Microelectronic Circuit Design

Richard C. Jaeger

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Preface

The overall objective of this book is to develop a comprehensive understanding of the basic techniques of modern electronic circuit design—analog and digital, discrete and integrated. Even though most readers may not ultimately be engaged in the design of integrated circuits (ICs) themselves, a thorough understanding of the internal circuit structure is prerequisite to avoiding many of the pitfalls that prevent effective and reliable application of integrated circuits.

Digital electronics has evolved into an important area of circuit design, but it is included almost as an afterthought in most introductory electronics texts. This book presents a much more balanced coverage of analog and digital circuits. I have integrated my extensive industrial background in precision analog and digital design with my many years of classroom experience. A broad spectrum of topics is included, and material can easily be selected to satisfy either a two-semester or three-quarter sequence in electronics.

OVERVIEW

The book is divided into three parts. Part I, **Solid-State Devices and Circuits,** introduces electronics and solid-state devices. Chapter 1 is an historical overview of electronics, a subject that unfortunately has been eliminated from many recent textbooks. I feel that it is important to instill in readers a perspective of just how far electronics has advanced in a relatively short period and to provide a view of the true economic impact of electronics. I also believe strongly that readers should have a basic understanding of the origin of electrons and holes in solid-state materials. Chapter 2 treats solid-state electronics thoroughly enough to provide a basic understanding of the mechanisms that control electron and hole concentrations and of how one manipulates the doping concentrations to produce a *pn* junction or bipolar transistor. Hence, the material here is more extensive than that in many current textbooks.

Chapters 3 to 5 emphasize the economically important devices: the diode, MOSFET, and BJT. In my view, moving from the diode to the MOSFET is a smoother and less confusing transition than attempting to work with the less intuitive internal behavior of the bipolar device. The MOSFET is presented with a derivation of the linear region *i-v* characteristic; although enough discussion is provided so that readers will understand the basic fundamentals of device operation, the major focus is on device behavior from the terminals. A similar approach is used to develop the transport (simplified Gummel-Poon) model for the BJT.

Part II, **Digital Circuit Design,** emphasizes digital circuits before analog circuits, to point out the relative importance of digital circuit design in modern electronics. Placement of this discussion first also helps students outside of electrical engineering, particularly computer engineering or computer science majors, who may take only the first course in a sequence of electronics courses. Also, in classroom testing, I have found that dealing with digital circuit concepts first is less confusing for students, and design can be emphasized.

The material in Part II deals primarily with the internal design of logic gates and storage elements. Chapter 6 introduces the subject of logic gates and reviews boolean algebra. Chapters 7 and 8 comprehensively discuss NMOS and CMOS logic design. Chapter 9 covers memory cells and peripheral circuits in depth. Chapter 10, Bipolar Logic Circuits, includes detailed discussion of emitter-coupled logic and transistor-transistor logic. However, the material on bipolar logic has been reduced in deference to the importance of MOS technology. In addition, little discussion is given to design at the logic block level, a topic fully covered in digital system design courses.

Parts I and II deal only with the large-signal characteristics of the transistors. This constraint lets readers become comfortable with device behavior and *i-v* characteristics before they have to grasp the concept of splitting circuits into different pieces (and possibly different topologies) to perform dc and ac small-signal analyses. (The concept of a small signal is not formally introduced until Chapter 13.)

Although the treatment of digital circuits here is more extensive than in most textbooks, Part III, **Analog Circuit Design,** represents more than 50 percent of the book. Chapter 11 begins the traditional discussion; Chapter 12 thoroughly covers the operational amplifier and its many limitations. Knowledge of this basic material can be used to realize more complex circuits; it is used in subsequent chapters with MOSFETs and BJTs.

Design concepts and device and circuit comparisons are emphasized wherever possible. Significantly stronger emphasis is given to MOS analog circuits than in many textbooks. The treatment of bipolar and FET analog circuits is merged from Chapter 14 onward, permitting continual comparison of design options and reasons for choosing one device over another in a particular circuit. The hybrid-pi model and pi-models for the BJT and FET are used throughout.

Chapters 13 to 17 discuss in depth single-stage and multistage amplifier design using transistors. Chapter 16 discusses techniques important in IC design, explores the classic 741 operational amplifier, and details A/D and D/A converters.

