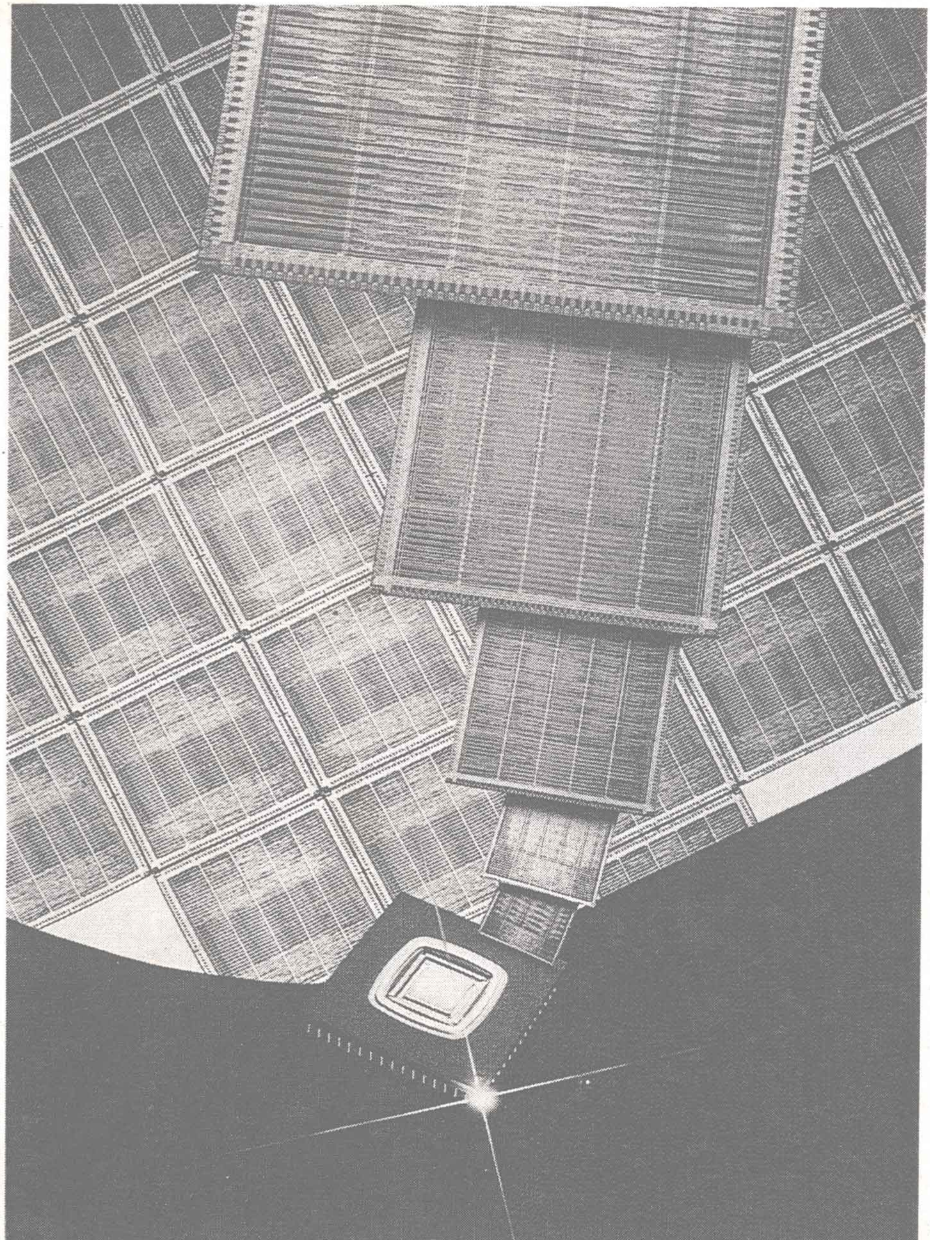
Engineering Electronics

A Practical Approach



ROBERT MAURO

Engineering Electronics

A Practical Approach

Robert Mauro
Department of Electrical Engineering
Manhattan College

PRENTICE HALL
Englewood Cliffs
New Jersey 07632

Library of Congress Cataloging-in-Publication Data

Mauro, Robert

Engineering electronics : a practical approach / Robert Mauro.

p. cm.

