_4$

**Fig. 1-10** An *RC* circuit with two sources.

10 V 10 V 10 V 10 V 10 V

0 V
0 V
0 V
0 V
0 V

+5 V +5 V +5 V +5 V 0 V
+5 V 0 V
0 V
0 V
–5 V
0 V
–5 V –5 V –5 V –5 V

0 V
0 V
0 V
0 V
0 V

+5 V +5 V +5 V +5 V 0 V
+5 V 0 V
0 V
0 V
0 V

0 V
0 V
0 V
0 V
0 V
Node A Node A Node A Node A

Node B Node B Node B Node B Node B

Node C Node C Node C Node C Node C

Node D Node D Node D Node D Node D

Node E Node E Node E Node E Node E

Let's summarize two points: (1) the capacitors are open circuits for direct current, and (2) the capacitors are short circuits for ac signals when the signal frequency is relatively high. These two concepts are applied over and over again in analog electronic circuits. Please try to remember them.

What happens at other frequencies? At higher frequencies, the capacitive reactance is even lower, so the capacitors can still be viewed as shorts. At lower frequencies, the capacitors show more reactance, and the short-circuit viewpoint may no longer be correct. As long as the reactance is less than one-tenth of the effective resistance, the short-circuit viewpoint is generally good enough.

**EXAMPLE 1-3**

Determine the reactance of the capacitors in Fig. 1-10 at a frequency of 100 Hz. Will the short-circuit viewpoint be appropriate at this frequency?

$$X_C = \frac{1}{2\pi fC}$$

$$= \frac{1}{6.28 \times 100 \times 1 \times 10^{-6}}$$

$$= 1.59\ \text{k}\Omega$$

This reactance is in the 1,000-Ω range, so  the capacitors *cannot* be viewed as short cir cuits at this frequency.

Figure 1-12 illustrates the equivalent circuits for  Fig. 1-10. The dc equivalent circuit shows the bat tery, $R_1$, and $R_2$. Where did the other resistors and

**Surface-Mount Technology and the Technician**

Although SMT has reduced the amount of time spent on component-level troubleshooting, technicians with these troubleshoot ing skills are still in demand.

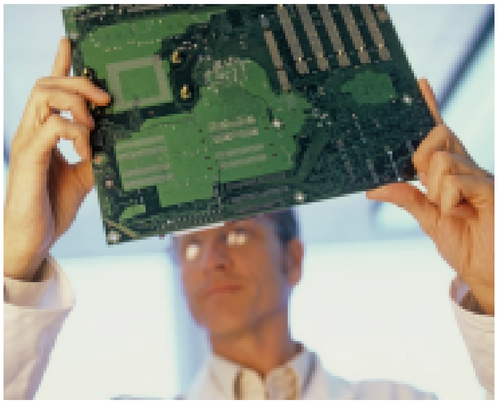




**Fig. 1-11** Waveforms for Fig. 1-10.



**Superposition theorem**

**Bypassing**

3.3 kΩ

$R_3$

A

10 kΩ $R_1$

D

10 kΩ $R_2$

10 V

10 kΩ

DC equivalent circuit C, D, E

10 kΩ $R_1$

at one end and connected to Node D at the other. The equivalent resistance of three 10-kΩ resistors in parallel is one-third of 10 kΩ, or 3.33 kΩ—almost equal to the value of $R_3$.

Resistor $R_3$ and the equiva lent resistance of 3.33 kΩ form a voltage divider. So, the ac voltage at Nodes C, D, and E will be about  half the value of the ac source, or 5 $V_{p-p}$.

When the dc and ac equivalent circuits are taken together, the result at Node D is 5 V di rect current and 5 $V_{p-p}$ alternating current. This explains the waveform at Node D shown in Fig. 1-11. The *superposition theorem,* which you  may have studied, provides the explanation for  the combining effect.

There is another very important concept used  in electronic circuits, called *bypassing.* Look at

AC equivalent circuit

Fig. 1-12 Equivalent circuits for Fig. 1-10.

**Coupling**

10 kΩ $R_2$

Fig. 1-13 and note the $C_2$ is grounded at its right $R_4$

end. This effectively shorts Node D as far as the ac signal is concerned. The waveform shows that Node D has only 5 V dc, since the ac signal has been *bypassed.* Bypassing is used at nodes in cir cuits in which the ac signal must be eliminated. Capacitors are used in many ways. Capacitor $C_2$ in Fig. 1-10 is often called a *coupling capacitor.*

**capacitor**

**Blocking capacitor**

**Bypass capacitor**

the ac source go? They are “disconnected” by the capacitors, which are open circuits for direct cur rent. Since $R_1$ and $R_2$ are equal in value, the dc voltage at Node D is half the battery voltage, or 5 V.

The ac equivalent circuit is more complicated. Note that resistors $R_1$, $R_2$, and $R_4$ are in parallel. Since $R_2$ and $R_4$ are connected by $C_2$ in Fig. 1-10, they can be joined by a short circuit in the ac equivalent cir cuit. Remember that the capacitors can be viewed as short circuits for signals at 10 kHz. An equivalent short at $C_2$ puts $R_2$ and $R_4$ in parallel. Resistor $R_1$ is also in parallel because the internal ac resistance of a dc voltage source is taken to be 0 Ω. Thus, $R_1$ in the ac equivalent circuit is effectively grounded

function is to cou ple the ac signal from Node D to Node E. How ever, while it couples the ac signal, it *blocks* the dc component. So, it may also be called a *blocking capacitor.* Capacitor $C_2$ in Fig. 1-13 serves a dif ferent function. It eliminates the ac signal at Node D and is called a *bypass capacitor.* Figure 1-14 shows a clever application of the ideas presented here. Suppose there is a prob lem with weak signals from a television station. An amplifier can be used to boost a weak signal. The best place for one is at the antenna, but the antenna is often on the roof. The amplifier needs power, so one solution would be to run power

A

10 kΩ $R_1$

This name serves well since its

D

$C_1$ $C_2$ 10 kΩ $R_2$

10 $V_{p-p}$ 10 kHz

B $R_3$ C 3.3 kΩ

5 V Node D 0 V

10 V

1 μF 1 μF

Fig. 1-13 The concept of bypassing.



Antenna Pure direct current

Amplifier

$C_1$

RFC RFC

$C_2$ $C_3$ Coaxial cable

$R_L$

Pure alternating current

Pure alternating current

Direct and alternating current

**Fig. 1-14** Sending power and signal on the same cable.

wires to the roof along with a separate cable for the television signal. The one coaxial cable can serve both needs (power and signal).

The battery in Fig. 1-14 powers an amplifier located at the opposite end of the coaxial cable. The outer conductor of the coaxial cable serves as the ground for both the battery and the remote amplifier. The inner conductor of the coaxial cable serves as the positive connection point for both the battery and the amplifier. Radio-frequency chokes (RFCs) are used to isolate the signal from the power circuit. RFCs are coils wound with copper wire. They are inductors and have more reactance for higher frequencies.

. . . that inductive reactance increases with frequency:

$$X_L = 2\pi fL$$

Frequency and reactance are *directly* related in an inductor. As one increases, so does the other.

At direct current ($f$ = 0 Hz), the induc tive reactance is zero. The dc power passes through the chokes with no loss. As frequency increases, so does the inductive reactance. In Fig. 1-14 the inductive reactance of the choke on the right side of the figure prevents the battery from shorting the high-frequency signal to ground. The inductive reactance of the choke on the left side of Fig. 1-14 keeps the ac signal out of the power wiring to the amplifier.

Chokes are so named because they "choke off" high-frequency current flow.

**EXAMPLE 1-4**

Assume that the RFCs in Fig. 1-14 are 10 μH. The lowest-frequency television channel starts at 54 MHz. Determine the minimum inductive reactance for television signals. Compare the minimum choke reactance with the impedance of the coaxial cable, which is 72 V.

$$X_L = 2\pi fL = 6.28 \times 54 \times 10^6 \times 10 \times$$

$10^{-6} = 3.39\ k\Omega$

The reactance of the chokes is almost 50 times the cable impedance. This means the chokes effectively isolate the cable signal from the battery and from the power circuit of the amplifier.



waveform for Node D and for Node E in Fig. 1-10 if the battery provides 25 V.

## 1-5 Trends in Electronics

Trends in electronics are characterized by enor mous growth and sophistication. The growth is the result of the *learning curve* and competition. The learning curve simply means that as more ex perience is gained, more efficiency results. Elec tronics is maturing as a technology. The yield of integrated circuits is a good example of this. A new integrated circuit (IC), especially a sophis ticated one, may yield less than 10 percent. Nine out of ten do not pass the test and are thrown away, making the price of a new device very high. Later, after much is learned about making that part, the yield goes up to 90 percent. The price drops drastically, and many new applications are found for it because of the lower price. Although

battery. Capacitor $C_1$ is a bypass capacitor. It ensures that the amplifier is powered by pure direct current. Resistor $R_L$ in Fig. 1-14 is the load for the ac signal. It represents the televi sion receiver.

19. Which components are used in electronics to block direct current, to couple ac sig nals, and for bypassing?
20. What is the function of $C_1$ in Fig. 1-14? 21. What is the function of $C_2$ in Fig. 1-14?

applications. SMT is an alternative to insertion technology for the fabrication of circuit boards. With insertion technology, device leads pass through holes in the circuit board. The insides of the holes are usually plated with metal to electrically connect the various board layers. Circuit boards designed for insertion technol ogy have more plated-through holes, are larger, and cost more. The devices intended for SMT have a different appearance. As Fig. 1-15 shows, the

### Learning curve

Capacitors $C_2$ and $C_3$ in Fig. 1-14 are cou pling capacitors. They couple the ac signal into and out of the coaxial cable. These capacitors act as short circuits at the signal frequency, and they are open circuits for the dc signal from the

*Solve problems 17 to 21.*

17. Determine the average value of the bot tom waveform shown in Fig. 1-9 if the battery develops 7.5 V.
18. Find the average value of the

capacitors,

Resistors,

**Microminiatur ization**

the new parts are complex and sophisticated, the usual result is a product that is easier to use. In fact, "user-friendly" is a term used to describe so phisticated products. The IC is the key to most electronic trends. These marvels of *microminiaturization* keep ex panding in performance and usually decrease the cost of products. They also require less energy and offer high reliability. One of the most popu lar ICs, the microprocessor, has created many new products. DSP chips are now fast and inex

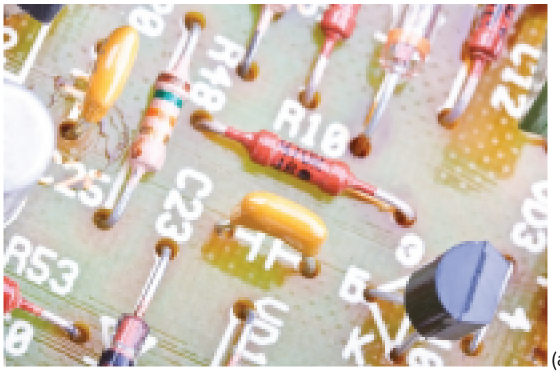
Diodes and transistors and inductors

(SMT)
pensive, encouraging rapid growth.
Along with ICs, *surface-mount technol ogy* (SMT) also helps to expand electronics
Integrated circuits

**Fig. 1-15** Device packaging for surface-mount technology.

## Surface-mount technology




(a)

(b)

A comparison of conventional-mount and surface-mount technologies. (*a*) The photo and the drawing show conventional component mounting. (*b*) Photo and drawing of a surface-mount technology (SMT ) circuit board.

(top left): ©Andrii Chernov/123 RF; (bottom left): ©Montypeter/Shutterstock.com RF

device packages have very short leads or just end terminals. These packages are designed to be soldered onto the surface of printed circuit boards. The short leads save material and re duce the stray effects associated with the longer leads used in insertion technology. SMT pro vides better electrical performance, especially in high-frequency applications.

Two other advantages of SMT are lower cir cuit assembly cost, since it is easier to automate, and a lower profile. Since more boards can be packed into a given volume, smaller, less expen sive products will become available.

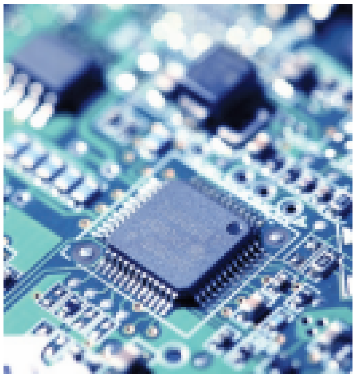
A disadvantage of SMT technology is the close spacing of IC leads. Troubleshooting and repair are difficult. Figure 1-16 shows some tools that should be on hand to make measurements on modern circuit boards. The probe allows mo mentary contact to be made safely at one IC pin. An ordinary probe is uninsulated and will likely slip between two SMT device leads. When this happens, the two leads will be shorted together, and damage could result. The single contact test clip in Fig. 1-16 is preferred for making connec tions that will be used for more than one mea surement. The IC test clip in Fig. 1-16 is the best tool for SMT IC measurements. It clips onto an SMT IC and provides larger and widely spaced test contacts for safe probing or test-clip con nections. Different models are available for the various SMT IC packages.

The uses for electronic devices, products, and systems are expanding. Computer technol ogy finds new applications almost on a daily basis. Electronic communications is expanding

care to avoid shorting device pins together.

©Janka Dharmasena/Getty Images RF

Yes, it is possible to probe surface-mount integrated circuits safely. Probing surface mount devices requires great

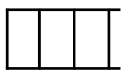




Insulator Metal tip

clip

Probe



IC contacts

IC test clip

Handle

Test contacts

Single-contact test

**Fig. 1-16** Tools for SMT measurements.

rapidly. Thanks to compression and process ing breakthroughs, the growth is brisk. Three dimensional image processing is providing systems for product inspection, automated security monitoring, and even virtual reality for education and entertainment. Computer tech nology is merging with telecommunications to provide new methods of information transfer, education, entertainment, and shopping. New sensors are being developed to make systems energy efficient and less damaging to the envi ronment. As an example, heating, ventilating, and air-conditioning systems will use oxygen sensors to direct airflow in buildings on an as-needed basis.

Product features continue to expand. Digi tal cameras might have a built-in GPS re ceiver to identify the locations where shots were taken and perhaps a built-in projector to share images without relying on an exter nal device or a tiny on-board LCD screen. More accessories such as pointing devices, scanners, keyboards, and printers offer wire less connectivity. Television receivers have built-in Ethernet, WiFi, HDMI, and USB ports for Internet access and easy integration with other devices, and some receivers offer vivid three-dimensional viewing. Mobile de vices with WiFi or 3G replace computers for e-mail, Internet browsing, social networking,

and so on. Smartphones integrate functions once dependent on computers.

The information age is merging databases to reduce errors and improve safety and effi ciency. A patient is more likely to get the tests she or he needs, the correct medications, the correct procedures, and all in a timely fash ion. Health care professionals have instant access to medical history, test results, notes, and comments from other professionals. And the patient wrist tag might have an embedded radio-frequency (RF) chip. Medical imaging continues to improve to hasten the diagnostic procedure, increase accuracy, and eliminate the need for some invasive procedures or more costly or dangerous tests.

Homes and other structures are becom ing more energy efficient thanks to sophis ticated but affordable control systems and improved appliances and lighting. Renew able sources such as photovoltaic arrays can feed surplus energy into the grid; this would not be safe or practical without electronic devices such as inverters, controllers, and smart converters.

The outlook is bright for those with careers in electronics. The new products, the new applications, and the tremendous growth mean good jobs for the future. The jobs will be chal lenging and marked by constant change.



Diagnostics (CAN)
Communications and entertainment Smart turn signals
Event data recorder
Noise suppression
Anti theft
Antilock brakes
Lane control
Blindspot detection Comfort control
Active yaw control
Active suspension
Adaptive cruise
Auto parking
Tire pressure monitor
Auto dim mirror
Head up display
Airbag deployment
Stability control and adaptive steering
Engine and transmission control
Adaptive lighting
Ignition, valve, and injection timing
control Automatic braking

On the way to driverless automobiles, many new electronic systems are added all the time.

A large array of photovoltaic panels.

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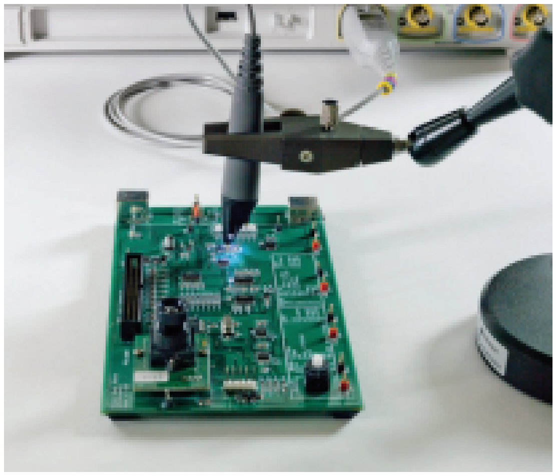


devices. ©Keysight Technologies. All Rights reserved

*Determine whether each statement is true or false.*

22. Integrated circuits will be used less in the future.

Agilent 1145A probe for surface-mount

23. The learning curve makes electronic devices less expensive as time goes on. 24. In the future, more circuits will be fab ricated using insertion technology and fewer with SMT.



