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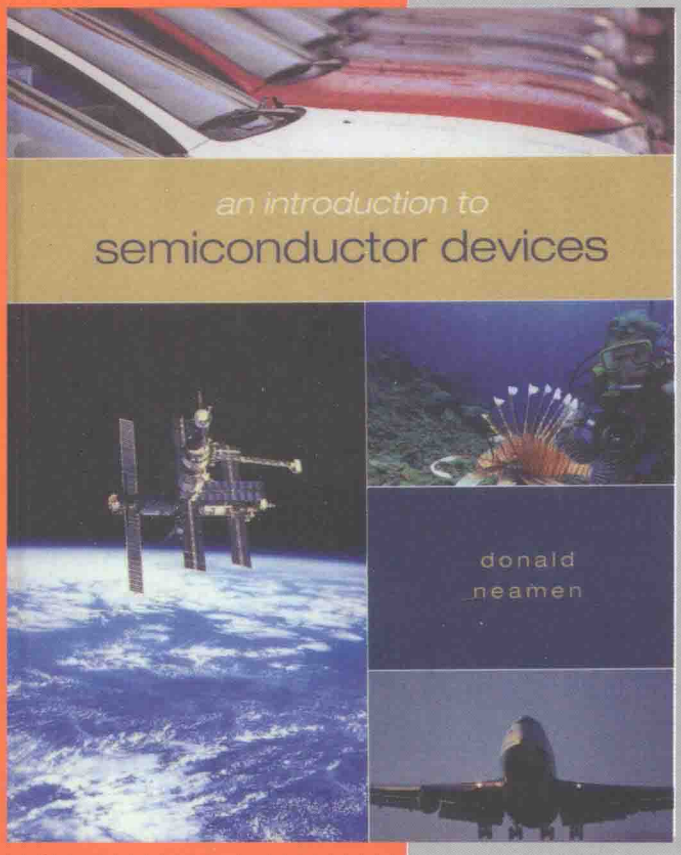
Donald A. Neamen

半导体器件导论



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An Introduction to Semiconductor Devices

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出 版 前 言

微电子技术是信息科学技术的核心技术之一，微电子产业是当代高新技术产业群的核心和维护国家主权、保障国家安全的战略性产业。我国在《信息产业“十五”计划纲要》中明确提出：坚持自主发展，增强创新能力和核心竞争力，掌握以集成电路和软件技术为重点的信息产业的核心技术，提高具有自主知识产权产品的比重。发展集成电路技术的关键之一是培养具有国际竞争力的专业人才。

微电子技术发展迅速，内容更新快，而我国微电子专业图书数量少，且内容和体系不能反映科技发展的水平，不能满足培养人才的需求，为此，我们系统挑选了一批国外经典教材和前沿著作，组织分批出版。图书选择的几个基本原则是：在本领域内广泛采用，有很大影响力；内容反映科技的最新发展，所述内容是本领域的研究热点；编写和体系与国内现有图书差别较大，能对我国微电子教育改革有所启示。本套丛书还侧重于微电子技术的实用性，选取了一批集成电路设计方面的工程技术用书，使读者能方便地应用于实践。本套丛书不仅能作为相关课程的教科书和教学参考书，也可作为工程技术人员的自学读物。

我们真诚地希望，这套丛书能对国内高校师生、工程技术人员以及科研人员的学习和工作有所帮助，对推动我国集成电路的发展有所促进。也衷心期望着广大读者对我们一如既往的关怀和支持，鼓励我们出版更多、更好的图书。

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2003.9

An Introduction to Semiconductor Devices

影 印 版 序

本书是美国新墨西哥大学电机与计算机工程系 Neamen 教授所著的“Semiconductor Physics and Devices (3rd edition)”一书的改进版本。

在原书的基础上，本书主要进行了以下的调整：

(1) 重新组织编排了原书的章节和内容，特别将有关 MOSFET 器件物理的内容放在了 BJT 之前，这反映了 MOSFET 在当代主流 CMOS 工艺中的重要位置；

(2) 结合不同类型半导体器件原理的介绍，增加了相应的微电子制造工艺方面的内容；

(3) 压缩了有关量子力学方面的内容，力图以较少的篇幅和比较浅显易懂的方式来介绍固体的量子理论和半导体物理方面必要的基础知识；

(4) 增加了一些介绍新器件结构方面的内容，例如 MEMS 器件等，以便进一步拓宽学生的知识面。

与原书相比，本书更好地将固体晶格结构、量子力学入门知识、固体的量子理论以及半导体物理和半导体器件有机地结合在一起。利用本书，学生只需要具有高等数学和大学普通物理的基础，用一个学期就可以系统地学习到半导体器件的基本理论，从而为进入微电子学研究领域打下一个良好的基础。这一特点也是目前国内出版的同类教材很难达到的。

另外，本书还尽量保持了原书的主要优点：

(1) 注重基本概念和方法。本书从内容的整体编排到具体章节的叙述，都体现了突出物理概念、强调基本分析方法的指导思想。书中的数学推导和物理分析融为一体，得出的结论不仅对理解物理概念十分重要，而且经得住反复推敲。书中还采用了大量非常清晰的插图，这从另一个侧面也可以帮助读者更好地理解基本概念。