Includes index.
ISBN 0-13-278029-1
1. Electronics. I. Title.
TK7816.M35 1989 87-28091
621.381—dc 19 CIP

Editorial/production supervision: Joan McCulley/Colleen Brosnan
Interior design: Lorraine Mullaney with assistance from Jayne Conte
Cover design: Linda Conway
Manufacturing buyer: Mary Noonan
Page layout: Lorraine Mullaney
Cover photo: Courtesy of NEC Electronics, Inc.

Printed in the United States of America

10 9 8 7 6 5 4 3 2 1

ISBN 0-13-278029-1

Prentice-Hall International (UK) Limited, *London*
Prentice-Hall of Australia Pty. Limited, *Sydney*
Prentice-Hall Canada Inc., *Toronto*
Prentice-Hall Hispanoamericana, S.A., *Mexico*
Prentice-Hall of India Private Limited, *New Delhi*
Prentice-Hall of Japan, Inc., *Tokyo*
Simon & Schuster Asia Pte. Ltd., *Singapore*
Editora Prentice-Hall do Brasil, Ltda., *Rio de Janeiro*

Engineering Electronics

Preface

Engineering Electronics: A Practical Approach is a text designed to provide the reader with a strong understanding of analog and digital electronics using both discrete and integrated components. It is a direct outgrowth of the author's teaching and practical engineering experience, and it has been written to provide the proper blend of theory and practice needed for the reader to become a skilled electronics engineer.

The earlier chapters are meant to be used for an introductory core course in an electrical engineering program. However, because of the many new analysis techniques introduced in these chapters and also because of the wealth of up-to-date information given in the later chapters, the book should also provide excellent self-study material for practicing engineers. Furthermore, with careful selection of the material to be presented, this text can also be useful in two-year engineering technology programs.

The material contained in the book is rigorous and provides the reader with a carefully chosen mathematical justification for all information presented so that he or she should never feel that any of the material or the formulas have been "pulled out of the air." Although the text delves quite heavily into the aspects of electronics that are pertinent to a pedagogically sound understanding of electronic principles, it is sparse in the inclusion of material that is not strictly relevant to the study of electronics. As such, for example, in the area of digital electronics little time is spent covering the introductory subjects of Karnaugh maps, combinational circuit design, sequential circuit design, and so on. These matters are fully explained in other courses in nearly all EE programs. On the other hand, in this area a good deal of the text is devoted to a detailed investigation of the electronic circuit behavior of logic gates, flip-flops, semiconductor memories, and other digital logic devices.

It was the author's intention to provide the reader with a complete basic understanding of electronics. The text contains a minimum of extraneous material. It employs a practical engineering approach to the design and analysis of electronic circuits. Great care is taken in developing the operational theory of the devices examined to ensure that the reader has a good physical and mathematical understanding of their behavior. Additional attention is given to the development of the device models to be sure that the reader has an equally good understanding of where the models come from and what their limitations are.

The use of simplified models and simplified equivalent circuits is stressed for the practical solution of real electronics problems. The text is structured to teach the reader how to "look at" complex electronic circuits and reduce them to single-loop analysis problems where feasible, instead of having to rely solely on complex mesh equations, nodal analysis equations, or computer solutions. It emphasizes the use of intuitive methods for the analysis and design of electronic circuits. This book is light on formulas and strong on the use of techniques that provide for a physical understanding of the operation of electronic circuits. Along these lines, the simplified equivalent circuits developed in the early chapters are used throughout the text for multitransistor circuit analysis, frequency response analysis, transient response analysis, feedback circuit analysis, and dc bias analysis.

In examining the performance of circuits in this book, the author frequently combines the dc and ac responses of the circuit to give the reader a better idea of the actual waveshapes that will be obtained in the laboratory when probing the circuit point by point with an oscilloscope. This is important, as it helps the reader to understand more fully the relationship between small-signal circuit performance, dc biasing, and device saturation and cutoff.

