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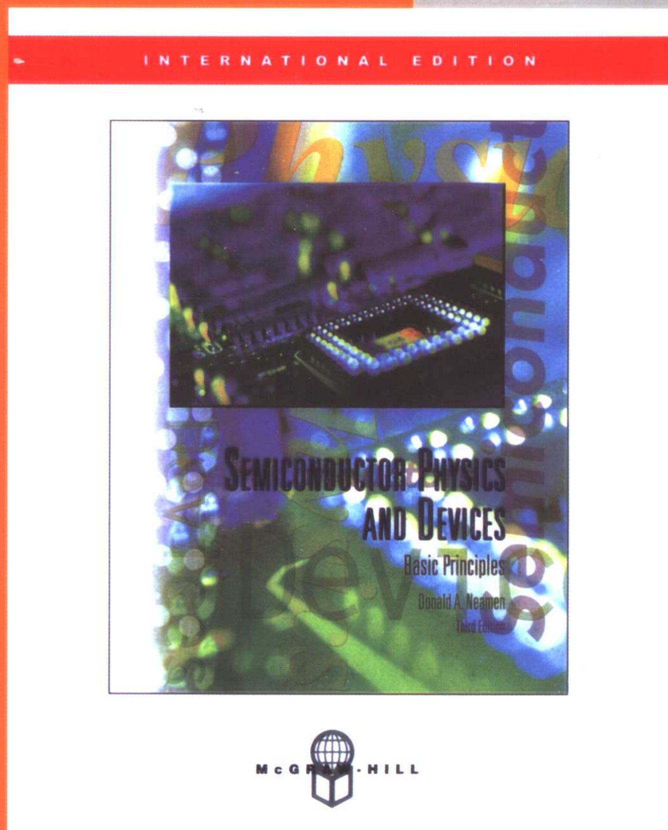
国外大学优秀教材——微电子类系列（影印版）

Donald A. Neamen

半导体物理与器件

——基本原理（第3版）



清华大学出版社

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半导体物理与器件
——基本原理（第3版）

Semiconductor Physics and Devices
Basic Principles
Third Edition

Donald A. Neamen

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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，这套丛书能给国内高校师生、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。

清华大学出版社
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Semiconductor Physics and Devices: Basic Principles (3^{th} Edition)

影 印 版 序

非常感谢清华大学出版社选择 Neamen 教授的 Semiconductor Physics and Devices (Third Edition)一书影印出版，这让中国的大学生们在学习半导体物理和半导体器件课程时又多了一本很好的英文教科书和参考书。与目前我国大学本科生的同类教材相比，这本书具有以下特点：

（1）全新的体系结构。目前国内的电子科学与技术专业（工科）和微电子学专业（理科）的教学体系是先学理论物理（包括统计物理、量子力学等）、固体物理，再学半导体物理，最后学半导体器件。一般说来，学完上述 4 门课程需要用 2 至 3 个学期。这本书将上述 4 门课的有关内容（如固体晶格结构、量子力学简介、固体的量子理论、半导体材料和半导体器件物理）有机地结合在一起。学生只需具有高等数学和大学物理的基础、用 1 至 2 个学期时间就可以系统地学习到半导体物理与器件课程的基本内容。

（2）注重概念方法。从内容的整体编排到具体内容的叙述，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，而且经得住推敲。本书还采用了大量的插图，从另一侧面帮助读者理解概念。

（3）可读性强，便于自学。全书思路清晰，说理清楚，易于读者理解和掌握。每一章的开头都有引言，告诉读者可以从本章学到什么，应该掌握什么；每一章中都有例题和读者自测题；每一章末还有总结、复习提纲和大量习题（其中一些是计算机模拟的练习题）；在全书末附有部分习题答案。通过举例和练习加深对概念的理解是本书突出的特点。

