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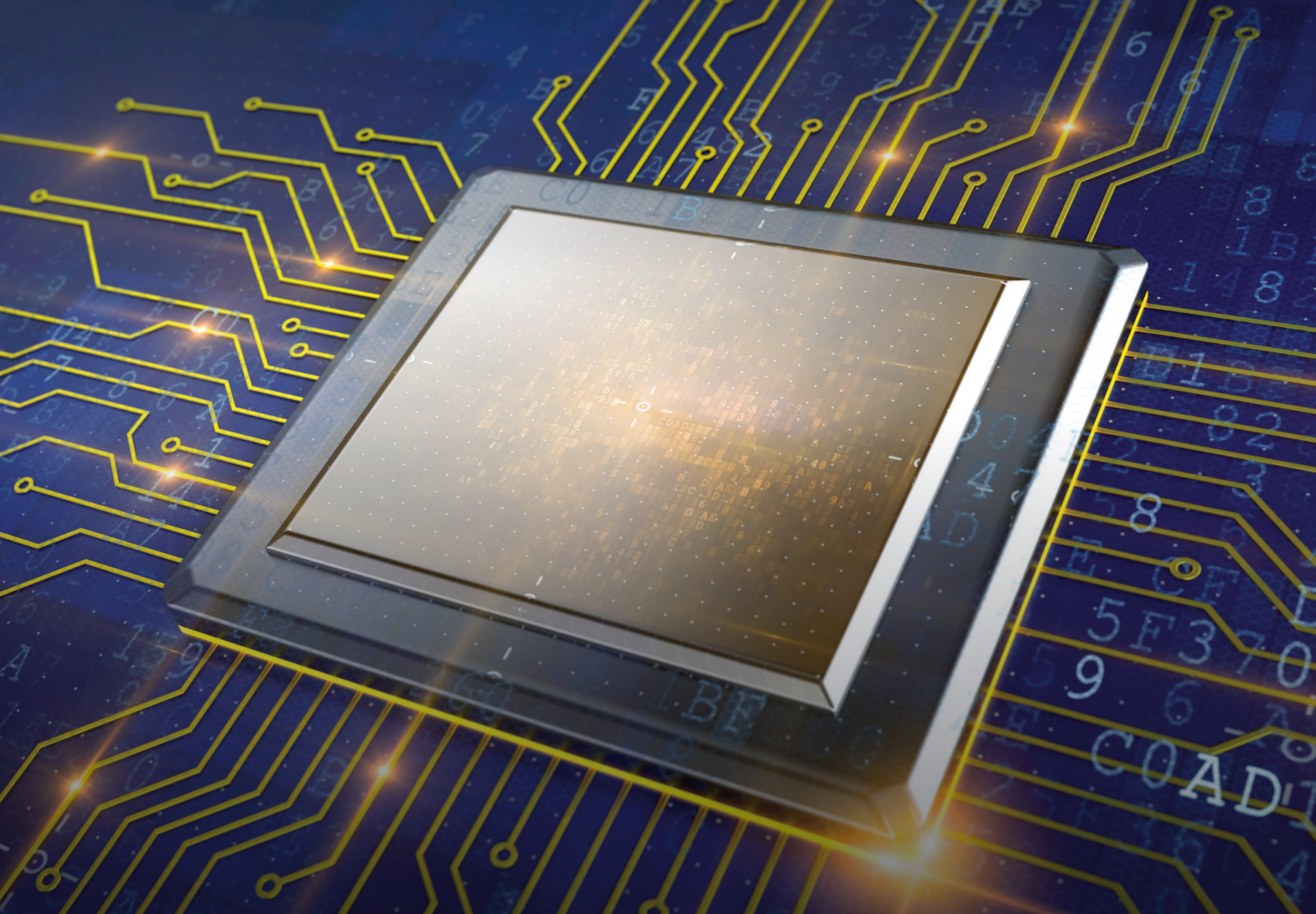
NINTH EDITION

ELECTRONIC PRINCIPLES



ALBERT MALVINO
DAVID BATES
PATRICK HOPPE

Mc Graw Hill

Electronic Principles

Ninth Edition

Albert Malvino
David J. Bates
Patrick E. Hoppe

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ELECTRONIC PRINCIPLES

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Dedication

Electronic Principles, *9th ed.* is dedicated to all students who are striving to learn the fundamentals and principles of electronics.

Albert P. Malvino *was an electronics technician while serving in the U.S. Navy from 1950 to 1954. He graduated from the University of Santa Clara Summa Cum Laude in 1959 with a B.S. degree in Electrical Engineering. For the next five years, he worked as an electronics engineer at Microwave Laboratories and at Hewlett-Packard while earning his MSEE from San Jose State University in 1964. He taught at Foothill College for the next four years and was awarded a National Science Foundation Fellowship in 1968. After receiving a Ph.D. in Electrical Engineering from Stanford University in 1970, Dr. Malvino embarked on a full-time writing career. He has written 10 textbooks that have been translated into 20 foreign languages with over 108 editions. Dr. Malvino was a consultant and designed control circuits for SPD-Smart™ windows. In addition, he wrote educational software for electronics technicians and engineers. He also served on the Board of Directors at Research Frontiers Incorporated. His website address is www.malvino.com*

David J. Bates *was an instructor in the Electronic Technologies Department of Western Wisconsin Technical College located in La Crosse, Wisconsin. Along with working as an electronic servicing technician and as an electrical engineering technician, he has over 30 years of teaching experience.*

Credentials include an A.S. degree in Industrial Electronics Technology, a B.S. degree in Industrial Education, and an M.S. degree in Vocational/Technical Education. Certifications include an A+ certification as a computer hardware technician, and Journeyman Level certifications as a Certified Electronics Technician (CET) by the Electronics Technicians Association International (ETA-I) and by the International Society of Certified Electronics Technicians (ISCET). David J. Bates is presently a certification administrator (CA) for ETA-I and serves as an Education and Technology Program Coordinator for SpaceTEC Partners, Inc., located in Titusville, Florida.

David J. Bates is also a co-author of "Basic Electricity" a text-lab manual by Zbar, Rockmaker, and Bates.

Patrick E. Hoppe *is a full-time Electrical Engineering Technology instructor and the Chair of Engineering at Gateway Technical College, located in Kenosha, Wisconsin. Since joining Gateway, he revised their Electronics program and developed their Electrical Engineering Technology program. Pat has earned local, state, and national teaching awards, including the NISOD Teaching Excellence award.*

Pat's educational preparation began at Milwaukee Area Technical College where he earned an A.A.S. degree in Biomedical Electronics in 1985. After graduation, he started his electronics career working on medical instrumentation. Pat continued his educational journey at the Milwaukee School of Engineering while he worked full time. Pat graduated with a B.S. degree in Biomedical Engineering and an M.S. degree in Perfusion. Pat continued working in healthcare until he accepted a teaching position at Gateway Technical College in 1999.

Patrick E. Hoppe is also a co-author of the experiments manual for this textbook.

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Preface

The ninth edition of *Electronic Principles* continues its tradition as a clearly explained, in-depth introduction to electronic semiconductor devices, circuits, and their use in system applications. This textbook is intended for students who are taking their first course in linear electronics but due to the comprehensive topical coverage, can be used in second- and third-semester solid-state electronics courses as well. The prerequisites are a fundamental knowledge of dc/ac circuits, algebra, and some trigonometry. *Electronic Principles*, ninth edition, can serve as an excellent follow-on textbook for *Grob's Basic Electronics* by Mitchel Schultz.

Electronic Principles provides essential understanding of semiconductor characteristics, testing, and the practical circuits in which they are found. The text provides clearly explained concepts—written in an easy-to-read conversational style—establishing the foundation needed to understand the operation and troubleshooting of electronic systems. Practical circuit examples, applications, and troubleshooting exercises are found throughout the chapters. Multisim circuit simulation files are used in the textbook to "bring the circuits to life" and help develop troubleshooting skills. These simulation files can be found and downloaded from the associated Online Learning Center (OLC) at http://mhhe.com/malvino9e. Extensive work was done to match the content in this textbook to its companion experiments manual, *Experiments Manual to Accompany Electronic Principles*.

Chapter 1, "Introduction," sets the framework for the rest of the textbook. While some of the topics will be a review, this chapter is used to ensure all students understand the fundamentals of voltage sources, current sources, Thevenin's theorem, and Norton's theorem and introduces the use of approximations as applied to electronics. Troubleshooting concepts are reviewed and expanded on with dc and ac troubleshooting techniques examined.

