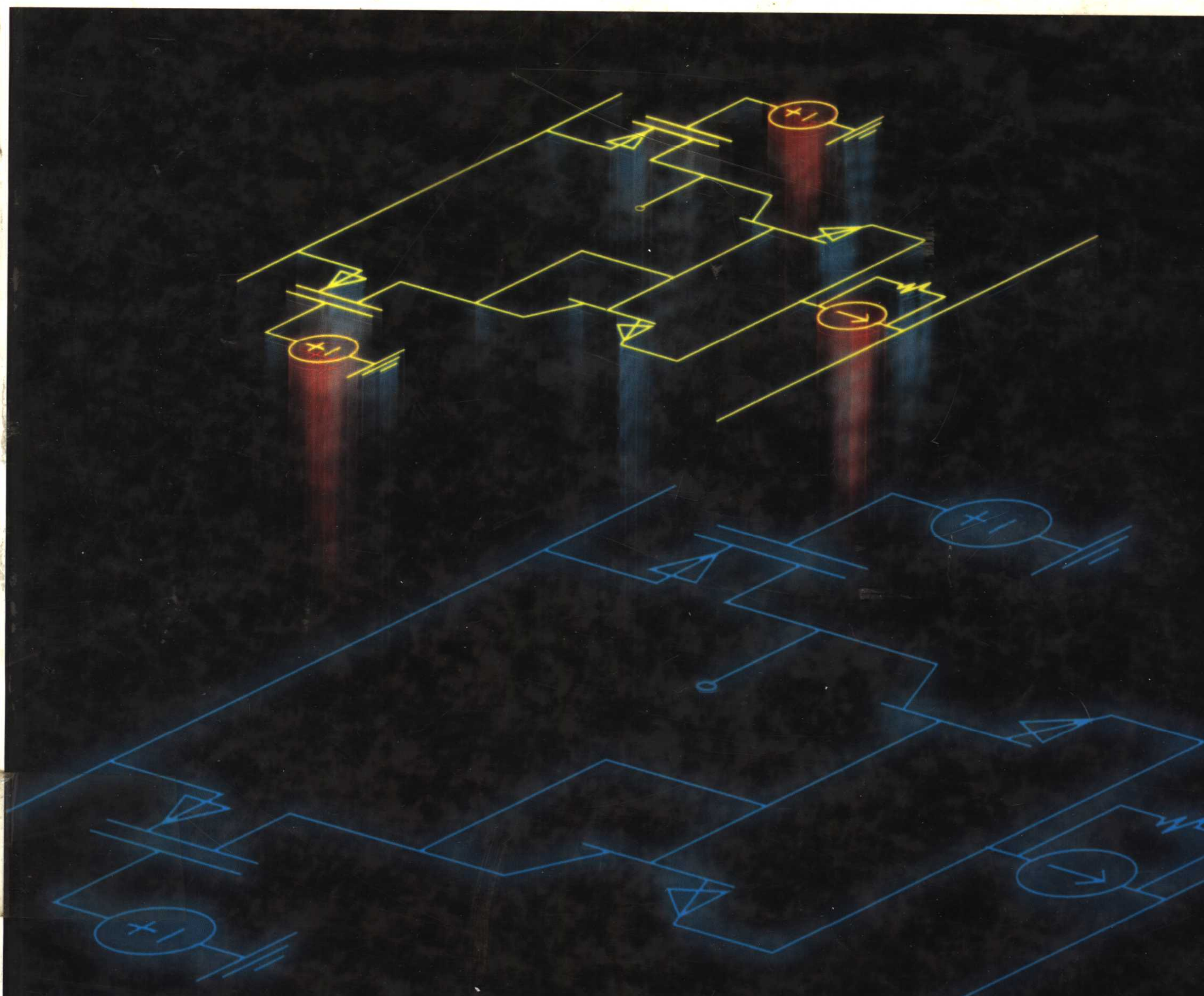
MICROELECTRONIC CIRCUITS AND DEVICES

SECOND EDITION



MARK N. HORENSTEIN

Second Edition

MICROELECTRONIC CIRCUITS AND DEVICES

MARK N. HORENSTEIN

Boston University

PRENTICE HALL

Englewood Cliffs, New Jersey 07632

Preface

Microelectronic Circuits and Devices, second edition, is intended as an introductory electronics text for students majoring in electrical, computer, and related engineering disciplines. It also has been written to serve practicing engineers who wish to update their knowledge or acquire a reference volume on the subject of electronics.