# Chapter 1 Summary and

# Review

1. Electronics is a relatively young field. Its history began in the 20th century.
2. Electronic circuits can be classified as digital or analog.
3. The number of states or voltage levels is limited in a digital circuit (usually to two).
4. An analog circuit has an infinite number of voltage levels.
5. In a linear circuit, the output signal is a replica of the input.
6. All linear circuits are analog, but not all analog circuits are linear. Some analog circuits distort signals.
7. Analog signals can be converted to a digital format with an A/D converter.
8. Digital-to-analog converters are used to produce a simulated analog output from a digital system. 9. The quality of a digital representation of an analog signal is determined by the sampling rate and the number of bits used.
10. The number of output levels from a D/A converter is equal to 2 raised to the power of the number of bits used.
11. Digital signal processing uses computers to enhance signals.
12. Block diagrams give an overview of electronic system operation.
13. Schematic diagrams show individual part wiring and are usually required for component-level troubleshooting.
14. Troubleshooting begins at the system level.
15. Alternating current and direct current signals are often combined in electronic circuits.
16. Capacitors can be used to couple ac signals, to block direct current, or to bypass alternating current. 17. SMT is replacing insertion technology.

Number of levels in a binary system: levels = $2^n$ Capacitive reactance: $X_C = \dfrac{1}{2\pi fC}$

Inductive reactance: $X_L = 2\pi fL$

*Determine whether each statement is true or false.*

1-1. Most digital circuits can output only two states, high and low. (1-2)

1-2. Digital circuit outputs are usually sine waves. (1-2)

1-3. The output of a linear circuit is an exact replica of the input. (1-2)

1-4. Linear circuits are classified as analog. (1-2) 1-5. All analog circuits are linear. (1-2)

1-6. The output of a 4-bit D/A converter can produce 128 different voltage levels. (1-2)

1-7. An attenuator is an electronic circuit used to make signals stronger. (1-3)

1-8. Block diagrams are best for component-level troubleshooting. (1-3)

1-9. In Fig. 1-8, if the signal at point 4 is faulty, then the signal at point 3 must also be faulty. (1-3) 1-10. Refer to Fig. 1-8. The power supply should be checked first. (1-3)

1-11. Refer to Fig. 1-10. Capacitor $C_2$ would be called a bypass capacitor. (1-4)

1-12. Node C in Fig. 1-10 has no dc component since $C_1$ blocks direct current. (1-4)

1-13. In Fig. 1-11, Node D is the only waveform with dc and ac components. (1-4)

1-14. Refer to Fig. 1-14. The reactance of the coils is high for dc signals. (1-4)

1-1. Functions now accomplished by using electron ics may be accomplished in different ways in the future. Can you think of any examples?

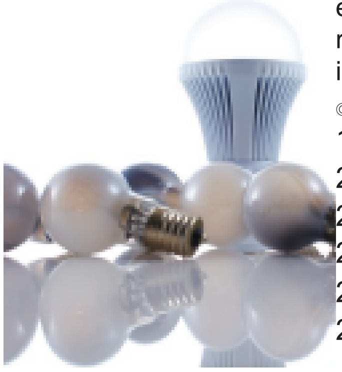
1-2. Can you describe a simple system that uses only two wires but will selectively signal two differ ent people?

1-3. What could go wrong with capacitor $C_2$ in Fig. 1-10, and how would the fault affect the waveform at Node D?

1-4. What could go wrong with capacitor $C_2$ in Fig. 1-13, and how would the fault affect the waveform at Node D?

18. 12.5 V, 0 V

1. T 2. T 3. F 4. T 5. F 6. T
7. T 8. F 9. T
10. F 11. F 12. T
13. F
14. F
15. T
16. F
17. −7.5 V



Contrast between an LED light source and incandescent lamps. The LEDs are much more efficient and will be replacing the older incandescent types.



19. capacitors
20. bypass
21. coupling (dc block)
22. F
23. T
24. F

## Learning Outcomes

*This chapter will help you to:*

2-1 *Identify* some common electronic materials as conductors or semiconductors. [2-1] 2-2 *Predict* the effect of temperature on conductors. [2-1]

2-3 *Predict* the effect of temperature on semiconductors. [2-2]

2-4 *Show* the directions of electron and hole currents in semiconductors. [2-3, 2-4]

2-5 *Identify* the majority and minority carriers in N-type semiconductors. [2-5]

2-6 *Identify* the majority and minority carriers in P-type semiconductors. [2-5]

2-7 *Explain* the term band gap. [2-7]

# Semiconductors

Electronic circuits used to be based on

the flow of electrons in devices called vacuum tubes. Today, almost all electronic circuits are based on current flow in semi conductors. The term "solid state" means that semiconducting crystals are being used to get the job done. The mechanics of cur rent flow in semiconductors is different from that in conductors. Some current carriers are not electrons. High temperatures create additional carriers in semiconductors. These are important differences between semicon ductors and conductors. The transistor is considered to be one of the most important developments of all time. It is a semiconduc tor device. Diodes and integrated circuits are also semiconductors. This chapter covers the basic properties of semiconductors.

## 2-1 Conductors and Insulators

All materials are made from atoms. At the cen ter of any atom is a small, dense core called the *nucleus.* Figure 2-1(*a*) shows that the nu cleus of a copper atom is made up of positive (+) particles called *protons* and neutral (N) particles called *neutrons.* Around the nucleus are orbiting *electrons* that are negative (−) particles. Copper, like all atoms, has an equal number of protons and electrons. Thus, the net atomic charge is zero.

In electronics, the main interest is in the orbit that is farthest away from the nucleus. It is called the *valence orbit.* In the case of copper, there is only one valence electron. A *copper atom* can be simplified as shown in Fig. 2-1(*b*). Here, the nucleus and the first three orbits are combined into a net positive (+) charge. This is balanced by the single valence electron.

**Proton**

**Neutron**

**Electron**

**Valence orbit Copper atom**

**Nucleus**



N
N N N

electron is very important since it acts as the *current carrier.*

Even a very small copper wire contains billions of atoms, each with one valence elec tron. These electrons are only weakly attracted to the nuclei of the atoms. They are very easy to move. If an *electromotive force (a voltage)* is applied across the wire, the valence electrons will respond and begin drifting toward the posi

N
N N N

N

N
N

**Current carrier**

**Electromotive force (a voltage)**

N N

tive end of the source voltage. Since there are so many valence electrons and since they are so easy to move, we can expect tremendous numbers of electrons to be set in motion by even a small voltage. Thus, copper is an excellent electric conductor. It has very *low resistance.* Heating a copper wire will change its resistance.

**Low resistance**

charged

tance. As the wire becomes warmer, the valence electrons become more active. They move farther away from their nuclei, and they move more rapidly. This activity increases the chance for collisions as current-carrying electrons drift toward the positive end of the wire. These collisions absorb energy and increase the resistance to current flow. The resistance of the wire increases as it is heated.

All conductors show this effect. As they become hotter, they conduct less efficiently, and their resistance increases. Such materials are said to have a *positive temperature coefficient.* This simply means that the relationship between

**Positive temperature coefficient**

(a) Bohr model of the copper atom (not to scale)

(b) Simplified model

**Fig. 2-1** Atomic copper.

*Conductors* form the fundamental paths for electronic circuits. Figure 2-2 shows how a copper wire supports the flow of electrons. A copper atom contains a positively nucleus and negatively charged electrons that orbit around the nucleus. Figure 2-2 is simplified to show only the outermost orbiting electron, the *valence electron.* The valence

**Conductor**

**Valence electron**

Superconductivity occurs at extremely low temperatures. MRI machines used in medicine use liquid hydrogen to achieve −442°F.

Valence electrons

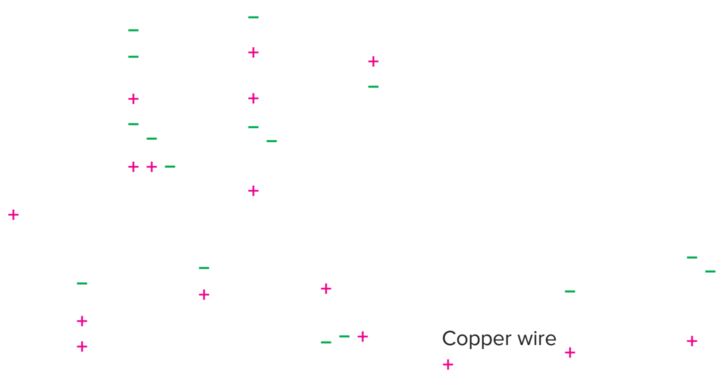



**Fig. 2-2** The structure of a copper conductor.

**Printed circuit**

**Insulator**

**Compound**

temperature and resistance is positive—that is, they increase together.

Copper is the most widely applied conductor in electronics. Most of the wire used in elec tronics is made from copper. *Printed circuits* use copper foil to act as circuit conductors. Copper is a good conductor, and it is easy to solder. This makes it very popular.

Aluminum is a good conductor, but not as good as copper. It is used more in power transformers and transmission lines than it is in electronics. Aluminum is less expensive than copper, but it is difficult to solder and tends to corrode rapidly when brought into contact with other metals.

Silver is the best conductor because it has the least resistance. It is also easy to solder. The high cost of silver makes it less widely applied than copper. However, silver-plated conduc tors are sometimes used in critical electronic circuits to minimize resistance.

Gold is a good conductor. It is very stable and does not corrode as badly as copper and silver. Some sliding and moving electronic contacts are gold-plated. This makes the con
tacts very reliable.

The opposite of a conductor is called an *insulator.* In an insulator, the valence electrons are tightly bound to their parent atoms. They are not free to move, so little or no current flows when a voltage is applied. Practically all insula
tors used in electronics are based on compounds. A *compound* is a combination of two or more different kinds of atoms. Some of the widely applied insulating materials include rubber, plastic, Mylar, ceramic, Teflon, and polystyrene.

Whether a material will insulate depends on how the atoms are arranged. Carbon is such a material. Figure 2-3(*a*) shows carbon arranged in the diamond structure. With this crystal or diamond structure, the valence electrons cannot move to serve as current car
riers. Diamonds are insulators. Figure 2-3(*b*) shows carbon arranged in the graphite struc ture. Here, the valence electrons are free to move when a voltage is applied. It may seem odd that both diamonds and graphite are made from carbon. One insulates, and the other does not. It is simply a matter of whether the valence electrons are locked into the struc ture. Carbon in graphite form is used to make resistors and electrodes. So far, the diamond structure of carbon has not been used to make electrical or electronic devices.

(a) Diamond

carbon.

- Crystal radio receivers were an early application of semiconductors.

### Materials Used for Dopants, Semiconductors, and Microwave Devices

- Gallium arsenide (GaAs) works better than silicon in microwave devices because it allows faster movement of electrons.
- Materials other than boron and arsenic are used as dopants.
- It is theoretically possible to make semiconductor devices from crystalline

(b) Graphite

**Fig. 2-3** Structures of diamond and graphite.



*Determine whether each statement is true or false.*

1. Valence electrons are located in the nucleus of the atom.
2. Copper has one valence electron.
3. In conductors, the valence electrons are strongly attracted to the nucleus.
4. The current carriers in conductors are the valence electrons.
5. Cooling a conductor will decrease its resistance.
6. Silver is not often used in electronic circuits because of its high resistance.
7. Aluminum is not used as much as copper in electronic circuits because it is difficult to solder.

## 2-2 Semiconductors

*Semiconductors* do not allow current to flow as easily as conductors do. Under some conditions semiconductors can conduct so poorly that they behave as insulators.

Valence orbit

**Semiconductor**

*Silicon* is the most widely used semiconductor material. It is used to make *diodes*, *transistors*, and integrated circuits. These and other components make modern electronics possible.

**Diode**

**Transistor**

**Silicon**

N +

– – –

N

It is important to understand some of the details about silicon. Figure 2-4 shows atomic silicon. The com pact bundle of particles in the center of the atom [Fig. 2-4(*a*)] contains protons and neutrons. This bundle is called the *nucleus of the atom.* The protons show a positive (+) electric charge, and the neutrons show no electric charge (N).

N + –

+ + –

– –

– – N –

Negatively charged electrons travel around the nucleus in orbits. The first orbit has two elec trons. The second orbit has eight electrons. The last, or outermost, orbit has four electrons. The outermost or valence orbit is the most impor tant atomic feature in the electrical behavior of materials.

Because we are interested mainly in the valence orbit, it is possible to simplify the drawing of the silicon atom. Figure 2-4(*b*) shows only the nucleus and the valence orbit of a silicon atom. Remember that there are four electrons in the valence orbit.

Materials with four valence electrons are not stable. They tend to combine chemically with other materials. They can be called *active mate rials.* This activity can lead them to a more stable state. A law of nature makes certain materials

**Fig. 2-4** Atomic silicon.

(a) The structure of a silicon atom

N

**Active material**

(b) A simplified silicon atom



a symbolic diagram of a crystal of pure silicon. The dots represent valence electrons.

Count the valence electrons around the nucleus of one of the atoms shown in Fig. 2-5.

Doping graphene with lithium can produce superconductivity.

structure that results is called a *crystal.* Figure 2-5 is

**Crystal**

**Silicon dioxide Ionic bond**

**Intrinsic silicon Insulator**

**Thermal carrier**

**Covalent bonding**

tend to form combinations that will make eight electrons available in the valence orbit. Eight is an important number because it gives stability.

One possibility is for silicon to combine with oxygen. A single silicon atom can join, or link, with two oxygen atoms to form *silicon dioxide* ($SiO_2$). This linkage is called an *ionic bond.* The new structure, $SiO_2$, is much more stable than either silicon or oxygen. It is inter esting to consider that chemical, mechanical, and electrical properties often run parallel.

Silicon dioxide is stable chemically. It does not react easily with other materials. It is also sta ble mechanically. It is a hard, glasslike mate rial. Finally, it is stable electrically. It does not conduct; in fact, it is used as an *insulator* in in tegrated circuits and other solid-state devices. $SiO_2$ insulates because all of the valence elec trons are tightly locked into the ionic bonds. They are not easy to move and therefore do not support the flow of current.

Sometimes oxygen or another material is not available for silicon to combine with. The silicon still wants the stability given by eight valence electrons. If the conditions are right, silicon atoms will arrange to share valence electrons. This pro cess of sharing is called *covalent bonding.* The

Select one of the internal nuclei as represented by a circled N. You will count eight electrons. Thus, the silicon crystal is very stable. At room temperature, pure silicon is a very poor conduc tor. If a moderate voltage is applied across the crystal, very little current will flow. The valence electrons that normally would support current flow are all tightly locked up in covalent bonds.

Pure silicon crystals behave like *insula tors.* Yet silicon itself is classified as a semi conductor. Pure silicon is sometimes called *intrinsic silicon.* Intrinsic silicon contains very few free electrons to support the flow of current and therefore acts as an insulator.

Crystalline silicon can be made to semicon duct. One way to improve its conduction is to heat it. Heat is a form of energy. A valence elec tron can absorb some of this energy and move to a higher orbit level. The high-energy electron has *broken* its covalent bond. Figure 2-6 shows a high-energy electron in a silicon crystal. This electron may be called a *thermal carrier.* It is free to move, so it can support the flow of current. Now, if a voltage is placed across the crystal, current will flow.

Silicon has a *negative temperature coef ficient.* As temperature increases, resistance

N

N N N N N N

N N N N N N

N

N N N N N N

N

Covalent bonds

**Fig. 2-5** A crystal of pure silicon.

N N N

N N N N



N N N N N N

Broken covalent bond

N N N

Heat energy

**Fig. 2-6** Thermal carrier production.

Free electron

half for every 10°C rise in temperature. This would seem to make germanium more stable with temperature change.

The big difference between germanium and silicon is the amount of heat energy needed to move one of the valence electrons to a higher orbit level, breaking its covalent bond. This is far easier to do in a germanium crystal. A com parison between two crystals, one germanium and one silicon, of the same size and at room temperature will show about a 1,000:1 ratio in resistance. The silicon crystal will actually have 1,000 times the resistance of the germa nium crystal. So even though the resistance of silicon drops more rapidly than that of germa nium with increasing temperature, silicon is still going to show greater resistance than ger manium at a given temperature.

Circuit designers prefer silicon devices for

*decreases* in silicon. It is difficult to predict exactly how much the resistance will change in a given case. One rule of thumb is that the resistance will be cut in half for every 6°C rise in temperature.

The semiconductor material *germanium* is used to make transistors and diodes, too. Ger manium has four valence electrons and can form the same type of crystalline structure as silicon. It is interesting to observe that the first transistors were all made of germanium. The first silicon transistor was not developed until 1954. Now silicon has almost entirely replaced germanium. One of the major reasons for this shift from germanium to silicon is the *tempera ture response.* Germanium also has a negative temperature coefficient. The rule of thumb for germanium is that the resistance will be cut in

*Determine whether each statement is true or false.*

8. Silicon is a conductor.
9. Silicon has four valence electrons. 10. Silicon dioxide is a good conductor. 11. A silicon crystal is formed by covalent bonding.
12. Intrinsic silicon acts as an insulator at room temperature.

most uses. The thermal, or heat, effects are usu ally a source of trouble. Temperature is not easy to control, and we do not want circuits to be in fluenced by it. However, all circuits are changed by temperature. Good designs minimize that change.

Sometimes heat-sensitive devices are nec essary. A sensor for measuring temperature can take advantage of the temperature coeffi cient of semiconductors. So the temperature coefficient of semiconductors is not always a disadvantage.