（4）内容丰富，覆盖面广。本书除了包含比以往的同类书籍都要多的物理内容外，对器件的介绍也相当丰富。除了最基本和常用的 BJT 和 MOSFET 器件，还详细介绍了半导体光电器件和功率器件。不仅讲述器件的基本原理，而且介绍了器件的发展，例如 MOSFET 器件尺寸缩小带来的各种物理效应等。每一章后面的参考文献可以让读者进行进一步的学习。

Neamen 教授在美国 University of Mexico 任教长达 25 年之久，且与工业界合作密切，书中很多内容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，也非常适合做工程技术人员的参考书。

田立林，张莉

清华大学

2003 年 10 月

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 EECE 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 EECE 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 EECE 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,* 2nd edition.

phenomena of the charge carriers in a semiconductor. The nonequilibrium excess carrier characteristics are then developed in Chapter 6. Understanding the behavior of excess carriers in a semiconductor is vital to the goal of understanding the device physics.

The physics of the basic semiconductor devices is developed in Chapters 7 through 13. Chapter 7 treats the electrostatics of the basic pn junction, and Chapter 8 covers the current-voltage characteristics of the pn junction. Metal-semiconductor junctions, both rectifying and nonrectifying, and semiconductor heterojunctions are considered in Chapter 9, while Chapter 10 treats the bipolar transistor. The physics of the metal-oxide-semiconductor field-effect transistor is presented in Chapters 11 and 12, and Chapter 13 covers the junction field-effect transistor. Once the physics of the pn junction is developed, the chapters dealing with the three basic transistors may be covered in any order—these chapters are written so as not to depend on one another. Chapter 14 considers optical devices and finally Chapter 15 covers power semiconductor 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 allows each instructor some flexibility in designing the course to his/her own specific needs. Two possible orders of presentation are discussed later in a separate section in this preface. However, the text is not an encyclopedia. Sections in each chapter that can be skipped without loss of continuity are identified by an asterisk in both the table of contents and in the chapter itself. These sections, although important to the development of semiconductor device physics, can be postponed to a later time.

The material in the text has been used extensively in a course that is required for junior-level electrical engineering students at the University of New Mexico. Slightly less than half of the semester is devoted to the first six chapters; the remainder of the semester is devoted to the pn junction, the bipolar transistor, and the metal-oxide-semiconductor field-effect transistor. A few other special topics may be briefly considered near the end of the semester.

Although the bipolar transistor is discussed in Chapter 10 before the MOSFET or JFET, each chapter dealing with one of the three basic types of transistors is written to stand alone. Any one of the transistor types may be covered first.

NOTES TO THE READER

This book introduces the physics of semiconductor materials and devices. Although many electrical engineering students are more comfortable building electronic circuits or writing computer programs than studying the underlying principles of semiconductor devices, the material presented here is vital to an understanding of the limitations of electronic devices, such as the microprocessor.

Mathematics is used extensively throughout the book. This may at times seem tedious, but the end result is an understanding that will not otherwise occur. Although some of the mathematical models used to describe physical processes may seem abstract, they have withstood the test of time in their ability to describe and predict these physical processes.

The reader is encouraged to continually refer to the preview sections so that the objective of the chapter and the purposes of each topic can be kept in mind. This constant review is especially important in the first five chapters, dealing with basic physics.

The reader must keep in mind that, although some sections may be skipped without loss of continuity, many instructors will choose to cover these topics. The fact that sections are marked with an asterisk does not minimize the importance of these subjects.

It is also important that the reader keep in mind that there may be questions still unanswered at the end of a course. Although the author dislikes the phrase, "it can be shown that . . . ," there are some concepts used here that rely on derivations beyond the scope of the text. This book is intended as an introduction to the subject. Those questions remaining unanswered at the end of the course, the reader is encouraged to keep "in a desk drawer." Then, during the next course in this area of concentration, the reader can take out these questions and search for the answers.