Chapters 2 through 10 cover the basics of semiconductor structure, diode theory, diode circuits with power supply applications, special-purpose diodes including the zener diode, optoelectronic devices, the bipolar junction transistor (BJT) introduction, BJT biasing, and BJT amplifiers, along with multistage and BJT power amplifiers.

Chapters 11 through 13 investigate field effect transistors (FETs) and thyristors. This includes device characteristics, circuits, and applications of junction field effect transistors (JFETs) and MOSFETs, along with an introduction to wide bandgap (WBG) power transistors using gallium nitride (GaN) and silicon carbide (SiC). The concepts of power half-bridge and H-bridge circuits are also explained. Included in the thyristors topics are SCRs, diacs, triacs, UJTs, and IGBTs.

Chapters 14 through 17 cover amplifier frequency response, Bode plots, bandwidth, basic differential amplifier concepts, the electrical characteristics and behavior of operational amplifiers (op amps), and concepts of negative feedback.

Chapters 18 through 22 explore op-amp applications. Included are linear op-amp applications, active filters, nonlinear op-amp applications, oscillators, and regulated power supplies.

We have entered the fourth industrial revolution and it is called "Industry 4.0." Chapter 23, written by Pat Hoppe, is brand new to this textbook. It provides an overview of Industry 4.0, along with insight into the associated technology that makes this next revolution possible: smart sensors, passive sensors, active sensors, data conversion, and data exchange. The examples used in this chapter tie in concepts from throughout the textbook, giving practical applications for the semiconductor components and circuits previously covered.

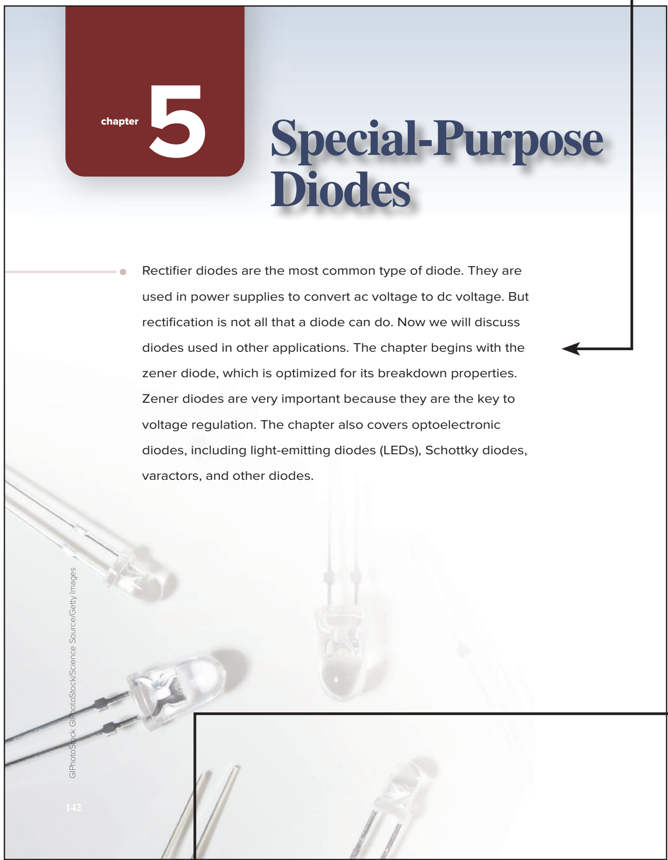
New to This Edition

- **ELECTRONICS Innovators** inserts have been added to the margins in several chapters giving students a sense of the development and significant discoveries in the electronics field.
- Expanded **Good To Know** items present additional and interesting facts about semiconductor devices and applications.
- Increased use of electronic devices photos.
- Listing of correlated lab experiments at the end of each chapter. Much effort has been applied to having the textbook and experiments manual work together as a unified knowledge and performance competency package.
- New Sec. 1-7, "AC Circuit Troubleshooting" with oscilloscope signal-tracing techniques and split-half troubleshooting methods presented. This mirrors new troubleshooting procedures in the associated experiments manual.
- Application Example of a light detection and ranging system (LiDAR) in the optoelectronics section of Chap 5.
- The Multisim primer, which was formerly in Appendix C, has been moved to the associated Online Learning Center (OLC).
- Introduction to silicon carbide (SiC) and gallium nitride (GaN) wide bandgap semiconductors.
- Expanded material on Multistage Amplifier Troubleshooting using signal tracing and split-half troubleshooting techniques.
- Expanded troubleshooting of Class-AB power amplifiers.
- New Sec. 12-12, "Wide Bandgap (WBG) MOSFETs," including the material characteristics, structures, and operation of GaN and SiC high electron mobility transistors (HEMTs).
- New Chap. 23, "Industry 4.0," introduces the concepts of the fourth industrial revolution. Extensive coverage of sensors and data conversion, with examples linking semiconductor devices and circuits covered in previous chapters, acts as a capstone chapter that ties the whole textbook together.

Guided Tour

Learning Features

Many learning features have been incorporated into the ninth edition of *Electronic Principles.* These learning features, found throughout the chapters, include:



chapter 5

Special-Purpose Diodes

Rectifier diodes are the most common type of diode. They are used in power supplies to convert ac voltage to dc voltage. But rectification is not all that a diode can do. Now we will discuss diodes used in other applications. The chapter begins with the zener diode, which is optimized for its breakdown properties. Zener diodes are very important because they are the key to voltage regulation. The chapter also covers optoelectronic diodes, including light-emitting diodes (LEDs), Schottky diodes, varactors, and other diodes.

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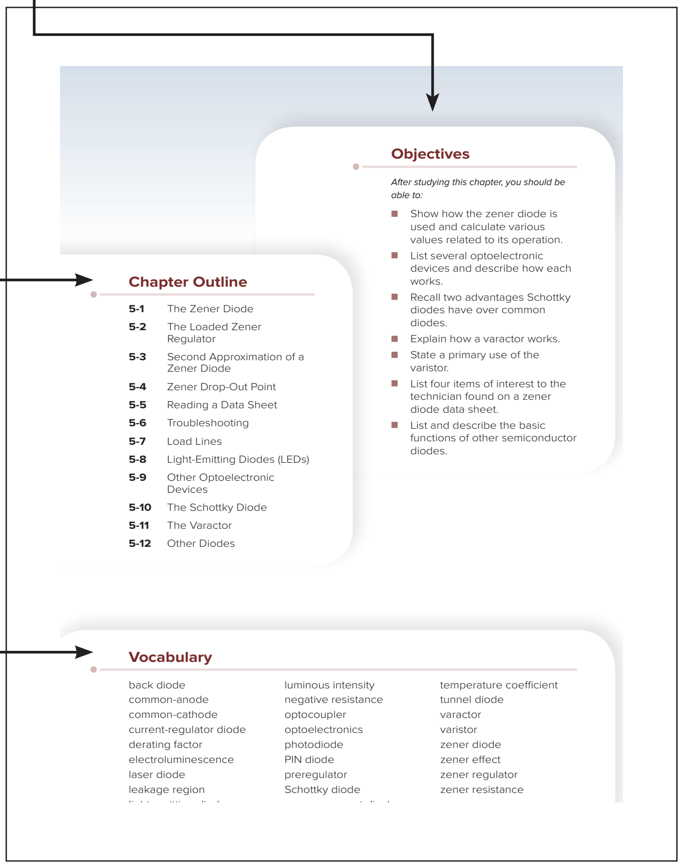
CHAPTER INTRODUCTION

Each chapter begins with a brief introduction setting the stage for what the student is about to learn.

CHAPTER OBJECTIVES

Chapter Objectives provide a concise statement of expected learning outcomes.



Objectives

After studying this chapter, you should be able to:

- Show how the zener diode is used and calculate various values related to its operation.
- List several optoelectronic devices and describe how each works.
- Recall two advantages Schottky diodes have over common diodes.
- Explain how a varactor works.
- State a primary use of the varistor.
- List four items of interest to the technician found on a zener diode data sheet.
- List and describe the basic functions of other semiconductor diodes.

