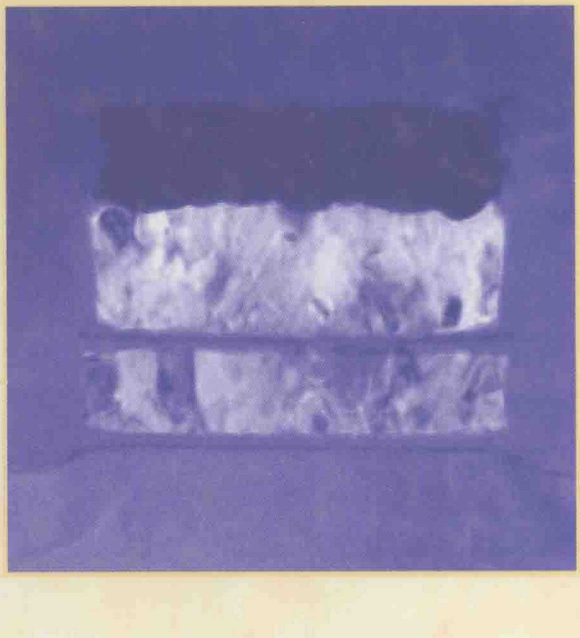
SEMICONDUCTOR DEVICES

Physics and Technology

2nd Edition



S.M. Sze

2ND EDITION

Semiconductor Devices

Physics and Technology

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JOHN WILEY & SONS, INC.

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Production Management Services *Argosy Publishing Services*

Cover Photography: A transmission-electron micrograph of a floating-gate nonvolatile semiconductor memory with a magnification of 100,000 times. (Photography courtesy of George T. T. Sheng.) For a discussion of the device, see Chapters 1, 6, and 14.

This book was typeset in *New Caledonia* by *Argosy Publishing* and printed and bound by *R. R. Donnelley and Sons, Inc. (Willard)*. The cover was printed by *The Lehigh Press*.

The paper in this book was manufactured by a mill whose forest management programs include sustained yield harvesting of its timberlands. Sustained yield harvesting principles ensure that the number of trees cut each year does not exceed the amount of new growth.

The book is printed on acid-free paper. ∞

Library of Congress Cataloging in Publication Data:
Sze, S. M., 1936-
Semiconductor devices, physics and technology/S.M. Sze.—2nd ed.
p. cm.
Includes bibliographical references and index.
ISBN 0-471-33372-7 (cloth: alk. paper)
1. Semiconductors. I. Title.
TK7871.85 .S9883 2001

621.3815'2—dc21

2001026003

ISBN 0-471-33372-7

Printed in the United States of America

10 9 8 7 6 5 4

In Memory of My Mentors

Dr. L. J. Chu	*Academia Sinica*
Dr. R. M. Ryder	*Bell Laboratories*

Preface

The book is an introduction to the physical principles of modern semiconductor devices and their advanced fabrication technology. It is intended as a textbook for undergraduate students in applied physics, electrical and electronics engineering, and materials science. It can also serve as a reference for practicing engineers and scientists who need an update on device and technology developments.

WHAT'S NEW IN THE SECOND EDITION

- 50% of the material has been revised or updated. We have added many sections that are of contemporary interest such as flash memory, Pentium chips, copper metallization, and eximer-laser lithography. On the other hand, we have omitted or reduced sections of less important topics to maintain the overall book length.
- We have also made substantial changes in updating the pedagogy. We have adopted a two-color format for all illustrations to enhance their presentation; and all important equations are boxed.
- All device and material parameters have been updated or corrected . For example, the intrinsic carrier concentration in silicon at 300K is 9.65×10^9 cm^{-3}, replacing the old value of 1.45×10^{10} cm^{-3}. This single change has an impact on at least 30% of the problem solutions.
- To improve the development of each subject, sections that contain graduate-level mathematics or physical concepts have been omitted or moved to the Appendixes, at the back of the book.