Germanium started the solid-state revolu tion in electronics, but silicon has taken over. The integrated circuit is a key part of most electronic equipment today. It is not practical to make integrated circuits from germanium, but silicon works well in this application.

13. Heating semiconductor silicon will decrease its resistance.
14. An electron that is freed from its covalent bond by heat is called a thermal carrier.
15. Germanium has less resistance than silicon.
16. Silicon transistors and diodes are not used as often as germanium devices.
17. Integrated circuits are made from germanium.

**Germanium**

**Temperature response**



## 2-3 N-Type Semiconductors

**N-type semiconductor material**

Thus far we have seen that pure semiconductor crystals are very poor conductors. High tem peratures can make them semiconduct because thermal carriers are produced. For most ap plications, there is a better way to make them semiconduct.

**Doping**

*Doping* is a process of adding other mate rials called *impurities* to the silicon crystal to change its electrical characteristics. One such impurity material is *arsenic.* Arsenic is known as a *donor impurity* because each arsenic atom donates one free electron to the crystal. Fig ure 2-7 shows a simplified arsenic atom. Arse nic is different from silicon in several ways, but the important difference is in the valence orbit. Arsenic has *five* valence electrons.

**Arsenic**

When an arsenic atom enters a silicon crys tal, a free electron will result. Figure 2-8 shows what happens. The covalent bonds with neigh boring silicon atoms will capture four of the arsenic atom's valence electrons, just as if it were another silicon atom. This tightly locks the arsenic atom into the crystal. The fifth valence electron cannot form a bond. It is a *free* electron as far as the crystal is concerned. This makes the electron very easy to move. It can serve as a current carrier. Silicon with some arsenic atoms will semiconduct even at room temperature.

Doping lowers the resistance of the sili con crystal. When donor impurities with five valence electrons are added, free electrons are produced. Since electrons have a negative charge, we say that an *N-type semiconductor material* results.

Si Si Si Si As Si

Si Si Si **Fig. 2-8** N-type silicon.

**Fig. 2-7** A simplified arsenic

Extra electron

atom.

N

*statement.*

18. Arsenic is a impurity. 19. Arsenic has valence electrons. 20. When silicon is doped with arsenic, each arsenic atom will give the crystal one free .
21. Free electrons in a silicon crystal will serve as current .
22. When silicon is doped, its resistance .

*Supply the missing word in each*



## 2-4 P-Type Semiconductors

Doping can involve the use of other kinds of impurity materials. Figure 2-9 shows a simpli fied *boron atom.* Note that boron has only three valence electrons. If a boron atom enters the silicon crystal, another type of current carrier will result. Figure 2-10 shows that one of the covalent bonds with neighboring silicon atoms cannot be formed. This produces a *hole*, or *missing electron.* The hole is assigned a *positive charge* since it is capable of attracting, or being filled by, an electron.

Boron is known as an *acceptor*

*impurity.* Each boron atom in the crystal will create a hole that is capable of accepting an electron. car to move up one position. The driver of that car takes the opportunity to do so, and this makes a space for directly behind it. The driver of the second car also moves up one position. This continues with the third car, the fourth car, and so on down the line.

The cars are moving from left to right. Note that the space is moving from right to left. A hole may be considered as a space for an electron. This is why hole current is opposite in direction to electron current.

**Boron atom**

Si Si Si

**Hole, or missing electron**

Holes serve as current carriers. In a conduc tor or an N-type semiconductor, the carriers are electrons. The free electrons are set in motion by an applied voltage, and they drift toward the positive terminal. But in a P-type semiconduc

Si B +

Si

Missing electron (hole)

negative end of the voltage source.

– – – – – –

– – – –

tor, the holes move toward the negative termi nal of the voltage source. Hole current is equal to electron current but *opposite* in direction. Figure 2-11 illustrates the difference between N-type and *P-type semiconductor materials.* In Fig. 2-11(*a*) the carriers are electrons, and they drift toward the positive end of the voltage source. In Fig. 2-11(*b*) the carriers are holes, and they drift toward the

Figure 2-12 shows a simple analogy for hole current. Assume that a line of cars is stopped for a red light, but there is space for the first

+–

(a)

P-type semiconductor

Si Si Si **Fig. 2-10** P-type silicon.

N-type semiconductor

**P-type semiconductor material**

+ +

+

+

+

+

+

+

+ +

N

+−

(b)

Fig. 2-11 Conduction in N- and P-type silicon.

Fig. 2-9 A simplified boron atom.



23. Boron is an impurity. 24. Boron has valence electrons. 25. Electrons are assigned a negative charge, and holes are assigned a charge.

with boron will produce current carriers called .

27. Electrons will drift toward the positive end of the energy source, and holes will drift toward the __________ end.

## 2-5 Majority and Minority Carriers

When N- and P-type semiconductor materials are made, the doping levels can be as small as 1 part per million or 1 part per billion. Only a tiny trace of impurity materials having five or three valence electrons enters the crystal. It is not possible to make the silicon crystal absolutely pure. Thus, it is easy to imagine that an occasional atom with three valence elec trons might be present in an N-type semiconduc tor. An unwanted hole will exist in the crystal. This hole is called a *minority carrier.* The free electrons are the *majority carriers.*

In a P-type semiconductor, one expects holes to be the carriers. They are in the majority. A few free electrons might also be present. They will be the minority carriers in this case.

Minority carrier Majority carrier

Fig. 2-12 Hole current analogy.

## Self-Test

*Supply the missing word in each statement.*

26. Doping a semiconductor crystal



The majority carriers will be electrons for N-type material and holes for P-type material. Minority carriers will be holes for N-type ma terial and electrons for P-type material.

Today very high-grade silicon can be manu factured. This high-grade material has very few unwanted impurities. Although this keeps the number of minority carriers to a minimum, their numbers are increased by high tempera tures. This can be quite a problem in electronic circuits. To understand how heat produces mi nority carriers, refer to Fig. 2-6. As additional heat energy enters the crystal, more and more electrons will gain enough energy to break their bonds. Each broken bond produces both a free electron and a hole. Heat produces carriers in *pairs.* If the crystal was manufactured to be N-type material, then every thermal hole be comes a minority carrier and the thermal electrons join the other majority carriers. If the crystal was made as P-type material, then the thermal holes join the majority carriers and the thermal electrons become minority carriers.

Carrier production by heat decreases the crystal's resistance. The heat also produces mi nority carriers. Heat and the resulting minority carriers can have an adverse effect on the way semiconductor devices work.

This chapter has focused on silicon be cause most semiconductors are made from it.

### Niels Bohr and the Atom

Scientists change the future by
improving on the ideas of others.
Niels Bohr proposed a model
of atomic structure in 1913 that
applied energy levels (quantum
mechanics) to the Rutherford model of the atom. Bohr also used some of the work of Max Planck.

*Source:* Library of Congress Prints and Photographs Division [LC-USZ62-112063]

However, other materials called *compound semiconductors* are becoming important. They are the result of intensive aerospace and indus trial research to find materials that are better than silicon in certain areas. The three most important areas where the compound semi conductors offer advantages are at very high frequencies (often called microwaves), in pho tonics (the production, sensing, control, and transmission of light), and in hostile environ ments such as extreme cold and high radiation. The following is a partial list of compound semiconductors:

· Gallium arsenide
· Indium phosphide
· Mercury cadmium telluride
· Silicon carbide
· Cadmium sulfide
· Cadmium telluride

*Determine whether each statement is true or false.*

28. In the making of N-type semiconductor material, a typical doping level is about 10 arsenic atoms for every 90 silicon atoms.
29. A free electron in a P-type crystal is called a majority carrier.
30. A hole in an N-type crystal is called a minority carrier.
31. As P-type semiconductor material is heated, one can expect the number of minority carriers to increase.
32. As P-type semiconductor material is heated, the number of majority carriers decreases.
33. Heat increases the number of minority and majority carriers in semiconductors.

Compound semiconductors



## 2-6 Other Materials

Silicon accounts for almost all of the devices currently being made. However, silicon is "running out of room" in that additional performance increases are becoming more difficult to achieve. This is especially true with integrated circuits.

IC devices such as transistors have become progressively smaller, and this has progressively improved speed since the holes and electrons do not have as far to travel. Now, they have become small enough so that atomic interactions are beginning to interfere with proper operation.

What is needed is a way to have higher carrier mobility, that is, get the holes and electrons to move faster. Mobility can be improved by using other materials, such as gallium arsenide. You might have run across the term GASFET, which is an acronym for gallium arsenide field effect transistor. GASFETs are used in very high-frequency applications.

Carrier mobility can also be improved by using a variety of new silicon technologies, including strained silicon, silicon germanium (SiGe), and silicon on insulator (SOI), as well as combinations of these materials.

Strained silicon is formed by the growth of a silicon-germanium layer on top of a traditional silicon wafer. Wafers of silicon are the basic raw material used in the manufacture of integrated circuits, which is covered in Chap. 13. A layer of germanium is grown onto a silicon wafer. Then, another layer of silicon is grown on top of that. This final layer of silicon is strained at the interface because silicon and germanium atoms differ in size, with germanium being about 4 percent larger. The larger crystalline lattice exerts a strain on the top silicon layer, which slightly stretches the silicon lattice. By controlling the amount of germanium, the amount of strain produced in the overlying silicon layer can be manipulated. Improvements of carrier mobility up to 75 percent can be achieved by straining silicon.

Silicon carbide devices can safely handle thousands of volts.

Conduction

Silicon-germanium transistors are noted for their high-speed and high-frequency performance. Transistors are introduced in Chap. 5.

Another promising development is the *organic* semiconductor. These devices use semiconduct ing and sometimes conducting materials that are made of molecules containing carbon, mostly in combination with hydrogen and oxygen. Slower than silicon, but more flexible and potentially much cheaper, organic electronics has already produced circuits with hundreds of transistors printed on plastic, experimental sensors and memories, and displays that bend like paper. Or ganic displays might compete with liquid crystal displays, as they are brighter and faster and don't suffer from a limited viewing angle.

## 2-7 Band Gaps

In a semiconductor, such as silicon, the energy difference between the top of the valence band and the bottom of the conduction band is called the *band gap.* Or it is the amount of energy, in electron volts (eV), required to free a valence electron from its orbit and boost it to the con
duction level.

$$1 \text{ eV} = 1.602 \times 10^{-19} \text{ joules}$$

The joule is the SI unit of work or energy and amounts to a force of 1 newton applied over a distance of 1 meter, or to a current of 1 am pere through a 1-ohm resistor for 1 second. The band gap for silicon is 1.1 eV, and for gallium arsenide, it's 1.43 eV.

As Fig. 2-13 shows, there is no energy gap between the valence band and the conduction

Valence

band

band

Band gap

Dopant band

Conductor Insulator Intrinsic silicon Doped silicon **Fig. 2-13**

Energy band diagrams.



band in a conductor. In fact, the bands overlap as shown in red. An insulator has a large band gap. This means that it is very difficult to move a valence electron into the conduction band. However, it can be done. This is why insula
tors can break down and conduct if subjected to very high voltages. Now, look at the graph for intrinsic silicon. The band gap is smaller than that of an insulator, but it's still too large for most applications. Finally, look at doped silicon. The electrons provided by the dopant material (green) fall just below the conduction band. The band gap is small for doped semicon ductors. This is important for the operation of devices such as diodes and solar cells, both of which are explained in the next chapter.

In the case of a solar cell, to free an elec tron, the energy of a photon (a light particle or a quantum unit of light energy) must be at least as great as the band gap energy. Photons with more energy than the band gap energy will ex pend the extra energy as heat. So it's important for a solar cell to be optimized through slight modifications to the silicon's molecular struc ture. A key to obtaining an efficient solar cell

*Determine whether each statement is true or false.*

34. The band gap of materials is measured in volts.
35. The band gap for copper or silver is zero. 36. The electron volt is a unit of work or energy.

is to convert as much sunlight as possible into electricity.

The photon energy of light varies according
to the different wavelengths of the light. The entire spectrum of sunlight, from infrared to ultraviolet,

covers a range from about 0.5 eV to about 2.9 eV. For example, red light has an energy of about 1.7 eV, and blue light has an energy of about 2.7 eV. Most solar cells cannot use about 55 percent of the energy of sunlight, because this energy is either below the band gap of the material or is excessive. There is currently intense interest in finding new semi
conductor materials to improve the efficiency and lower the cost of solar cells. It is possible to stack cells that have different band gaps to increase efficiency.

Diamond might someday make extremely high-voltage/ high-power devices possible. Diamond has a band gap of 5.5 eV and excellent heat conductivity.

37. If a photon has more energy than the band gap of a solar cell, it cannot boost an elec tron into the conduction band.
38. Doping semiconductors increases their band gaps.

# Chapter 2 Summary and Review

1. Good conductors, such as copper, contain a large number of current carriers.
2. In a conductor, the valence electrons are weakly attracted to the nuclei of the atoms.
3. Heating a conductor will increase its resistance. This response is called a positive temperature coefficient.
4. Silicon atoms have four valence electrons. They can form covalent bonds that result in a stable crystal structure.
5. Heat energy can break covalent bonds, making free electrons available to conduct current. This gives silicon and other semiconductor materials a negative temperature coefficient.
6. At room temperature, germanium crystals have 1,000 times more thermal carriers than silicon crystals do. This makes germanium diodes and transistors less useful than silicon devices for many applications.
7. The process of adding impurities to a semiconductor crystal is called doping.
8. Doping a semiconductor crystal changes its electrical characteristics.
9. Donor impurities have five valence electrons and produce free electrons in the crystal. This forms N-type semiconductor material.
10. Free electrons serve as current carriers. 11. Acceptor impurities have three valence electrons and produce holes in the crystal.
12. Holes in semiconductor materials serve as current carriers.
13. Hole current is opposite in direction to electron current.
14. Semiconductors with free holes are classified as P-type materials.
15. Impurities with five valence electrons produce N-type semiconductors.
16. Impurities with three valence electrons produce P-type semiconductors.
17. Holes drift toward the negative end of a voltage source.
18. Electrons are majority carriers for N-type material. Holes are majority carriers for P-type material. 19. Holes are minority carriers for N-type material. Electrons are minority carriers for P-type material. 20. The number of minority carriers increases with temperature.
21. To move a valence electron to the conduction band, an amount of energy equal to or greater than the band gap must be applied.

*Determine whether each statement is true or false.*

2-1. The current carriers in conductors such as copper are holes and electrons. (2-1)

2-2. It is easy to move the valence electrons in conductors. (2-1)

2-3. A positive temperature coefficient means the re - sistance goes up as temperature goes down. (2-1) 2-4. Conductors have a positive temperature coefficient. (2-1)

2-5. Silicon does not semiconduct unless it is doped or heated. (2-2)

2-6. Silicon has five valence electrons. (2-2)

2-7. A silicon crystal is built by ionic bonding. (2-2) 2-8. Materials with eight valence electrons tend to be unstable. (2-2)

2-9. Semiconductors have a negative temperature coefficient. (2-2)



2-10. Silicon is usually preferred to germanium because it has higher resistance at any given temperature. (2-2)

2-11. When a semiconductor is doped with arsenic, free electrons are placed in the crystal. (2-3) 2-12. N-type material has free electrons available to support current flow. (2-3)

2-13. Doping a crystal increases its resistance. (2-3) 2-14. Doping with boron produces free electrons in the crystal. (2-4)

2-15. Hole current is opposite in direction to electron current. (2-4)

2-16. Holes are current carriers and are assigned a positive charge. (2-4)

2-17. If a P-type semiconductor shows a few free electrons, the electrons are called minority carriers. (2-5)

2-18. If an N-type semiconductor shows a few free holes, the holes are called minority carriers. (2-5)

2-1. Suppose that you could perfect a method of inexpensively making ultrapure carbon crystals and then doping them. How could these crystals be used in electronics? (*Hint:* Diamonds are noted for their extreme hardness and ability to withstand high temperatures.)

2-2. Some semiconductors, such as gallium arsenide, show better carrier mobility than silicon. That is, the carriers move faster in the crystal. What kinds of devices could benefit from this?

2-3. Semiconductors respond to temperature by showing decreased resistance leading to prob lems in many, but not all, electronic products. Can you think of an application where their temperature sensitivity is desired?

2-4. You have learned that conductors and semicon ductors have opposite temperature coefficients. How could you use this knowledge to design a circuit that remains stable over a wide tempera ture range?

1. F

2. T 3. F 4. T 5. T 6. F
7. T 8. F 9. T 10. F
11. T
12. T
13. T
14. T
15. T

16. F
17. F
18. donor 19. five
20. electron
21. carriers 22. decreases 23. acceptor 24. three

25. positive 26. holes
27. negative 28. F
29. F
30. T
31. T 32. F 33. T 34. F 35. T 36. T 37. F
38. F





# Diodes

## Learning Outcomes

*This chapter will help you to:*

3-1 *Predict* the conductivity of diodes under the conditions of forward and reverse bias. [3-1]
3-2 *Interpret* volt-ampere characteristic curves for diodes. [3-2]
3-3 *Identify* the cathode and anode leads of some diodes by visual inspection. [3-3]
3-4 *Identify* the cathode and anode leads of diodes by ohmmeter testing. [3-3]
3-5 *Identify* diode schematic symbols. [3-3]
3-6 *List* several diode types and applications. [3-4]
3-7 *Describe* the structure and characteristics of photovoltaic devices. [3-5]

This chapter introduces the most basic semiconductor device, the diode. Diodes are very important in electronic circuits. Everyone working in electronics must be familiar with them. Your study of diodes will enable you to predict when they will be on and when they will be off. You will be able to read their characteristic curves and identify their symbols and their terminals. This chapter also introduces several impor tant types of diodes and some of the many applications for them.

