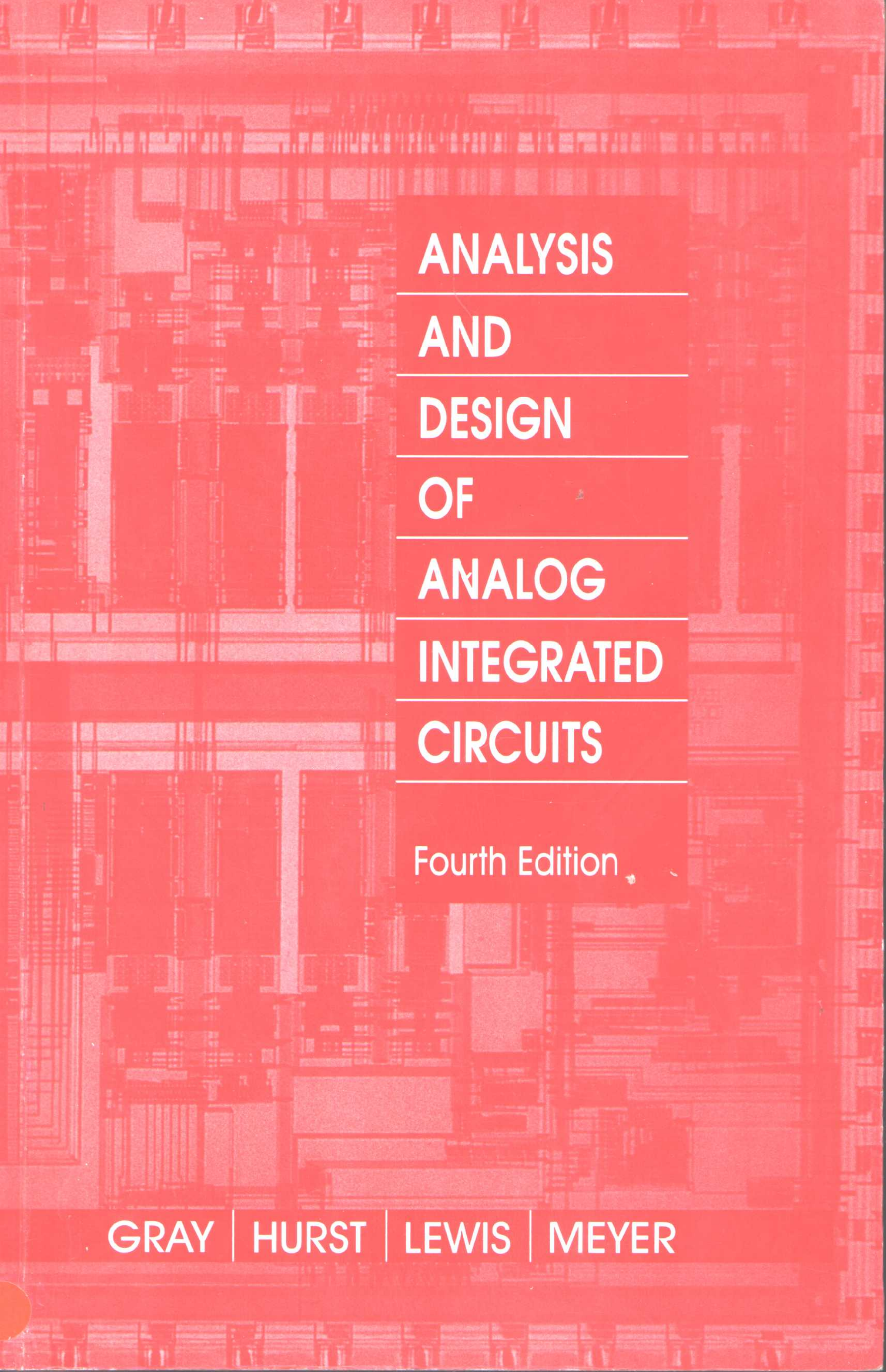

ANALYSIS AND DESIGN OF ANALOG INTEGRATED CIRCUITS

Fourth Edition

GRAY | HURST | LEWIS | MEYER

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Preface

In the 23 years since the publication of the first edition of this book, the field of analog integrated circuits has developed and matured. The initial groundwork was laid in bipolar technology, followed by a rapid evolution of MOS analog integrated circuits. Furthermore, BiCMOS technology (incorporating both bipolar and CMOS devices on one chip) has emerged as a serious contender to the original technologies. A key issue is that CMOS technologies have become dominant in building digital circuits because CMOS digital circuits are smaller and dissipate less power than their bipolar counterparts. To reduce system cost and power dissipation, analog and digital circuits are now often integrated together, providing a strong economic incentive to use CMOS-compatible analog circuits. As a result, an important question in many applications is whether to use pure CMOS or a BiCMOS technology. Although somewhat more expensive to fabricate, BiCMOS allows the designer to use both bipolar and MOS devices to their best advantage, and also allows innovative combinations of the characteristics of both devices. In addition, BiCMOS can reduce the design time by allowing direct use of many existing cells in realizing a given analog circuit function. On the other hand, the main advantage of pure CMOS is that it offers the lowest overall cost. Twenty years ago, CMOS technologies were only fast enough to support applications at audio frequencies. However, the continuing reduction of the minimum feature size in integrated-circuit (IC) technologies has greatly increased the maximum operating frequencies, and CMOS technologies have become fast enough for many new applications as a result. For example, the required bandwidth in video applications is about 4 MHz, requiring bipolar technologies as recently as 15 years ago. Now, however, CMOS can easily accommodate the required bandwidth for video and is even being used for radio-frequency applications.

In this fourth edition, we have combined the consideration of MOS and bipolar circuits into a unified treatment that also includes MOS-bipolar connections made possible by BiCMOS technology. We have written this edition so that instructors can easily select topics related to only CMOS circuits, only bipolar circuits, or a combination of both. We believe that it has become increasingly important for the analog circuit designer to have a thorough appreciation of the similarities and differences between MOS and bipolar devices, and to be able to design with either one where this is appropriate.