ORDER OF PRESENTATION

Each instructor has a personal preference for the order in which the course material is presented. Listed below are two possible scenarios. The first case, called the classical approach, covers the bipolar transistor before the MOS transistor. However, because the MOS transistor topic is left until the end of the semester, time constraints may shortchange the amount of class time devoted to this important topic.

The second method of presentation listed, called the nonclassical approach, discusses the MOS transistor before the bipolar transistor. Two advantages to this approach are that the MOS transistor will not get shortchanged in terms of time devoted to the topic and, since a "real device" is discussed earlier in the semester, the reader may have more motivation to continue studying this course material. A possible disadvantage to this approach is that the reader may be somewhat intimidated by jumping from Chapter 7 to Chapter 11. However, the material in Chapters 11 and 12 is written so that this jump can be made.

Unfortunately, because of time constraints, every topic in every chapter cannot be covered in a one-semester course. The remaining topics must be left for a second-semester course or for further study by the reader.

Chapter 1	Crystal structure
Chapters 2, 3	Selected topics from quantum mechanics and theory of solids
Chapter 4	Semiconductor physics
Chapter 5	Transport phenomena
Chapter 6	Selected topics from nonequilibrium characteristics
Chapters 7, 8	The pn junction and diode
Chapter 9	A brief discussion of the Schottky diode
Chapter 10	The bipolar transistor
Chapters 11, 12	The MOS transistor

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FEATURES OF THE THIRD EDITION

- *Preview section:* A preview section introduces each chapter. This preview links the chapter to previous chapters and states the chapter's goals, i.e., what the reader should gain from the chapter.
- *Examples:* An extensive number of worked examples are used throughout 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.
- *Test your understanding:* Exercise or drill problems are included throughout each chapter. These problems are generally placed immediately after an example problem, rather than at the end of a long section, so that readers can immediately test their understanding of the material just covered. Answers are given for each drill problem so readers do not have to search for an answer at the end of the book. These exercise problems will reinforce readers' grasp of the material before they move on to the next section.
- *Summary section:* A summary section, in bullet form, follows the text of each chapter. This section summarizes the overall results derived in the chapter and reviews the basic concepts developed.
- *Glossary of important terms:* A glossary of important terms follows the Summary section of each chapter. This section defines and summarizes the most important terms discussed in the chapter.
- *Checkpoint:* A checkpoint section follows the Glossary 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 on 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 large number of problems are given at the end of each chapter, organized according to the subject of each section in the chapter

body. A larger number of problems have been included than in the second edition. Design-oriented or open-ended problems are included at the end in a Summary and Review section.

- *Computer simulation:* Computer simulation problems are included in many end-of-chapter problems. Computer simulation has not been directly incorporated into the text. However, a website has been established that considers computer simulation using MATLAB. This website contains computer simulations of material considered in most chapters. These computer simulations enhance the theoretical material presented. There also are exercise or drill problems that a reader may consider.
- *Reading list:* A reading list finishes up each chapter. The references, that are at an advanced level compared with that of this text, are indicated by an asterisk.
- *Answers to selected problems:* Answers to selected problems are given in the last appendix. Knowing the answer to a problem is an aid and a reinforcement in problem solving.

ICONS


Computer Simulations


Design Problems and Examples

SUPPLEMENTS

This book is supported by the following supplements:

- Solutions Manual available to instructors in paper form and on the website.
- Power Point slides of important figures are available on the website.
- Computer simulations are available on the website.

ACKNOWLEDGMENTS

I am indebted to the many students I have had over the years who have helped in the evolution of the third edition as well as the first and second editions of this text. I am grateful for their enthusiasm and constructive criticism. The University of New Mexico has my appreciation for providing an atmosphere conducive to writing this book.

I want to thank the many people at McGraw-Hill, for their tremendous support. A special thanks to Kelley Butcher, senior developmental editor. Her attention to details and her enthusiasm throughout the project are especially recognized and appreciated. I also appreciate the efforts of Joyce Watters, project manager, who guided the work through its final phase toward publication.