The book builds upon the theme introduced in the first edition in which a circuit is viewed as an entire electronic system, rather than as a collection of individual devices. In the past, electronic design involved the creation of individual modules using a small number of components. Larger systems would then be built by interconnecting compatible modules. Today, the design engineer must build the same large-scale system as a single circuit composed of many elements on the same integrated circuit, or "chip." Even the engineer who merely uses such circuits to perform tasks must understand how the various parts of the circuit interact with each other to achieve the desired set of circuit properties. The principal goal of this text is to give all students, whether destined to become circuit designers or engineers who simply use electronics, the tools necessary to make intelligent choices in the design of analog and digital systems.

PHILOSOPHY

Many electronic texts in use today focus first on the properties of devices, and second on their use in electronic circuits. Such texts typically include separate chapters on the bipolar junction transistor (BJT), the metal-oxide-semiconductor field-effect transistor (MOSFET), and possibly the junction field-effect transistor (JFET). Each device chapter will include examples of circuits in which the device is used; similar circuit types will be re-examined in subsequent device chapters. This approach may prompt students to memorize a set of traditional, "standard," rote design rules that apply to each type of device. This pedagogical approach, though appropriate at one time, is no longer practical as a method of teaching modern electronics.

This book adopts a more practical and realistic approach to the teaching of electronics. The principal focus is on the function of the circuit and its role in the overall electronic system. The properties of specific devices are considered only after the primary function of the circuit has been addressed. Under this approach, for example, the designer might first determine whether an inverter or follower, a single-stage or differential amplifier, is appropriate for processing a particular signal. Only then would the designer decide upon which devices to be used in synthesizing the circuit. In an attempt to orient the student to this "function-of-circuits" approach, the MOSFET, BJT, and JFET are all introduced in a single chapter on device properties. Subsequent chapters address the functions of important circuit configurations, and then show examples of how these circuits can be synthesized using any of these semiconductor devices. This underlying philosophy, which is carried throughout the book wherever practical, gives the text its unique character.

KEY FEATURES

PROBLEM MATERIAL

The second edition contains over 2000 end-of-chapter problems, representing a substantial increase over the first edition. Each of the principal chapters contains at *least* 100 problems, with some chapters exceeding the 150-problem level. Problems are now clearly organized by chapter section, with a *minimum* of 10 problems per principal section and 5 problems per minor section.

Over 80% of the problem material is newly developed since the first edition, and approximately 25% of the problems are design-oriented. Problems are also identified for difficulty. The division of problems into these categories is based on the joint considerations of length and the requirement that the student extend beyond the standard formulations of the text in solving the problem.

DESIGN CONTENT

The design component of the text is addressed in several ways. End-of-chapter problems with significant design content are denoted by the symbol next to the problem number. The body of the text contains numerous design examples and exercises. Finally, Chapter 16 contains an overview of the design process and a comprehensive set of open-ended design problems that require the student to integrate many of the design principles developed throughout the text. Most all of the design problems in Chapter 16 have been "field tested" in our electronics courses at Boston University and are well within the capabilities of the typical undergraduate student.

COVERAGE OF SPICE

One noticeable change from to the first edition is the appearance of separate SPICE examples at the end of each chapter. These examples, together with the material in Appendix C, provide a comprehensive coverage of SPICE that fully integrates with the material of each chapter. The SPICE examples are written so that they can be omitted without affecting the continuity of the text body, but augment chapter material by highlighting the useful features of the SPICE program. This type of organization, chosen by the author from a detailed sampling of readers, represents a compromise between two opposing philosophies – one requiring that SPICE be fully integrated into the curriculum, and one desiring that computer-aided methods be postponed until students acquire a firm understanding of electronic circuits. It is hoped that the approach to SPICE adopted in this text will serve the needs of both communities. For those who wish to include SPICE, a lengthy set of SPICE-oriented problems is included at the end of each of Chapters 3 through 14.