TOPICAL COVERAGE

- Chapter 1 gives a brief historical review of major semiconductor devices and key technology developments. The text is then organized into three parts.
- Part I, Chapters 2–3, describes the basic properties of semiconductors and their conduction processes, with special emphasis on the two most important semiconductors: silicon (Si) and gallium arsenide (GaAs). The concepts in Part I will be used throughout this book. These concepts requires a background knowledge of modern physics and college calculus.
- Part II, Chapters 4–9, discusses the physics and characteristics of all major semiconductor devices. We begin with the *p–n* junction which is the key building block of most semiconductor devices. We proceed to bipolar and field-effect devices and then cover microwave, quantum-effect, hot-electron, and photonic devices.
- Part III, Chapters 10–14, deals with processing technology from crystal growth to impurity doping. We present the theoretical and practical aspects of the major steps in device fabrication with an emphasis on integrated devices.

KEY FEATURES

Each chapter includes the following features:

- The chapter starts with an overview of the topical contents. A list of learning goals is also provided.
- The second edition has tripled the worked-out examples that apply basic concepts to specific problems.
- A chapter summary appears at the end of each chapter to summarize the important concepts and to help the student review the content before tackling the homework problems that follow.
- The book includes about 250 homework problems, over 50% of them new to the second edition. Answers to odd-numbered problems, which have numerical solutions are provided in Appendix L at the back of the book.

COURSE DESIGN OPTIONS

The second edition can provide greater flexibility in course design. The book contains enough material for a full-year sequence in device physics and processing technology. Assuming three lectures per week, a two-semester sequence can cover Chapters 1–7 in the first semester, leaving Chapters 8–14 for the second semester. For a three-quarter sequence, the logical break points are Chapters 1–5, Chapters 6-9, and Chapters 10–14.

A two-quarter sequence can cover Chapters 1–5 in the first quarter. The instructor has several options for the second quarter. For example, covering Chapters 6, 11, 12, 13, and 14 produces a strong emphasis on the MOSFET and its related process technologies, while covering Chapters 6–9 emphasizes all major devices. For a one-quarter course on semiconductor device processing, the instructor can cover Section 1.2 and Chapters 10–14.

A one-semester course on basic semiconductor physics and devices can cover Chapters 1–7. A one-semester course on microwave and photonic devices can cover Chapters 1–4, 7–9. If the students already have some familiarity with semiconductor fundamentals, a one-semester course on Submicron MOSFET: Physics and Technology can cover Chapters 1, 6, 10–14. Of course, there are many other course design options depending on the teaching schedule and the instructor's choice of topics.

TEXTBOOK SUPPLEMENTS

- Instructor's Manual. A complete set of detailed solutions to all the end-of-chapter problems has been prepared. These solutions are available free to all adopting faculty.
- The figures used in the text are available, in electronic format, to instructors from the publisher. Instructors can find out more information at the publisher's website at: http: //www.wiley.com/college/sze

Acknowledgments

Many people have assisted me in revising this book. I would first like to express my deep appreciation to my colleagues at the National Nano Device Laboratories for their contributions in improving the content of the text, in suggesting state-of-the-art illustrations, and in providing homework problems and solutions: Dr. S. F. Hu on Chapter 2, Dr. W. F. Wu on Chapter 3, Dr. S. H. Chan on Chapter 4, Dr. T. B. Chiou on Chapter 5, Dr. H. C. Lin on Chapter 6, Dr. J. S. Tsang on Chapter 7, Dr. G. W. Huang on Chapter 8, Dr. J. D. Guo on Chapter 9, Dr. S. C. Wu on Chapter 10, Dr. T. C. Chang on Chapter 11, Drs. M. C. Liaw and M. C. Chiang on Chapter 12, Dr. F. H. Ko on Chapter 13, and Dr. T. S. Chao on Chapter 14.