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Leon McCaughan, *University of Wisconsin*
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Since the third edition is an outgrowth of the first edition of the text, the following reviewers of the first edition deserve my continued thanks for their thorough reviews and valuable suggestions:

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Anand Kulkarni, *Michigan Technological University*
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I appreciate the many fine and thorough reviews—your suggestions have made this a better book.

Donald A. Neamen

Semiconductors and the Integrated Circuit

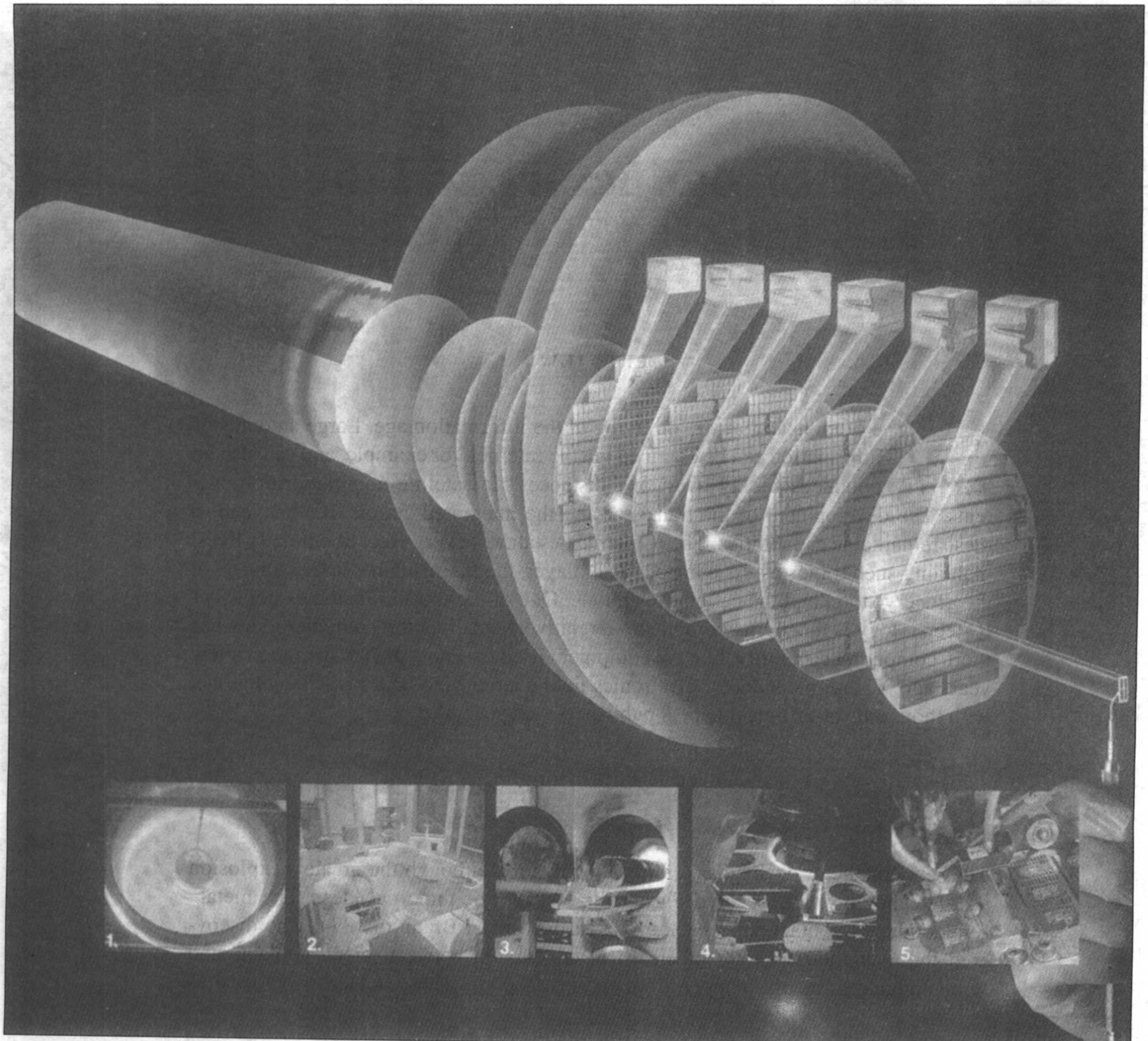
PREVIEW

We often hear that we are living in the information age. Large amounts of information can be obtained via the Internet, for example, and can also be obtained quickly over long distances via satellite communication systems. The development of the transistor and the integrated circuit (IC) has lead to these remarkable capabilities. The IC permeates almost every facet of our daily lives, including such things as the compact disk player, the fax machine, laser scanners at the grocery store, and the cellular telephone. One of the most dramatic examples of IC technology is the digital computer—a relatively small laptop computer today has more computing capability than the equipment used to send a man to the moon a few years ago. The semiconductor electronics field continues to be a fast-changing one, with thousands of technical papers published each year. ■

HISTORY

The semiconductor device has a fairly long history, although the greatest explosion of IC technology has occured during the last two or three decades.[1] The metal–semiconductor contact dates back to the early work of Braun in 1874, who discovered the asymmetric nature of electrical conduction between metal contacts and semiconductors, such as copper, iron, and lead sulfide. These devices were used as

[1]This brief introduction is intended to give a flavor of the history of the semiconductor device and integrated circuit. Thousands of engineers and scientists have made significant contributions to the development of semiconductor electronics—the few events and names mentioned here are not meant to imply that these are the only significant events or people involved in the semiconductor history.



Compliments of Texas Instruments Incorporated detectors in early experiments on radio. In 1906, Pickard took out a patent for a point contact detector using silicon and, in 1907, Pierce published rectification characteristics of diodes made by sputtering metals onto a variety of semiconductors.