## 3-1 The PN Junction

A basic use for P- and N-type semiconduc tor materials is in *diodes.* Figure 3-1 shows a representation of a *PN-junction diode.* Notice that it contains a P-type region with free holes and an N-type region with free electrons. The diode structure is continuous from one end to the other. It is one complete crystal of silicon. The junction shown in Fig. 3-1 is the bound ary, or dividing line, that marks the end of one section and the beginning of the other. It does not represent a mechanical joint. In other words, the *junction* of a diode is that part of the crystal where the P-type material ends and the N-type material begins.

Free holes P N Free electrons

## PN-junction diode

## Diode

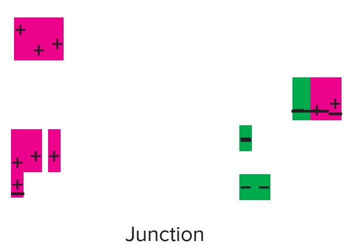



Fig. 3-1 The structure of a junction diode.

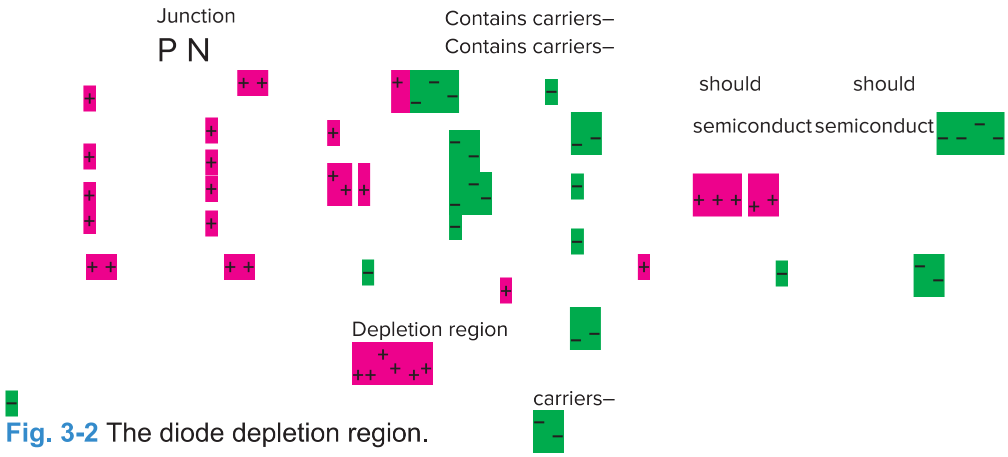



**Fig. 3-2** The diode depletion region.

Because the diode is a continuous crystal, free electrons can move across the junction. When a diode is manufactured, some of the free electrons cross the junction to fill some of the holes. Figure 3-2 shows this effect. The result is that a *depletion region* is formed. The electrons that have filled holes are effectively captured (shown in gray) and are no longer available to support current flow. With the electrons gone and the holes filled, no free carriers are left. The region around the junction has become *depleted* (shown in yellow).

The depletion region will not continue to grow for very long. An electric potential, or force, forms along with the depletion region and prevents all the electrons from crossing over and filling all the holes in the P-type material. Figure 3-3 shows why this potential is formed. Any time an atom loses an electron, it becomes unbalanced. It now has more protons in its nucleus than it has electrons in orbit. This gives it an overall positive charge. It is called a *positive ion.* In the same way, if an atom gains an extra electron, it shows an overall negative charge and is called a *negative ion.* When one of the free electrons in the N-type material leaves its parent atom, that atom becomes a positive ion. When the electron joins another atom on

Junction
P N
should insulate

**Fig. 3-4** Depletion region as an insulator.

the P-type side, that atom becomes a negative ion. The ions form a charge that prevents any more electrons from crossing the junction.

So when a diode is manufactured, some of the electrons cross the junction to fill some of the holes. The action soon stops because a neg ative charge forms on the P-type side to repel any other electrons that might try to cross over. This negative charge is called the *ionization potential*, or the *barrier potential.* “Barrier” is a good name since it does stop additional electrons from crossing the junction.

Now that we know what happens when a PN junction is formed, we can investigate how it will behave electrically. Figure 3-4 shows a summary of the situation. There are two regions with free carriers. Since there are carriers, we can expect these regions to *semiconduct.* But right in the middle there is a region with no carriers. When there are no carriers, we can expect it to *insulate.*

Any device having an insulator in the mid dle will not conduct. So we can assume that PN-junction diodes are insulators. However, a depletion region is not the same as a fixed insulator. It was formed in the first place by electrons moving and filling holes. An external

**Depletion region**

**Barrier potential**

**Positive ion Negative ion**

+
+
+
+

connected to an external battery in such a way that the depletion region is eliminated. The positive terminal of the battery repels the holes on the P-type side and pushes them toward the

–
–
–
–
–
–

Loses one

voltage can *eliminate* the depletion region. In Fig. 3-5, a PN-junction diode is

Gains one

+
+

electron and becomes a negative ion

Ionization or barrier potential

positive ion

junction. The negative terminal of the battery repels the electrons and pushes them toward the junction. This *collapses* (eliminates) the depletion region.

electron and becomes a

Fig. 3-3 Formation of the barrier potential.



Depletion region has collapsed

P N

+
+

current without correcting for the diode drop: $I = \frac{1\text{ V}}{1\text{ k}\Omega} = 1\text{ mA}$

voltage drop. First, calculate the

Make a second calculation that includes the correction:

$$I = \frac{1\text{ V} - 0.6\text{ V}}{1\text{ k}\Omega} = 0.4\text{ mA}$$

It is important to correct for the diode drop when the supply voltage is relatively low.

Junction

–+

Current limiter

Fig. 3-5 Forward bias.

## Forward bias

With the depletion region collapsed, the diode can semiconduct. Figure 3-5 shows elec tron current leaving the negative side of the battery, flowing through the diode, through the current limiter (a resistor), and returning to the positive side of the battery. The current limiting resistor is needed in some cases to keep the current flow at a safe level. Diodes can be destroyed by excess current. Ohm's law can be used to find current in diode circuits. For example, if the battery in Fig. 3-5 is 6 V and the resistor is 1 kilohm (kΩ),

$I = \frac{V}{R} = \frac{6\ V}{}$

$1\ k\Omega$ = 6 milliamperes (mA)

The above calculation ignores the diode's resistance and voltage drop. It is only an *approximation* of the circuit current. If we know the drop across the diode, it is possible to accurately predict the current. The diode drop is simply subtracted from the supply voltage:

$I = \frac{6\ V - 0.6\ V}{}$

$1\ k\Omega$ = 5.4 mA

A typical silicon diode drops about 0.6 V when it is conducting. This is still an approxi mation, but it is more accurate than our first attempt.

**EXAMPLE 3-1**

Calculate the current in Fig. 3-5 for a 1-V battery and a 1-kΩ resistor. Determine the importance of correcting for the diode

**EXAMPLE 3-2**

Schottky diodes drop about 0.3 V when con ducting. These diodes are explained in Sec. 3-4. Calculate the current in Fig. 3-5 for a Schottky diode, a 1-V battery, and a 1-kV resistor.

$I = \frac{1\ V - 0.3\ V}{}$

$1\ k\Omega$ = 0.7 mA

The small voltage drop of Schottky diodes makes a significant difference in low-voltage circuits.

**EXAMPLE 3-3**

Calculate the current in Fig. 3-5 for a 100-V battery and a 1-kΩ resistor. Determine the importance of correcting for the voltage drop of a silicon diode.

$I = \frac{100\ V}{}$

$1\ k\Omega$ = 100 mA

$I = \frac{100\ V - 0.6\ V}{}$

1 kΩ = 99.4 mA

It is not as important to correct for the diode drop when the supply voltage is relatively high.

The condition of Fig. 3-5 is called *forward bias.* In electronics, a bias is a voltage or a cur rent applied to a device. Forward bias indicates that the voltage or current is applied so that it turns the device *on.* The diode in Fig. 3-5 has been turned on by the battery, so it is an example of forward bias.



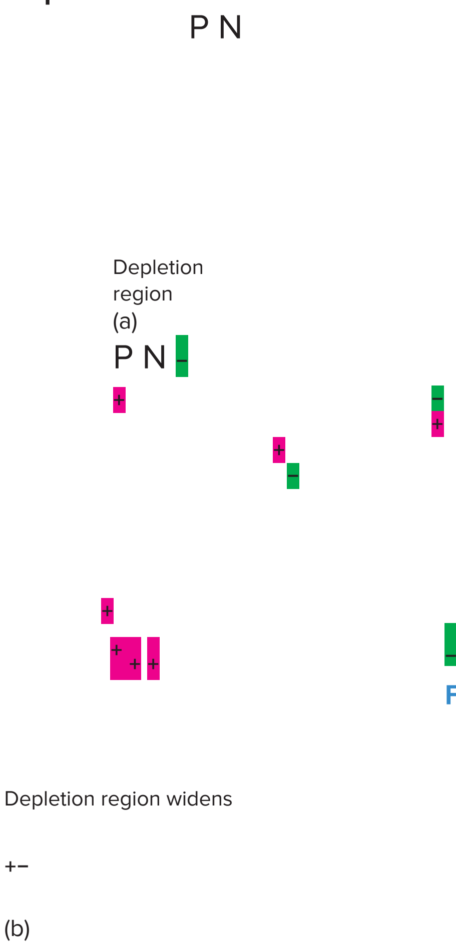
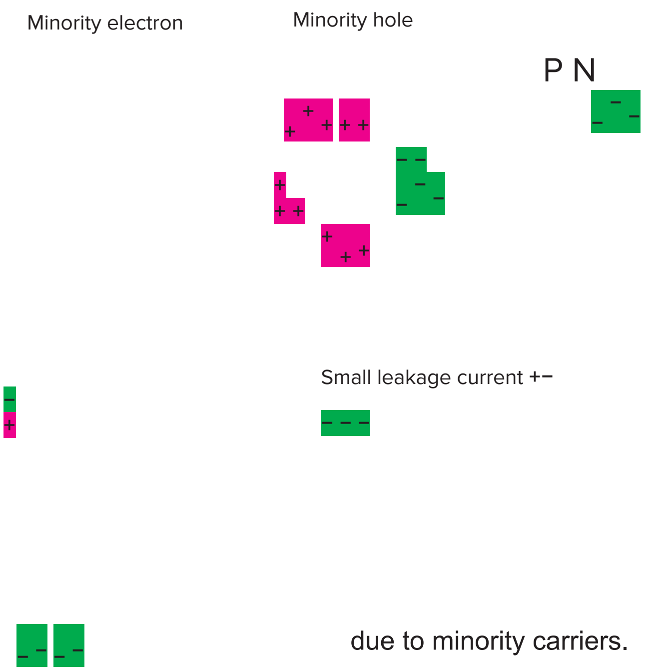



Fig. 3-6 The effect of reverse bias on the depletion region.




due to minority carriers.

Fig. 3-7 Leakage current

*Reverse bias* is another possibility. With zero bias connected to the diode, the depletion region is as shown in Fig. 3-6(*a*). When reverse bias is applied to a junction diode, the depletion region does not collapse. In fact, it becomes wider than it was. Figure 3-6(*b*) shows a diode with reverse bias applied. The positive side of the battery is applied to the N-type material. This attracts the free electrons away from the junction. The nega tive side of the battery attracts the holes in the P-type material away from the junction. This makes the depletion region wider than it was when no voltage was applied.

Because reverse bias widens the depletion region, it can be expected that no current flow will result. The depletion region is an insulator, and it will block the flow of current. Actually, a small current will flow because of *minority carriers.* Figure 3-7 shows why this happens.

## Diodes Provide Protection from Reverse Polarity

A diode can provide reverse polarity protection. One approach is to use a series protection diode, and the other is to use a shunt protection diode that causes a fuse to blow when polarity is reversed.

that it cannot be measured with ordinary me ters. At room temperature, there are only a few minority carriers in silicon, so the reverse leakage

can be ignored.
Germanium diodes have more leakage. At room temperature, germanium has about 1,000 times as many minority carriers as sili con. Silicon diodes cost less, show very low leakage current, and are better choices for most applications. Germanium diodes do have cer tain advantages, such as low turn-on voltage and low resistance, and are therefore still used in a few specific areas.
In summary, the PN-junction diode will con duct readily in one direction and very little in the other. The direction of easy conduction is

The P-type material has a few minority elec trons. These are pushed to the junction by the repulsion of the negative side of the battery. The N-type material has a few minority holes. These are also pushed toward the junction. Reverse bias forces the minority carriers together, and a small *leakage current* results. Diodes are not perfect, but modern silicon di odes usually show a leakage current so small from the N-type material to the P-type mate rial. If a voltage is applied across the diode to move the current in this direction, it is called forward bias. The diode is very useful because it can steer current in a given direction. It can also be used as a switch and a means of chang ing alternating current to direct current. Other diodes perform many special jobs in electric and electronic circuits.

**Reverse bias**

**Leakage current**



*Determine whether each statement is true or false.*

1. A junction diode is doped with both P and N-type impurities.
2. The depletion region is formed by elec trons crossing over the P-type side of the junction to fill holes on the N-type side of the junction.
3. The barrier potential prevents all the electrons from crossing the junction and filling all the holes.
4. The depletion region is a good conductor.
5. Once the depletion region forms, it can not be removed.
6. Forward bias expands the depletion region.
7. Reverse bias collapses the depletion region and turns on the diode.
8. A reverse-biased diode may show a little leakage current because of minority carrier action.
9. High temperatures will increase the num ber of minority carriers and diode leakage current.

## 3-2 Characteristic Curves of Diodes

Diodes conduct well in one direction but not in the other. This is the fundamental property of diodes. They have other characteristics too, and some of these must be understood in order to have a working knowledge of electronic circuits.

Characteristics of electronic devices can be shown in several ways. One way is to list the amount of current flow for each of several val ues of voltage. These values could be presented in a table. A better way to do it is to show the values on a graph. Graphs are easier to use than tables of data.

One of the most frequently used graphs in elec tronics is the volt-ampere characteristic curve. Units of voltage make up the horizontal axis, and units of current make up the vertical axis. Fig ure 3-8 shows a volt-ampere characteristic curve indicates the forward voltage. At −5 V, the current through the resistor will be −50 mA. The minus signs indicate that when

can quickly and easily find the current for any value of voltage. At 10 V, the current is 100 mA. We can check this using

$I_F$

Ohm's law: $I = \frac{V}{R} = \frac{10}{100} = 0.1 \text{A} = 100 \text{ mA}$

R = 100 Ω

Moving to the left of the origin in Fig. 3-8, we can obtain current levels for values of reverse voltage. Reverse voltage is indicated by $V_R$, and $V_F$

100 mA

50 mA

for a 100-Ω resistor. The origin is the point where the two axes cross. This point indicates zero volt age and zero current. Note that the resistor curve passes through the origin. This means that with zero voltage across a resistor, we can expect zero current through it. Ohm's law will verify this:

−100 mA

$V_R$

$I = \frac{V}{R} = \frac{0}{100} = 0 \text{ A}$

At 5 V on the horizontal axis, the curve

$I_R$

$V_F$

−10 V −5 V

5 V 10 V

−50 mA

mA on the vertical axis. By looking at the curve, we

**Fig. 3-8** A volt-ampere characteristic curve for a resis tor.

passes through a point exactly opposite 50



the voltage across a resistor is reversed in po larity, the resistor current will reverse (change direction). Forward current is indicated by $I_F$, and $I_R$ indicates reverse current.

The characteristic curve for a resistor is a straight line. For this reason, it is said to be a linear device. Resistor curves are not necessary. With Ohm's law to help us, we can easily obtain any data point without a graph.

**EXAMPLE 3-4**

How would Fig. 3-8 appear for a 50-Ω resistor?

$$I = \frac{V}{R} = \frac{10 \text{ V}}{50 \text{ Ω}} = 200 \text{ mA}$$

The curve would be a straight line passing through the origin and through data points at ±10 V and ±200 mA. Thus, the 50-Ω curve would be steeper (have more slope) than the 100-Ω curve.

Diodes are more complicated than resistors. Their volt-ampere characteristic curves give more information than can be provided with a simple equation. Figure 3-9 shows volt-ampere curves for both an ideal diode and a real diode. These curves are not linear like the one shown in Fig. 3-8. Ideal diodes do not exist, but real diodes can come close to being ideal in some situations. It was already mentioned that the forward voltage drop can be ignored in high voltage circuits. Thus, the ideal diode volt-am

pere curve shows zero forward voltage. Also,

an ideal diode has no leakage current and never conducts at all when subjected to reverse volt age, no matter how much.