(2) 可读性强，便于自学。全书脉络清楚，说理透彻，易于读者理解和掌握。每章的开头都有引言，告诉读者可以从本章学到什么，应该掌握什么；每章中都有例题和读者自测题；每章的最后还有总结、复习提纲和大量习题（其中包含一些采用计算机进行模拟计算的练习题）。通过举例和练习加深读者对基本概念的理解是本书突出的特点。

本书的第 1 章至第 4 章介绍了固体晶格结构、固体的量子理论和半导体物理的基本知识，为后续的半导体器件分析打下了基础。第 5 章至第 10 章是全书的重点，详细讨论了 PN 结二极管、MOSFET 和 BJT 器件的原理和分析方法。第 11 章和第 12 章介绍了一些其他类型的半导体器件，包括异质结器件、功率

器件、MEMS 器件和半导体光电器件等。从上述内容安排上我们不难看出，本书十分符合目前国内高等院校电子信息类各专业在“微电子器件与电路”方面开设公共平台课的教学需求。

本书的作者 Neamen 教授在美国新墨西哥大学任教长达 25 年，且与工业界合作密切，书中很多内容（包括例题和习题）反映了工业界的最新发展，因此本书不仅是一本很好的教科书，同时对微电子领域的工程技术人员也具有很高的参考价值。

张莉，许军

2005 年 12 月于清华园

To the many students I've had the privilege of teaching over the years who have contributed in many ways to the broad field of electrical engineering, and to future students who will contribute in ways we cannot now imagine.

ABOUT THE AUTHOR

Donald A. Neamen is a professor emeritus in the Department of Electrical and Computer Engineering at the University of New Mexico where he taught for more than 25 years. He received his Ph.D. from the University of New Mexico and then became an electronics engineer at the Solid State Sciences Laboratory at Hanscom Air Force Base. In 1976, he joined the faculty in the ECE department at the University of New Mexico, where he specialized in teaching semiconductor physics and devices courses and electronic circuits courses. He is still a part-time instructor in the department.

In 1980, Professor Neamen received the Outstanding Teacher Award for the University of New Mexico. In 1983 and 1985, he was recognized as Outstanding Teacher in the College of Engineering by Tau Beta Pi. In 1990, and each year from 1994 through 2001, he received the Faculty Recognition Award, presented by graduating ECE students. He was also honored with the Teaching Excellence Award in the College of Engineering in 1994.

In addition to his teaching, Professor Neamen served as Associate Chair of the ECE department for several years and has also worked in industry with Martin Marietta, Sandia National Laboratories, and Raytheon Company. He has published many papers and is the author of *Electronic Circuit Analysis and Design,* Second Edition and *Semiconductor Physics and Devices: Basic Principles,* Third Edition.

PREFACE

PHILOSOPHY AND GOALS

The purpose of this text is to provide a basis for understanding the characteristics, operation, and limitations of semiconductor devices. In order to gain this understanding, it is essential to have a thorough knowledge of the physics of the semiconductor material. The goal of this book is to bring together the fundamental physics of the semiconductor material and the semiconductor device physics.

Since the objective of this text is to provide an introduction to the theory of semiconductor devices, there is a great deal of advanced theory that is not considered. This material is found in more advanced texts. There are occasions in the text where equations and relationships are simply stated with no or very little derivation. Again, the details are found in more advanced texts. However, the author feels that there is enough mathematics included to provide a good foundation for the basic understanding of semiconductor devices in this first course.

PREREQUISITES

This text is intended for junior and senior undergraduates in electrical engineering. The prerequisites for understanding the material are college mathematics, up to and including differential equations, and college physics, including an introduction to modern physics and electrostatics. Prior completion of an introductory course in electronic circuits is helpful, but not essential.

ORDER OF PRESENTATION

Each instructor has a personal preference for the order in which the course material is presented. The order of presentation of topics in this text is somewhat different compared to many semiconductor textbooks. Chapters 1–4 cover the basic physics of the semiconductor material and contain topics normally covered initially in any semiconductor device course. Chapter 5 discusses the electrostatics of the pn and Schottky junctions. This material is necessary and sufficient for the understanding of the MOS transistor presented in Chapters 6 and 7. There are two reasons for discussing the MOS transistor at this point. First, since the MOS transistor is fundamental to integrated circuits, this material is presented early enough in the course so that it doesn't get "short changed," as it might when covered at the end of a course. Second, since a "real" semiconductor device is discussed fairly early in the course, the reader may have more motivation to continue studying this course material.

After the MOS transistor is presented, the nonequilibrium characteristics of the semiconductor material is presented in Chapter 8 and then the forward-biased pn junction and Schottky diodes are discussed in Chapter 9. The bipolar transistor is

presented in Chapter 10. Chapter 11 covers additional devices such as junction field-effect transistors and thyristors. Finally, optical devices are discussed in Chapter 12.

