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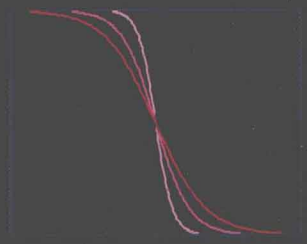
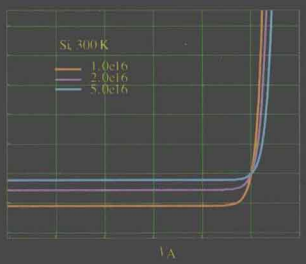
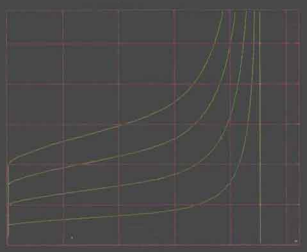
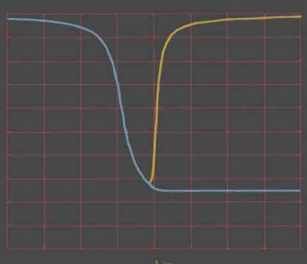




Semiconductor Device Fundamentals





with Computer-Based Exercises and Homework Problems

SEMICONDUCTOR DEVICE FUNDAMENTALS

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"The little voice inside never grows any older."

Frank Pierret (1906–1994)

PREFACE

Why another text on solid state devices? The author is aware of at least 14 undergraduate texts published on the subject during the past decade. Although several motivating factors could be cited, a very significant factor was the desire to write a book for the next millennium (a Book 2000 so to speak) that successfully incorporates computer-assisted learning. In a recent survey, members of the Undergraduate Curriculum Committee in the School of Electrical and Computer Engineering at Purdue University listed integration of the computer into the learning process as the number one priority. Nationally, university consortiums have been formed which emphasize computer-assisted learning. In January 1992, distribution began of the *Student Edition of* MATLAB, essentially a copy of the original MATLAB manual bundled with a low-cost version of the math-tools software. Over 37,000 copies of the book/software were sold in the first year! Texts and books on a variety of topics from several publishers are now available that make specific use of the MATLAB software. The direction is clear as we proceed into the second millennium: Computer-assisted learning will become more and more prevalent. In dealing with solid state devices, the computer allows one to address more realistic problems, to more readily experiment with "what-if" scenarios, and to conveniently obtain a graphical output. An entire device characteristic can often be computer generated with less time and effort than a small set of manually calculated single-point values.

It should be clarified that the present text is not a totally new entry in the field, but is derived in part from Volumes I–IV of the Addison-Wesley Modular Series on Solid State Devices. Lest there be a misunderstanding, the latest versions of the volumes in the Modular Series were not simply glued together. To the contrary, more than half of the material coverage in the four volumes was completely rewritten. Moreover, several supplemental sections and two additional chapters were added to the Volumes I–IV outline. The new text also contains computer-based text exercises and end-of-chapter problems, plus a number of other special features that are fully described in the General Introduction.

In just about any engineering endeavor there are tradeoffs. Device design is replete with tradeoffs. Tradeoffs also enter into the design of a book. For example, a few topics can be covered in detail (depth) or lesser coverage can be given to several topics (breadth). Similarly one can emphasize the understanding of concepts or optimize the transmission of factual information. Volumes I–IV in the Modular Series are known for their pedantic depth of coverage emphasizing concepts. While retaining the same basic depth of coverage, four "read-only" chapters have been specifically added herein to broaden the coverage and enhance the transmission of factual information. In the read-only chapters the emphasis is more on describing the exciting world of modern-day devices. Compound semiconductor devices likewise receive increased coverage throughout the text. There is also a natural

tradeoff between the effort devoted to developing qualitative insight and the implementation of a quantitative analysis. Careful attention has been given to avoid slighting the development of "intuition" in light of the greatly enhanced quantitative capabilities arising from the integrated use of the computer. Lastly, we have not attempted to be all-inclusive in the depth and breadth of coverage—many things are left for later (another course, other books). Hopefully, the proper tradeoffs have been achieved whereby the reader is reasonably knowledgeable about the subject matter and acceptably equipped to perform device analyses after completing the text.