I have benefited significantly from suggestions made by the reviewers: Profs. C. Y. Chang, C. H. Chen, T. Y. Huang, B. Y. Tsui, and T. J. Yang of the National Chiao Tung University, Profs. Y. C. Chen and M. K. Lee of the National Sun Yet-sen University, Prof. C. S. Lai of the Chang Gung University, Prof. W. Y. Liang of the University of Cambridge, Dr. K. K. Ng of Bell Laboratories, Lucent Technologies, Prof. W. J. Tseng of the National Cheng Kung University, Prof. T. C. Wei of the Chung Yuan University, Prof. Y. S. G. Wu of the National Tsing Hwa University, Dr. C. C. Yang of the National Nano Device Laboratories, Prof. W. L. Yang of Feng Chia University, and Dr. A. Yen of the Taiwan Semiconductor Manufacturing Company.

I am further indebted to Mr. N. Erdos for technical editing of the manuscript, Ms. Iris Lin for typing the many revisions of the draft and the final manuscript, and Ms. Y. G. Yang of the Semiconductor Laboratory, the National Chiao Tung University who furnished the hundreds of technical illustrations used in the book. In each case where an illustration was used from another published source, I have received permission from the copyright holder. Even through all illustrations were then adopted and redrawn, I appreciate being granted these permissions. I wish to thank Mr. George T. T. Sheng of the Macronix International Company for providing the flash-memory transmission electron micrography, which is shown in the cover design. I wish also to thank Mr. A. Mutlu, Mr. S. Short, and Ms. R. Steward of Intel Corporation for providing the photographs of the first microprocessor (Intel 4004) and its latest version (Pentium 4).

At John Wiley and Sons, I wish to thank Mr. G. Telecki and Mr. W. Zobrist who encouraged me to undertake the project. I wish also to acknowledge the Spring Foundation of the National Chiao Tung University for the financial support. I would especially like to thank the United Microelectronics Corporation (UMC), Taiwan, ROC, for the UMC Chair Professorship grant that provided the environment to work on this book.

Finally, I am grateful to my wife Therese for her continued support and assistance in this and many previous book projects. I also like to thank my son Raymond (Doctor of Medicine) and my daughter-in-law Karen (Doctor of Medicine), and my daughter Julia (Certified Financial Analyst) and my son-in-law Bob (President, Cameron Global Investment, LLC), who have helped me in their capacities as my medical advisors and financial advisors, respectively.

S. M. Sze
Hsinchu, Taiwan
March 2001

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CHAPTER 1

Introduction

As an undergraduate in applied physics, electrical engineering, electronics engineering, or materials science, you might ask why you need to study semiconductor devices. The reason is that semiconductor devices are the foundation of the electronic industry, which is the largest industry in the world with global sales over one trillion dollars since 1998. A basic knowledge of semiconductor devices is essential to the understanding of advanced courses in electronics. This knowledge will also enable you to contribute to the Information Age, which is based on electronic technology.

Specifically, we cover the following topics:

- Four building blocks of semiconductor devices.
- Eighteen important semiconductor devices and their roles in electronic applications.
- Twenty important semiconductor technologies and their roles in device processing.
- Technology trends toward high-density, high-speed, low-power consumption, and nonvolatility.

1.1 SEMICONDUCTOR DEVICES

Figure 1 shows the sales volume of the semiconductor-device–based electronic industry in the past 20 years and projects sales to the year 2010. Also shown are the gross world product (GWP) and the sales volumes of automobile, steel, and semiconductor industries.[1,2] We note that the electronic industry has surpassed the automobile industry in 1998. If the current trends continue, in year 2010 the sales volume of the electronic industry will reach three trillion dollars and will constitute about 10% of GWP. The semiconductor industry, which is a subset of the electronic industry, will grow at an even higher rate to surpass the steel industry in the early twenty-first century and to constitute 25% of the electronic industry in 2010.