One possible disadvantage to this order of presentation is that the discussion of the pn junction is "interrupted." However, the author feels that a "just-in-time" approach is justified. Some discussion of the pn junction is necessary before presenting the MOS transistor. However, if the entire discussion of the pn junction, including the discussion of nonequilibrium excess carriers, took place before the MOS transistor, then much of the knowledge gained of forward-biased pn junctions would be lost by the reader by the time the bipolar transistor is discussed.

The following table lists the textbook approach to the order of presentation of topics. Unfortunately, because of time constraints, every topic in every chapter cannot be covered in a one-semester course.

Textbook Approach	
Chapter 1	Crystal structure
Chapter 2	Selected topics from quantum mechanics and theory of solids
Chapter 3	Semiconductor material physics
Chapter 4	Transport phenomena
Chapter 5	Electrostatics of the pn junction
Chapter 6	The MOS transistor
Chapter 7	Selected topics for advanced MOSFETs
Chapter 8	Selected topics from nonequilibrium semiconductor physics
Chapter 9	The pn junction diode
Chapter 10	The bipolar transistor
Chapter 11	Selected topics from other devices
Chapter 12	Selected topics from optical devices

For those instructors who prefer the classical approach and wish to cover the bipolar transistor before the MOS transistor, the following table lists the order of presentation. The chapters are written so that this order of presentation is very plausible.

Classical Approach	
Chapter 1	Crystal structure
Chapter 2	Selected topics from quantum mechanics and theory of solids
Chapter 3	Semiconductor material physics
Chapter 4	Transport phenomena
Chapter 8	Selected topics from Nonequilibrium semiconductor physics
Chapter 5	Electrostatics of the pn junction
Chapter 9	The pn junction diode
Chapter 10	The bipolar transistor
Chapter 6	The MOS transistor
Chapter 7	Selected topics from advanced MOSFETs
Chapter 11	Selected topics from other devices
Chapter 12	Selected topics from optical devices

USE OF THE BOOK

The text is intended for a one-semester course at the junior or senior level. As with most textbooks, there is more material than can be conveniently covered in one semester; this enables each instructor some flexibility in designing the course to his or her own specific needs.

At the end of several chapters, there is a section dealing with fabrication technology. In Chapter 1, this topic deals with the growth of semiconductor materials and the oxidation process. In Chapter 3, this topic deals with the introduction of specific impurities into the semiconductor by either diffusion or ion implantation. In later chapters, this topic deals with the fabrication of specific devices. In each case, the fabrication discussion is relatively short and intended only to give the reader a basic understanding of the fabrication technology. These sections, as well as a few other sections in the text, are denoted by the symbol Σ in front of the section heading. The symbol Σ shows that reading these sections will aid in the total summation of the understanding of semiconductor devices. However, a basic understanding of semiconductor device physics can be accomplished without studying these sections in detail during this first introductory course.

FEATURES OF THE BOOK

- *Preview section:* A preview section introduces each chapter. This preview links the chapter to previous chapters and states the chapter's goals, that is, what the reader should gain from the chapter.
- *Historical and Present-Day Insights:* A Historical Insight section relates the chapter material to a few historical events and a Present-Day Insight section relates the chapter material to current research and manufacturing events.
- *Icon:* Σ, indicates sections that are to be read for understanding to increase the total summation of knowledge of semiconductor devices. However, a detailed study of these sections is not required during this first introductory course.
- *Key terms in the margin:* Key terms are listed in the margin of the text. Quickly finding a key term adjacent to the text in which the material is discussed should aid the student in reviewing the material.
- *Examples:* There are a liberal number of examples given in the text to reinforce the theoretical concepts being developed. These examples contain all the details of the analysis or design, so the reader does not have to fill in missing steps.
- *Exercise problems:* An exercise problem is given after each example. These exercises are similar in scope to the preceding example. The ability to solve these exercise problems should be an indication as to whether the student has mastered the previous material. Answers to these problems are given.
- *Test Your Understanding exercises:* At the end of major sections, additional exercise problems are given. These exercise problems tend to be more comprehensive than the exercise problems given after each example. Answers to these problems are also given.

- *Summary:* A summary section follows the text of each chapter. This section summarizes the overall results derived in the chapter and reviews the basic concepts developed.
- *Checkpoint:* A checkpoint section follows the Summary section. This section states the goals that should have been met and states the abilities the reader should have gained. The Checkpoints will help assess progress before moving to the next chapter.
- *Review questions:* A list of review questions is included at the end of each chapter. These questions serve as a self-test to help the reader determine how well the concepts developed in the chapter have been mastered.
- *End-of-chapter problems:* A substantial number of problems are provided at the end of each chapter, organized according to the subject of each section. An asterisk in front of a problem indicates a more difficult problem. Answers to a selected number are provided in Appendix F.
- *Reading list:* A reading list finishes up each chapter. The references indicated by an asterisk are at a more advanced level compared with this text.
- *Answers to selected problems:* Answers to selected problems are given in Appendix F. Knowing the answer to a problem can aid and reinforce the problem solving.

SUPPLEMENTS

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