CONTENTS OF THE SECOND EDITION

Chapter 1 begins with a review of linear circuit theory that should hep students recall key concepts from a first course on linear circuit theory. Experience has shown that an initial, brief review of such material better prepares students to appreciate the nuances of nonlinear devices. In a change from the first edition, Chapter 1 now includes material on first-order resistor-capacitor circuits in both the time and frequency domains. These concepts are then used throughout the text when needed.

Chapter 2 consists of a stand-alone treatment of operational amplifiers and op-amp circuits. Because some curricula now include the op-amp in linear circuits courses, Chapter 2 is designed so that it can be skipped entirely without any loss of continuity. Similarly, because some instructors may choose to motivate this material by covering it after basic transistor circuits, the chapter is written so that it can be covered virtually anywhere in the text sequence. Sections in which the op-amp does appear in Chapters 3 to 9 (e.g., the precision rectifier of Chapter 4) are clearly separated and can be easily omitted should the instructor choose to delay coverage of op-amps. Similarly, any problems that reference the op-amp in Chapters 3 to 9 appear in easily omitted clusters.

In a departure from the approach of the first edition, the nonideal properties of op-amps, including offset voltage, bias current, offset current, slew rate, and frequency limitations, are now covered in Chapter 2. These sections are written so that they can be understood with little prior knowledge of transistor theory.

Chapter 3, which can follow Chapter 1 without loss of continuity, introduces the reader to two-terminal devices including the *pn* junction and the zener diode. The effects of nonlinear elements on circuit behavior are demonstrated by defining the two-terminal square-law device that serves as a prelude to the MOSFET of subsequent chapters. Chapter 3 also includes material on the graphical, numerical, and piecewise linear modeling methods of solution.

Chapter 4 examines practical circuits made from the two-terminal devices introduced in Chapter 3. Examples include the diode limiting circuit, half-, full-, and bridge-rectifier circuits, power supplies, zener regulator, and AM demodulator. The chapter concludes with a separate section on precision diode rectifier, and limiter circuits made from op-amps. This section may be included or omitted at the instructor's discretion.

In Chapter 5, the three-terminal device is introduced as a circuit element whose v–i characteristic is controlled by a third input variable. This approach leads to detailed discussions of the BJT, MOSFET, and JFET. Chapter 5 also includes self-contained sections on the physical bases of device operation. These qualitative treatments of semiconductor physics can be augmented by the optional quantitative treatment of Appendix A, where the v–i characteristics of the *pn* junction, BJT, and MOSFET are derived from first principles.

Chapter 5 in the second edition now also contains material on photonic devices, including the photodiode, phototransistor, light-emitting diode, and laser diode. This optional section, designed to introduce the student to the emerging field of photonics and its link to traditional electronics, can be omitted if desired with no loss of continuity. The chapter concludes with sections on the temperature and power limitations of device operation.

Chapter 6 introduces the reader to the three principal transistor circuit topologies: the inverter, voltage follower, and current follower. These terms, which describe circuit function, are used in lieu the traditional device-dependent designations "common-emitter," "common-collector," and "common-base," or "common-source," "common-drain," and "common-gate" amplifiers. In a change from the first edition, the term "tracking" configuration has been replaced by the more intuitive term current follower.

The inverter, voltage-follower, and current-follower topologies are first developed from a circuit function point of view. Examples are then provided in which each circuit topology is built first with BJTs, then with MOSFETs. The second edition now includes a discussion of the MOSFET body effect as well as a much expanded treatment of CMOS circuits in which *n*-channel and *p*-channel MOSFETs appear together in the same circuit.

In a change from the first edition, the final sections of Chapter 6 now introduce the digital regime as a limiting case of analog circuit operation. Given the prominence of digital circuits in electronics today, and the tendency of high-speed digital circuits to behave more like analog circuits at their limits of performance, the well-prepared student of electronics must develop an early fluency in both types of circuit operation.

The topic of traditional analog amplification is addressed in detail in Chapter 7. In a significant change from the first edition, the previously lengthy separate chapter on biasing has been condensed (with no loss of topical coverage) and is now included together in one chapter with small-signal modeling. This new organization allows the interrelationship between these two concepts to be clearly presented. The treatment of analog amplification includes a development of small-signal gain, input resistance, output resistance, two-port amplifier representation, and the MOS body effect.