Since the SPICE computer analysis program is now readily available to virtually all electrical engineering students and professionals, we have included extensive use of SPICE in this edition, particularly as an integral part of many problems. We have used computer analysis as it is most commonly employed in the engineering design process–both as a more accurate check on hand calculations, and also as a tool to examine complex circuit behavior beyond the scope of hand analysis. In the problem sets, we have also included a number of open-ended design problems to expose the reader to real-world situations where a whole range of circuit solutions may be found to satisfy a given performance specification.

This book is intended to be useful both as a text for students and as a reference book for practicing engineers. For class use, each chapter includes many worked problems; the problem sets at the end of each chapter illustrate the practical applications of the material in the text. All the authors have had extensive industrial experience in IC design as well as in the teaching of courses on this subject, and this experience is reflected in the choice of text material and in the problem sets.

Although this book is concerned largely with the analysis and design of ICs, a considerable amount of material is also included on applications. In practice, these two subjects are closely linked, and a knowledge of both is essential for designers and users of ICs. The latter compose the larger group by far, and we believe that a working knowledge of IC design is a great advantage to an IC user. This is particularly apparent when the user must choose from among a number of competing designs to satisfy a particular need. An understanding of the IC structure is then useful in evaluating the relative desirability of the different designs under extremes of environment or in the presence of variations in supply voltage. In addition, the IC user is in a much better position to interpret a manufacturer's data if he or she has a working knowledge of the internal operation of the integrated circuit.

The contents of this book stem largely from courses on analog integrated circuits given at the University of California at the Berkeley and Davis campuses. The courses are undergraduate electives and first-year graduate courses. The book is structured so that it can be used as the basic text for a sequence of such courses. The more advanced material is found at the end of each chapter or in an appendix so that a first course in analog integrated circuits can omit this material without loss of continuity. An outline of each chapter is given below together with suggestions for material to be covered in such a first course. It is assumed that the course consists of three hours of lecture per week over a 15-week semester and that the students have a working knowledge of Laplace transforms and frequency-domain circuit analysis. It is also assumed that the students have had an introductory course in electronics so that they are familiar with the principles of transistor operation and with the functioning of simple analog circuits. Unless otherwise stated, each chapter requires three to four lecture hours to cover.