Chapter 18 takes the classic two-port approach in presenting feedback. However, a section that stresses the errors which can occur when the approach is incorrectly applied is also included. Feedback amplifier stability and oscillators are discussed, as is the method of determining loop gain using successive voltage and current injection.

DESIGN

Part II launches directly into the issues associated with the design of NMOS and CMOS logic gates. The effects of device and passive element tolerances are discussed throughout the book. In today's world, low-power, low-voltage design—often supplied from batteries—is playing an increasingly important role. Low-voltage design issues are discussed throughout this book, and the text includes many problems in this important area. The use of the computer, including MATLAB, spreadsheets, and standard high-level languages, to explore design options is a thread running throughout the text.

Methods for making design estimates and decisions are stressed throughout the analog sections. Expressions for amplifier behavior are simplified beyond the standard hybrid-pi model expressions whenever appropriate. For example, the expression for the voltage gain of an amplifier is simply written in most textbooks as $|A_V| = g_m R_L$, which tends to hide the power supply voltage as the fundamental design variable. Rewriting this expression in approximate form as $g_m R_L \approx 10V_{CC}$ for the BJT and $g_m R_L \approx V_{DD}$ for the FET emphasizes the dependence of amplifier design on the choice of power supply voltage and provides a simple first-order design estimate for the voltage gain of the common-emitter and common-source amplifiers. Similar results are developed for the differential- and common-mode behavior of differential amplifiers and simple operational amplifiers. These approximation techniques and methods for performance estimation are included as often as possible.

Worst-case and Monte Carlo analysis techniques are introduced in Part I. Design using standard components and tolerance assignment is discussed in examples and included in many problems, particularly in the analog portion of the book. Comparisons and design tradeoffs between the properties of BJTs and FETs are included throughout Part III.

PROBLEMS AND INSTRUCTOR SUPPORT

Specific design, computer, and SPICE problems are included at the end of each chapter and indicated by the icons , , and , respectively. The problems are keyed to the topics in the text and also graded into three levels of difficulty, with the more difficult or time-consuming problems indicated by * and **. Problem numbers in blue indicate that the answer is available in the back of the book. The accompanying *Instructor's Manual* has solutions to all the problems. In addition, copies of the original versions of all graphs and figures are available as PowerPoint files and can be retrieved from the World Wide Web.

COMPUTER USAGE AND SPICE

The computer is used as a tool throughout the book. I firmly believe that using a computer involves more than just using the SPICE circuit analysis program. In today's computing environment, it is often appropriate to use the computer to explore a complex design space rather than to try to reduce a complicated set of equations to some manageable analytic form. Examples of this process of setting up equations for iterative evaluation by computer through the use of spreadsheets, MATLAB, and/or standard high-level language programs are illustrated in many places in the book. MATLAB is also used for Nyquist and Bode plot generation and is useful for Monte Carlo analysis.

Results from SPICE simulation are included as appropriate in the book, and numerous SPICE problems appear. A PSPICE Simulation Data section is included with most chapters. These sections give the statement listings used to generate the simulation results presented in the figures in that chapter. Appendix B contains SPICE model parameters for various solid-state devices. However, I do not consider SPICE "embedded" in the text, and I omitted a detailed SPICE appendix because details of the SPICE language can be found in many supplementary textbooks.

CHAPTER SUMMARY

Part I, Solid-State Electronics and Devices. *Chapter 1* is a historical perspective of the field of electronics, beginning with vacuum tubes and advancing to very-large-scale integration (VLSI) and its impact on the global economy. The chapter also classifies electronic signals and reviews important tools from network analysis.

Chapter 2 discusses semiconductor materials, including covalent-bond and energy-band models. It also discusses intrinsic-carrier density; electron and hole populations; *n*- and *p*-type material; impurity doping; and mobility, resistivity, and carrier transport by both drift and diffusion.