Chapter 8 introduces the reader to the differential amplifier. Given the widespread use of this circuit configuration in operational and wideband amplifiers, signal detection, and ECL logic, the differential amplifier deserves special attention in a first or second course on electronics. Following the approach of the rest of the text, the differential amplifier is first developed from a circuit function point of view. Examples are then provided of differential-amplifier implementation using BJT, MOSFET, JFET, and CMOS configurations. The BiCMOS differential amplifier is presented as a natural symbiosis of BJT and MOS technologies.

Frequency and time response of circuits are covered in Chapter 9. The chapter begins with a discussion of capacitance and its physical origins in electronic circuits and devices. Inductance is also covered to a lesser extent. The chapter then moves to the frequency domain, first by reviewing Bode plots, then by highlighting the key features of analog circuit behavior under sinusoidal-steady-state excitation conditions. The important concepts of high-, low-, and midband-frequency limits, superposition of poles, the dominant-pole concept, and Miller multiplication are all introduced in this context. The term "Thévenin resistance method" is used to describe the methods of "short-circuit" and "open-circuit" times constants. These latter terms are used in some texts, but the method is the same. Frequency-response concepts are reinforced via examples of circuits using the various circuit topologies of Chapters 6, 7, and 8, including the differential-amplifier and cascode (current-follower) configurations.

Chapter 9 concludes with a discussion of the time response of diode and transistor circuits under the conditions of step excitation. These sections help to prepare students for the detailed discussions of the time response of digital circuits presented in Chapter 14. Alternatively, they can be omitted or postponed without loss of continuity.

Chapter 10 on feedback circuits and stability has been considerably expanded and improved since the first edition. The chapter begins with a discussion of the general properties of feedback circuits, including the effect of feedback on amplifier gain, linearity, and bandwidth. The chapter next introduces the four basic amplifier types, including the voltage, current, transresistance, and transconductance amplifiers. The four classic feedback topologies are next introduced as natural methods of implementing feedback in each of the four principal amplifier types. The effects of shunt and series mixing on amplifier input resistance, and of shunt and series sampling on amplifier output resistance, are presented as a prelude to examples of real feedback circuits. These discussions help to illustrate the load of amplifier ports by the input and output resistances of the feedback network. Chapter 10 concludes with a discussion of feedback-loop stability, gain and phase margins, and frequency compensation. Expanded discussion of frequency compensation is deferred to Chapter 12, where the internal circuitry of the operational amplifier is examined.

Chapter 11 includes material on multistage amplification, input, output, and interstage loading, dc level shifting, and multistage biasing. The chapter concludes with a discussion of power-amplification stages and power devices. Given the frequent appearance of power output stages as the last stage of a multistage cascade, as in the operational amplifier, the positioning of power-amplification circuits alongside multistage amplifiers is most appropriate.

Chapter 12 provides case studies of the internal circuitry of two types of operational amplifiers—the tradition LM741 op-amp and a generic CMOS op-amp. This material is included for instructors who may wish to indulge in a detailed discussion of analog IC design principles.

Chapter 13 deals with the topics of active filters and oscillators. Much expanded since the first edition, the chapter now includes material on the various classical filter configurations, including the biquad, Butterworth, and Chebyshev filters. The response characteristics and design principles of these filter types are developed from first principles. Sections are also included on magnitude scaling, frequency scaling, switched-capacitor filters, the Wien-bridge oscillator, and the phase-shift oscillator. Oscillator circuits are treated as examples in which the feedback-stability criteria of Chapter 10 are intentionally violated.

Chapter 14 deals exclusively with the realm of digital circuits. The chapter is designed to serve either as a capstone treatment to a one-semester course or as a springboard to subsequent courses on digital electronics. The chapter begins with a discussion of standard logic families and general definitions important to digital circuits. The CMOS, NMOS, TTL, ECL, and BiCMOS logic families are then covered in separate sections. In each case, discussions focus on the static and dynamic behavior in a single-input digital inverter, as well as the synthesis of NAND and NOR gates.