Chapter Outline

5-1 The Zener Diode
5-2 The Loaded Zener Regulator
5-3 Second Approximation of a Zener Diode
5-4 Zener Drop-Out Point
5-5 Reading a Data Sheet
5-6 Troubleshooting
5-7 Load Lines
5-8 Light-Emitting Diodes (LEDs)
5-9 Other Optoelectronic Devices
5-10 The Schottky Diode
5-11 The Varactor
5-12 Other Diodes

Vocabulary

back diode	luminous intensity	temperature coefficient
common-anode	negative resistance	tunnel diode
common-cathode	optocoupler	varactor
current-regulator diode	optoelectronics	varistor
derating factor	photodiode	zener diode
electroluminescence	PIN diode	zener effect
laser diode	preregulator	zener regulator
leakage region	Schottky diode	zener resistance

CHAPTER OUTLINE

Students use the outline to get a quick overview of the chapter and to locate specific chapter topic content.

VOCABULARY

A comprehensive list of new vocabulary words alerts the students to key words found in the chapter. Within the chapter, these key words are highlighted in bold print the first time used.

EXAMPLES

Each chapter contains worked-out circuit Examples and Application Examples that demonstrate important concepts or circuit operation, including circuit analysis, applications, troubleshooting, and basic design.

Application Example 5-12

Figure 5-22*a* shows a voltage-polarity tester. It can be used to test a dc voltage of unknown polarity. When the dc voltage is positive, the green LED lights up. When the dc voltage is negative, the red LED lights up. What is the approximate LED current if the dc input voltage is 50 V and the series resistance is 2.2 kΩ?

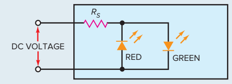


Figure 5-22 (*a*) Polarity indicator; (*b*) continuity tester.

(*a*)

PRACTICE PROBLEMS

Students can obtain critical feedback by performing the Practice Problems that immediately follow most Application Examples. Answers to these problems are found at the end of each chapter.

SOLUTION When the input terminals are shorted (continuity), the internal 9-V battery produces an LED current of:

$$I_S = \frac{9\text{ V} - 2\text{ V}}{470\ \Omega} = 14.9\text{ mA}$$

PRACTICE PROBLEM 5-13 Using Fig. 5-22*b*, what value series resistor should be used to produce 21 mA of LED current?

MULTISIM

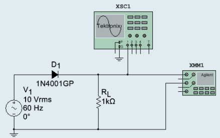
Students can "bring to life" many of the circuits found in each chapter. The Instructor Resources section on the Online Learning Center (OLC) at http://mhhe.com/malvino9e for *Electronic Principles* contains Multisim files for use with this textbook. Over 350 new or updated Multisim files and images are available for this edition; with these files, students can change the value of circuit components and instantly see the effects, using realistic Tektronix and Agilent simulation instruments. Troubleshooting skills can be developed by inserting circuit faults and making circuit measurements. Students new to computer simulation software will find a Multisim Primer on the OLC at http://mhhe.com/malvino9e.

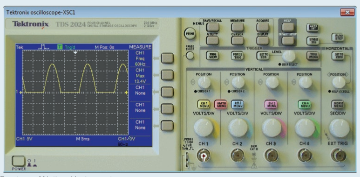
Application Example 4-1 — MultiSim

Figure 4-3 shows a half-wave rectifier that you can build on the lab bench or on a computer screen with Multisim. An oscilloscope is across the 1 kΩ. Set the oscilloscope's vertical input coupling switch or setting to dc. This will show us the half-wave load voltage. Also, a multimeter is across the 1 kΩ to read the dc load voltage. Calculate the theoretical values of peak load voltage and the dc load voltage. Then compare these values to the readings on the oscilloscope and the multimeter.

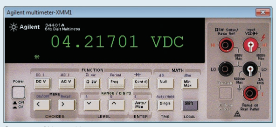
SOLUTION Figure 4-3 shows an ac source of 10 V and 60 Hz. Schematic diagrams usually show ac source voltages as effective or rms values. Recall that the *effective value* is the value of a dc voltage that produces the same heating effect as the ac voltage.

Figure 4-3 Lab example of half-wave rectifier.





Courtesy of National Instruments



Courtesy of National Instruments

DATA SHEETS

Full and partial component data sheets are provided for many semiconductor devices; key specifications are examined and explained. Complete data sheets of these devices can be found on the Instructor Resources section of the Online Learning Center (OLC) at http://mhhe.com/malvino9e.

Figure 3-15 Data sheet for 1N4001–1N4007 diodes. (Copyright Fairchild Semiconductor Corporation. Used by permission.)

FAIRCHILD SEMICONDUCTOR®

May 2009

1N4001 - 1N4007
General Purpose Rectifiers

1N4001 - 1N4007 — General Purpose Rectifiers

Features

- Low forward voltage drop.
- High surge current capability.

DO-41
COLOR BAND DENOTES CATHODE

Absolute Maximum Ratings * T_A = 25°C unless otherwise noted

Symbol	Parameter	Value 4001	4002	4003	4004	4005	4006	4007	Units
V_{RRM}	Peak Repetitive Reverse Voltage	50	100	200	400	600	800	1000	V
$I_{F(AV)}$	Average Rectified Forward Current .375 " lead length @ T_A = 75°C	1.0							A
I_{FSM}	Non-Repetitive Peak Forward Surge Current 8.3ms Single Half-Sine-Wave	30							A
I^2t	Rating for Fusing (t<8.3ms)	3.7							A^2sec
T_{STG}	Storage Temperature Range	-55 to +175							°C
T_J	Operating Junction Temperature	-55 to +175							°C

* These ratings are limiting values above which the serviceability of any semiconductor device may by impaired.

Thermal Characteristics

Symbol	Parameter	Value	Units
P_D	Power Dissipation	3.0	W
$R_{\theta JA}$	Thermal Resistance, Junction to Ambient	50	°C/W

Electrical Characteristics T_A = 25°C unless otherwise noted

Symbol	Parameter	Value	Units
V_F	Forward Voltage @ 1.0A	1.1	V
I_{rr}	Maximum Full Load Reverse Current, Full Cycle T_A = 75°C	30	µA
I_R	Reverse Current @ Rated V_R T_A = 25°C / T_A = 100°C	5.0 / 50	µA / µA
C_T	Total Capacitance V_R = 4.0V, f = 1.0MHz	15	pF

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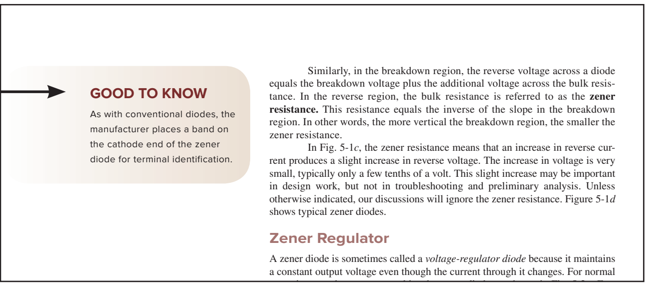
1N4001 - 1N4007 Rev. C2 1

(*a*)

GOOD TO KNOW

Good To Know statements, found in the margins, provide interesting added insights to topics being presented.



GOOD TO KNOW

As with conventional diodes, the manufacturer places a band on the cathode end of the zener diode for terminal identification.

Similarly, in the breakdown region, the reverse voltage across a diode equals the breakdown voltage plus the additional voltage across the bulk resistance. In the reverse region, the bulk resistance is referred to as the **zener resistance.** This resistance equals the inverse of the slope in the breakdown region. In other words, the more vertical the breakdown region, the smaller the zener resistance.

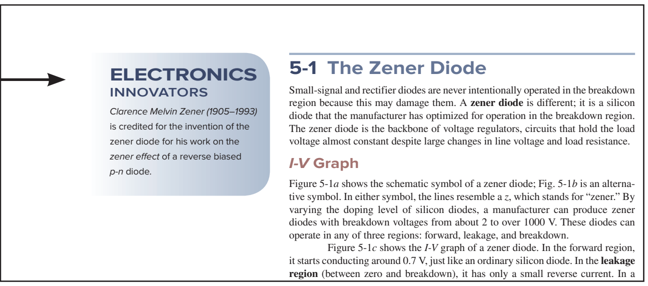
In Fig. 5-1*c*, the zener resistance means that an increase in reverse current produces a slight increase in reverse voltage. The increase in voltage is very small, typically only a few tenths of a volt. This slight increase may be important in design work, but not in troubleshooting and preliminary analysis. Unless otherwise indicated, our discussions will ignore the zener resistance. Figure 5-1*d* shows typical zener diodes.

Zener Regulator

A zener diode is sometimes called a *voltage-regulator diode* because it maintains a constant output voltage even though the current through it changes. For normal

ELECTRONICS INNOVATORS

ELECTRONICS INNOVATORS margin inserts have been added to help students understand the evolution and some of the important discoveries in the Electronics industry.