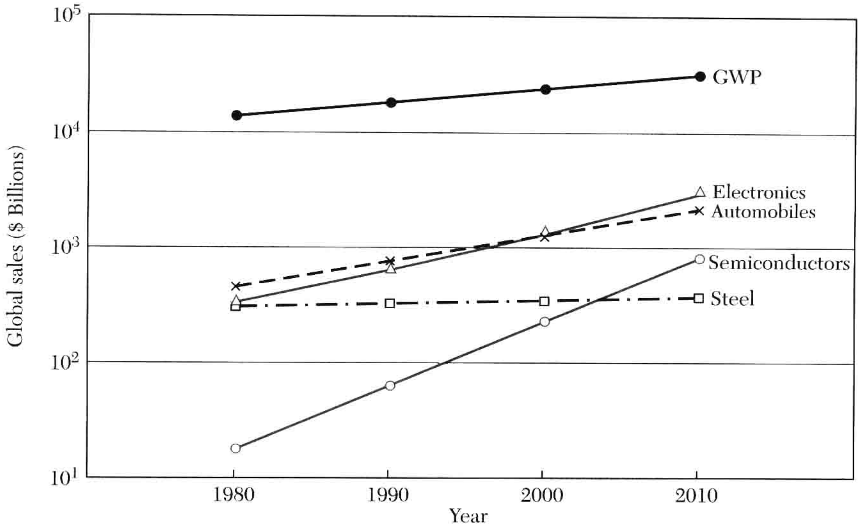

Fig. 1 Gross world product (GWP) and sales volumes of the electronics, automobile, semiconductor, and steel industries from 1980 to 2000 and projected to 2010.[1,2]

1.1.1 Device Building Blocks

Semiconductor devices have been studied for over 125 years.[3] To date, we have about 60 major devices, with over 100 device variations related to them.[4] However, all these devices can be constructed from a small number of device building blocks.

Figure 2*a* is the metal-semiconductor interface, which is an intimate contact between a metal and a semiconductor. This building block was the first semiconductor device ever studied (in the year 1874). This interface can be used as a rectifying contact, that is, the device allows electrical current to flow easily only in one direction, or as an ohmic contact, which can pass current in either direction with a negligibly small voltage drop. We can use this interface to form many useful devices. For example, by using a rectifying contact as the *gate*[*] and two ohmic contacts as the *source* and *drain*, we can form a *MESFET* (metal-semiconductor field-effect transistor), an important microwave device.

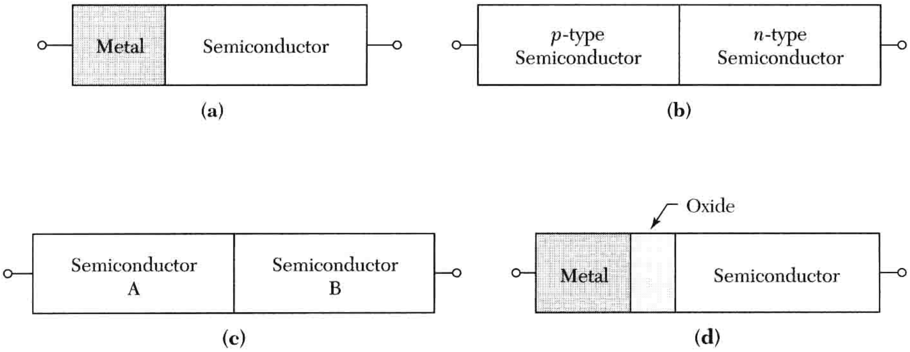

Fig. 2 Basic device building blocks. (*a*) Metal-semiconductor interface; (*b*) *p*–*n* junction; (*c*) heterojunction interface; and (*d*) metal-oxide-semiconductor structure.

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[*] The italicized terms in this paragraph and in subsequent paragraphs are defined and explained in Part II of the book.

The second building block is the *p–n* junction (Fig. 2*b*), which is formed between a *p- type* (with positively charged carriers) and an *n-type* (with negatively charged carriers) semiconductors. The *p–n* junction is a key building block for most semiconductor devices, and *p–n* junction theory serves as the foundation of the physics of semiconductor devices. By combining two *p–n* junctions, that is, by adding another *p*-type semiconductor, we form the *p–n–p bipolar transistor*, which was invented in 1947 and had an unprecedented impact on the electronic industry. If we combine three *p–n* junctions to form a *p–n–p–n* structure, it is a switching device called a *thyristor*.