The present text is intended for undergraduate juniors or seniors who have had at least an introductory exposure to electric field theory. Chapters are grouped into three major divisions or "parts," with Part II being further subdivided into IIA and IIB. With some deletions, the material in each of the three parts is covered during a five-week segment of a one-semester, three-credit-hour, junior-senior course in Electrical and Computer Engineering at Purdue University. A day-by-day course outline is supplied on the Instructor's Disk accompanying the Solutions Manual. If necessary to meet time constraints, read-only Chapters 4, 9, 13, and 19 could be deleted from the lecture schedule. (An instructor might preferably assign the chapters as independent readings and reward compliant students by including extra-credit examination questions covering the material.) Standard Chapters 12, 14, and 15, except for the general field-effect introduction in Section 15.1, may also be omitted with little or no loss in continuity.

Although a complete listing of special features is given in the General Introduction, instructors should take special note of the Problem Information Tables inserted prior to the end-of-chapter problems. These tables should prove useful in assigning problems and in dealing with homework graders. When faced with constructing a test, instructors may also be interested in examining the Review Problem Sets found in the mini-chapters (identified by a darkened thumb tab) at the end of the three book parts. The Review Problem Sets are derived from old "open-book" and "closed-book" tests. Concerning the computer-based exercises and problems, the use of either the student or professional version of MATLAB is recommended but not required. The in-text exercise solutions and the problem answers supplied to the instructor, however, do make use of MATLAB. Although it would be helpful, the user need not be familiar with the MATLAB program at the beginning of the book. The MATLAB problems in successive chapters make increasingly sophisticated use of the program. In other words, the early exercises and homework problems provide a learning MATLAB by using MATLAB experience. It is critical, however, that the user complete a large percentage of the computer-based exercises and problems in the first three chapters. The exercises and problems found in later chapters not only assume a reasonably competent use of MATLAB, but also build upon the programs developed in the earlier chapters.

The author gratefully acknowledges the assistance of associates, EE305 students, the respondents to an early marketing survey, the manuscript reviewers, and Addison-Wesley personnel in making Book 2000 a reality. Deserving of special thanks is Ali Keshavarzi for arranging the author's sabbatical at Intel Corporation and for providing photographs of equipment inside the Albuquerque fabrication facility. Prof. Mark Lundstrom at Purdue University was also most helpful in supplying key information and figures for several book sections. Of the undergraduate students asked to examine the manuscript for readability

and errors, Eric Bragg stands out as especially perceptive and helpful. The very conscientious manuscript reviewers were Prof. Kenneth A. James, California State University, Long Beach; Prof. Peter Lanyon, Worcester Polytechnic Institute; Prof. Gary S. May, Georgia Institute of Technology; Prof. Dieter K. Schroder, Arizona State University; and Prof. G. W. Stillman, University of Illinois at Urbana-Champaign. In recognition of a fruitful association, a special thanks to Don Fowley, the former editor at Addison-Wesley who enticed the author into writing the book. Last but not least, editor Katherine Harutunian is to be credited with smoothly implementing the project, and executive assistant Anita Devine with cheerfully handling many of the early details.

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GENERAL INTRODUCTION

Coincident with the writing of this book, there has been considerable media discussion about the "Information Superhighway." The envisioned highway itself, the physical link between points supporting the information traffic, is fiber optic cable. Relative to the topic of this book, the on and off ramps, which insert and extract the information from the highway, are semiconductor (solid state) devices. Traffic control, the information processing and the conversion to and from the human interface, is performed by computers. The central processing unit (CPU), memory, and other major components inside the computer are again semiconductor devices. In the modern world, semiconductor devices are incorporated in just about every major system from automobiles to washing machines.

Although roughly a half-century old, the field of study associated with semiconductor devices continues to be dynamic and exciting. New and improved devices are being developed at an almost maddening pace. While the device count in complex integrated circuits increases through the millions and the side-length of chips is measured in centimeters, the individual devices are literally being shrunk to atomic dimensions. Moreover, semiconductor properties desired for a given device structure but not available in nature are being produced artificially; in essence, the semiconductor properties themselves are now being engineered to fit device specifications.

This book should be viewed as a gateway to what the reader will hopefully agree is the fascinating realm of semiconductor devices. It was written for junior- or senior-level students who have at least an introductory exposure to electric field theory. The coverage includes a representative sampling of information about a wide variety of devices. Primary emphasis, however, is placed on developing a fundamental understanding of the internal workings of the more basic device structures. As detailed below, this book contains a number of unique features to assist the reader in learning the material. Alerted at an early stage to their existence, the reader can plan to take full advantage of the cited features.