The real diode shown in Fig. 3-9 has some forward voltage drop and a small amount of leakage current, and perhaps most important, it has a limit called the *breakdown voltage*. This breakdown usually occurs at hundreds of volts, so the scale of the horizontal axis is much larger to the left of the origin. The scale for the left side is perhaps from 0 to 1,000 V and from 0 to 2 V on the right side. The forward turn-on voltage is about 0.65 V for a silicon diode. This occurs with a small value of forward current, perhaps 1 mA. With larger values of forward current, the forward voltage increases, perhaps to 1 V at 1 A. The reverse leakage current is often less than 1 mA, and so the reverse current axis is often calibrated in much smaller units of current.

A comparison of the characteristic curves for a silicon diode and a germanium diode is shown in Figure 3-10. It is clear that the ger manium diode requires much less forward bias to conduct. This can be an advantage in low voltage circuits. Also, note that the germanium diode will show a lower voltage drop for any given level of current than the silicon diode will. Germanium diodes have less resistance for forward current because germanium is a better conductor. However, the silicon diode is still superior for most applications because of its low cost and lower leakage current.

Figure 3-10 also shows how silicon and ger manium diodes compare under conditions of

current

Forward

Forward voltage increases as current increases

Reverse current voltage (Scale change)

Forward current

Breakdown voltage

voltage

Reverse

Reverse leakage

Forward turn-on voltage

(a) An ideal diode (b) A real diode **Fig. 3-9** Diode volt-ampere characteristic curves.



$I_F$

Ge Si

are several categories of devices that can absorb transient voltages, but the avalanche types are the fastest acting (rated in picoseconds) and are preferred for some applications. Zener diodes, covered in the next section, are also manufactured to

**Reverse breakdown point**

**Avalanche voltage**

$V_R$ $V_F$ 0.3 V 0.6 V

$I_R$

**Fig. 3-10** Comparison of silicon and germanium diodes.

reverse bias. At reasonable levels of $V_R$, the leakage current of the silicon diode is very low. The germanium diode shows much more leak age. However, if a certain critical value of $V_R$ is reached, the silicon diode will show a rapid increase in reverse current. This is shown as the *reverse breakdown point.* It is also referred to as the *avalanche voltage.* Avalanche break down occurs when carriers accelerate and gain enough energy to collide with

break down at a specified

valence electrons and knock them loose. This causes an "ava lanche" of carriers, and the reverse current flow increases tremendously.

The avalanche voltage for silicon diodes ranges from 50 to over 1,000 V, depending on how the diode was manufactured. If the reverse current at avalanche is not limited, the diode will be destroyed. Avalanche is avoided by using a diode that can safely withstand circuit voltages.

Some diodes are manufactured to break down, or avalanche, at a specified voltage and to do so without harm to the diode, provided that the energy is limited. Ordinary diodes are often de stroyed by reverse breakdown. The reverse cur rent tends to be concentrated in one spot, which causes heat and damage. Avalanche diodes can be used to safely absorb high-voltage transients and, by doing so, protect the rest of the circuit or another piece of equipment from damage. There

voltage. However, the voltages are usually less, and the actual breakdown mechanism is differ ent. *Avalanche* implies what the term refers to; for example, on a steep hillside one rock can break loose and strike other rocks and result in a shower of rocks flowing down the hill. In an avalanche diode, a valence electron, subject to the field of the reverse voltage, can break loose and strike other valence electrons, leading to a large increase of reverse current. Avalanche can occur in solids, liquids, or gases. Ions can be in volved, but in avalanche diodes, the mechanism is due to valence electrons breaking loose.

Avalanche diodes can give increased reli ability in many applications, particularly those where voltage transients are expected. Due to their high speed and ability to withstand large numbers of transients, avalanche diodes are used to protect circuits against surges, lightning, and other transients. They are faster than metal oxide variances (MOVs), zeners, and gas tubes. Avalanche diodes are the diodes of choice in high-voltage circuits, such as voltage multipli ers and where diodes are connected in series to achieve high-voltage operation. Inductive loads often generate voltage tran sients when the circuit is interrupted. Diodes are often used to control these transients (Fig. 3-27, p. 49) and to allow current to flow so as to discharge the inductor. These are often called free-wheeling diodes and are discussed in more detail in later chapters. Avalanche diodes are often preferred for free-wheeling applications.

Figure 3-11 shows how volt-ampere charac teristic curves can be used to indicate the effects of temperature on diodes. The temperatures are in degrees Celsius (°C). Electronic circuits may have to work over a range of temperatures from −50° to +100°C. At the low end mercury will freeze; at the high end water will boil. The range

Controlled avalanche diodes like the 1N5059 can survive reverse breakdown under certain conditions that would destroy other diodes.

for military-grade electronic circuitry is −55° to +125°C. For circuits to operate in such a wide temperature range, extreme care must be taken in the selection of materials, the manufacturing processes used, and the handling and testing of the finished product. This is why military-grade

25°C
100°C −50°C 200

175

150

125

100

75

50

25

0 0.5
1.0

elevated temperatures. Since the forward volt age drop $V_F$ decreases as temperature goes

1.5
Forward voltage drop (V)
$V_F$

**Fig. 3-11** Characteristic curves showing the effect of temperature on a typical silicon diode.

**Silicon Diodes and the Auto Industry** The development of silicon diodes allowed automobile designers to use alternators rather than generators. This greatly improved the performance and reliability of the charging system.

devices are more expensive than industrial- and commercial-grade devices.

By examining the curves in Fig. 3-11, you can conclude that silicon conducts better at

*Supply the missing word in each statement.*

10. The characteristic curve for a linear device is shaped like a .
11. A volt-ampere characteristic curve for a resistor is shaped like a .
12. A volt-ampere characteristic curve for a 1,000-Ω resistor will, at 10 V on the hori zontal axis, pass through a point opposite _on the vertical axis.
13. The volt-ampere characteristic curve for an open circuit (∞ Ω) will be a straight line on the axis.

## 3-3 Diode Lead Identification

Diodes have *polarity.* Components such as resistors can be wired either way into a cir cuit, but diodes must be installed properly.

up, its resistance must be going down. This agrees with silicon's negative temperature co efficient. Figure 3-11 also shows that diodes can be used as temperature sensors.

14. The volt-ampere characteristic curve for a short circuit (0 Ω) will be a straight line on the axis.
15. Resistors are linear devices. Diodes are devices.
16. A silicon diode does not begin conduct ing until V of forward bias is applied.
17. Diode avalanche, or reverse breakdown, is caused by excess reverse .

P-type material makes up the *anode* of the diode. The word "anode" is used to identify the terminal that attracts electrons. The N-type material makes up the *cathode* of the diode.

Connecting a diode backward can destroy it and may also damage many other parts of a circuit. A technician must always be absolutely sure that the diodes are correctly connected. Technicians often refer to schematic diagrams when checking diode polarity. Figure 3-12 shows the *schematic symbol* for a diode. The

**Schematic symbol**

N-type material

Cathode

Direction of
forward current

**Fig. 3-12** Diode schematic symbol.

P-type material

Anode

**Anode Polarity Cathode**

CATHODE A

C

A

C A ANODE

Schematic symbol

A

C C

Fig. 3-13. Some older package styles used a bevel or a plus sign (+) to denote the cathode lead. Other packages use various schemes for lead identification. A few use an imprint of the diode symbol. This method can be used with the 194-05 package in Fig. 3-13, although the illus tration does not show it. The TO-220AC style

TO-236AB

TO-92 DO-41 A

A

C

has both a cathode lead and a metal tab, which also serves as a cathode contact. Either the lead or the tab can be used to connect the diode to the rest of the circuit. The TO-220AB case shows two anode leads. This is a different situation be cause there are two diodes inside the package.

C

60–1 194–05

Manufacturers can offer diodes in both a normal polarity version and a reverse polarity version. For example, the threaded stud end of the 257-01 package in Fig. 3-13 is the anode in

C

C

The anodes of the two diodes are available as separate terminals, but the cathodes are con nected internally.

C C

is followed by an "R" to denote the reverse polar ity version. However, the part number is rarely marked on the device. Another problem is that manufacturers use the same package to house different devices. Both the

TO-236AB package and the TO-220AB package shown in Fig. 3-13 can also be used for transistors. In other words, a casual inspection of an electronic circuit will not always allow you to positively iden

C

A

A
C
A

TO-220AC

A

A

C
TO-220AB

the reverse polarity version. The part number

terminal that gives off, or emits, electrons. Note that the forward current moves from the cathode to the anode (against the arrowhead). Diodes are available in many package styles. Some examples are shown in Fig. 3-13. Manu facturers use plastic, glass, metal, ceramic, or a combination of these to package diodes. There are quite a few sizes and shapes available. Gen erally, the larger devices have higher current ratings. The diode package is often marked to de note the *cathode lead.* This can be done with one or more bands near the cathode lead. An example of this method is shown on the DO-41 package in

tify components and their leads. You should use schematics or other service literature to be certain.

It is easy to check a diode and identify the leads using a volt-ohmmilliammeter (VOM), or a digital multimeter (DMM). This check uses the ohmmeter function of the meter or, in the case of some DMMs, the diode test function. The ohmmeter is connected across the diode and the resistance is noted as in Fig. 3-14(*a*). When the diode is on or forward biased a relatively low reading on the ohm's scale will occur or the forward voltage drop will be displayed in the case of a DMM. Then the ohmmeter leads are reversed as shown in Fig. 3-14(*b*). The resistance should change drastically . . . usually to infin ity, or the DMM should indicate over range or overload (OL). In Fig. 3-14 we conclude that the diode is good and that the cathode lead is at the left. When the positive lead of the ohmmeter was

**Cathode lead**

339–02 257–01

**Fig. 3-13** Diode package styles.

The word "cathode" refers to the



Analog meter Digital meter

5 VDC

0.5917

VDC

0

'

OL VDC

0

Manual Range

01234 (a) The diode is on (forward bias)

Manual Range

012 3

**Fig. 3-14** Diode testing and lead identification.

4 5 VDC

(b) The diode is o (reverse bias)

on the right lead, the diode was turned on. For ward current is from cathode to anode. Making the anode positive is necessary if the anode is going to attract electrons. Remember, in order to turn on the diode, the anode must be positive with respect to the cathode.

Diode testing is usually straight forward, but there are a few qualifiers to consider. An older meter might have reverse polarity on resistance ranges. Another meter might not apply enough voltage to turn on a diode. Yet another meter could have a low ohms function that will show a good diode to be open circuit. You must know the characteristics and limitations of your test equipment.

Modern DMMs have an ohms range and a diode range. The diode range is usually marked with the diode schematic symbol. Use the diode range when testing diodes.

Some DMMs have an audible output on the diode range. They beep once when a good diode is forward-biased and beep continuously for a shorted diode. They make no sound when a good diode is reverse-biased.

The diode test function on some DMMs sends approximately 0.6 mA through the component connected to the meter display reads the voltage drop across the com ponent. A normal, forward-biased junction will read somewhere between 0.250 and 0.700 using this type of meter. A reverse-biased junction will cause the meter display to indicate overrange. Table 3-1 shows some typical readings ob tained using a DMM on its ohms function

**Table 3-1**

| | Results | |
|---|---|---|
| Device Tested | Ohms Function (kΩ) | Diode Function |
| Small silicon | | 0.571 |

terminals. The digital

diode 19
1-A silicon

diode 17 0.525 5-A silicon

diode 14 0.439 100-A silicon

diode 8.5 0.394 Small Schottky

diode 7 0.339 Small

germanium diode 3 0.277



and on its diode function to test various diode

1.6

types. In every case, the diode was normal and

1.4

was forward-biased by the meter. Notice that

as the current capacity (size) of the silicon di

1.2
0.7 V

$V_D$

$R_D$ = = = 500 Ω

next section.
Diodes are nonlinear devices. They will not

**Schottky diode**

$I_D$

odes increases, the diode's forward resistance decreases when using the ohms function, and

1.0

the voltage drop across the diode is smaller

0.8

when using the diode function. Also notice that

the Schottky and germanium diodes show the

0.6

lowest resistances and voltage drops. Schottky

0.4

diodes are explained in the

0.2
1.4 mA 0.6 V

show the same resistance when operated at

different levels of forward bias. For example,

0.12 mA $R_D$ = = 5 kΩ

0.2

a silicon diode might show

500 Ω of forward resistance when measured on a 2-kΩ range and

0.4

$V_D$ (V)

0.6 0.8

law is used to calculate diode resistance at two different operating points on the *characteristic curve.* At the upper operating point the diode's resistance is 500 Ω, and it is 5 kΩ at the lower operating point.

Beginners may be confused by diode polar ity. There is a good reason, too. One of the older

**Fig. 3-15** Diode resistance at different operating points.

**Characteristic curve**

5 kΩ of forward resistance when measured on a 20-kΩ range. This is to be expected since the ohmmeter operates the diode at different points on its characteristic curve when differ ent ranges are selected. Figure 3-15 illustrates this idea. Ohm's

used to help technicians find the load polarity. Rectifier circuits are covered briefly in the next section and in detail in Chap. 4.

ways to mark the cathode lead was to use a plus (+) symbol (this is no longer done by diode manufacturers). Yet, we have said that the diode is turned on when its *anode lead* is made posi tive. This seems to be a contradiction. However, the reason the plus sign was used to indicate the cathode lead is related to how the diode be haves in a *rectifier circuit.* In a rectifier circuit, it is the cathode lead that is in contact with the positive end of the load. So, the plus sign was

$$R_D = \frac{V_D}{}$$

**EXAMPLE 3-5**

Find $R_D$ for Fig. 3-15 when $V_D = 0.2$ V. If we attempt to use Ohm's law,

$$I_D = \frac{0.2\text{ V}}{0} = \text{undefined}$$

Division by 0 is undefined. However, as the denominator of a fraction approaches 0, the value of the fraction approaches infinity:

$$R_D \Rightarrow \infty$$

The important idea here: the resistance of a diode is infinite if the voltage drop across the diode is less than its barrier potential.

*Supply the missing word in each statement.*

18. Assume that a diode is forward-biased. The diode lead that is connected to the negative side of the source is called the .
19. The diode lead near the band or bevel on the package is the lead.
20. A plus (+) sign on an older diode indi cates the lead.
21. An ohmmeter is connected across a diode. A low resistance is shown. The leads are reversed. A low resistance is still shown. The diode is .



22. When the positive lead from an ohmmeter is applied to the anode lead of a diode, the diode is turned .

because they are .

## 3-4 Diode Types and Applications

There are many diode types and applications in electronic circuits. Some of the important ones are presented in this section.

*Rectifier diodes* are widely applied. A recti fier is a device that changes alternating current to direct current. Since a diode will conduct easily in one direction only, just half of the ac cycle will pass through the diode. A diode can be used to supply direct current in a simple battery charger (Fig. 3-16.) A secondary bat tery can be charged by passing a direct cur rent through it that is opposite in direction to its discharge current. The rectifier will permit only that direction of current that will restore (recharge) the battery.

23. Diodes show different values of forward resistance on different ohmmeter ranges

Notice in Fig. 3-16 that the diode is con nected so the current flow during charging is opposite to the current flow during discharging. The cathode of the diode *must* be connected to the positive terminal of the battery. A mistake in this connection would discharge the battery

+ –

Load

Discharging

Discharge current flows in this direction

+ –

AC source

Charging

Silicon carbide diodes are available with recovery timed around 10 nanoseconds.

or damage the diode. It is very important to connect diodes correctly. An ideal rectifier would turn off at the in stant it is reverse-biased. PN-junction diodes cannot turn off instantaneously. There are quite a few holes and electrons around the junction when a diode is conducting. Applying reverse bias will not immediately turn the diode off since it takes time to sweep these carriers away from the junction and establish a depletion re gion. This effect is not a problem when rectify

Diode will allow current to flow in this direction only

ing low frequencies such as 60 Hz. However, it is a factor in high-frequency circuits. So far we have looked at an interface of two types of semiconductors to produce diode ac tion. Some metal-to-semiconductor interfaces will also rectify. This type of interface is called a *barrier. Schottky diodes* (or *barrier diodes*) use an N-type chip of silicon bonded to plati num. This semiconductor-to-metal barrier pro vides diode action and turns off much more quickly than a PN junction. Figure 3-17 shows the schematic symbol for a Schottky diode. When a Schottky diode is forward-biased, electrons in the N-type cathode must gain energy to cross the barrier to the metal anode. The term *hot-carrier diode* is sometimes used because of this fact. Once the "hot carriers" reach the metal, they join the great number of free electrons there and quickly give up their extra energy. When reverse bias is applied, the diode stops conduct ing almost immediately since a depletion region does not have to be established to block current flow. The electrons cannot cross back over the barrier because they have lost the extra energy

**Rectifier diode**

## Hot-carrier diode

Fig. 3-16 Battery charging with a diode. Fig. 3-17 Schottky diode schematic symbol.



$I_F$

Very small change in $V_R$

$V_R$

Cathode Anode Symbol

Zener diodes are not normally operated with forward bias

Large change in $I_R$

Zener

$V_R$

$V_F$

knee

Operating near the knee can provide poor voltage stabilization

Normal operating range

$I_R$

(a)

Current limiter

+

+

$I_R$

Operating at excessive reverse current may damage the device

Stabilized output Input

(b)

Fig. 3-18 Characteristic curve and symbol of a zener diode.

–

Zener diode

–

required to do so. However, if more than about

**Voltage regulation Zener diode**

**Clippers or limiter**

50 V of reverse bias is applied, the electrons will gain the required energy, and the barrier will break over and conduct. This prevents barrier type devices from being used in high-voltage circuits. Schottky diodes require only about 0.3 V of forward bias to establish forward cur rent. They are well suited for high-frequency,

low-voltage applications. They are commonly used in switch mode power supplies, which are covered in Chap. 15.