In Chapters 1 and 2 the diode is introduced. In particular, in the first chapter the characteristics of the ideal diode and the *pn* junction diode are covered, as are the applications of diodes in clipping and clamping circuits. Both graphical and modeling techniques are presented for the analysis of circuits containing diodes. The large- and small-signal analysis of diodes are also dealt with in this chapter, as is the subject of zener diodes. The chapter concludes with a detailed investigation of the device physics of the *pn* junction diode.

In Chapter 2 we examine the rectification properties of diodes. The role of the transformer in electronic power supply design is reviewed and the subjects of half-wave and full-wave rectification are covered in some detail. The capacitive-input filter is discussed, and the design of zener-diode-regulated power supplies is examined.

Chapter 3 begins with a discussion of the properties of electronic amplifiers. Next, the principles of operation of the bipolar junction transistor (BJT) are introduced and the device physics are then carefully investigated. Techniques are presented in this chapter for determining the operating point of BJT circuits, and the question of dc bias point stability is covered. Both graphical and modeling techniques are employed in the analysis of these problems. The chapter concludes with a discussion of graphical techniques for the analysis of BJT circuits containing ac sources.

In Chapter 4 the investigation of the ac performance of BJT circuits is continued but this time from a small-signal approach. The hybrid parameter model is developed and related to the graphical characteristics of the transistor, and the small-signal equivalent circuits for the BJT are derived. The application of these equivalent circuits to the analysis of multitransistor circuit problems is also considered.

The theory of operation of the junction field-effect transistor (JFET) and the metal-oxide-semiconductor field-effect transistor (MOSFET) are introduced in Chapter 5, and graphical analysis techniques for assessing the operating point stability of various FET circuits is considered. A detailed small-signal model for the field-effect transistor is developed from its volt-ampere characteristics, and this model is simplified and used to derive the equivalent circuits for the FET. The chapter concludes with an investigation of the factors governing the design of multistage BJT and FET amplifier circuits.

Chapter 6 examines the frequency response of electronic circuits by employing conventional network analysis methods and then by using circuit impedance techniques. Simple approximations are used to analyze the frequency response of multistage transistor circuits. The relationship between the transient response and the frequency response of circuits is carefully developed.

Chapter 7 deals with the important subjects of feedback and the operational amplifier (op amp). The chapter begins with a detailed discussion of the effects of feedback on the performance of electronic amplifiers and presents techniques for determining the input impedance, output impedance, and gain of feedback circuits. The ideal operational amplifier is introduced and elementary linear applications of the op amp are discussed. Use of the op amp in conventional active filter and in switched-capacitor active filter designs is also covered in some detail, as are the nonlinear applications of the operational amplifier. Also presented in this chapter is an in-depth look into the internal structure of modern operational amplifiers. Topics discussed include current sources, current mirrors, active loads, and techniques for analyzing the ac and dc internal circuit performance of op amps. The chapter concludes with a discussion of second-order effects in op amps, including input and output impedance levels, dc offset effects, bandwidth, and slew rate.

The question of amplifier stability and also that of oscillator design is addressed in Chapter 8. Several different amplifiers are examined and the effect of feedback on their stability is discussed. Amplifier compensation techniques are introduced and the trade-offs of using different compensation schemes are compared. Techniques for the generation of sinusoidal oscillations in discrete transistor circuits and in op amps are presented, and the questions of amplitude and frequency stabilization in oscillator circuits are carefully examined. Methods for producing nonsinusoidal oscillations are also considered.

Chapter 9 deals with the subject of power electronics. Single-ended and push-pull linear power amplifiers are investigated, and techniques are presented for estimating the distortion levels in both the BJT and FET versions of these circuits. Linear and switching regulated power supplies are covered, and power supply overload protection schemes are discussed. The control of ac power using SCRs and triacs is investigated, and a detailed examination of thermal problems in power semiconductor circuits is included.

Chapter 10 is concerned with digital electronics and the chapter begins with a discussion of the switching characteristics of diodes, BJTs, and FET devices. The transfer characteristics and switching performance of TTL, ECL, MOS, and the CMOS logic families are carefully examined. Interfacing techniques between logic families are discussed, and an in-depth analysis of transmission-line effects in digital circuits is presented.