Chapter 15 expands upon the coverage of Chapter 14 by introducing more complex digital circuits, including the various types of flip-flops, digital multivibrator circuits, memory elements, and analog-to-digital-interface circuits.

Chapter 16, the last chapter of the book, is a new addition. It presents an overview of the electronic design process and provides numerous open-ended design problems. These comprehensive design statements require the student to integrate key topics from throughout the text and to use them in the synthesis of electronic circuits or systems. The designs may be performed on paper or, where resources permit, in the laboratory. Chapter 16 also includes four analog IC design problems that ask the student to specify the component values of a predetermined circuit layout such that design specifications are met.

The text includes several appendices designed to introduce maximum flexibility into the course structure. Appendix A provides a quantitative treatment of semiconductor physics and semiconductor devices, and derivations of device v–i characteristics. Appendix B discusses the fabrication techniques used to make discrete devices and intergrated circuits. Appendix C, which provides an introduction to SPICE and PSpice, has depth sufficient to encompass all of the problems and examples in the text. The instructor may wish to augment coverage of SPICE via one of the several excellent SPICE reference books listed at the end of Appendix C. Appendix D contains information about resistor color codes, tolerance limits, and selection. Appendix B consists of a detailed bibliography of other recommended texts and articles. Answers to selected problems are provided in Appendix F.

FLEXIBILITY IN ORGANIZATION AND COVERAGE

In the second edition, material on BJTs and MOSFETs is no longer mixed at random within each chapter. Rather, coverage of circuits using these two classes of devices follows a much more ordered approach. With the discussion of each circuit topology (e.g., inverter, voltage follower, or current follower), use of BJTs and MOSFETs is treated in separate sections that are completely uncoupled. An instructor can approach the book "vertically" by teaching first the circuit functions and then the BJT and MOSFET examples in the sequence in which they appear in each chapter. Alternatively, the material can be approached "horizontally" by selecting across sequential chapters the sections dealing with the properties, circuits, and design principles of the BJT, followed later by coverage of the corresponding sections using the MOSFET. This organization permits instructors who prefer the traditional "properties-of-devices" approach of other books to still adopt this text.

The two different approaches to course organization are illustrated in the following table, which lists some of the key topics of Chapters 5 to 8:

HORIZONTAL APPROACH →

VERTICAL APPROACH ↓	*Chapter 5* (Device characteristics)	*Chapter 6* (Circuit topologies)	*Chapter 7* (Analog amplification)	*Chapter 8* (Differential amplifiers)
	BJT characteristics	BJT inverter and follower	BJT biasing and small signal amplifier	BJT differential amplifier
	FET characteristics	MOS inverter and follower	MOS biasing and small signal amplifier	NMOS differential amplifier
		CMOS inverter		CMOS and BiCMOS differential amplifier

SUPPLEMENTARY TEACHING AIDS

INSTRUCTORS' RESOURCE MANUAL

The book is accompanied by an *Instructors' Resource Manual*, which contains solutions to all end-of-chapter problems. In most cases, a detailed and instructive description of the problem solution, rather than just a brief answer, is provided. This feature allows the solution to be used for student handouts, if desired.

STUDENT PROBLEM SET WITH SOLUTIONS

A *Student Problem Set* is available which provides sets of additional problems with solutions. These problems are topically similar to the end-of-chapter problems from the text. The accompanying solutions walk the student through each step of the problem and provide assistance in obtaining the correct answers. The use of this material can be of valuable assistance to the instructor when teaching material from the text.

LABORATORY MANUAL TO ACCOMPANY THE TEXT

A coordinated *Laboratory Manual* containing 10 experiments has been prepared by Dr. Pao-Lo Liu of the State University of New York at Buffalo. Each experiment is coordinated with appropriate sections from the text, and is designed to heighten the student's practical understanding of various topics within the text.

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I am grateful to my editors at Prentice Hall for their efforts in bringing the book from conception to completion. Alan Apt and Sondra Chavez have demonstrated a superb knowledge and understanding of the world of college textbooks, and Bayani DeLeon deserves special recognition for shepherding the book through the critical stages of production.

Lastly, I would like to thank my family, Roxanne, Rachel, and Arielle. Without their support and understanding, the second edition could never have been written.

Mark Horenstein

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