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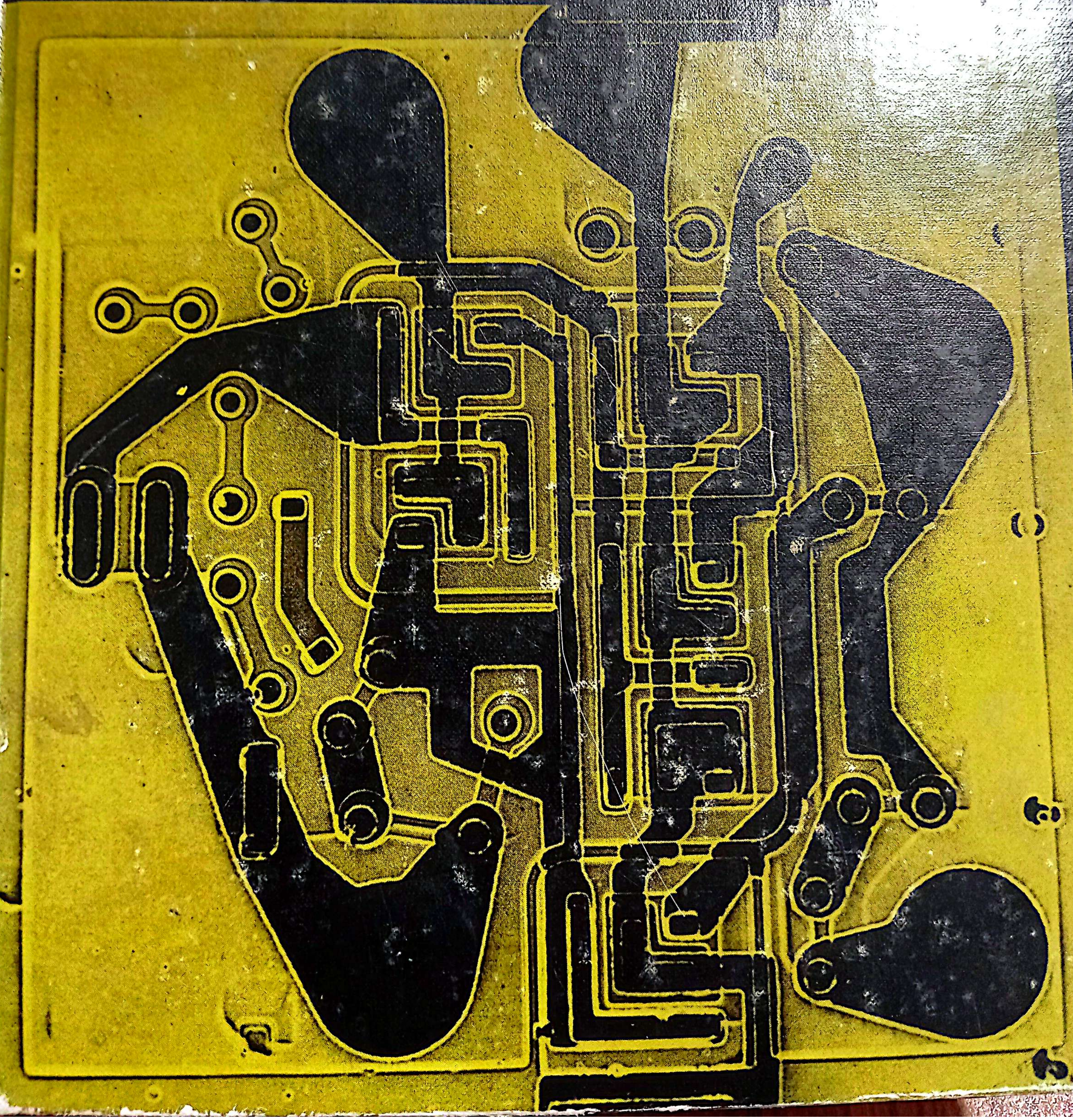
ELECTRONIC PRINCIPLES

Physics, Models, and Ci



PREFACE

The trend toward the use of integrated circuits in electronic systems, which started in the early 1960's, is now firmly established. This revolutionary change in the conceptualization and fabrication of electronic systems has almost obliterated the traditional boundaries between the three disciplines of device or component design, circuit design, and system design. Instead, two broadly defined disciplines are emerging from the areas of activity that encompass electronics from devices through systems. The first of these disciplines is concerned with the general area of devices and circuits; the second is concerned with circuits and systems.

The devices-and-circuits area is primarily the province of those who design and manufacture integrated circuits, discrete semiconductor devices, and other "components" of modern electronics. Engineers who work in this area of activity must be knowledgeable in semiconductor fabrication technology, in the physical electronics and circuit modeling of semiconductor components, and in the methods and techniques of circuit analysis and design; their activity is subject to the constraints and opportunities of both device technology and circuit theory. In addition, the device-and-circuits engineer must have a sufficient knowledge of systems engineering to enable him to communicate with the users of his products who work at the systems design level.