A diode can be used to hold a voltage constant. This is called *voltage regulation.* A special type called a *zener diode* is used as a voltage regulator. The characteristic curve and symbol for a zener diode are shown in Fig. 3-18. The symbol is similar to that of a rectifier diode except that the cathode is drawn as a bent line representing the letter Z. Zener diodes are manufactured to regulate voltages from 3.3 to 200 V. As an example, the 1N4733 is a popular 5.1-V zener.

The important difference between zener

**Fig. 3-19** A zener diode used as a voltage regulator.

A change in zener diode current will cause only a small change in the

zener voltage. This can be seen clearly in Fig. 3-19($a$). Within the normal operating range, the zener voltage is reasonably stable. Figure 3-19($b$) shows how a zener diode can be used to stabilize a voltage. A current limiting resistor is included to prevent the zener diode from conducting too much and overheat ing. The stabilized output is available across the diode itself. Notice that conduction is from anode to cathode. Zener voltage regulators are covered in more detail in Chap. 4.

Diodes may be used as *clippers* or *limiters.* Refer to Fig. 3-20. Diode $D_1$ clips (limits) the input signal at −0.6 V, and $D_2$ clips it at +0.6 V. A signal that is too small to forward-bias either diode will not be affected by the diodes. Diodes have a very high resistance when they are off.

circuits. As long as rated voltage plus or

diodes and rectifier diodes is in how they are

zeners are operated within their normal range, their volt age drop will equal their

− +

D2

R2

+.6 0

R1

D1 D2

used in electronic

minus a small error voltage. They are operated *backward* compared with a rectifier diode. In a rectifier, the normal current is from cathode to anode. Zeners are operated in reverse break over and conduct from anode to cathode.

−.6

D1

+ −

**Fig. 3-20** Diode clipper.



However, a large signal will turn the diodes on, and they will conduct. When this happens, the excess signal voltage is dropped across $R_1$. Therefore, the total output swing is limited to

D3

D3 and D4

R1

+5.3

R2 0

D1

D2

1.2 V peak-to-peak. This kind of limiting ac

D4 D1

tion may be used if a signal gets too large. For example, audio clippers can be used to keep signals from exceeding some loudness limit.

−5.3 and $D_2$

Figure 3-20 shows that the input signal is a sine wave, but the output signal is more like a square wave. Sometimes a clipping circuit is used to change the shape of a signal. A third way that clippers can be used is to remove noise pulses riding on a signal. If the noise pulses exceed the clipping points, they will be clipped off or limited. The resulting signal is more noise-free than the original.

Diode $D_2$ clips the positive part of the sig nal in Fig. 3-20. As the signal voltage begins increasing from 0 V, nothing happens at first. Then, when the signal voltage reaches 0.6 V, $D_2$ turns on and begins to conduct. Now its re

sistance is much less than the resistance of $R_1$. Resistor $R_1$ drops the signal source voltage that exceeds 0.6 V. Later the negative alternation be gins. As the signal first goes negative, nothing happens. When it reaches −0.6 V, $D_1$ turns on. As $D_1$ conducts, $R_1$ drops the signal voltage in excess of −0.6 V. The total output swing is the difference between +0.6 and −0.6 V, or 1.2 V peak-to-peak. Germanium diodes would turn on at 0.3 V and produce a total swing of 0.6 V peak-to-peak if used in a clipper circuit.

The clipping points can be changed to a higher voltage by using series diodes. Examine Fig. 3-21. It will require 0.6 V + 0.6 V, or 1.2 V, to turn on $D_3$ and $D_4$. Notice that the positive clip ping point is now shown on the graph at +1.2 V. In a similar fashion, $D_1$ and $D_2$ will turn on when the signal swings to −1.2 V. The output signal in Fig. 3-21 has been limited to a total swing of 2.4 V peak-to-peak. Higher clipping

$R_1$

**Fig. 3-22** Using zener diodes to set a higher clipping threshold.

$R_1$

$D_1$

$R_2$

$D_2$

**Fig. 3-23** A simplified high-threshold clipper.

voltages can be obtained by using zener diodes, as shown in Fig. 3-22. Assume that $D_2$ and $D_4$ are 4.7-V zeners. The positive-going signal will be clipped at +5.3 V since it takes 4.7 V to turn on $D_4$ and another +0.6 V to turn on $D_3$. Di odes $D_1$ and $D_2$ clip the negative alternation at −5.3 V. The total peak-to-peak output signal in Fig. 3-22 is limited to 10.6 V.

When a zener diode is *forward-biased*, it drops a bit more than a rectifier diode (about 0.7 V). Therefore, the circuit in Fig. 3-22 can be simplified by using two zeners back to back, as shown in Fig. 3-23. If the current is flowing up, then the bottom zener will drop 0.7 V, and the top zener will drop its rated voltage. When the current is flowing down, the top zener will drop 0.7 V, and the bottom zener will drop its rated voltage. For example, if the circuit uses two 1N4733s (5.1-V devices), the total output swing will be limited to 5.1 + 0.7 = 5.8 V peak voltage, or 11.6 V peak-to-peak.

Diodes may also be used as *clamps* or *dc restorers.* (Refer to Fig. 3-24.) The signal source

## Clamps or dc restorer

waveform. The graph shows that the output signal that appears across the resistor is not ordinary alternating current. It does

$D_1$

$D_3$

+1.2

$R_2$ 0

$D_3$ and $D_4$

generates an ac

not

$D_2$

$D_4$ $D_1$

−1.2

**Fig. 3-21** Clipping at a higher threshold.

and $D_2$

have an average value of 0 V. It averages to some positive voltage. Such signals are common in electronic circuits and are said to have both an ac component and a dc component. Where does



C
− +

+

0
D
R

0.6 V
$V_{dc}$
− +

**Fig. 3-24** Positive clamp.

$V_{ac}$ R
$V_{dc}$ 0

**Fig. 3-25** Clamp equivalent circuit.

C
+ −

0.6 V

0
D
R
−

**Fig. 3-26** Negative clamp.

the dc component come from? The diode cre ates it by charging the capacitor. Note that diode *D* in Fig. 3-24 will allow a charging current to flow into the left side of capacitor *C*. This current places extra electrons on the left side of the ca pacitor, and a negative charge results. Electrons flow off the right plate of the capacitor and make it positive. If the discharge time of the circuit ($T = R \times C$) is long compared with the period of the signal, the capacitor will maintain a steady charge from cycle to cycle.

## Negative clamp

**EXAMPLE 3-6**

Evaluate the discharge time for Fig. 3-24 if the capacitor is 1 $\mu$F, the resistor is 10 kΩ, and the source develops 1 kHz. Find the *RC* time constant by

$T = R \times C$

$= 10 \times 10^3\ \Omega \times 1 \times 10^{-6}$ F

$= 0.01$ s

Find the period of the signal:

$$t = \frac{1}{f} = \frac{1}{1 \times 10^3 \text{ Hz}} = 0.001 \text{ s}$$

The discharge time ($T$) is 10 times larger than the signal period ($t$).

Figure 3-25 is the equivalent circuit. It ex plains the clamp by showing that the charged capacitor acts as a battery in series with the ac signal source. The battery voltage $V_{dc}$ ac counts for the upward shift shown in the graph.

Refer again to Fig. 3-24. Note that the graph shows that the output signal goes 0.6 V below the zero axis. This −0.6 V point is when diode *D* turns on and conducts. The charging current flows briefly once every cycle when the signal source reaches its maximum negative voltage.

Figure 3-26 shows what happens if the diode is reversed. The charging current is reversed, and the capacitor develops a negative voltage on its right plate. Notice that the graph shows that the output signal has a negative dc component. This circuit is called a *negative clamp*.

Clamping sometimes happens when we do not want it. For example, a signal generator is often used for circuit testing. Some signal generators use a coupling capacitor between their output circuitry and their output jack. If you connect such a generator to an unbalanced diode load that allows a charge to build up on the built-in coupling capacitor, confusing results may occur. The resulting dc charge will act in series with the ac signal and may change the way the test cir cuit works. A dc voltmeter or a dc-coupled os cilloscope can be connected from ground to the output jack to verify that clamping is occurring. Figure 3-27 shows how diodes are some times used to prevent arcing and component damage. When the current is suddenly inter rupted in a coil, a large counterelectromotive force (CEMF) is generated across the coil. This high voltage can cause arcing and can also de stroy sensitive devices, such as integrated cir cuits and transistors. Note that in Fig. 3-27(*a*), there is an arc when the switch in series with the relay coil opens. In Fig. 3-27(*b*), there is a protection diode across the coil. This diode is forward-biased by the CEMF. The diode safely discharges the coil and prevents arcing or damage.



+12 V

Light energy

Anode
Cathode

Switch
opens
Arc

+ −

(a)
Schematic symbol

Relay coil

Anode Cathode

P + − N

+ −

Carriers combining at junction

(a) Inductive kick causes an arc when switch opens

Current limiter
+ −

+12 V

(b) A simple LED circuit

Epoxy encapsulation
−

−

LED chip

CEMF +

Diode turns on because of
magnifying dome lens

Wire bond

Protection diode
across coil

Cathode post

Anode post

+

Flat on side of dome

No CEMF when switch opens
arc

(b) No arc

**Fig. 3-27** Using a diode to stop "inductive kick."

Anode lead indicates cathode lead

Cathode lead is shorter than anode lead

Another important diode type is the *light emitting diode,* or LED. Its schematic symbol is shown in Fig. 3-28(*a*). Figure 3-28(*b*) shows that as the electrons of the LED cross the junc tion, they combine with holes. This changes their status from one energy level to a lower energy level. The extra energy they had as free electrons must be released. Silicon diodes give off this extra energy as heat. *Gallium arsenide diodes* release some of the energy as heat and some as infrared light. This type of diode is called an infrared-emitting diode (IRED). In frared light is not visible to the human eye. By doping gallium arsenide with various materials, manufacturers can produce diodes with visible outputs of red, green, or yellow light.

(c) Features of a T-1¾ plastic LED

**Fig. 3-28** Light-emitting diode.

More recently, blue LEDs have become more efficient and less expensive to manufacture. A white LED is a blue LED that's surrounded by a phosphorescent dye that glows white when it is struck by blue light. This is a similar process to that in fluorescent lamps where the coating glows white when it is irradiated by the ultraviolet light generated inside the tube. White LEDs are now replacing incandescent lamps in some applications. They are more efficient, don't pro duce as much unwanted infrared, and have an operating life of 100,000 hours compared with only 8,000 hours for many incandescent types.

**Light-emitting diode (LED)**

### Seven-segment display

### Photodiode

LEDs have now exceeded the efficiency of com pact fluorescent lights and don't contain any hazardous materials. They are becoming very attractive for many applications.

Ultraviolet LEDs (UV LEDs) are now being produced. These "black light" sources are find ing applications in currency validation equip ment, medical and biological detectors, security systems, and leak detectors.

The laser diode is an LED or IRED with carefully controlled physical dimensions that produce a resonant optical cavity. The light en ergy builds up as the resonant cavity is pumped by semiconductor photon emission. The cav ity acts as a sharply tuned filter, and all of the output energy is at the same wavelength. This yields monochromatic (single-color) light. Also, all of the light waves are in phase, as is typi cal of all laser sources. Laser diodes are used in fiber-optic communications systems, inter ferometric measuring and positioning systems, scanners, and optical storage devices such as CDs and DVDs.

High-intensity LEDs, UV LEDs, and laser LEDs *must be handled with caution*. Serious eye damage can result from looking directly into their beams. Highly reflective surfaces or fiber-optic cables can also lead to eye damage. This is particularly critical with "black light" and infrared laser sources, since the devices can appear not to be working. UV LEDs are often directed onto a fluorescent surface to de termine if they are producing light energy.

The LEDs and IREDs have a higher forward voltage drop than do silicon diodes. This drop varies from 1.5 to 2.5 V depending on diode current, the diode type, and its color. If the manufacturer's data is not available, 2 V is a good starting point. Assume that the diode circuit in Fig. 3-28(*b*) is being designed for an LED current of 20 mA and that the supply (bat tery) produces 5 V. Ohm's law is used to find the value of the current-limiter resistor. The diode drop must be subtracted from the supply to find the voltage across the resistor:

$$R = \frac{V_S - V_D}{I_D} = \frac{5\text{V} - 2\text{V}}{20\text{ mA}} = 150\ \Omega$$

Figure 3-28(*c*) shows the physical appear ance of a T-1$\frac{3}{4}$ LED package. The T-1$\frac{3}{4}$ pack age is 5 millimeters (mm) in diameter and is a common size. Another common size is the T-1

package, which is 3 mm in diameter. The fig ure shows that the cathode lead is shorter than the anode lead and also that the flat side of the dome can be used to identify the cathode lead. As with other diode types, LEDs *must* be in stalled with the correct polarity. Light-emitting diodes are rugged and small, and they have a very long life. They can be switched rapidly since there is no thermal lag caused by gradual cooling or heating in a fila
ment. They lend themselves to certain pho tochemical fabrication methods and can be made in various shapes and patterns. They are much more flexible than incandescent lamps. Light-emitting diodes may be used as numeric

**EXAMPLE 3-7**

Select a current-limiting resistor for an au tomotive circuit in which the diode current needs to be 15 mA. Such circuits use 12 V,
and we can assume a 2-V diode

drop: $R = \frac{12\text{ V} - 2\text{V}}{15\text{ mA}} = 667\ \Omega$

The power dissipation in a current-limiting resistor can also be important:

$P = I^2R = (15\text{ mA})^2 \times 667\Omega = 150$ mW

For better reliability, power dissipation is nor mally doubled. Since 300 mW is more than ¼ W, a ½-W resistor would be a good choice.

displays to indicate the numerals 0 through 9. A typical *seven-segment display* is shown in Fig. 3-29. By selecting the correct segments, the de sired number is displayed.
*Photodiodes* are silicon devices sensitive to light input. They are normally operated in

Turning on these LED segments makes the number 7

**Fig. 3-29** An LED numeric display.

Input circuit Output circuit

$R_1$ $R_2$

$B_1$ $B_2$ $S_1$

Optocoupler

Output signal

**Fig. 3-30** An optocoupler circuit.

reverse bias. When light energy enters the depletion region, pairs of holes and electrons are generated and support the flow of current. Thus, a photodiode shows a very high reverse resistance with no light input and less reverse resistance with light input. Figure 3-30 shows an optocoupler circuit. An *optocoupler* is a package containing an LED or IRED and a photodiode or phototransistor. When $S_1$ is open, the LED is off and no light enters the photodiode. The resistance of the photodiode is high, and the output signal will be high. When $S_1$ is closed, the LED is on. Light enters the photodiode so its resistance drops, and the output signal drops to a lower level because of the voltage drop across $R_2$. Optocouplers are used to electrically isolate one circuit from another. They are also called *optoisolators.* The only thing connecting the input circuit to the output circuit in Fig. 3-30 is light, so they are electrically isolated from each other.

Light-emitting diodes and photodiodes are often used in conjunction with fiber-optic cable for the purpose of data transmission. Compared with wire, fiber-optic cable is more expensive but has several advantages:

1. Elimination of electrical and magnetic field interference
2. Greater data capacity for long runs
3. Data security
4. Safe in explosive environments
5. Smaller and lighter

Both LEDs and laser diodes can be pulsed rapidly to allow high-speed data transmission. At the other end, a light detector is needed to change the light back into electrical pulses. Photodiodes are used to accomplish this. Figure 3-31 shows that light from a diode enters one end of a cable and leaves the other end where it strikes another diode.

Figure 3-31 also shows the construction and types of *fiber-optic cables*. These cables are light pipes. The principle of operation is total internal reflection of light. When light strikes a transparent surface, it is divided into a reflected beam and a refracted (bent) beam. If a ray of light strikes at some angle less than a so-called critical angle, all the light is reflected. If a core material is cladded with a different material having a smaller refractive index, total reflection is achieved for those rays that strike the cladding at shallow angles. Most light cables use various blends of silica glass for the core and for the cladding.

The step-index multimode fiber shown in Fig. 3-31 uses a relatively large core. Thus, some of the light rays that make up a light pulse may travel a direct route, whereas others zig and zag as they bounce off the cladding. Different rays arrive at the detector diode at different times, depending on different path lengths. The output pulse is spread in time. Look closely at the relationship between input and output pulses in Fig. 3-31. You can see that the pulse spreading in the multimode cable does not allow high speed transmission. High-speed pulse transmission requires that the pulses be spaced very close together in time. As the pulses are spaced closer and closer, spreading makes it impossible to separate them into individual pulses. Multimode fibers are not used for long-distance, high-speed communication.

A graded-index multimode fiber is also shown in Fig. 3-31. This cable type suffers less output pulse spreading. Here, the refractive index of a smaller core changes gradually from the

center out toward the cladding.
Light

## Optocoupler Optoisolator

## Fiber-optic cables



LED or
laser diode
Fiber-optic transmission cable

Photodiode
Protective sheath

Cladding

Core

Step-index multimode fiber

Time

Input pulse

Output pulse

Time

Input pulse Time

multimode fiber

Time

Output pulse Time

Cross-section

Single-mode fiber

Graded-index

Cross-section

Time

Input pulse

**Fig. 3-31** Fiber-optic cables.

traveling down the core curves rather than zigzags; this is due to the gradual change in the index. Also, the bent (curved) rays wind up arriving at the diode detector at about the same time as the direct rays because the di
rect rays must travel more slowly in the core's center.