Chapter 1 contains a summary of bipolar transistor and MOS transistor device physics. We suggest spending one week on selected topics from this chapter, the choice of topics depending on the background of the students. The material of Chapters 1 and 2 is quite important in IC design because there is significant interaction between circuit and device design, as will be seen in later chapters. A thorough understanding of the influence of device fabrication on device characteristics is essential.

Chapter 2 is concerned with the technology of IC fabrication and is largely descriptive. One lecture on this material should suffice if the students are assigned to read the chapter.

Chapter 3 deals with the characteristics of elementary transistor connections. The material on one-transistor amplifiers should be a review for students at the senior and graduate levels and can be assigned as reading. The section on two-transistor amplifiers can be covered in about three hours, with greatest emphasis on differential pairs. The material on device mismatch effects in differential amplifiers can be covered to the extent that time allows.

In Chapter 4, the important topics of current mirrors and active loads are considered. These configurations are basic building blocks in modern analog IC design, and this material should be covered in full, with the exception of the material on band-gap references and the material in the appendices.

Chapter 5 is concerned with output stages and methods of delivering output power to a load. Integrated-circuit realizations of Class A, Class B, and Class AB output stages are described, as well as methods of output-stage protection. A selection of topics from this chapter should be covered.

Chapter 6 deals with the design of operational amplifiers (op amps). Illustrative examples of dc and ac analysis in both MOS and bipolar op amps are performed in detail, and the limitations of the basic op amps are described. The design of op amps with improved characteristics in both MOS and bipolar technologies is considered. This key chapter on amplifier design requires at least six hours.

In Chapter 7, the frequency response of amplifiers is considered. The zero-value time-constant technique is introduced for the calculations of the −3-dB frequency of complex circuits. The material of this chapter should be considered in full.

Chapter 8 describes the analysis of feedback circuits. Two different types of analysis are presented: two-port and return-ratio analyses. Either approach should be covered in full with the section on voltage regulators assigned as reading.

Chapter 9 deals with the frequency response and stability of feedback circuits and should be covered up to the section on root locus. Time may not permit a detailed discussion of root locus, but some introduction to this topic can be given.

In a 15-week semester, coverage of the above material leaves about two weeks for Chapters 10, 11, and 12. A selection of topics from these chapters can be chosen as follows. Chapter 10 deals with nonlinear analog circuits, and portions of this chapter up to Section 10.3 could be covered in a first course. Chapter 11 is a comprehensive treatment of noise in integrated circuits, and material up to and including Section 11.4 is suitable. Chapter 12 describes fully differential operational amplifiers and common-mode feedback and may be best suited for a second course.

We are grateful to the following colleagues for their suggestions for and/or evaluation of this edition: R. Jacob Baker, Bernhard E. Boser, A. Paul Brokaw, John N. Churchill, David W. Cline, Ozan E. Erdoğan, John W. Fattaruso, Weinan Gao, Edwin W. Greeneich, Alex Gros-Balthazard, Tünde Gyurics, Ward J. Helms, Timothy H. Hu, Shafiq M. Jamal, John P. Keane, Haideh Khorramabadi, Pak-Kim Lau, Thomas W. Matthews, Krishnaswamy Nagaraj, Khalil Najafi, Borivoje Nikolić, Robert A. Pease, Lawrence T. Pileggi, Edgar Sánchez-Sinencio, Bang-Sup Song, Richard R. Spencer, Eric J. Swanson, Andrew Y. J. Szeto, Yannis P. Tsividis, Srikanth Vaidianathan, T. R. Viswanathan, Chorng-Kuang Wang, and Dong Wang. We are also grateful to Kenneth C. Dyer for allowing us to use on the cover of this book a die photograph of an integrated circuit he designed and to Zoe Marlowe for her assistance with word processing. Finally, we would like to thank the people at Wiley and Publication Services for their efforts in producing this fourth edition.