The engineers who design electronic systems must be competent in a broad area that includes circuits as well as systems, because this task involves both the exploitation of integrated-circuit functional blocks, such as operational amplifiers, logic gates, and memory elements, and the use of passive components and discrete transistors in "interfaces" between integrated assemblies. In addition to being thoroughly familiar with both circuit theory and system theory, these engineers should have some knowledge of device structure and behavior to facilitate communication with those who work in the devices-and-circuits area and to facilitate the intelligent design of circuits that make use of semiconductor components.

During the same time that semiconductor integrated circuits have come to the fore in electronics, there has occurred an explosive growth both in the use of high-speed computational methods in engineering design and in the availability of computational facilities on university campuses and at industrial laboratories. As a result, it is now commonplace to undertake the analysis of circuits and systems that are orders of magnitude more complex than those that could be studied only a few years ago.

This book has been shaped to meet the educational needs implied by the dominance of integrated circuits in electronic technology and by the use of digital computers in engineering design. Thus the book begins with the physical principles that are involved in the operation of semiconductor components, proceeds through the physical electronics, modeling, and circuit characteristics of these components, and engages the questions and problems that arise in the computer-aided design of complex multistage amplifiers and functional assemblies of the type found in modern integrated-circuit packages.

The book covers five principal areas:

An introduction to electronics
Semiconductor physics
Device physical electronics, models, and properties
Multistage circuits in which transistors are used as linear amplifiers
Multistage circuits in which transistors are used as switches

Chapter 1 serves as an introduction by illustrating the nature and use of an electronic control valve. Many of the device and circuit issues that are studied in detail later are introduced in this chapter. The semiconductor active device that is used as a vehicle in this introductory motivational development is the metal-oxide-semiconductor-field-effect transistor—the MOSFET. It was chosen because its physical operation is, at the qualitative level, relatively transparent. For those users of this book who prefer to employ vacuum tubes as the vehicle, Appendix A provides a parallel development of the introductory material in which the vacuum triode is used as a representative control valve. Those who wish to develop the physical electronics of vacuum tubes beyond the qualitative level will find the material in Appendix B appropriate for that purpose.

Chapters 2 through 5 provide a self-contained treatment of those aspects of the electrical properties of semiconductors, the physical electronics of *pn* junctions, and semiconductor-device-fabrication technology that are essential to an understanding, at the quantitative level, of the behavior of semiconductor active devices and integrated circuits. Although familiarity with elementary electrostatics and with the general concepts of the structure of atoms and of solids is assumed, no quantitative background in modern physics or in quantum theory is assumed or expected.

The fundamental features of electrical conduction in semiconductors, which involves the flow of two independent, oppositely charged carriers—holes and conduction electrons—are made plausible by use of the qualitative valence-bond model of a semiconductor. The dynamical features of charge carriers—drift, diffusion, and recombination—are introduced as postulates amply supported by direct experimental evidence. Following this development of the pertinent features of semiconductor behavior, the internal physical behavior of *pn* junction structures is developed in quantitative terms.

We have chosen to introduce the electrical behavior of semiconductors in this way rather than in terms of elementary wave mechanics, quantization in the hydrogen atom, and the energy-band model of a semiconductor, for two reasons. First, there is generally not enough time available in a first course in electronics to do justice, in quantitative terms, to the energy-band model of a semiconductor. Consequently, most efforts to introduce these concepts at this level in the undergraduate curriculum amount only to the establishment of a vocabulary; they develop very little real understanding or facility with the quantitative capabilities of the model. Second, it has been our experience that the level of development of the electrical aspects of semiconductor physics presented in this book is entirely adequate as a basis for the detailed quantitative development of the physical electronics of semiconductor active devices.

Chapters 6 through 14 deal with the physical electronics, circuit modeling, and circuit properties of the most important semiconductor components, including junction diodes, bipolar junction transistors, unipolar (field-effect) junction transistors, and metal-oxide-semiconductor unipolar or field-effect transistors. Throughout this development the emphasis is on the establishment of a framework of internal physical behavior, a framework that supports and relates a hierarchy of circuit models. For example, the picture of the distribution and flow of excess carriers in the base region of the bipolar transistor provides a basis for the Ebers-Moll total-variable static model, the charge-control total-variable dynamic model, and the hybrid-pi linear incremental model. In exploring the elementary circuit properties of transistors we have emphasized the importance of choosing a circuit model that is appropriate to the circuit issues of concern.

Chapters 15 through 20 are concerned with multistage applications of transistors, in which the active devices are used as linear control valves. The important topic of feedback in linear amplifier is considered in detail. Throughout this portion of the text, extensive use is made of automatic-computational methods for the analysis of complex circuits. However, such computations rarely provide the insight required for good circuit design; hence simple approximate design methods are also developed, and their limitations and ranges of validity are explored.