The third building block (Fig. 2*c*) is the heterojunction interface, that is, an interface formed between two dissimilar semiconductors. For example, we can use *gallium arsenide* (GaAs) and *aluminum arsenide* (AlAs) to form a heterojunction. Heterojunctions are the key components for high-speed and photonic devices.

Figure 2*d* shows the metal-oxide-semiconductor (MOS) structure. The structure can be considered a combination of a metal-oxide interface and an oxide-semiconductor interface. By using the MOS structure as the gate and two *p–n* junctions as the source and drain, we can form a *MOSFET* (MOS field-effect transistor). The MOSFET is the most important device for advanced *integrated circuits*, which contains tens of thousands of devices per integrated circuit chip.

1.1.2 Major Semiconductor Devices

Some major semiconductor devices are listed in Table 1 in chronological order; those with a superscript *b* are two-terminal devices, otherwise they are three-terminal or four-terminal devices.[3] The earliest systematic study of semiconductor devices (metal-semiconductor contacts) is generally attributed to Braun,[5] who in 1874 discovered that the resistance of contacts between metals and metal sulfides (e.g., copper pyrite) depended on the magnitude and polarity of the applied voltage. The electroluminescence phenomenon (for the *light-emitting diode*) was discovered by Round[6] in 1907. He observed the generation of yellowish light from a crystal of carborundom when he applied a potential of 10 V between two points on the crystals.

TABLE 1 Major Semiconductor Devices

Year	Semiconductor Device[a]	Author(s)/Inventor(s)	Ref.
1874	Metal-semiconductor contact[b]	Braun	5
1907	Light emitting diode[b]	Round	6
1947	Bipolar transistor	Bardeen, Brattain, and Shockley	7
1949	*p–n* junction[b]	Shockley	8
1952	Thyristor	Ebers	9
1954	Solar cell[b]	Chapin, Fuller, and Pearson	10
1957	Heterojunction bipolar transistor	Kroemer	11
1958	Tunnel diode[b]	Esaki	12
1960	MOSFET	Kahng and Atalla	13
1962	Laser[b]	Hall et al	15
1963	Heterostructure laser[b]	Kroemer, Alferov and Kazarinov	16,17
1963	Transferred-electron diode[b]	Gunn	18
1965	IMPATT diode[b]	Johnston, DeLoach, and Cohen	19

(continued)

TABLE 1 *(continued)*

Year	Semiconductor Device[a]	Author(s)/Inventor(s)	Ref.
1966	MESFET	Mead	20
1967	Nonvolatile semiconductor memory	Kahng and Sze	21
1970	Charge-coupled device	Boyle and Smith	23
1974	Resonant tunneling diode[b]	Chang, Esaki, and Tsu	24
1980	MODFET	Mimura et al.	25
1994	Room-temperature single-electron memory cell	Yano et al.	22
2001	20 nm MOSFET	Chau	14

[a] MOSFET, metal-oxide-semiconductor field-effect transistor; MESFET, metal-semiconductor field-effect transistor; MODFET, modulation-doped field-effect transistor.

[b] Denotes a two-terminal device, otherwise it is a three- or four-terminal device.

In 1947, the point-contact transistor was invented by Bardeen and Brattain.[7] This was followed by Shockley's[8] classic paper on *p–n* junction and bipolar transistor in 1949. Figure 3 shows the first transistor. The two point contacts at the bottom of the triangular quartz crystal were made from two stripes of gold foil separated by about 50 μm ($1 \mu m = 10^{-4}$ cm) and pressed onto a semiconductor surface. The semiconductor used was germanium. With one gold contact forward biased, that is, positive voltage with respect to the third terminal, and the other reverse biased, the *transistor action* was observed, that is, the input signal was amplified. The bipolar transistor is a key semiconductor device and has ushered in the modern electronic era.