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Berkeley and Davis, CA, 2001

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Contents

CHAPTER 2

Bipolar, MOS, and BiCMOS Integrated-Circuit Technology 78

CHAPTER 3

Single-Transistor and Multiple-Transistor Amplifiers 170

CHAPTER 5
Output Stages 344

CHAPTER 6
Operational Amplifiers with Single-Ended Outputs 404

CHAPTER 10

Nonlinear Analog Circuits 702

CHAPTER 11

Noise in Integrated Circuits 748

CHAPTER 12

Fully Differential Operational Amplifiers

CHAPTER 1

Models for Integrated-Circuit Active Devices

1.1 Introduction

The analysis and design of integrated circuits depend heavily on the utilization of suitable models for integrated-circuit components. This is true in hand analysis, where fairly simple models are generally used, and in computer analysis, where more complex models are encountered. Since any analysis is only as accurate as the model used, it is essential that the circuit designer have a thorough understanding of the origin of the models commonly utilized and the degree of approximation involved in each.

This chapter deals with the derivation of large-signal and small-signal models for integrated-circuit devices. The treatment begins with a consideration of the properties of *pn* junctions, which are basic parts of most integrated-circuit elements. Since this book is primarily concerned with circuit analysis and design, no attempt has been made to produce a comprehensive treatment of semiconductor physics. The emphasis is on summarizing the basic aspects of semiconductor-device behavior and indicating how these can be modeled by equivalent circuits.

1.2 Depletion Region of a *pn* Junction

The properties of reverse-biased *pn* junctions have an important influence on the characteristics of many integrated-circuit components. For example, reverse-biased *pn* junctions exist between many integrated-circuit elements and the underlying substrate, and these junctions all contribute voltage-dependent parasitic capacitances. In addition, a number of important characteristics of active devices, such as breakdown voltage and output resistance, depend directly on the properties of the depletion region of a reverse-biased *pn* junction. Finally, the basic operation of the junction field-effect transistor is controlled by the width of the depletion region of a *pn* junction. Because of its importance and application to many different problems, an analysis of the depletion region of a reverse-biased *pn* junction is considered below. The properties of forward-biased *pn* junctions are treated in Section 1.3 when bipolar-transistor operation is described.

Consider a *pn* junction under reverse bias as shown in Fig. 1.1. Assume *constant doping densities* of N_D atoms/cm^3 in the *n*-type material and N_A atoms/cm^3 in the *p*-type material. (The characteristics of junctions with nonconstant doping densities will be described later.) Due to the difference in carrier concentrations in the *p*-type and *n*-type regions, there exists a region at the junction where the mobile holes and electrons have been removed, leaving the fixed acceptor and donor ions. Each acceptor atom carries a negative charge and each donor atom carries a positive charge, so that the region near the junction is one of significant space charge and resulting high electric field. This is called

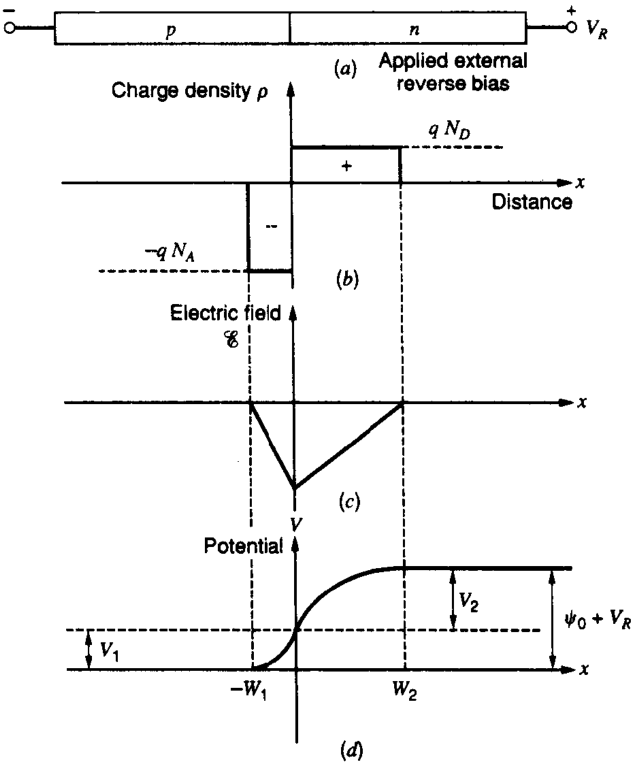

Figure 1.1 The abrupt junction under reverse bias V_R. (*a*) Schematic. (*b*) Charge density. (*c*) Electric field. (*d*) Electrostatic potential.

the *depletion* region or *space-charge* region. It is assumed that the edges of the depletion region are sharply defined as shown in Fig. 1.1, and this is a good approximation in most cases.