ELECTRONICS INNOVATORS

Clarence Melvin Zener (1905–1993) is credited for the invention of the zener diode for his work on the *zener effect* of a reverse biased *p-n* diode.

5-1 The Zener Diode

Small-signal and rectifier diodes are never intentionally operated in the breakdown region because this may damage them. A **zener diode** is different; it is a silicon diode that the manufacturer has optimized for operation in the breakdown region. The zener diode is the backbone of voltage regulators, circuits that hold the load voltage almost constant despite large changes in line voltage and load resistance.

I-V Graph

Figure 5-1*a* shows the schematic symbol of a zener diode; Fig. 5-1*b* is an alternative symbol. In either symbol, the lines resemble a *z*, which stands for "zener." By varying the doping level of silicon diodes, a manufacturer can produce zener diodes with breakdown voltages from about 2 to over 1000 V. These diodes can operate in any of three regions: forward, leakage, and breakdown.

Figure 5-1*c* shows the *I-V* graph of a zener diode. In the forward region, it starts conducting around 0.7 V, just like an ordinary silicon diode. In the **leakage region** (between zero and breakdown), it has only a small reverse current. In a

COMPONENT PHOTOS

Photos of actual electronic devices bring students closer to the device being studied.

SUMMARY TABLES

Summary Tables have been included at important points within many chapters. Students use these tables as an excellent review of important topics and as a convenient information resource.

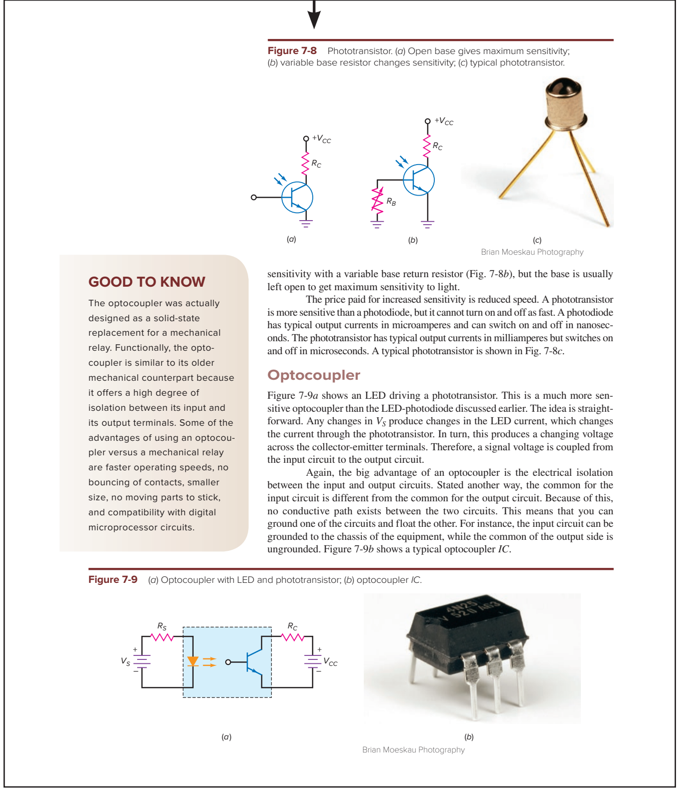


Figure 7-8 Phototransistor. (*a*) Open base gives maximum sensitivity; (*b*) variable base resistor changes sensitivity; (*c*) typical phototransistor.

Brian Moeskau Photography

GOOD TO KNOW

The optocoupler was actually designed as a solid-state replacement for a mechanical relay. Functionally, the optocoupler is similar to its older mechanical counterpart because it offers a high degree of isolation between its input and its output terminals. Some of the advantages of using an optocoupler versus a mechanical relay are faster operating speeds, no bouncing of contacts, smaller size, no moving parts to stick, and compatibility with digital microprocessor circuits.

sensitivity with a variable base return resistor (Fig. 7-8*b*), but the base is usually left open to get maximum sensitivity to light.

The price paid for increased sensitivity is reduced speed. A phototransistor is more sensitive than a photodiode, but it cannot turn on and off as fast. A photodiode has typical output currents in microamperes and can switch on and off in nanoseconds. The phototransistor has typical output currents in milliamperes but switches on and off in microseconds. A typical phototransistor is shown in Fig. 7-8*c*.

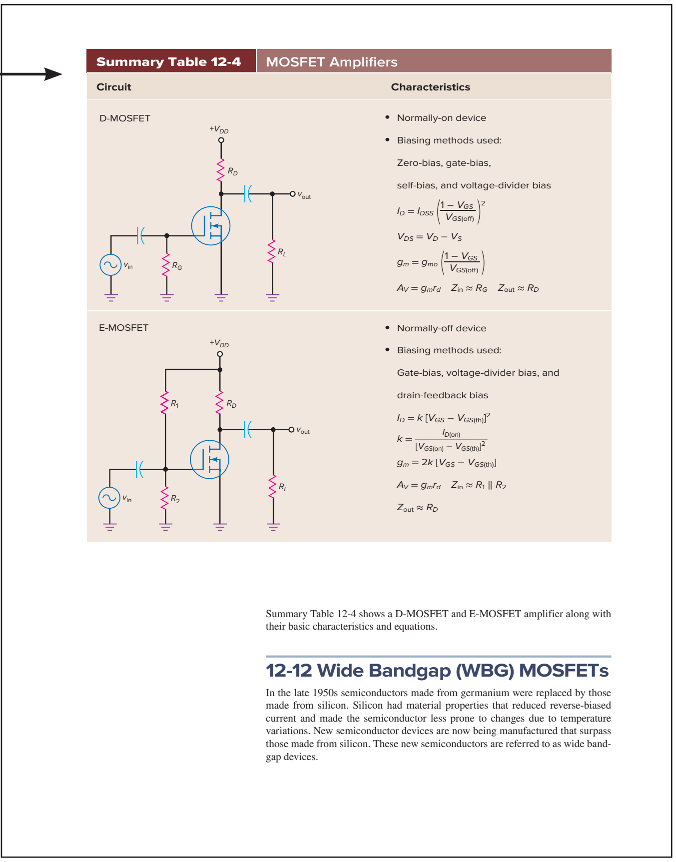
Optocoupler

Figure 7-9*a* shows an LED driving a phototransistor. This is a much more sensitive optocoupler than the LED-photodiode discussed earlier. The idea is straightforward. Any changes in V_S produce changes in the LED current, which changes the current through the phototransistor. In turn, this produces a changing voltage across the collector-emitter terminals. Therefore, a signal voltage is coupled from the input circuit to the output circuit.

Again, the big advantage of an optocoupler is the electrical isolation between the input and output circuits. Stated another way, the common for the input circuit is different from the common for the output circuit. Because of this, no conductive path exists between the two circuits. This means that you can ground one of the circuits and float the other. For instance, the input circuit can be grounded to the chassis of the equipment, while the common of the output side is ungrounded. Figure 7-9*b* shows a typical optocoupler *IC*.

Figure 7-9 (*a*) Optocoupler with LED and phototransistor; (*b*) optocoupler *IC*.

Brian Moeskau Photography



Summary Table 12-4	MOSFET Amplifiers
Circuit	**Characteristics**
D-MOSFET	• Normally-on device • Biasing methods used: Zero-bias, gate-bias, self-bias, and voltage-divider bias $I_D = I_{DSS}\left(1 - \frac{V_{GS}}{V_{GS(off)}}\right)^2$ $V_{DS} = V_D - V_S$ $g_m = g_{mo}\left(1 - \frac{V_{GS}}{V_{GS(off)}}\right)$ $A_V = g_m r_d \quad Z_{in} \approx R_G \quad Z_{out} \approx R_D$
E-MOSFET	• Normally-off device • Biasing methods used: Gate-bias, voltage-divider bias, and drain-feedback bias $I_D = k\,[V_{GS} - V_{GS(th)}]^2$ $k = \frac{I_{D(on)}}{[V_{GS(on)} - V_{GS(th)}]^2}$ $g_m = 2k\,[V_{GS} - V_{GS(th)}]$ $A_V = g_m r_d \quad Z_{in} \approx R_1 \parallel R_2$ $Z_{out} \approx R_D$

Summary Table 12-4 shows a D-MOSFET and E-MOSFET amplifier along with their basic characteristics and equations.