In 1952, Ebers[9] developed the basic model for the thyristor, which is an extremely versatile switching device. The *solar cell* was developed by Chapin, et al.[10] in 1954 using a silicon *p–n* junction. The solar cell is a major candidate for obtaining energy from the sun because it can convert sunlight directly to electricity and is environmentally benign. In 1957, Kroemer[11] proposed the heterojunction bipolar transistor to improve the transistor performance; this device is potentially one of the fastest semiconductor devices. In 1958, Esaki[12] observed negative resistance characteristics in a heavily doped *p–n* junction, which led to the discovery of the *tunnel diode*. The tunnel diode and its associated tunneling phenomenon are important for ohmic contacts and carrier transport through thin layers.

The most important device for advanced integrated circuits is the MOSFET, which was reported by Kahng and Atalla[13] in 1960. Figure 4 shows the first device using a thermally oxidized silicon substrate. The device has a gate length of 20 μm and a gate oxide thickness of 100 nm ($1 \text{ nm} = 10^{-7}$ cm). The two keyholes are the source and drain contacts, and the top elongated area is the aluminum gate evaporated through a metal mask. Although present-day MOSFETs have been scaled down to the deep-submicron regime, the choice of silicon and thermally grown silicon dioxide used in the first MOSFET remains the most important combination of materials. The MOSFET and its related integrated circuits now constitute about 90% of the semiconductor device market. An ultrasmall MOSFET with a channel length of 20 nm has been demonstrated recently.[14] This device can serve as the basis for the most advanced integrated circuit chips containing over one trillion ($>10^{12}$) devices.

In 1962, Hall et al.[15] first achieved lasing in semiconductors. In 1963, Kroemer[16] and Alferov and Kazarinov[17] proposed the *heterostructure laser*. These proposals laid the foundation for modern laser diodes, which can be operated continuously at room temperature. Laser diodes are the key components for a wide range of applications, including

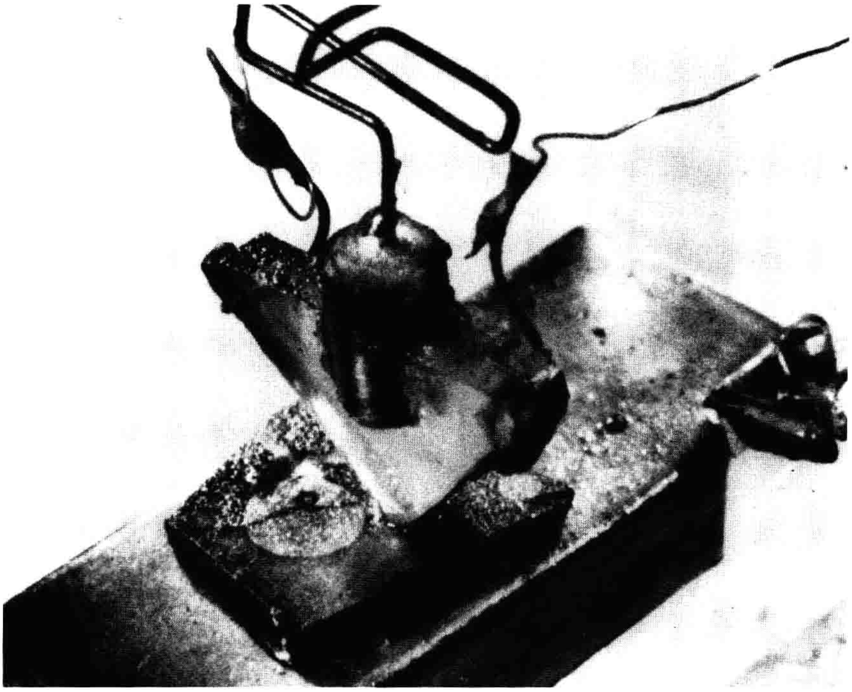

Fig. 3 The first transistor.[7] (Photograph courtesy of Bell Laboratories.)