Chapter 11 deals with the subjects of digital timing and memory circuits. The use of logic gates and Schmitt triggers as digital oscillators is examined, and their use as monostable multivibrators (one-shots) is also investigated. Techniques for the electrical debouncing of mechanical switches are presented. The architecture of semiconductor memories at the system level is discussed, and the design of both read/write memories (RAMs) and read-only memories (ROMs) is covered. The cell designs of MOS flip-flops are presented, and the expressions for the switching performance of these cells is derived. The design of RAM and ROM memory arrays at the chip level is also covered, as are the operation of programmable read-only memories (PROMs), erasable programmable read-only memories (EPROMs), and electrically alterable read-only memories (EAROMs). A detailed discussion of dynamic memories is included. Applications of ROMs and programmable logic arrays (PLAs) to the design of sequential circuits are also presented. The chapter and the text conclude with a discussion of gate arrays.

Two detailed appendices are also included which provide the reader with important background information. Appendix I contains a review of specific network theory points that are crucial to a full understanding of electronics, and covers such topics as voltage and current dividers, superposition, Thévenin and Norton equivalents, frequency response, transient response, and resonance. The second appendix reviews techniques for the analysis of transmission-line problems. It contains a derivation of the transmission-line equations, a development of the concept of the reflection diagram and the reflection coefficient, and a discussion of the use of impedance diagrams for the analysis of transmission-line circuits containing nonlinear sources and loads.

Chapters 1 through 5 taken together provide a basic introductory course in electronics and cover the low-frequency operation of diodes, BJTs, and FETs. The only prerequisites required for this material are a first-year college mathematics course and a course in basic network theory.

Starting with Chapter 6, the text begins to work with transfer functions, Laplace transforms, and the sinusoidal steady state. Because of this, it is a good idea for the reader intending to go beyond Chapter 5 to have had a second course in network analysis. Since an appendix covering these subjects is included at the end of the text, it may be possible to use this material to replace a formal networks course covering these subjects. Chapters 7 through 9 contain advanced material in analog electronics. Depending on the speed of the instructor, and on his or her willingness to choose judiciously the topics to be covered, it may be possible to cover Chapters 6 through 9 in a second course in electronics.

Chapters 10 and 11 can be used to form a course in digital electronics. Because this material is virtually independent of that covered in Chapters 7 through 9, it may, if desired, be covered earlier.

The textbook features a large number of solved text examples, as well as numerous exercises at the end of each section. A wide range of practical homework problems are also provided at the end of each chapter. Answers are given for selected homework problems at the end of the text, and a solutions manual for instructors is available from the publisher.

This text was written at Manhattan College, where the author is a member of the Electrical Engineering Department. He would like to thank the many people who assisted in the development of this text. Professor Borrmann provided many valuable discussions and was kind enough to read and comment on most of the manuscript. This book was used in note form by many members of the faculty and by numerous students. Their criticisms and suggestions are gratefully acknowledged. A special note of thanks is also due to two graduate students; Greg Nardozza, for testing many of the theoretical analysis methods presented in the later chapters, and to Lisa Governali, for assembling the solutions manual.

The author is also indebted to the staff at Prentice Hall for their invaluable assistance in the preparation of this manuscript, especially Bernard Goodwin, Tim Bozik, Elizabeth Kaster, Joan McCulley, and Colleen Brosnan.

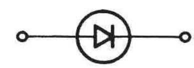
In closing, I wish especially to thank my wife, Jean, and my children, Luke and Kate, for their tolerance, support, and understanding during the many years involved in the preparation of this manuscript.

Robert Mauro

Contents

CHAPTER 1

Introduction to Electronics: The Diode



1.1 INTRODUCTION

In the twentieth century no other area of engineering has experienced the phenomenal growth and rapid changes seen by the electronics industry. The evolution from the vacuum tube to the transistor, and then from the transistor to the integrated circuit, has occurred with amazing speed. Today we accept as commonplace the miracles of radio, television, satellite communication, calculators, and computers, scarcely considering that none of these advances would have been possible without the incredible developments that have taken place in the field of electronics.