For zero applied bias, there exists a voltage ψ_0 across the junction called the ***built-in potential***. This potential opposes the diffusion of mobile holes and electrons across the junction in equilibrium and has a value[1]

$$\psi_0 = V_T \ln \frac{N_A N_D}{n_i^2} \tag{1.1}$$

where

$$V_T = \frac{kT}{q} \simeq 26\,\text{mV} \quad \text{at} \quad 300°\text{K}$$

the quantity n_i is the intrinsic carrier concentration in a pure sample of the semiconductor and $n_i \simeq 1.5 \times 10^{10}\text{cm}^{-3}$ at 300°K for silicon.

In Fig. 1.1 the built-in potential is augmented by the applied reverse bias, V_R, and the total voltage across the junction is $(\psi_0 + V_R)$. If the depletion region penetrates a distance W_1 into the p-type region and W_2 into the n-type region, then we require

$$W_1 N_A = W_2 N_D \tag{1.2}$$

because the total charge per unit area on either side of the junction must be equal in magnitude but opposite in sign.

Poisson's equation in one dimension requires that

$$\frac{d^2V}{dx^2} = -\frac{\rho}{\epsilon} = \frac{qN_A}{\epsilon} \quad \text{for} \quad -W_1 < x < 0 \tag{1.3}$$

where ρ is the charge density, q is the electron charge (1.6×10^{-19} coulomb), and ϵ is the permittivity of the silicon (1.04×10^{-12} farad/cm). The permittivity is often expressed as

$$\epsilon = K_S \epsilon_0 \tag{1.4}$$

where K_S is the dielectric constant of silicon and ϵ_0 is the permittivity of free space (8.86×10^{-14} F/cm). Integration of (1.3) gives

$$\frac{dV}{dx} = \frac{qN_A}{\epsilon}x + C_1 \tag{1.5}$$

where C_1 is a constant. However, the electric field $\mathscr{E}$ is given by

$$\mathscr{E} = -\frac{dV}{dx} = -\left(\frac{qN_A}{\epsilon}x + C_1\right) \tag{1.6}$$

Since there is zero electric field outside the depletion region, a boundary condition is

$$\mathscr{E} = 0 \quad \text{for} \quad x = -W_1$$

and use of this condition in (1.6) gives

$$\mathscr{E} = -\frac{qN_A}{\epsilon}(x + W_1) = -\frac{dV}{dx} \quad \text{for} \quad -W_1 < x < 0 \tag{1.7}$$

Thus the dipole of charge existing at the junction gives rise to an electric field that varies linearly with distance.

Integration of (1.7) gives

$$V = \frac{qN_A}{\epsilon}\left(\frac{x^2}{2} + W_1 x\right) + C_2 \tag{1.8}$$

If the zero for potential is arbitrarily taken to be the potential of the neutral p-type region, then a second boundary condition is

$$V = 0 \quad \text{for} \quad x = -W_1$$

and use of this in (1.8) gives

$$V = \frac{qN_A}{\epsilon}\left(\frac{x^2}{2} + W_1 x + \frac{W_1^2}{2}\right) \quad \text{for} \quad -W_1 < x < 0 \tag{1.9}$$

At $x = 0$, we define $V = V_1$, and then (1.9) gives

$$V_1 = \frac{qN_A}{\epsilon}\frac{W_1^2}{2} \tag{1.10}$$

If the potential difference from $x = 0$ to $x = W_2$ is V_2, then it follows that

$$V_2 = \frac{qN_D}{\epsilon}\frac{W_2^2}{2} \tag{1.11}$$

and thus the total voltage across the junction is

$$\psi_0 + V_R = V_1 + V_2 = \frac{q}{2\epsilon}(N_A W_1^2 + N_D W_2^2) \tag{1.12}$$