Fig. 4 The first metal-oxide-semiconductor field-effect transistor.[13] (Photograph courtesy of Bell Laboratories.)

digital video disk, optical-fiber communication, laser printing, and atmospheric–pollution monitoring.

Three important microwave devices were invented or realized in the next 3 years. The first device is the *transferred-electron diode* (TED; also called Gunn diode) by Gunn[18] in 1963. The TED is used extensively in such millimeter-wave applications as detection systems, remote controls, and microwave test instruments. The second device is the *IMPATT diode*; its operation was first observed by Johnston et al.[19] in 1965. IMPATT diodes can generate the highest continuous wave (CW) power at millimeter-wave frequencies of all semiconductor devices. They are used in radar systems and alarm systems. The third device is the MESFET, invented by Mead[20] in 1966. It is a key device for monolithic microwave integrated circuits (MMIC).

An important semiconductor memory device was invented by Kahng and Sze[21] in 1967. This is the *nonvolatile semiconductor memory* (NVSM), which can retain its stored information when the power supply is switched off. A schematic diagram of the first NVSM is shown in Fig.5*a*. Although it is similar to a conventional MOSFET, the major difference is the addition of the *floating gate*, in which semipermanent charge storage is possible. Because of its attributes of nonvolatility, high device density, low-power consumption, and electrical rewritability (e.g., the stored charge can be removed by applying voltage to the control gate), NVSM has become the dominant memory for portable electronic systems such as the cellular phone, notebook computer, digital camera, and smart card.

A limiting case of the floating-gate nonvolatile memory is the *single-electron memory cell* (SEMC) shown in Fig.5*b*. By reducing the length of the floating gate to ultra-

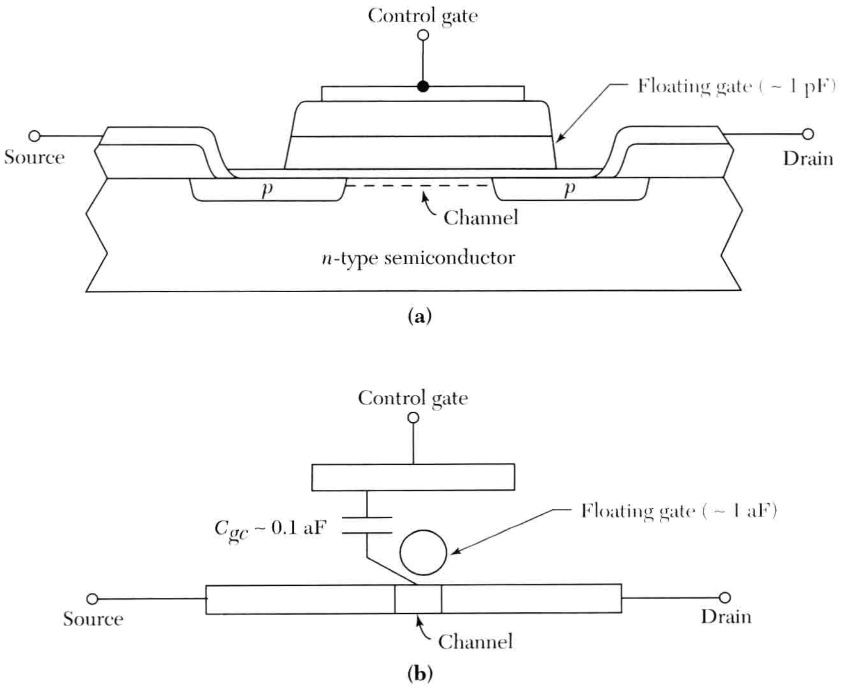

Fig. 5 (*a*) A schematic diagram of the first nonvolatile semiconductor memory (NVSM) with a floating gate.[21] (*b*) A limiting case of the floating-gate NVSM—the single-electron memory cell.[22]

small dimensions (e.g., 10 nm), we obtain the SEMC. At this dimension, when an electron moves into the floating gate, the potential of the gate will be altered so that it will prevent the entrance of another electron. The SEMC is an ultimate floating-gate memory cell, since we need only one electron for information storage. The operation of a SEMC at room temperature was first demonstrated by Yano et al.[22] in 1994. The SEMC can serve as the basis for the most advanced semiconductor memories that can contain over one trillion bits.