12-12 Wide Bandgap (WBG) MOSFETs

In the late 1950s semiconductors made from germanium were replaced by those made from silicon. Silicon had material properties that reduced reverse-biased current and made the semiconductor less prone to changes due to temperature variations. New semiconductor devices are now being manufactured that surpass those made from silicon. These new semiconductors are referred to as wide bandgap devices.

Figure 6-28 *NPN* transistor.

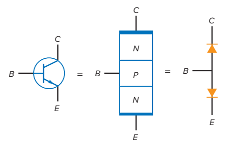
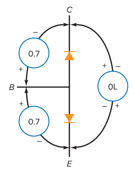


Figure 6-29 *NPN* DMM readings. (*a*) Polarity connections; (*b*) *pn* junction readings.

+	−	Reading
B	*E*	0.7
E	*B*	0L
B	*C*	0.7
C	*B*	0L
C	*E*	0L
E	*C*	0L

(*a*)



(*b*)

Many things can go wrong with a transistor. Since it contains two diodes, exceeding any of the breakdown voltages, maximum currents, or power ratings can damage either or both diodes. The troubles may include shorts, opens, high leakage currents, and reduced β_{dc}.

Out-of-Circuit Tests

A transistor is commonly tested using a DMM set to the diode test range. Figure 6-28 shows how an *npn* transistor resembles two back-to-back diodes. Each *pn* junction can be tested for normal forward- and reverse-biased readings. The collector to emitter can also be tested and should result in an overrange indication with either DMM polarity connection. Since a transistor has three leads, six DMM polarity connections are possible. These are shown in Fig. 6-29*a*. Notice that only two polarity connections result in approximately a 0.7-V reading. Also important to note here is that the base lead is the only connection common to both 0.7-V readings and it requires a (+) polarity connection. This is also shown in Fig. 6-29*b*.

A *pnp* transistor can be tested using the same technique. As shown in Fig. 6-30, the *pnp* transistor also resembles two back-to-back diodes. Again, using the DMM in the diode test range, Figs. 6-31*a* and 6-31*b* show the results for a normal transistor.

COMPONENT TESTING

Students will find clear descriptions of how to test individual electronic components using common equipment such as digital multimeters (DMMs).

Summary

SEC. 1-1 APPROXIMATIONS
Approximations are widely used in the electronics industry. The ideal approximation is useful for troubleshooting. The second approximation is useful for preliminary circuit calculations. Higher approximations are used with computers.

SEC. 1-2 VOLTAGE SOURCES
An ideal voltage source has no internal resistance. The second approximation of a voltage source has an internal resistance in series with the source. A stiff voltage source is defined as one whose internal resistance is less than 1⁄100 of the load resistance.

SEC. 1-3 CURRENT SOURCES
An ideal current source has an infinite internal resistance. The second approximation of a current source has a large internal resistance in parallel with the source. A *stiff current source* is defined as one whose internal resistance is more than 100 times the load resistance.

SEC. 1-4 THEVENIN'S THEOREM
The *Thevenin voltage* is defined as the voltage across an open load. The *Thevenin resistance* is defined as the resistance an ohmmeter would measure with an open load and all sources reduced to zero. Thevenin proved that a Thevenin equivalent circuit will produce the same load current as any other circuit with sources and linear resistances.

SEC. 1-5 NORTON'S THEOREM
The Norton resistance equals the Thevenin resistance. The Norton current equals the load current when the load is shorted. Norton proved that a Norton equivalent circuit produces the same load voltage as any other circuit with sources and linear resistances. Norton current equals Thevenin voltage divided by Thevenin resistance.

SEC. 1-6 DC CIRCUIT TROUBLESHOOTING
The most common troubles are shorts, opens, and intermittent troubles. A short always has zero voltage across it; the current through a short must be calculated by examining the rest of the circuit. An open always has zero current through it; the voltage across an open must be calculated by examining the rest of the circuit. An intermittent trouble is an on-again, off-again trouble that requires patient and logical troubleshooting to isolate it.

SEC. 1-7 AC CIRCUIT TROUBLESHOOTING
To effectively troubleshoot many ac circuits, a technique called signal-tracing is commonly used. Place channel 1 on the input signal source, and use channel 2 to measure the voltage waveforms at other test points. Compare these measurements to known normal values.

CHAPTER SUMMARIES

Students can use the summaries when reviewing for examinations, or just to make sure they haven't missed any key concepts. Important circuit derivations and definitions are listed to help solidify learning outcomes.

TROUBLESHOOTING TABLES

Troubleshooting Tables allow students to easily see what the circuit point measurement value will be for each respective fault. Used in conjunction with Multisim, students can build their troubleshooting skills.

Troubleshooting

Use Fig. 7-42 for the remaining problems.

7-49 Find Trouble 1.

7-50 Find Trouble 2.

7-51 Find Troubles 3 and 4.

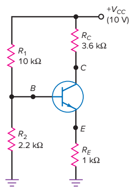
7-52 Find Troubles 5 and 6.

7-53 Find Troubles 7 and 8.

7-54 Find Troubles 9 and 10.

7-55 Find Troubles 11 and 12.

Figure 7-42



MEASUREMENTS

Trouble	V_B (V)	V_E (V)	V_C (V)	R_2 (Ω)
OK	1.8	1.1	6	OK
*T*1	10	9.3	9.4	OK
*T*2	0.7	0	0.1	OK
*T*3	1.8	1.1	10	OK
*T*4	2.1	2.1	2.1	OK
*T*5	0	0	10	OK
*T*6	3.4	2.7	2.8	∞
*T*7	1.83	1.212	10	OK
*T*8	0	0	10	0
*T*9	1.1	0.4	0.5	OK
*T*10	1.1	0.4	10	OK
*T*11	0	0	0	OK
*T*12	1.83	0	10	OK

END-OF-CHAPTER PROBLEMS

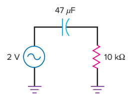
A wide variety of questions and problems are found at the end of each chapter. These include circuit analysis, troubleshooting, critical thinking, and job interview questions.

Problems

SEC. 8-1 BASE-BIASED AMPLIFIER

8-1 MultiSim In Fig. 8-31, what is the lowest frequency at which good coupling exists?

Figure 8-31



8-2 MultiSim If the load resistance is changed to 1 kΩ in Fig. 8-31, what is the lowest frequency for good coupling?

8-8 If the lowest input frequency of Fig. 8-32 is 1 kHz, what *C* value is required for effective bypassing?

SEC. 8-3 SMALL-SIGNAL OPERATION

8-9 If we want small-signal operation in Fig. 8-33, what is the maximum allowable ac emitter current?

8-10 The emitter resistor in Fig. 8-33 is doubled. If we want small-signal operation in Fig. 8-33, what is the maximum allowable ac emitter current?

SEC. 8-4 AC BETA

8-11 If an ac base current of 100 μA produces an ac collector current of 15 mA, what is the ac beta?

8-12 If the ac beta is 200 and the ac base current is 12.5 μA, what is the ac collector current?

8-13 If the ac collector current is 4 mA and the ac beta is 100, what is the ac base current?

Job Interview Questions

1. Tell me about the three classes of amplifier operation. Illustrate the classes by drawing collector current waveforms.
2. Draw brief schematics showing the three types of coupling used between amplifier stages.
3. Draw a VDB amplifier. Then, draw its dc load line and ac load line. Assuming that the *Q* point is centered on the ac load lines, what is the ac saturation current? The ac cutoff voltage? The maximum peak-to-peak output?
4. Draw the circuit of a two-stage amplifier and tell me how to calculate the total current drain on the supply.
5. Draw a Class-C tuned amplifier. Tell me how to calculate the resonant frequency, and tell me what happens to the ac signal at the base. Explain how it is possible that the brief pulses of collector current produce a sine wave of voltage across the resonant tank circuit.
6. What is the most common application of a Class-C amplifier? Could this type of amplifier be used for an audio application? If not, why not?
7. Explain the purpose of heat sinks. Also, why do we put an insulating washer between the transistor and the heat sink?
8. What is meant by the duty cycle? How is it related to the power supplied by the source?
9. Define *Q*.
10. Which class of amplifier operation is most efficient? Why?
11. You have ordered a replacement transistor and heat sink. In the box with the heat sink is a package containing a white substance. What is it?
12. Comparing a Class-A amplifier to a Class-C amplifier, which has the greater fidelity? Why?
13. What type of amplifier is used when only a small range of frequencies is to be amplified?
14. What other types of amplifiers are you familiar with?