By 1935, selenium rectifiers and silicon point contact diodes were available for use as radio detectors. With the development of radar, the need for detector diodes and mixers increased. Methods of achieving high-purity silicon and germanium were developed during this time. A significant advance in our understanding of the metal–semiconductor contact was aided by developments in the semiconductor physics. Perhaps most important during this period was Bethe's thermionic-emission theory in 1942, according to which the current is determined by the process of emission of electrons into the metal rather than by drift or diffusion.

Another big breakthrough came in December 1947 when the first transistor was constructed and tested at Bell Telephone Laboratories by William Shockley, John Bardeen, and Walter Brattain. This first transistor was a point contact device and used polycrystalline germanium. The transistor effect was soon demonstrated in silicon as well. A significant improvement occurred at the end of 1949 when single-crystal material was used rather than the polycrystalline material. The single crystal yields uniform and improved properties throughout the whole semiconductor material.

The next significant step in the development of the transistor was the use of the diffusion process to form the necessary junctions. This process allowed better control of the transistor characteristics and yielded higher-frequency devices. The diffused mesa transistor was commercially available in germanium in 1957 and in silicon in 1958. The diffusion process also allowed many transistors to be fabricated on a single silicon slice, so the cost of these devices decreased.

THE INTEGRATED CIRCUIT (IC)

Up to this point, each component in an electronic circuit had to be individually connected by wires. In September 1958, Jack Kilby of Texas Instruments demonstrated the first integrated circuit, which was fabricated in germanium. At about the same time, Robert Noyce of Fairchild Semiconductor introduced the integrated circuit in silicon using a planar technology. The first circuit used bipolar transistors. Practical MOS transistors were then developed in the mid-'60s. The MOS technologies, especially CMOS, have become a major focus for IC design and development. Silicon is the main semiconductor material. Gallium arsenide and other compound semiconductors are used for special applications requiring very high frequency devices and for optical devices.