Chapters 21 through 24 deal with application of the transistor as a switch. The emphasis is on multiple-component circuits that are used for the processing of information in digital form. Once again, automatic-computational methods are used extensively in circuit analysis to indicate the nature and limitations of approximate methods of analysis.

The material in this book can be covered in two or three semesters, depending on the amount of classroom time devoted to the many worked-out examples that are included in the text. More of such examples have been included than would normally be used in one particular year, to provide the instructor with more flexibility in his teaching. We have taught essentially all of this material to undergraduates in the Department of Electrical Engineering at M.I.T. at least twice, in the following sequence:

Second term, sophomore year (the first course in electronics): Chapters 1 through 7, selected topics from Chapters 8 through 11.

First and second terms, junior year (an elective in semiconductor electronics): Chapters 12 through 22, Chapter 24, selected topics from Chapter 23.

Obviously we have arranged the twenty-four chapters in the order in which we believe they are best taught. Nevertheless, in an effort to meet the diverse needs of other users we have organized the book in a flexible format, and other orderings of the chapters are possible. For example, Chapter 8, on the active-region charge-control model can be delayed until after Chapter 20 without loss of continuity. Alternatively, the four chapters on digital circuits, Chapters 21 through 24, can be moved to a much earlier point, for example, ahead of the multistage linear amplifier discussion starting with Chapter 15. On a smaller scale, many sections (marked with an asterisk) throughout the book can be delayed or omitted entirely without loss of continuity.

We have, in teaching this material over a period of many years, made intensive use of lecture demonstrations to reinforce concepts presented in the classroom. Such demonstrations allow the students to see, in graphic sequential terms, the consequences of the variation of a particular parameter. Also, demonstrations provide a forceful tie to the "real world," a tie that is of great value to both student and teacher: on more than one occasion a discussion or a lecture has been revised to conform more closely to the final arbiter—the reality of an experiment. Whatever the reason, there is no denying that lecture demonstrations are a profoundly effective teaching tool. We have, therefore, included suggested demonstrations at the end of many chapters. These should not be allowed to limit the individual instructor; rather, they should serve as a point of departure for the imagination and interests of the teacher and student. The only nonstandard equipment required is a television camera ($300 to $400), with an $f/1.6$ close-up lens ($165) and one or two 23-inch television monitors.

In teaching this material we have found it possible to make effective use of open-ended design problems, problems that emphasize the interdependent roles of experience, intuition, and analysis in the development of new solutions to real problems. For example, the presentation of the instructional sequence on multistage amplifiers culminates in a two-week take-home quiz that requires the students to design a video amplifier with a voltage gain magnitude of 3000 and a bandwidth of 10 MHz. Computer verification of the design has been required, and in many cases students also checked their amplifiers experimentally in the laboratory. Students have been uniformly enthusiastic about such design problems. They find it exciting and challenging to work on their own designs, rather than regurgitating some material already predigested by the instructor. In 65 solutions received during one recent semester, there were 14 topologically different designs, and of course no two of the 65 solutions were completely alike. The designs submitted ranged all the way from a three-stage common-emitter cascade to a six-transistor amplifier made up of a cascade of three cascode (common-emitter, common-base) circuits. Such a level of sophistication is well beyond what had been taught in class in previous years, let alone generated by students.

During the past eight years about 1200 M.I.T. undergraduate students have studied from portions of the material presented here. They have thus left their marks on this book, through their critical questions, their constructive criticism, and their insistent pressure for understanding in depth.

A few of our students have devoted substantial time to this effort outside the classroom: L. W. Banks, S. G. Finn, M. E. Jernigan, G. K. Montress, W. H. Ryder, R. K. Stockwell, and R. C. Walleigh. We gratefully acknowledge their efforts in proofreading manuscript and preparing computer solutions. The computer programs listed in the appendices were written by Robert Voit and William Ohm. Most of the lecture demonstrations were prepared by Michael Monet.

It will be clear to any reader who is familiar with the Semiconductor Electronics Education Committee texts that we have drawn heavily on our experience on that Committee in writing this text. We wish to acknowledge the indirect help of the members of that Committee. In addition, we wish to acknowledge the contributions made to this book by Professors R. B. Adler, R. D. Thornton, and B. D. Wedlock through many discussions in the course of teaching this material at M.I.T.

Most of the manuscript typing was done by Mrs. Donna T. Spencer and Miss Jean Gorrasi: their help and good humor in the face of impossible time schedules is gratefully acknowledged.

During both the initial and the final stages of preparation, the manuscript was reviewed in detail by professors from ten universities representing a broad spectrum of approaches to the teaching of semiconductor electronics. We wish to acknowledge the valuable advice provided by these reviewers, and hope that we have been responsive to their suggestions.

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