To the engineering student contemplating the study of electronics, mastery of this subject might at first appear to be a formidable, if not impossible task. At least it seemed so to this author when he first began his career in electrical engineering some years ago. Fortunately, things are not quite that bad. Two factors are in the student's favor. First, most electronic systems, regardless of their apparent complexity, can be reduced to an interconnection of basic building blocks. Once this fact is recognized, it becomes clear that expertise in this subject lies not in exhaustively studying all possible electronic circuits but in developing an understanding of their basic building blocks.

A second point to remember is that while new electronic devices are constantly being introduced, their application areas remain basically the same. As a result, if you thoroughly learn the fundamental concepts of electronic circuit theory using currently available components, then, later in your career when these components are replaced by new ones that are yet to be developed, you will easily be able to incorporate them into your designs.

Before beginning the formal text material on electronics, you should be reminded that the author is assuming that you are familiar with basic network theory. Consult Appendix I at the end of this text to review the following topics: voltage and current dividers, superposition, Thévenin and Norton equivalents, the transient and frequency response of electrical networks, Laplace transforms, resonance, and transformers.

1.2 THE IDEAL DIODE

The subject of electronics is concerned with the analysis and design of circuits containing diodes, transistors, integrated circuits, energy sources, and transformers as well as the more familiar *R*, *L*, and *C* components. We begin the study of this subject by examining the most fundamental electronic device, the diode.

As shown in Figure 1.2-1a, a diode is a two-terminal device; i_D defines the current flow through the diode and v_D the voltage drop across it. The side of the diode where i_D enters is called the anode, and that where it leaves is known as the cathode. Figure 1.2-1b illustrates the volt-ampere or *V–I* characteristics of a typical electronic diode. As the graph indicates, the diode is a device that permits current to flow easily in one direction while almost completely preventing its flow in the other. In this way the operation of the diode is quite similar to that of the mechanical check valve shown in Figure 1.2-2.

Here, when the pressure on the left-hand side of the check valve (P_1) is greater than that on the right (P_2), the door flips open and water flows through the valve. On the other hand, when the pressure P_2 exceeds P_1, the door remains closed and no water flows. It should be noted that when the check valve is open and water is flowing, P_1 and P_2 are approximately the same, so that P_v is nearly zero. Conversely, when the valve is closed and no water flows, P_v is negative.

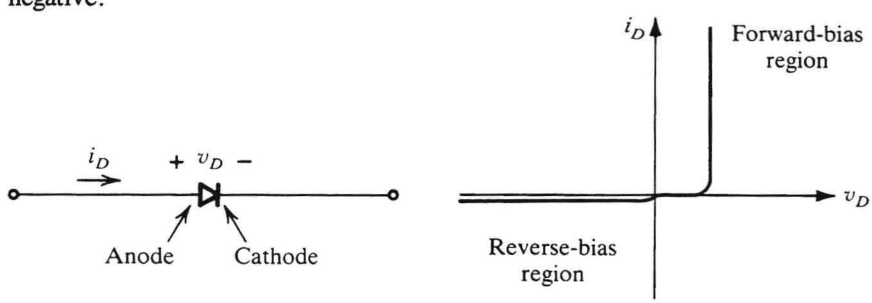


Figure 1.2-1

(a) Electronic Symbol for the Diode (b) Typical Volt-Ampere Characteristics of a Diode

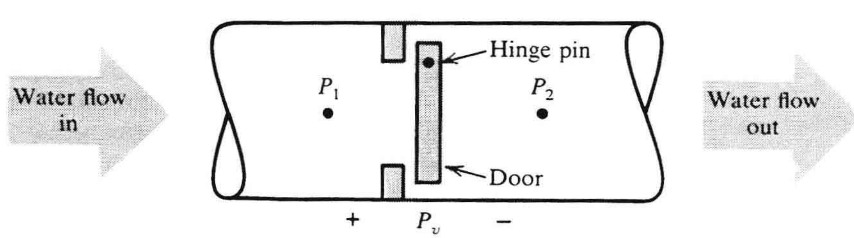


Figure 1.2-2
Water flow in a pipe containing a check value.