Since that first IC, circuit design has become more sophisticated, and the integrated circuit more complex. A single silicon chip may be on the order of 1 square centimeter and contain over a million transistors. Some ICs may have more than a hundred terminals, while an individual transistor has only three. An IC can contain the arithmetic, logic, and memory functions on a single semiconductor chip—the primary example of this type of IC is the microprocessor. Intense research on silicon processing and increased automation in design and manufacturing have led to lower costs and higher fabrication yields.

FABRICATION

The integrated circuit is a direct result of the development of various processing techniques needed to fabricate the transistor and interconnect lines on the single chip. The total collection of these processes for making an IC is called a *technology.* The following few paragraphs provide an introduction to a few of these processes. This introduction is intended to provide the reader with some of the basic terminology used in processing.

Thermal Oxidation A major reason for the success of silicon ICs is the fact that an excellent native oxide, SiO_2, can be formed on the surface of silicon. This oxide is used as a gate insulator in the MOSFET and is also used as an insulator, known as the field oxide, between devices. Metal interconnect lines that connect various devices can be placed on top of the field oxide. Most other semiconductors do not form native oxides that are of sufficient quality to be used in device fabrication.

Silicon will oxidize at room temperature in air forming a thin native oxide of approximately 25 Å thick. However, most oxidations are done at elevated temperatures since the basic process requires that oxygen diffuse through the existing oxide to the silicon surface where a reaction can occur. A schematic of the oxidation process is shown in Figure 0.1. Oxygen diffuses across a stagnant gas layer directly adjacent to the oxide surface and then diffuses through the existing oxide layer to the silicon surface where the reaction between O_2 and Si forms SiO_2. Because of this reaction, silicon is actually consumed from the surface of the silicon. The amount of silicon consumed is approximately 44 percent of the thickness of the final oxide.

Photomasks and Photolithography The actual circuitry on each chip is created through the use of photomasks and photolithography. The photomask is a physical representation of a device or a portion of a device. Opaque regions on the mask are made of an ultraviolet-light-absorbing material. A photosensitive layer, called photoresist, is first spread over the surface of the semiconductor. The photoresist is an

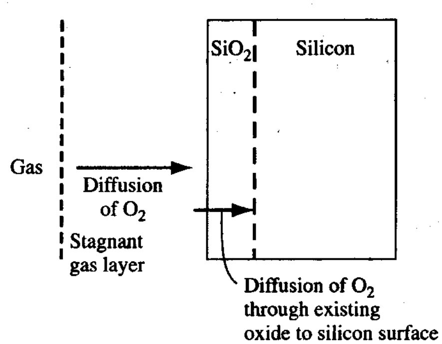


Figure 0.1 | Schematic of the oxidation process.

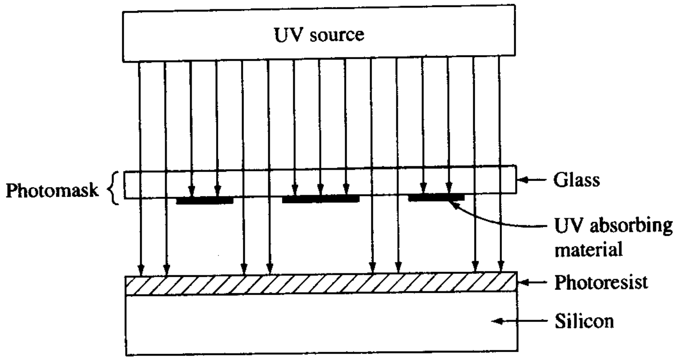


Figure 0.2 | Schematic showing the use of a photomask.

organic polymer that undergoes chemical change when exposed to ultraviolet light. The photoresist is exposed to ultraviolet light through the photomask as indicated in Figure 0.2. The photoresist is then developed in a chemical solution. The developer is used to remove the unwanted portions of the photoresist and generate the appropriate patterns on the silicon. The photomasks and photolithography process is critical in that it determines how small the devices can be made. Instead of using ultraviolet light, electrons and x-rays can also be used to expose the photoresist.