Self-Test Answers

1.	b	**13.**	b	**25.**	b
2.	b	**14.**	b	**26.**	c
3.	c	**15.**	b	**27.**	c
4.	a	**16.**	b	**28.**	a
5.	c	**17.**	c	**29.**	d
6.	d	**18.**	a	**30.**	d
7.	d	**19.**	a	**31.**	b
8.	b	**20.**	c	**32.**	c
9.	b	**21.**	b	**33.**	d
10.	d	**22.**	d	**34.**	c
11.	c	**23.**	a	**35.**	a
12.	d	**24.**	a		

Practice Problem Answers

10-1 $I_{CQ} = 100$ mA; $V_{CEQ} = 15$ V

10-2 $i_{c(sat)} = 350$ mA; $V_{CE(cutoff)} = 21$ V; MPP = 12 V

10-3 $A_p = 1122$

10-5 $R = 200\ \Omega$

10-6 $I_{CQ} = 331$ mA; $V_{CEQ} = 6.7$ V; $r_e = 8\ \Omega$

10-7 MPP = 5.3 V

10-8 $P_{D(max)} = 2.8$ W; $P_{out(max)} = 14$ W

10-9 Efficiency = 63%

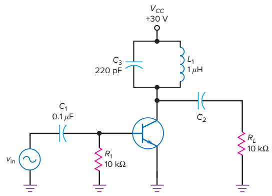
10-10 Efficiency = 78%

10-11 $f_r = 4.76$ MHz; $v_{out} = 24\ V_{p\text{-}p}$

10-13 $P_D = 16.6$ mW

10-14 $P_{D(max)} = 425$ mW

Figure 10-44



10-43 If the *Q* of the inductor is 125 in Fig. 10-44, what is the bandwidth of the amplifier?

10-44 What is the worst-case transistor power dissipation in Fig. 10-44 ($Q = 125$)?

SEC. 10-10 TRANSISTOR POWER RATING

10-45 A 2N3904 is used in Fig. 10-44. If the circuit has to operate over an ambient temperature range of 0° to 100°C, what is the maximum power rating of the transistor in the worst case?

10-46 A transistor has the derating curve shown in Fig. 10-34. What is the maximum power rating for an ambient temperature of 100°C?

10-47 The data sheet of a 2N3055 lists a power rating of 115 W for a case temperature of 25°C. If the derating factor is 0.657 W/°C, what is $P_{D(max)}$ when the case temperature is 90°C?

Critical Thinking

10-48 The output of an amplifier is a square-wave output even though the input is a sine wave. What is the explanation?

10-49 A power transistor like the one in Fig. 10-36 is used in an amplifier. Somebody tells you that since the case is grounded, you can safely touch the case. What do you think about this?

10-50 You are in a bookstore and you read the following in an electronics book: "Some power amplifiers can have an efficiency of 125 percent." Would you buy the book? Explain your answer.

10-51 Normally, the ac load line is more vertical than the dc load line. A couple of classmates say that they are willing to bet that they can draw a circuit whose ac load line is less vertical than the dc load line. Would you take the bet? Explain.

10-52 Draw the dc and ac load lines for Fig. 10-38.

Multisim Troubleshooting Problems

The Multisim troubleshooting files are found on the Online Learning Center (OLC) at http://www.mhhe.com/malvino9e, in a folder named Multisim Troubleshooting Circuits (MTC). For this chapter, the files are labeled MTC10-53 through MTC10-57 and are based on the circuit of Fig. 10-43.

Open up and troubleshoot each of the respective files. Take measurements to determine if there is a fault and, if so, determine the circuit fault.

10-53 Open up and troubleshoot file MTC10-53.

10-54 Open up and troubleshoot file MTC10-54.

10-55 Open up and troubleshoot file MTC10-55.

10-56 Open up and troubleshoot file MTC10-56.

10-57 Open up and troubleshoot file MTC10-57.

Digital/Analog Trainer System

The following questions, 10-58 through 10-62, are directed toward the schematic diagram of the Digital/Analog Trainer System found in Appendix C. A full Instruction Manual for the Model XK-700 trainer can be found at www.elenco.com.

10-58 What type of circuit do the transistors Q_1 and Q_2 form?

10-59 What is the MPP output that could be measured at the junction of R_{46} and R_{47}?

10-60 What is the purpose of diodes D_{16} and D_{17}?

10-61 Using 0.7 V for the diode drops of D_{16} and D_{17}, what is the approximate quiescent collector current for Q_1 and Q_2?

10-62 Without any ac input signal to the power amp, what is the normal dc voltage level at the junction of R_{46} and R_{47}?

Instructor Resources

- **Instructor's Manual** provides solutions and teaching suggestions for the text and Experiments Manual.
- **PowerPoint** slides for all chapters in the text, and **Electronic Testbanks** with additional review questions for each chapter can be found on the Instructor Resources section of the Online Learning Center (OLC) at http://mhhe.com/malvino9e.
- **Experiments Manual,** for *Electronic Principles,* correlated to the textbook, with lab follow-up information included on the Instructor Resources section of the Online Learning Center (OLC) at http://mhhe.com/malvino9e.

Student Resources

- The *Experiments Manual for Use with Electronic Principles*, correlated with the textbook, provides a full array of hands-on labs.
- Multisim "prelab" routines are included for those wanting to integrate computer simulation. These files are located on the Student Resources section of the Online Learning Center (OLC) at http://mhhe.com/malvino9e.
- Students new to computer simulation software can find a Multisim Primer on the Student Resources section of the Online Learning Center (OLC) at http://mhhe.com/malvino9e.

Acknowledgments

Here is a list of the reviewers who helped make this edition comprehensive and relevant.

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Electronic Principles

chapter 1

Introduction

Electronic Principles is the fundamental study of semiconductor devices, circuits, and systems as applied to a variety of worldwide applications. This important chapter serves as a framework for the rest of the textbook. The topics in this chapter include formulas, voltage sources, current sources, two circuit theorems, dc circuit troubleshooting, and ac circuit troubleshooting. Although some of the discussion will be review, you will find new ideas, such as circuit approximations, that can make it easier for you to understand semiconductor devices.

Objectives

After studying this chapter, you should be able to:

- Explain why approximations are often used instead of exact formulas.
- Define an ideal voltage source and an ideal current source.
- Describe how to recognize a stiff voltage source and a stiff current source.
- State Thevenin's theorem and apply it to a circuit.
- State Norton's theorem and apply it to a circuit.
- List two facts about an open device and two facts about a shorted device.
- Apply dc troubleshooting techniques.
- Apply ac signal-tracing techniques.

Chapter Outline

1-1 Approximations
1-2 Voltage Sources
1-3 Current Sources
1-4 Thevenin's Theorem
1-5 Norton's Theorem
1-6 DC Circuit Troubleshooting
1-7 AC Circuit Troubleshooting

Vocabulary

cold-solder joint
duality principle
formula
ideal (first) approximation
Norton current
Norton resistance
open device
second approximation
shorted device
signal-tracing
solder bridge
split-half troubleshooting
stiff current source
stiff voltage source
theorem
Thevenin resistance
Thevenin voltage
third approximation
troubleshooting

1-1 Approximations

We use approximations all the time in everyday life. If someone asks you how old you are, you might answer 21 (ideal). Or you might say 21 going on 22 (second approximation). Or, maybe, 21 years and 9 months (third approximation). Or, if you want to be more accurate, 21 years, 9 months, 2 days, 6 hours, 23 minutes, and 42 seconds (exact).

The foregoing illustrates different levels of approximation: an ideal approximation, a second approximation, a third approximation, and an exact answer. The approximation to use will depend on the situation. The same is true in electronics work. In circuit analysis, we need to choose an approximation that fits the situation.

The Ideal Approximation

Did you know that 1 foot of AWG 22 wire that is 1 inch from a chassis has a resistance of 0.016 Ω, an inductance of 0.24 μH, and a capacitance of 3.3 pF? If we had to include the effects of resistance, inductance, and capacitance in every calculation for current, we would spend too much time on calculations. This is why everybody ignores the resistance, inductance, and capacitance of connecting wires in most situations.

The **ideal approximation,** sometimes called the **first approximation,** is the simplest equivalent circuit for a device. For instance, the ideal approximation of a piece of wire is a conductor of zero resistance. This ideal approximation is adequate for everyday electronics work.