Chapter 3 introduces the structure and *i-v* characteristics of solid-state diodes and discusses Schottky diodes, variable-capacitance diodes, photodiodes, solar cells, and LEDs. The concept of modeling and the use of different levels of modeling to achieve various approximations to reality are covered, and the concepts of bias, operating point, and the load line are all introduced. Iterative mathematical solutions are used to find the operating point, including spreadsheets and MATLAB. Diode applications include rectifiers, clipping and clamping circuits, and dc-to-dc converters. The dynamic switching characteristics of diodes are also presented.

Chapter 4 presents MOS and junction field-effect transistors (JFETs), starting with a qualitative description of the MOS capacitor. I believe that the concept of a voltage-controlled resistor is easier to grasp than the more complex operation of the BJT. Models are developed for the FET *i-v* characteristics, and a complete discussion of the regions of operation of the device is presented. Body effect is actively covered, as are biasing, load-line analysis, and several applications of FETs.

Chapter 5 covers the bipolar junction transistor (BJT) and presents an heuristic development of the transport (simplified Gummel-Poon) model of the BJT based on superposition. The various regions of operations are discussed in detail. Common-emitter and common-base current gains are defined, and base transit-time, diffusion capacitance, and cutoff frequency are all discussed.

Part II, Digital Circuit Design. *Chapter 6* is a compact introduction to digital electronics. Terminology discussed includes V_{OH}, V_{OL}, V_{IH}, V_{IL}, noise margin, rise and fall time, propagation delay, fan out, fan in, and power-delay product. A short review of boolean algebra is followed by a discussion of simple diode AND and OR gates. This brief chapter has been designed to stand alone, so it can be easily followed by either the discussion of MOS logic design in Chapters 7 and 8 or by the bipolar logic material in Chapter 10.

Chapter 7 follows the historical evolution of MOS logic gates, focusing on the design of NMOS saturated-load, linear-load, and depletion-mode-load circuit families. The impact of body effect on MOS logic circuit design is discussed in detail. The concept of reference inverter scaling is used to effect the design of other inverters, NAND gates, NOR gates, and complex logic functions throughout Chapters 7 and 8. Capacitance in MOS circuits is discussed, and analyses of the propagation delay and power-delay product of NMOS logic are presented.

CMOS is today's most important VLSI technology, and *Chapter 8* is an in-depth look at the design of CMOS logic gates, including inverters, NAND gates, NOR gates, and complex logic gates. In this case, the designs are based on the simple scaling of the delay of a reference inverter. Noise margin and latchup are discussed, and the power-delay products of various MOS logic families are compared.

Chapter 9 ventures into the design of memory and more advanced logic circuits, including the six-, three-, and one-transistor memory cells. Basic sense-amplifier circuits are introduced, as are the peripheral address and decoding circuits needed in memory designs. Cascade buffer design, dynamic logic circuits, ROMs, and PLAs are several of the advanced techniques covered.

Chapter 10 discusses modern bipolar logic circuits, including emitter-coupled logic (ECL) and transistor-transistor logic (TTL). The use of the differential pair as a current switch and the large-signal properties of the emitter follower are introduced. Operation of the BJT as a saturated switch is also covered, followed by discussion of low voltage and standard TTL.

Part III, Analog Circuit Design. *Chapter 11* provides a brief introduction to analog electronics. The concepts of voltage gain, current gain, and power gain are developed. Much care has been taken throughout the book to ensure consistency in the use of the notation that defines these quantities as well as in the use of dc, ac, and total signal notation. Two-port theory and Bode plots are reviewed, and amplifiers are classified by frequency response. MATLAB is introduced as a tool for producing Bode plots.

Chapter 12 is a comprehensive introduction to the design of circuits involving operational amplifiers. Classic ideal op-amp circuits are presented, and then the effects of using real amplifiers in single-stage and multistage designs are discussed in detail. Design, including the effects of device and component tolerances, is explored, and tolerance assignment is discussed and included in an array of problems. Design of the frequency response of op-amp circuits is also explored, and macromodeling of operational amplifiers is included. The chapter ends with a discussion of continuous-time filters and switched-capacitor circuits.

Chapter 13 starts with the general discussion of linear amplification using the BJT and FET as C-E and C-S amplifiers. Biasing for linear operation and the concepts of small-signal modeling are introduced, and small-signal models of the diode, BJT, and FET are all developed. The limits for small-signal operations are carefully defined. Appropriate points for signal injections and extraction are identified, and the use of coupling and bypass capacitors and inductors to separate the ac and dc designs is explored. The important 10 to 20 V_{CC} and 1 to 2 V_{DD} design estimates for the voltage gain of amplifiers are introduced, and the role of transistor amplification factor in bounding circuit performance is covered.