Etching After the photoresist pattern is formed, the remaining photoresist can be used as a mask, so that the material not covered by the photoresist can be etched. Plasma etching is now the standard process used in IC fabrication. Typically, an etch gas such as chlorofluorocarbons are injected into a low-pressure chamber. A plasma is created by applying a radio-frequency voltage between cathode and anode terminals. The silicon wafer is placed on the cathode. Positively charged ions in the plasma are accelerated toward the cathode and bombard the wafer normal to the surface. The actual chemical and physical reaction at the surface is complex, but the net result is that silicon can be etched anisotropically in very selected regions of the wafer. If photoresist is applied on the surface of silicon dioxide, then the silicon dioxide can also be etched in a similar way.

Diffusion A thermal process that is used extensively in IC fabrication is diffusion. Diffusion is the process by which specific types of "impurity" atoms can be introduced into the silicon material. This doping process changes the conductivity type of the silicon so that pn junctions can be formed. (The pn junction is a basic building block of semiconductor devices.) Silicon wafers are oxidized to form a layer of silicon dioxide and windows are opened in the oxide in selected areas using photolithography and etching as just described.

The wafers are then placed in a high-temperature furnace (about 1100°C) and dopant atoms such as boron or phosphorus are introduced. The dopant atoms gradually diffuse or move into the silicon due to a density gradient. Since the diffusion process requires a gradient in the concentration of atoms, the final concentration of diffused atoms is nonlinear, as shown in Figure 0.3. When the wafer is removed from the furnace and the wafer temperature returns to room temperature, the diffusion coefficient of the dopant atoms is essentially zero so that the dopant atoms are then fixed in the silicon material.

Ion Implantation A fabrication process that is an alternative to high-temperature diffusion is ion implantation. A beam of dopant ions is accelerated to a high energy and is directed at the surface of a semiconductor. As the ions enter the silicon, they collide with silicon atoms and lose energy and finally come to rest at some depth within the crystal. Since the collision process is statistical in nature, there is a distribution in the depth of penetration of the dopant ions. Figure 0.4 shows such an example of the implantation of boron into silicon at a particular energy.

Two advantages of the ion implantation process compared to diffusion are (1) the ion implantation process is a low temperature process and (2) very well defined doping layers can be achieved. Photoresist layers or layers of oxide can be used to block the penetration of dopant atoms so that ion implantation can occur in very selected regions of the silicon.

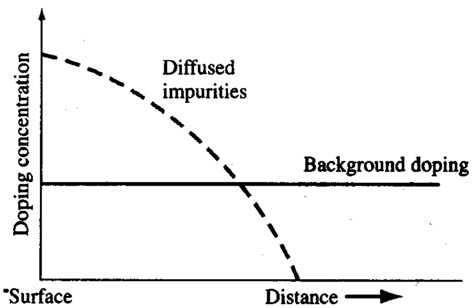


Figure 0.3 | Final concentration of diffused impurities into the surface of a semiconductor.

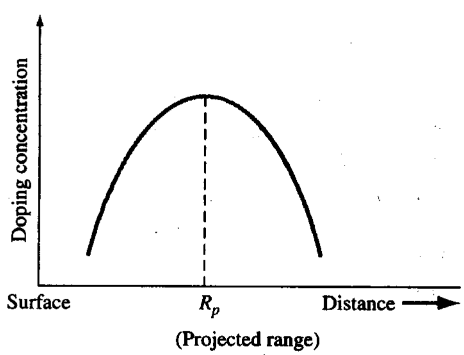


Figure 0.4 | Final concentration of ion-implanted boron into silicon.