The exception occurs at higher frequencies, where you have to consider the inductance and capacitance of the wire. Suppose 1 inch of wire has an inductance of 0.24 μH and a capacitance of 3.3 pF. At 10 MHz, the inductive reactance is 15.1 Ω and the capacitive reactance is 4.82 kΩ. As you see, a circuit designer can no longer idealize a piece of wire. Depending on the rest of the circuit, the inductance and capacitive reactances of a connecting wire may be important.

As a guideline, we can idealize a piece of wire at frequencies under 1 MHz. This is usually a safe rule of thumb. But it does not mean that you can be careless about wiring. In general, keep connecting wires as short as possible, because at some point on the frequency scale, those wires will begin to degrade circuit performance.

When you are troubleshooting, the ideal approximation is usually adequate because you are looking for large deviations from normal voltages and currents. In this book, we will idealize semiconductor devices by reducing them to simple equivalent circuits. With ideal approximations, it is easier to analyze and understand how semiconductor circuits work.

The Second Approximation

The ideal approximation of a flashlight battery is a voltage source of 1.5 V. The **second approximation** adds one or more components to the ideal approximation. For instance, the second approximation of a flashlight battery is a voltage source of 1.5 V and a series resistance of 1 Ω. This series resistance is called the *source* or *internal* resistance of the battery. If the load resistance is less than 10 Ω, the load voltage will be noticeably less than 1.5 V because of the voltage drop across the source resistance. In this case, accurate calculations must include the source resistance.

The Third Approximation and Beyond

The **third approximation** includes another component in the equivalent circuit of the device. An example of the third approximation will be examined when we discuss semiconductor diodes.

Even higher approximations are possible with many components in the equivalent circuit of a device. Hand calculations using these higher approximations can become difficult and time consuming. Because of this, computers using circuit simulation software are often used. For instance, Multisim by National Instruments (NI) and PSpice are commercially available computer programs that use higher approximations to analyze and simulate semiconductor circuits. Many of the circuits and examples in this book can be analyzed and demonstrated using this type of software.

Conclusion

Which approximation to use depends on what you are trying to do. If you are troubleshooting, the ideal approximation is usually adequate. For many situations, the second approximation is the best choice because it is easy to use and does not require a computer. For higher approximations, you should use a computer and a software circuit simulation program like Multisim.

1-2 Voltage Sources

As you may recall from earlier studies, a formula is a rule that relates quantities. The rule may be an equation, an inequality, or other mathematical description. Formulas can be classified in one of these three categories:

Definitions: A formula invented for a new concept
Law: A formula for a relationship in nature
Derivation: A formula produced with mathematics

These classifications will be used in our next topics and throughout the textbook.

An *ideal dc voltage source* produces a load voltage that is constant. The simplest example of an ideal dc voltage source is a perfect battery, one whose internal resistance is zero. Figure 1-1*a* shows an ideal voltage source connected to a variable load resistance of 1 Ω to 10 MΩ. The voltmeter reads 10 V, exactly the same as the source voltage.

Figure 1-1*b* shows a graph of load voltage versus load resistance. As you can see, the load voltage remains fixed at 10 V when the load resistance changes from 1 Ω to 1 MΩ. In other words, an ideal dc voltage source produces a constant

Figure 1-1 (*a*) Ideal voltage source and variable load resistance; (*b*) load voltage is constant for all load resistances.

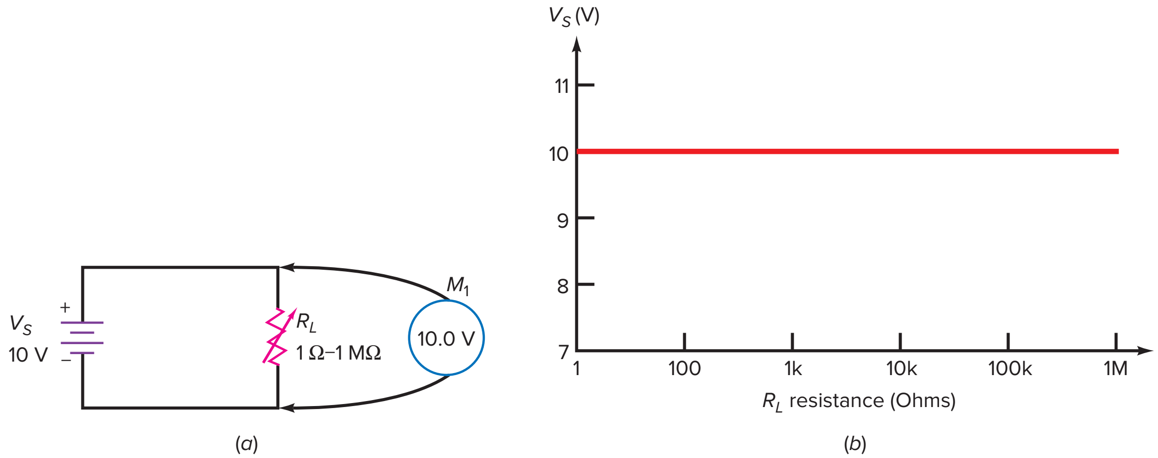
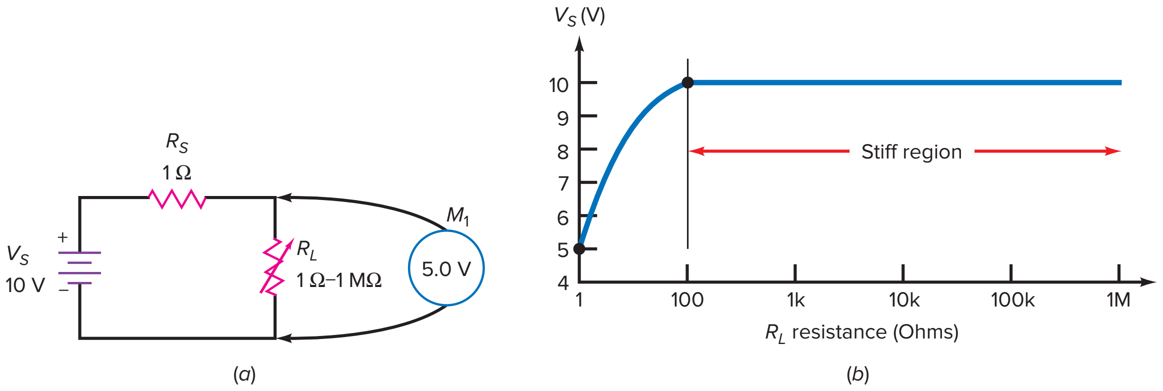


Figure 1-2 (*a*) Second approximation includes source resistance; (*b*) load voltage is constant for large load resistances.



load voltage, regardless of how small or large the load resistance is. With an ideal voltage source, only the load current changes when the load resistance changes.

Second Approximation

An ideal voltage source is a theoretical device; it cannot exist in nature. Why? When the load resistance approaches zero, the load current approaches infinity. No real voltage source can produce infinite current because a real voltage source always has some internal resistance. The second approximation of a dc voltage source includes this internal resistance.

Figure 1-2*a* illustrates the idea. A source resistance R_S of 1 Ω is now in series with the ideal battery. The voltmeter reads 5 V when R_L is 1 Ω. Why? Because the load current is 10 V divided by 2 Ω, or 5 A. When 5 A flows through the source resistance of 1 Ω, it produces an internal voltage drop of 5 V. This is why the load voltage is only half of the ideal value, with the other half being dropped across the internal resistance.

Figure 1-2*b* shows the graph of load voltage versus load resistance. In this case, the load voltage does not come close to the ideal value until the load resistance is much greater than the source resistance. But what does *much greater* mean? In other words, when can we ignore the source resistance?

Stiff Voltage Source

Now is the time when a new definition can be useful. So let us invent one. We can ignore the source resistance when it is at least 100 times smaller than the load resistance. Any source that satisfies this condition is a **stiff voltage source.** As a definition,

$$\textbf{Stiff voltage source: } R_S < 0.01R_L \tag{1-1}$$

This formula defines what we mean by a *stiff voltage source*. The boundary of the inequality (where < is changed to =) gives us the following equation:

$$R_S = 0.01R_L$$

Solving for load resistance gives the minimum load resistance we can use and still have a stiff source:

$$R_{L(\min)} = 100R_S \tag{1-2}$$

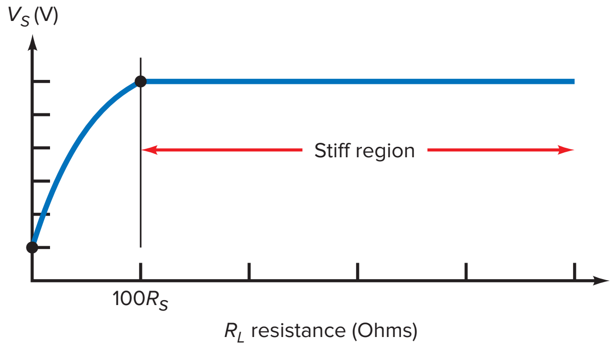
In words, the minimum load resistance equals 100 times the source resistance.