The single-mode fiber also shown in Fig. 3-31 is capable of the highest speeds. Note that the light travels in a narrow core and only by a direct route. Pulse spreading is minimal, and high speeds can be used. The current speed limit for fiber-optic transmission is about 10 billion bits (pulses) per second. One trillion bits per second is expected to be reached within the next few years.

Output pulse

Cross-section

Fiber-optic cables used for data transmission typically carry light signals at levels of 100 mi crowatts ($\mu$W) or less. Eye damage is not possible at these levels. However, other applications may use much higher power levels. Never look into the end of a fiber-optic cable unless the power level has been verified as absolutely safe. Also, remember that some systems use infrared light. What you can't see can hurt you.

## Varicap or Varactor

The *varicap* or *varactor* diode is a solid-state replacement for the variable capacitor. Much of the tuning and adjusting of electronic circuits involves changing capacitance. Variable capaci
tors are often large, delicate, and expensive parts. If the capacitor must be adjusted from the front panel of the equipment, a metal shaft or



Reverse bias

− +

P N

region

Depletion

**Fig. 3-32** Diode capacitance effect.

Semiconductor Insulator Semiconductor

500 400 300 200 100 0

1 2 3 4 5 6 7 8 9 10 11 12 13

Reverse voltage (V)

$V_R$

**Fig. 3-33** Junction capacitance versus reverse voltage characteristic curve of a varicap diode.

a complicated mechanical connection must be used. This causes some design problems. The varicap diode can be controlled by voltage. No control shaft or mechanical linkage is needed.

The varicap diodes are small, rugged, and inexpensive. They are used instead of variable capacitors in modern electronic equipment.

The capacitor effect of a PN junction is shown in Fig. 3-32. A capacitor consists of two conducting plates separated by a dielec tric material or insulator. Its capacitance de pends on the area of the plates as well as on their separation. A reverse-biased diode has a similar electrical format. The P-type material semiconducts and forms one plate. The N-type material also semiconducts and forms the other plate. The depletion region is an insulator and forms the dielectric. By adjusting the reverse bias, the width of the depletion region, that is, the dielectric, is changed; and this changes the capacity of the diode. With a high reverse bias, the diode capacitance will be low because the depletion region widens. This is the same effect as moving the plates of a variable capacitor far ther apart. With little reverse bias, the depletion region is narrow. This makes the diode capaci tance increase.

Figure 3-33 shows the capacitance in pico farads (pF) versus reverse bias for a varicap *tuning diode.* Capacitance decreases as re verse bias increases. The varicap diode can be used in a simple *LC* tuning circuit, as shown in Fig. 3-34. The tuned circuit is formed by an inductor (*L*) and two capacitors. The top ca pacitor $C_2$ is usually much higher in value than

Bias control circuitry

$R_1$ $R_2$ $R_3$

+ −

$C_2$

$C_1$

L

Tuned circuit resonant frequency $\frac{1}{2\pi \sqrt{\ } C_1}$

**Fig. 3-34** Tuning with a varicap diode.

the bottom varicap diode capacitor $C_1$. This makes the resonant frequency of the tuned cir cuit mainly dependent on the inductor and the varicap capacitor.

. . . that when capacitors are in series, their total or equivalent capacitance is found with the prod uct over sum formula:

$$C_S = \frac{C_1 \times C_2}{C_1 + C_2}$$

The series capacitance tunes the inductor in Fig. 3-34. This capacitance is determined by the bias control circuitry, so adjusting $R_2$ will change the resonant frequency of the $LC$ tuning circuit.

**Tuning diode**

resistance and isolates the tuned circuit from the bias-control circuit. This prevents the $Q$ of the tuned circuit, that is, the sharpness of the resonance, from

**EXAMPLE 3-8**

Calculate the equivalent series capacitance for Fig. 3-34 if $C_2$ is 0.005 $\mu$F and $C_1$ varies from 400 to 100 pF as the tuning voltage increases. First, convert 0.005 $\mu$F to picofarads:

$$0.005 \times 10^{-6} = 5{,}000 \times 10^{-12}$$

Next, determine the series capacitance for $C_1 = 400$ pF:

$$C_S = \frac{400 \times 5{,}000}{400 + 5{,}000} = 370 \text{ pF}$$

Then, determine the series capacitance for $C_1 = 100$ pF:

$$C_S = \frac{100 \times 5{,}000}{100 + 5{,}000} = 98 \text{ pF}$$

In both cases, the series capacitance is close to the value of $C_1$ alone.

being lowered by resistive loading. High resistance gives light loading and better $Q$. Resistors $R_2$ and $R_3$ form the variable-bias divider. As the wiper arm on the resistor is moved up, the reverse bias across the diode will increase. This will decrease the capacitance of the varicap diode and raise the resonant frequency of the tuned circuit. You should inspect the resonant frequency formula and verify this trend. Without $R_3$, the diode bias could be reduced to zero. In a varicap tuning diode, zero bias is not usually acceptable. An ac signal in the tuned circuit could switch the diode into forward conduction. This would

**EXAMPLE 3-9**

Find the frequency range for Fig. 3-34 for a varicap range of 100 to 400 pF if the coil is 1 $\mu$H. Assume that $C_2$ is large enough so that its value will not have a significant effect. Find the high frequency:

$$f_h = \frac{1}{6.28 \times \sqrt{100 \times 10^{-12} \times 1 \times 10^{-6}}} = 15.9 \text{ MHz}$$

Find the low frequency:

$$f_l = \frac{1}{6.28 \times \sqrt{400 \times 10^{-12} \times 1 \times 10^{-6}}} = 7.96 \text{ MHz}$$

Subtract to find the frequency range: $f_{range} = f_h - f_l = 15.9 \text{ MHz} - 7.96 \text{ MHz} = 7.94 \text{ MHz}$

Note that the *ratio* of the high frequency to the low frequency is 2:1 for a varicap capacitance range of 4 to 1. This is because frequency varies as the square root of capacitance.

**EXAMPLE 3-10**

Find the frequency ratio for Fig. 3-34 if the varicap has a

PIN diode

. . . that the resonant frequency of an $LC$ circuit may be determined with the formula

$$f_r = \frac{1}{2\pi\sqrt{LC}}$$

$R_1$ in Fig. 3-34 is a high value of

capacitance range of 10 to 1. The frequency ratio is equal to the square root of the capacitance range:

cause undesired effects. A circuit such as the one shown in Fig. 3-34 can be used for many tuning purposes in electronics.

Some diodes are built with an *intrinsic* layer between the P and the N regions. These are called *PIN diodes,* where the "I" denotes the intrinsic layer between the P material and the N material. The intrinsic layer is pure silicon (not doped). When a PIN diode is forward-biased, carriers are injected into the intrinsic region. Then, when the diode is reverse-biased, it takes a relatively long time to sweep these carriers out of the intrinsic region. This makes PIN di odes useless as high-frequency rectifiers.

The value of PIN diodes is that they can act as variable resistors for RF currents. Figure 3-35 shows how the resistance of a typical PIN diode varies with the direct current flowing through it. As the direct current increases, the diode's resistance drops.

$$f_{ratio} = \sqrt{10} = 3.16$$



500 400 300 200 100 0

0 2 4 6 8 10 12 Diode current in milliamperes

Fig. 3-35 PIN diode resistance versus current.

PIN diodes are also used for RF switching. They can be used to replace relays for faster, quieter, and more reliable operation. A typi cal situation that occurs in two-way radios is shown in Fig. 3-36. The transmitter and receiver

Direct current will flow from ground, through $D_2$, through the coil, through $D_1$, and through the radio-frequency choke (RFC) into the bias terminal. Both diodes will have a low resis tance, and the radio signal from the transmit ter will pass through $D_1$ and on to the antenna with little loss. $D_2$ also has low resistance when transmitting, and this prevents any significant RF voltage from appearing across the receiver input. The bias voltage is removed when receiv ing, and both diodes will then show a high resis tance. The antenna is effectively disconnected

share an antenna. The receiver must be isolated from the antenna when the transmitter is on or it may be damaged. This is accomplished by applying a positive voltage to the bias terminal in Fig. 3-36, which turns on both PIN diodes.
from the transmitter by $D_1$.
In addition to switching, PIN diodes can also provide *attenuation* of RF signals. Figure 3-37 shows a PIN diode attenuator circuit. When the control point is at 0 V, signals pass through from input to output with little loss. This is be cause $D_1$ is forward-biased and in a low-resis tance state. $D_2$ is now reverse-biased, and it has almost no effect on the signal. The bias condi tions can be determined by solving for the dc voltage drop across the 3,000-Ω resistor. With the control point at 0 V, there is 12 V across the series circuit containing the 3,000-Ω resistor,

## Attenuation

RFC
Antenna

Bias

D$_2$

Transmitter
D$_1$ D$_2$ Receiver

**Fig. 3-36** PIN diode transmit-receive switching.

Output

+12 V

2.7 kΩ

3 kΩ

+6 V Control

voltage

**Fig. 3-37** PIN diode attenuator.
0 V = min. attenuation +6 V = max. attenuation

D$_1$
Input

51 Ω 51 Ω

$D_1$, and the 2,700-Ω resistor. Follow the blue arrows. The diode resistance is small enough to be ignored. The drop across the 3,000-Ω resistor can be found with the voltage divider equation:

$$V = \frac{3,000}{3,000 + 2,700} \times 12\text{ V} = 6.32\text{ V}$$

The voltage at the top end of the left-hand 51-Ω resistor is found by subtracting the 6.32-V drop from the 12-V supply:

$$V = 12\text{V} - 6.32\text{V} = 5.68\text{V}$$

Thus, the cathode of $D_2$ is at +6 V, and the anode connects through a 51-Ω resistor to a voltage of 5.68 V. With the cathode more positive than the anode, $D_2$ is reverse-biased and has a very high resistance.

When the control voltage is changed to +6 V in Fig. 3-37, the situation reverses. Fol low the red arrows. $D_2$ is now on and $D_1$ is off. Little of the input signal can reach the output since $D_2$ is in a low-resistance state. The input

*Determine whether each statement is true or false.*

24. A rectifier is a device used to change alternating current to direct current.
25. Schottky diodes are used in low-voltage, high-frequency applications.
26. A zener diode that is serving as a voltage regulator has electron flow from its anode to its cathode.
27. A normally operating rectifier diode will conduct from its anode to its cathode.
28. A diode clamp is used to limit the peak to-peak swing of a signal.
29. A diode clamp may also be called a dc restorer.

## 3-5 Photovoltaic Energy Sources

There is a lot of interest in renewable energy sources. Sunlight is considered a renewable source since it cannot be depleted by using it.

signal dissipates in the left-hand 51-Ω resistor. This assumes that the cathode of $D_2$ is at RF ground (it is usually bypassed to ground with a capacitor that has low reactance at the signal frequency).

To prove that $D_1$ is off in Fig. 3-37 when the control is at 6 V, we will again use the voltage divider equation. The current is now through $D_2$, the 51-Ω resistor, and the 3,000-Ω resistor (look at the red arrows). The drop across the 3,000-Ω resistor is found by

$$V = \frac{3,000}{3,000 + 51} \times (12\text{V} - 6\text{V}) - 5.9\text{V}$$

The voltage at the anode end of $D_1$ is found by subtracting the drop from the 12-V supply:

$$V = 12\text{V} - 5.9\text{V} = 6.1\text{V}$$

Thus, the anode end of $D_1$ is only 0.1 V posi tive with respect to the cathode end. This is not enough to forward-bias it, so $D_1$ is off and in a high-resistance state.

30. A device containing an LED and a photo diode in the same sealed package is called an optoisolator.
31. Varactor diodes show large inductance change with changing bias.
32. The depletion region serves as the dielec tric in a varicap diode capacitor.
33. Increasing the bias (reverse) across a varicap diode will increase

its capacitance.

34. Decreasing the capacitance in a tuned circuit will raise its resonant frequency. 35. PIN diodes are used as high-frequency rectifiers.

Photovoltaic (PV) devices directly convert sun light into electric energy. They are often called solar cells, solar panels, solar modules, or solar arrays. Over 95 percent of all PV solar cells pro duced are composed of silicon. To make a PV solar cell, the silicon is doped, and a PN junction



PN junction

Front contact

P layer

Rear metal contact

–

Photovoltaic cell

External load

+

Antireflection film

N layer

**Fig. 3-38** Silicon PV cell construction.

is formed in much the same fashion as for the di odes already discussed in this chapter. One dif ference is that PV cells are designed so that light can enter through the front, or top, as shown in Fig. 3-38. There is an antireflection film, which is transparent. Also, the front contact is in the form of a grid so that light can pass through and reach the semiconductor layers below. The rear metal contact is solid. Thus light cannot enter from the bottom side. The rear metal contact provides the return path for electrons that have traveled through the load, and it also physically supports the semiconductor layers.

Light is made up of energetic particles called photons. A photon with enough energy (equal to or greater than the band gap) can dislodge a valence electron and make it available for con duction. Albert Einstein was the first person to correctly describe photoelectric emission, for which he was awarded a Nobel Prize. If a pho ton enters the P layer shown in Fig. 3-38 and knocks loose an electron, the liberated electron

recombining with holes. Ideally, the electrons are freed as close to the junction as possible. Solar cells produce the most load power when the load is of the correct value. They produce the most voltage ($V_{OC}$) when unloaded (open circuit) and the most current ($I_{SC}$) when shorted as shown in Fig. 3-39. Note that both of these conditions produce *zero load power* (the bottom curve). $V_{OC}$ is typically 0.5 V, and $V_{MP}$ (the voltage at maximum power) is typically 0.45 V. Figure 3-39 shows that the maximum power point ($P_{max}$) occurs at less than short circuit current and less than maximum output voltage. It occurs at only one value of load re sistance for a given amount of cell illumination: $R_{L(\text{Ideal})} = \frac{V_{MP}}{I_{MP}}$

The available output is a function of the brightness of the sunlight, as shown in

I

will be swept across the junction by the barrier potential and enter the N layer. If an external load is connected, the electron will be col lected by the front contact, travel through the load, and reenter the P layer via the rear meal contact. You might want to review Fig. 3-3 and verify that the *barrier potential* will indeed at

tract liberated electrons in the P layer. In a PV cell, photons must reach into the P layer to be useful. However, they should not penetrate too deeply into the P layer, because there they would likely combine with holes and thus be lost. The PV cell structure is carefully de

$I_{SC}$

$I_{MP}$

P

$P_{max}$

$P_{max}$

$V_{MP}$ $V_{OC}$

V V

signed and crafted to absorb as many photons as possible and to keep the liberated electrons from

Fig. 3-39 Current and power characteristics of a solar cell.



2 1

200 W/m$^2$

0

1,000 W/m$^2$

0

0.1 0.2 0.3 0.4 0.5 Voltage in V

Module

600 W/m$^2$

Cell

Fig. 3-40 Current characteristics of a solar cell.

Fig. 3-40. The maximum intensity of sunlight at the earth's surface is 1,000 W/m$^2$ (watts per square meter) with an average wavelength of 550 nm, which happens to be in the green part of the color spectrum. Human vision is most sensitive there.

At solar noon, on a clear March or September equinox day, the solar radiation at the equator is about 1,000 W/m$^2$. Obviously, the brightness varies with the time of day, latitude, atmospheric

**EXAMPLE 3-11**

Determine the output current for a cell that measures 10 cm × 10 cm, is 12 percent efficient, and is illuminated by sunlight with an intensity of 1,000 W/m$^2$, and compare the result to Fig. 3-40.

Cell area = 10 cm × 10 cm = 0.01 m$^2$

Cell power = 1,000 W/m$^2$ × 0.01 m$^2$ × 12% = 1.2 W

$$\text{Cell current} = \frac{P}{V} = \frac{1.2\ \text{W}}{0.45\ \text{V}} = 2.22\ \text{A}$$

This result agrees with Fig. 3-40.

**EXAMPLE 3-12**

Find the best load resistance (most load power) for Fig. 3-40 for an illumination intensity of 1,000 W/m$^2$. Is one value of load best for all levels of cell illumination?

$$R = \frac{V}{I} = \frac{0.45\ \text{V}}{2.22\ \text{A}} = 0.203\ \text{ohms}$$

No, the ideal load resistance varies with light intensity.

Array

**Fig. 3-41** PV cells are usually combined into modules and sometimes arrays.

conditions, time of year, and so on and is almost always less than 1,000 W/m$^2$.

To be useful, PV cells must be combined in modules or arrays of modules, as shown in Fig. 3-41. Series connections provide more voltage and parallel connections more current. The interconnected solar cells are often embedded in transparent ethyl-vinyl-acetate, supported by an aluminum frame and covered with glass on the front side.

The typical power ratings of a solar module are between 10 and 100 peak watts. The characteristic data refer to the standard test conditions of 1,000 W/m$^2$ solar radiation at a cell temperature of 25°C. Higher temperatures cause the power output to drop. Luckily, higher temperatures usually correspond to more sunlight, so this effect tends to make the performance more uniform over a range of solar brightness.