Chapter 14 begins with an in-depth comparison of the characteristics of single-transistor amplifiers, including small-signal amplitude limitations. Amplifiers are classified as inverting amplifiers (C-E, C-S), non-inverting amplifiers (C-B, C-G), and followers (C-C, C-D). The treatment of MOS and bipolar devices is merged from Chapter 14 on, and design tradeoffs between the use of BJTs and FETs in amplifier circuits is an important thread woven throughout Part III.

Chapter 15 explores the design of multistage amplifiers, including ac- and dc-coupled circuits. An evolutionary approach to multistage op-amp design is used. MOS and bipolar differential amplifiers are first introduced. Subsequent addition of a second gain stage and then an output stage convert the differential amplifiers into simple op amps. Class-A, -B, and -AB operations are defined. Electronic current sources are designed and used for biasing basic operational amplifiers. Darlington, cascode, and cascade C-E circuits are presented. Discussions of important FET-BJT design tradeoffs are included wherever appropriate.

Chapter 16 focuses on techniques of particular importance in integrated circuit design. A variety of current mirror circuits are introduced and applied in bias circuits and as active loads in operational amplifiers. Numerous circuits and analog design techniques are explored through the detailed analysis of the classic 741 operational amplifier. A detailed discussion of the characteristics and circuit implementations of D/A and A/D converters completes this chapter.

Chapter 17 presents the frequency response of analog circuits. The behavior of each of the three categories of single-stage amplifiers (C-E/C-S, C-B/C-G, and C-C/C-D) is discussed in detail, and BJT behavior is contrasted with that of the FET. The frequency response of the transistor is discussed, and high-frequency, small-signal models are developed for both the BJT and FET. The short-circuit and open-circuit time-constant techniques are used to obtain estimates of the lower- and upper-cutoff frequencies of complex multistage amplifiers. Miller multiplication, cascode amplifier frequency response, and tuned amplifiers are all covered. Basic single-pole op-amp compensation is discussed, and the unity-gain-bandwidth product is related to amplifier slew rate.

Chapter 18 discusses feedback amplifier design, using the classic two-port approach to account for the loading of the amplifier and feedback network on each other. Loop-gain calculations are also discussed, including a unique section on the use of the successive voltage and current injection technique for determining loop gain. This method does not require that the feedback loop be broken and is a useful technique in the laboratory and for SPICE simulation of high-gain feedback amplifiers. Another unique section discusses errors that must be avoided when applying the two-port analysis methods to the shunt-series and series-series feedback topologies.

Stability is covered as well, and Nyquist diagrams and Bode plots (with MATLAB) are used to explore the phase and gain margin of amplifiers. Relationships between the Nyquist and Bode techniques are explicitly discussed. The Barkhausen criteria for oscillation are introduced, and oscillator circuits, including *RC*, *LC*, and crystal implementations, are presented. The discussion of amplitude stabilization in oscillators includes techniques for calculating the amplitude of the oscillation.

The five *appendixes* introduce integrated circuit fabrication (Appendix A), summarize the device models and sample SPICE parameters (Appendix B), present tables of standard component values (Appendix C), show data sheets for representative solid-state devices and operational amplifiers (Appendix D), and lists fundamental material constants (Appendix E).

CHAPTER FLEXIBILITY

The chapters are designed to be used in various sequences, and as noted earlier, there is more than enough material for a two-semester or three-quarter sequence in electronics. One can obviously proceed directly through the book. Alternatively, Chapter 5, on BJTs, can be used immediately after Chapter 3, on diodes (that is, a 1-2-3-5-4 chapter sequence). Presently, the order actually used at Auburn University is 1-2-3-4-6-7-8-9-5-10 and 11 to 18.

The chapters were also written so Part II can be skipped and Part III can be used directly after completion of the coverage of solid-state devices in Part I. If so desired, many quantitative details in Chapter 2 can be skipped.

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Auburn University, 1997

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