- *Computer-Based Exercises and End-of Chapter (Homework) Problems.* The majority of chapters contain one or more MATLAB-based exercises requiring the use of a computer. MATLAB is a math-tools software program that has been adapted to run on most computer platforms. A low-cost student edition of MATLAB, which can be used to run all of the files associated with this book, is available in both IBM-compatible and Macintosh versions. The MATLAB program scripts yielding exercise answers are listed in the text and are available in electronic form as detailed below. Computer-based problems, identified by a bullet (•) before the problem number, make up approximately 25% of the

problem total. Although other math-tools programs could be employed, the use of MATLAB is recommended in answering computer-based problems. Because computer-based exercises and problems in the early chapters are specifically designed to progressively enhance MATLAB-use proficiency, the user need not be familiar with the MATLAB program at the beginning of the book. It is very important, however, to complete a large percentage of the computer-based exercises and problems in the first three chapters. The exercises and problems found in later chapters not only assume a reasonably competent use of MATLAB, but also build upon the programs developed in the earlier chapters.

- *Computer Program Files.* Program files of the MATLAB scripts associated with computer-based exercises are available via the Internet (`ftp.mathworks.com` in the directory `pub/books/pierret`) or on a floppy disk distributed free of charge by MathWorks, Inc. A pull-out card is provided herein for obtaining the free program disk which is formatted for use with either an IBM-compatible or Macintosh computer. Each floppy disk contains two sets of "m-files" to be used respectively with the pre-4.0 (student 1st edition) or post-4.0 (student 2nd edition) versions of MATLAB. The listings in the text are specifically derived from the Macintosh post-4.0 version, but they are identical to the corresponding IBM-compatible version except for the occasional appearance of a Greek letter.
- *Supplement and Review Mini-Chapters.* The book is divided into three parts. At the end of each part is a Supplement and Review mini-chapter. The mini-chapters, identified by a darkened thumb tab, contain an alternative/supplemental reading list and information table, reference citations for the preceding chapters, an extensive review-list of terms, and review problem sets with answers. The review problem sets are derived from "closed-book" and "open-book" examinations.
- *Read-Only Chapters.* Chapters 4, 9, 13, and 19 have been classified as "read-only." Chapters with the read-only designation contain mostly qualitative information of a supplemental nature. Two of the chapters survey some of the latest device structures. Intended to be fun-reading, the read-only chapters are strategically placed to provide a change of pace. The chapters contain only a small number of equations, no exercises, and few, if any, end-of-chapter problems. In a course format, the chapters could be skipped with little loss in continuity or preferably assigned as independent readings.
- *Problem Information Tables.* A compact table containing information about the end-of-chapter problems in a given chapter is inserted just before the problems. The information provided is (i) the text section or subsection after which the problem can be completed, (ii) the estimated problem difficulty on a scale of 1 (easy or straightforward) to 5 (very difficult or extremely time consuming), (iii) suggested credit or point weighting, and (iv) a short problem description. A bullet before the problem number identifies a computer-based problem. An asterisk indicates computer usage for part of the problem.
- *Equation Summaries.* The very basic carrier modeling equations in Chapter 2 and the carrier action equations in Chapter 3, equations referenced throughout the text, are organized and repeated in Tables 2.4 and 3.3, respectively. These tables would be ideal as "crib sheets" for closed-book examinations covering the material in Part I of the text.

- *Measurements and Data.* Contrary to the impression sometimes left by the sketches and idealized plots often found in introductory texts, device characteristics are real, seldom perfect, and are routinely recorded in measurement laboratories. Herein a sampling of measurement details and results, derived from an undergraduate EE laboratory administered by the author, is included in an attempt to convey the proper sense of reality. For added details on the described measurements, and for a description of additional measurements, the reader is referred to R. F. Pierret, *Semiconductor Measurements Laboratory Operations Manual*, Supplement A in the Modular Series on Solid State Devices, Addison-Wesley Publishing Company, Reading MA, © 1991.
- *Alternative Treatment.* Section 2.1 provides the minimum required treatment on the topic of energy quantization in atomic systems. Appendix A, which contains a more in-depth introduction to the quantization concept and related topics, has been included for those desiring supplemental information. Section 2.1 may be totally replaced by Appendix A with no loss in continuity.

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