There are three cell types according to the type of crystal structure: monocrystalline, polycrystalline, and amorphous. To produce a monocrystalline silicon cell, extremely pure semiconducting material is required. Monocrystalline ingots are extracted from molten silicon and then sawed into thin wafers. This is a tedious process and thus the most expensive. Silicon wafer production is discussed in Chap. 13.



Polycrystalline cells cost less to make. Here, liquid silicon is poured into blocks that are subsequently sawed into plates. During solidification of the material, crystal structures of varying sizes are formed, at whose borders defects (flaws) emerge. The flaws result in decreased cell efficiency.

Amorphous cells are made by depositing a very thin film of silicon on glass or another substrate material. These are sometimes called thin-film cells. The deposited layer thickness amounts to less than 1 $\mu$m, so the production costs are lower due to the lower material costs. Unfortunately, the efficiency of amorphous cells is much lower than that of the other two cell types. Because of this, they are primarily used in low-power applications and sometimes where flexibility is required (being very thin, they can withstand more flexing when deposited on a flexible substrate).

Typical efficiencies for the three types are:

Monocrystalline: 14 to 17 percent

Polycrystalline: 13 to 15 percent

Amorphous: 5 to 7 percent

An increase in PV efficiency is probably going to be required before PV arrays start ap pearing on lots of rooftops. The limiting factors include the following:

· Some wavelengths of light are not absorbed or converted.

· Excess photon energy is converted into heat rather than current flow.

· Electrical resistance losses occur in the crystal, contacts, and cables.

· Reflection losses occur off the face. · Surface defects prevent photon penetration.

· Crystal flaws and material impurities detract from performance.

The theoretical maximum efficiency for sili con PV devices is about 29 percent. This will likely never be achieved. Researchers are looking at other materials such as gallium arsenide and other technologies such as using more than one PN junction per cell to improve efficiency and provide more power. In a single-junction PV cell, only those photons whose energy is equal to or greater than the band gap of the cell material can free an electron. In other words, the photovoltaic response of single-junction cells is limited to the portion of the sun's spectrum whose energy is above the band gap of the absorbing material. Lower-energy photons are wasted.

One way to get around this limitation is to use cells with more than one band gap and more than one junction to generate current. These are referred to as multijunction cells (or cascade or tandem cells). Multijunction de vices can achieve a higher total conversion ef ficiency because they can convert more of the spectrum of sunlight to electricity. Efficien cies as high as 40 percent have been reached, but the costs are still too high for almost all commercial applications. A solar panel for an earth-orbiting satellite can be very costly because there is little or no competition from other energy sources.

PV troubleshooting involves visual inspec tion and some basic knowledge and sometimes ordinary test equipment. For example, output voltage is measurable with an ordinary mul timeter. *Caution:* Some solar arrays generate potentially lethal voltages. Current flow is al ways a problem when troubleshooting. People who work on PV energy systems should own or have access to clamp-on ammeters that work at direct current.

Fluke 80i 110S ac/dc current probe.
Courtesy of Fluke Corporation

Small (low-wattage) PV systems might con nect directly to storage batteries. Large PV sys tems cannot be connected directly. They must be connected via a power conditioner, controller, or inverter (see Fig. 3-42), and often overcurrent protection devices are part of the system. As mentioned earlier in this section, the ideal value of load varies with the light hitting the panel. Just as an automobile needs a transmission to match the engine to the road conditions and ve hicle speed, PV systems need maximum power point tracking (MPPT) systems (or similar

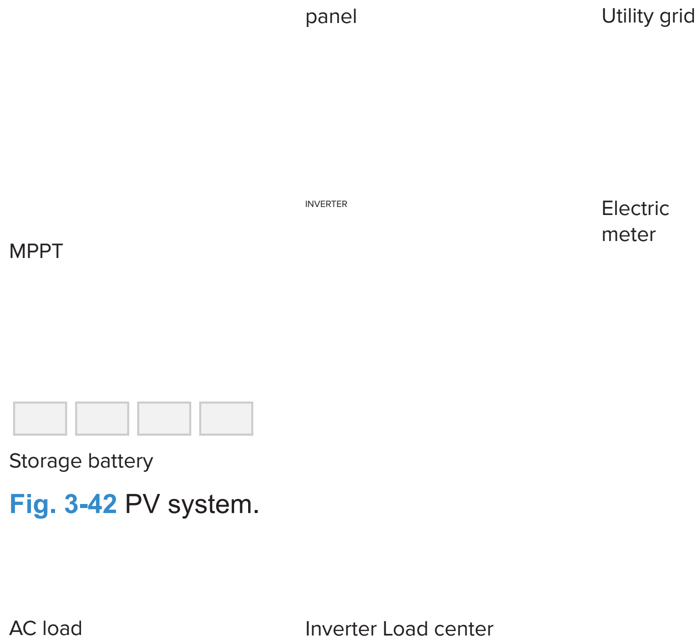
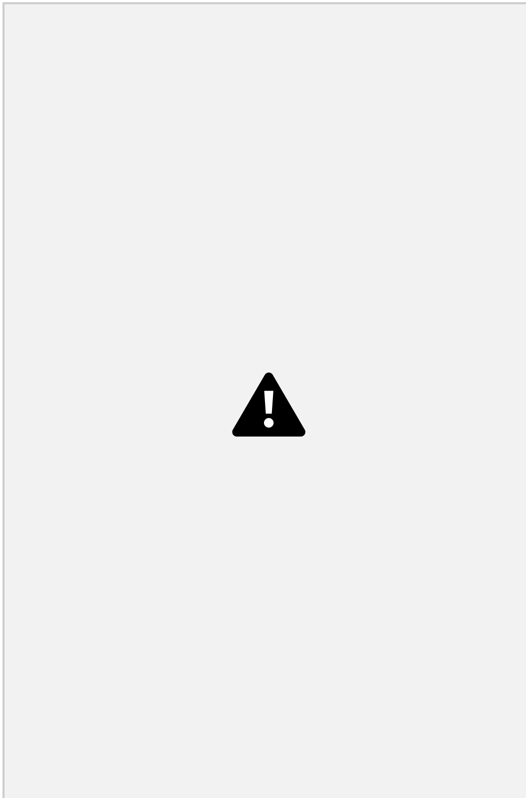



**Fig. 3-42** PV system.

devices) to maintain good performance over a range of light, load, and temperature conditions. MPPTs are dc-to-dc converters specially designed to match solar PV arrays to storage batteries. Troubleshooting converters and inverters is not covered here, but later parts of this book (e.g., Chap. 15) deal with them.

Finally, some commonsense items are worth mentioning. If PV system performance is dropping off, it might be time to wash off the built up dust and dirt. Also, is there a problem caused by partial blockage of the sun's rays? Have you taken the ambient conditions into account (e.g. overcast skies)?







*Supply the missing word in each statement.*

36. Energy sources that cannot be depleted are said to be .
37. A photon entering a PV cell might move an electron from the band to the conduction band.
38. An electron on the P side of the junction in a PV cell that has moved into the con duction band will be swept into the N side by the .
39. The liberated electrons in a PV cell can be lost to the load circuit if they are con sumed by recombination with .
40. The maximum power produced by a PV cell is than $I_{SC} \times V_{OC}$. 41. With more sunlight, more power and more are available from a PV cell.
42. PV cells sawn from silicon ingots are said to be .
43. A PV module is a combination of PC .
44. PV cells are wired in series to produce more power and .
45. Amorphous cells have the cost and the efficiency.
46. An MPPT is a(n) converter. 47. An inverter is a(n) converter.

# Chapter 3 Summary and Review

1. One of the most basic and useful electronic components is the PN-junction diode.

2. When the diode is formed, a depletion region appears that acts as an insulator.

3. Forward bias forces the majority carriers to the

junction and collapses the depletion region. The diode conducts. (Technically speaking, it semiconducts.)

4. Reverse bias widens the depletion region. The diode does not conduct.
5. Reverse bias forces the minority carriers to the junction. This causes a small leakage current to flow. It can usually be ignored.
6. Volt-ampere characteristic curves are used very often to describe the behavior of electronic devices. 7. The volt-ampere characteristic curve of a resistor is linear (a straight line).
8. The volt-ampere characteristic curve of a diode is nonlinear.
9. It takes about 0.3 V of forward bias to turn on a germanium diode, about 0.6 V for a silicon rectifier, and about 2 V for an LED.
10. A silicon diode will avalanche at some high value of reverse voltage.
11. Diode leads are identified as the cathode lead and the anode lead.
12. The anode must be made positive with respect to the cathode to make a diode conduct.
13. Manufacturers mark the cathode lead with a band, bevel, flange, or plus (+) sign.
14. If there is doubt, the ohmmeter test can identify the cathode lead. It will be connected to the negative terminal. A low resistance reading indicates that the negative terminal of the ohmmeter is connected to the cathode.
15. Caution should be used when applying the ohmmeter test. Some ohmmeters have reversed polarity. The voltage of some ohmmeters is too low to turn on a PN-junction diode. Some ohmmeters' voltages are too high and may damage delicate PN junctions.
16. A diode used to change alternating current to direct current is called a rectifier diode.
17. Schottky diodes do not have a depletion region and turn off much faster than silicon diodes.
18. A diode used to stabilize or regulate voltage is the zener diode.
19. Zener diodes conduct from anode to cathode when they are working as regulators. This is just the opposite of the way rectifier diodes conduct.
20. A diode clipper or limiter can be used to stabilize the peak-to-peak amplitude of a signal. It may also be used to change the shape of a signal or reduce its noise content.
21. Clamps or dc restorers add a dc component to an ac signal.
22. Light-emitting diodes are used as indicators and transmitters and in optoisolators.
23. Varicap diodes are solid-state variable capacitors. They are operated under conditions of reverse bias.
24. Varicap diodes show minimum capacitance at maximum bias. They show maximum capacitance at minimum bias.
25. PIN diodes are used to switch radio-frequency signals and also to attenuate them.
26. This chapter has presented quite a few diode types. Figure 3-43 will help you remember their names and symbols.

Diode forward current: $I_F = \dfrac{V_S - 0.6}{R}$ or $\dfrac{V_S - V_D}{R}$

RC time constant: $T = RC$

Resonant frequency: $f_R = \dfrac{1}{2\pi\sqrt{LC}}$

Series capacitance: $C_S = \dfrac{C_1C_2}{C_1 + C_2}$



*Determine whether each statement is true or false.*

3-1. A PN-junction diode is made by

mechanically joining a P-type crystal to an N-type crystal. (3-1) 3-2. The depletion region forms only on the P-type side of the PN junction in a solid-state diode. (3-1) 3-3. The barrier potential prevents all the electrons on the N-type side from crossing the junction to fill all the holes in the P-type side. (3-1)

3-4. The depletion region acts as an insulator. (3-1) 3-5. Forward bias tends to collapse the depletion region. (3-1)

3-6. Reverse bias drives the majority carriers toward the junction. (3-1)

3-7. It takes 0.6 V of forward bias to collapse the depletion region and turn on a silicon solid-state diode. (3-1)

3-8. A diode has a linear volt-ampere characteristic curve. (3-2)

3-9. Excessive reverse bias across a rectifier diode may cause avalanche and damage it. (3-2)

3-10. Silicon is a better conductor than germanium. (3-2)

3-11. Less voltage is required to turn on a germanium diode than to turn on a silicon diode. (3-2)

3-12. The behavior of electronic devices such as diodes changes with temperature. (3-2)

3-13. The Celsius temperature scale is used in electronics. (3-2)

3-14. Leakage current in a diode is from the cathode to the anode. (3-2)

3-15. Forward current in a diode is from the cathode to the anode. (3-2)

3-16. Diode manufacturers usually mark the package in some way so as to identify the cathode lead. (3-3) 3-17. Making the diode anode negative with respect to the cathode will turn on the diode. (3-3) 3-18. It is possible to test most diodes with an ohm meter and identify the cathode lead. (3-3) 3-19. Rectifier diodes are used in the same way as zener diodes. (3-4)

3-20. Zener diodes are normally operated with the cathode positive with respect to the anode. (3-4) 3-21. Two germanium diodes are connected as shown in Fig. 3-20. With a 10-V peak-to-peak input signal, the signal across $R_2$ would be 0.6 V peak-to-peak. (3-4)

3-22. The function of *D* in Fig. 3-24 is to limit the output signal swing to no more than 0.6 V peak to-peak. (3-4)

3-23. Light-emitting diodes emit light by heating a tiny filament red hot. (3-4)

3-24. The capacitance of a varicap diode is deter mined by the reverse bias across it. (3-4)

3-25. Germanium diodes cost less and are therefore more popular than silicon diodes in modern circuitry. (3-4)

3-26. Diode clippers are also called clamps. (3-4) 3-27. As the wiper arm of $R_2$ in Fig. 3-34 is moved up, $f_r$ will increase. (3-4)

3-1. Refer to Fig. 3-5. The diode is silicon, the battery is 3 V, and the current-limiter resistor is 150 V. Find the current flow in the circuit. (Hint: Don't forget to subtract the diode's forward voltage drop.) (3-1)

3-2. Refer to Fig. 3-11. Calculate the forward resistance of the diode at a temperature of 25°C and a forward current of 25 mA. (3-2)

3-3. Refer again to Fig. 3-11. Calculate the forward re sistance of the diode at a temperature of 25°C and a forward current of 200 mA. (3-2)

3-4. Refer to Fig. 3-23. Both resistors are 10 kV, both zeners are rated at 3.9 V, and the input signal is 2 V peak-to-peak. Calculate the output signal. (Hint: Don't forget the voltage divider action of $R_1$ and $R_2$.) (3-4)

3-5. Find the output signal for Fig. 3-23 for the same conditions as given in Prob. 3-4 but with an input signal of 20 V peak-to-peak. (3-4)

3-6. What value of current-limiter resistor should be used in an LED circuit powered by 8 V if the de sired LED current is 15 mA? You may assume an LED forward drop of 2 V. (3-4)

3-1. A nearly ideal diode would have, among other characteristics, a very small barrier potential (say a millivolt or so). What would be the advantage of such a tiny barrier potential?

3-2. Can you think of a way to use a diode to mea sure temperature?

3-3. High-power diodes can get very hot, and heat is a major factor in the failure of electronic devices. Does anything in this chapter suggest a possible solution?

3-4. Infrared remote control units are very popular in products such as television receivers and DVD players. Can you describe a simple circuit, to be used in conjunction with an oscilloscope, that could help in diagnosing problems with re mote control units?

3-5. Can you think of a reason why optocouplers are often used in medical electronics?

3-6. Why is the PIN diode transmit-receive circuit shown in Fig. 3-36 not useful for cellular telephones?

3-7. Can you identify two effects of adding a series rectifier to a string of decorative lights?

1. T
2. F
3. T
4. F
5. F
6. F
7. F
8. T
9. T
10. straight line 11. straight line 12. 10 mA (0.01 A)
13. horizontal
14. vertical
15. nonlinear
16. 0.6
17. bias (voltage)
18. cathode
19. cathode
20. cathode
21. shorted
22. on
23. nonlinear
24. T

General purpose

Zener

Light emitting

Schottky

Tunnel

Photo or photovoltaic

Varicap or varactor

25. T
26. T
27. F
28. F
29. T
30. T
31. F
32. T
33. F
34. T
35. F
36. renewable
37. valence
38. barrier potential 39. holes
40. less than
41. current
42. monocrystalline 43. cells
44. voltage
45. lowest, lowest 46. dc-to-dc
47. dc-to-ac

Fig. 3-43 A review of diode types and symbols.





# Power Supplies

## Learning Outcomes

*This chapter will help you to:*

4-1 *View* power supplies as systems. [4-1]

4-2 *Identify* and explain common rectifier circuits. [4-2, 4-3]

4-3 *Predict* and measure dc output voltage for unfiltered and filtered power supplies. [4-4, 4-5]

4-4 *Explain* how voltage multipliers work. [4-6]

4-5 *Measure* and calculate ripple and voltage regulation. [4-7]

4-6 *Explain* and make basic calculations for zener voltage regulators. [4-8]

4-7 *Troubleshoot* power supplies. [4-9]

4-8 *Select* replacement parts. [4-10]

Electronic circuits need energy to work.

In most cases, this energy is provided by a circuit called the power supply. A power supply failure will affect all of the other circuits. The supply is a key part of any electronic system. Power supplies use rectifier diodes to convert alternating current to direct current. They may also use zener diodes as voltage regulators. This chapter covers the circuits that use diodes in these ways. It also discusses component-level troubleshooting. Knowing what each part of a circuit does and how the circuit functions allows technicians to find faulty components.

### 4-1 The Power-Supply System

Most of today's power supplies are hybrids; they are a combination of linear and digital circuits. This chapter covers the linear portion. That's the part usually connected directly to the ac line or via a 60-Hz power transformer. It uses diodes and filter capacitors, usually elec trolytics, to convert ac to dc. The linear portion is often followed by a digital section called a *switcher* or a *switch-mode supply*. Chapter 15 covers the rest of what is needed to understand modern hybrid power supplies.

The power supply changes the available elec tric energy (usually ac) to the form required by the various circuits within the system (usually dc). One of the early steps in the troubleshoot ing of any electronic system is to check the sup ply voltages at various stages in the circuitry.

Power supplies range from simple to complex, depending on the requirements of the system. A simple power supply may be required to furnish 12 V dc. A more complicated power supply may provide several voltages, some positive and some negative with respect to the chas sis ground. A supply that provides voltages at