Equation (1-2) is a derivation. We started with the definition of a stiff voltage source and rearranged it to get the minimum load resistance permitted

GOOD TO KNOW

A well-regulated power supply is a good example of a stiff voltage source.

Figure 1-3 Stiff region occurs when load resistance is large enough.



with a stiff voltage source. As long as the load resistance is greater than $100R_S$, the voltage source is stiff. When the load resistance equals this worst-case value, the calculation error from ignoring the source resistance is 1 percent, small enough to ignore in a second approximation.

Figure 1-3 visually summarizes a stiff voltage source. The load resistance has to be greater than $100R_S$ for the voltage source to be stiff.

Example 1-1

The definition of a stiff voltage source applies to ac sources as well as to dc sources. Suppose an ac voltage source has a source resistance of 50 Ω. For what load resistance is the source stiff?

SOLUTION Multiply by 100 to get the minimum load resistance:

$$R_L = 100R_S = 100(50\ \Omega) = 5\ \text{k}\Omega$$

As long as the load resistance is greater than 5 kΩ, the ac voltage source is stiff and we can ignore the internal resistance of the source.

A final point: Using the second approximation for an ac voltage source is valid only at low frequencies. *At high frequencies, additional factors such as lead inductance and stray capacitance come into play*. We will deal with these high-frequency effects in a later chapter.

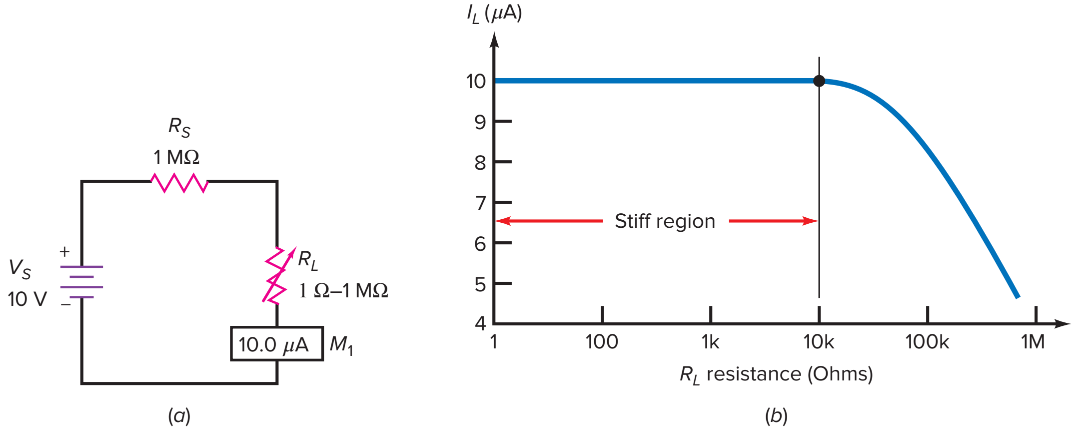
PRACTICE PROBLEM 1-1 If the ac source resistance in Example 1-1 is 600 Ω, for what load resistance is the source stiff?

1-3 Current Sources

A dc voltage source produces a constant load voltage for different load resistances. A *dc current source* is different. It produces a constant load current for different load resistances. An example of a dc current source is a battery with a large source resistance (Fig. 1-4*a*). In this circuit, the source resistance is 1 MΩ and the load current is:

$$I_L = \frac{V_S}{R_S + R_L}$$

Figure 1-4 (*a*) Simulated current source with a dc voltage source and a large resistance; (*b*) load current is constant for small load resistances.



GOOD TO KNOW

At the output terminals of a constant current source, the load voltage V_L increases in direct proportion to the load resistance.

When R_L is 1 Ω in Fig. 1-4*a*, the load current is:

$$I_L = \frac{10\text{ V}}{1\text{ M}\Omega + 1\ \Omega} = 10\ \mu\text{A}$$

In this calculation, the small load resistance has an insignificant effect on the load current.

Figure 1-4*b* shows the effect of varying the load resistance from 1 Ω to 1 MΩ. In this case, the load current remains constant at 10 μA over a large range. It is only when the load resistance is greater than 10 kΩ that a noticeable drop-off occurs in load current.

Stiff Current Source

Here is another definition that will be useful, especially with semiconductor circuits. We will ignore the source resistance of a current source when it is at least 100 times larger than the load resistance. Any source that satisfies this condition is a **stiff current source.** As a definition:

$$\textbf{Stiff current source: } \boldsymbol{R_S > 100R_L} \qquad \textbf{(1-3)}$$

The upper boundary is the worst case. At this point:

$$R_S = 100R_L$$

Solving for load resistance gives the maximum load resistance we can use and still have a stiff current source:

$$\boldsymbol{R_{L(\max)} = 0.01R_S} \qquad \textbf{(1-4)}$$

In words: The maximum load resistance equals ¹⁄₁₀₀ of the source resistance.

Equation (1-4) is a derivation because we started with the definition of a stiff current source and rearranged it to get the maximum load resistance. When the load resistance equals this worst-case value, the calculation error is 1 percent, small enough to ignore in a second approximation.

Figure 1-5 shows the stiff region. As long as the load resistance is less than $0.01R_S$, the current source is stiff.

Schematic Symbol

Figure 1-6*a* is the schematic symbol of an ideal current source, one whose source resistance is infinite. This ideal approximation cannot exist in nature, but it can

Figure 1-5 Stiff region occurs when load resistance is small enough.

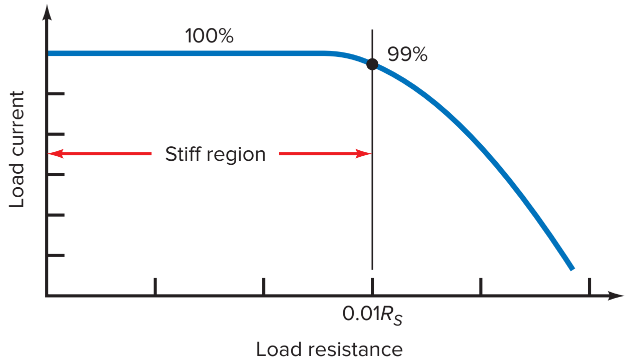
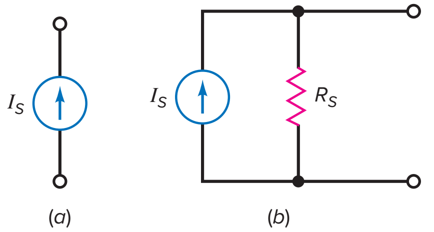


Figure 1-6 (*a*) Schematic symbol of a current source; (*b*) second approximation of a current source.



Summary Table 1-1 Properties of Voltage and Current Sources

Quantity	Voltage Source	Current Source
R_S	Typically low	Typically high
R_L	Greater than 100R_S	Less than 0.01R_S
V_L	Constant	Depends on R_L
I_L	Depends on R_L	Constant

exist mathematically. Therefore, we can use the ideal current source for fast circuit analysis, as in troubleshooting.

Figure 1-6*a* is a visual definition: It is the symbol for a current source. When you see this symbol, it means that the device produces a constant current I_S. It may help to think of a current source as a pump that pushes out a fixed number of coulombs per second. This is why you will hear expressions like "The current source pumps 5 mA through a load resistance of 1 kΩ."

Figure 1-6*b* shows the second approximation. The internal resistance is in parallel with the ideal current source, not in series, as it was with an ideal voltage source. Later in this chapter we will discuss Norton's theorem. You will then see why the internal resistance must be in parallel with the current source. Summary Table 1-1 will help you understand the differences between a voltage source and a current source.

Example 1-2

A current source of 2 mA has an internal resistance of 10 MΩ. Over what range of load resistance is the current source stiff?

SOLUTION Since this is a current source, the load resistance has to be small compared to the source resistance. With the 100:1 rule, the maximum load resistance is:

$$R_{L(\max)} = 0.01(10\text{ M}\Omega) = 100\text{ k}\Omega$$