The *charge-coupled device* (CCD) was invented by Boyle and Smith[23] in 1970. CCD is used extensively in video cameras and in optical sensing applications. The resonant tunneling diode (RTD) was first studied by Chang et al.[24] in 1974. RTD is the basis for most quantum-effect devices, which offer extremely high density, ultrahigh speed, and enhanced functionality because it permits a greatly reduced number of devices to perform a given circuit function. In 1980, Minura et al.[25] developed the *MODFET* (modulation-doped field-effect transistor). With the proper selection of heterojunction materials, the MODFET is expected to be the fastest field-effect transistor.

Since the invention of the bipolar transistor in 1947, the number and variety of semiconductor devices have increased tremendously as advanced technology, new materials, and broadened comprehension have been applied to the creation of new devices. In Part II of the book, we consider all the devices listed in Table 1. It is hoped that this book can serve as a basis for understanding other devices not included here and perhaps not even conceived of at the present time.

1.2 SEMICONDUCTOR TECHNOLOGY

1.2.1 Key Semiconductor Technologies

Many important semiconductor technologies have been derived from processes invented centuries ago. For example, the lithography process was invented in 1798; in this first process, the pattern, or image, was transferred from a stone plate (litho).[26] In this section, we consider the milestones of technologies that were applied for the first time to semiconductor processing or developed specifically for semiconductor-device fabrication.

Some key semiconductor technologies are listed in Table 2 in chronological order. In 1918, Czochralski[27] developed a liquid-solid monocomponent growth technique. The Czochralski growth is the process used to grow most of the crystals from which silicon wafers are produced. Another growth technique was developed by Bridgman[28] in 1925. The Bridgman technique has been used extensively for the growth of gallium arsenide and related compound semiconductor crystals. Although the semiconductor properties of silicon have been widely studied since early 1940, the study of semiconductor compounds was neglected for a long time. In 1952, Welker[29] noted that gallium arsenide and its related III–V compounds were semiconductors. He was able to predict their characteristics and to prove them experimentally. The technology and devices of these compounds have since been actively studied.

The diffusion of impurity atoms in semiconductors is important for device processing. The basic diffusion theory was considered by Fick[30] in 1855. The idea of using diffusion techniques to alter the type of conductivity in silicon was disclosed in a patent in 1952 by Pfann.[31] In 1957, the ancient lithography process was applied to semiconductor-device fabrication by Andrus.[32] He used photosensitive etch-resistant polymers (photoresist) for pattern transfer. Lithography is a key technology for the semiconductor industry. The continued growth of the industry has been the direct result of improved lithographic technology. Lithography is also a significant economic factor, currently representing over 35% of the integrated-circuit manufacturing cost.

TABLE 2 Key Semiconductor Technologies

Year	Technology[a]	Author(s)/Inventor(s)	Ref.
1918	Czochralski crystal growth	Czochralski	27
1925	Bridgman crystal growth	Bridgman	28
1952	III-V compounds	Welker	29
1952	Diffusion	Pfann	31
1957	Lithographic photoresist	Andrus	32
1957	Oxide masking	Frosch and Derrick	33
1957	Epitaxial CVD growth	Sheftal, Kokorish, and Krasilov	34
1958	Ion implantation	Shockley	35
1959	Hybrid integrated circuit	Kilby	36
1959	Monolithic integrated circuit	Noyce	37
1960	Planar process	Hoerni	38
1963	CMOS	Wanlass and Sah	39
1967	DRAM	Dennard	40
1969	Polysilicon self-aligned gate	Kerwin, Klein, and Sarace	41
1969	MOCVD	Manasevit and Simpson	42
1971	Dry etching	Irving, Lemons, and Bobos	43
1971	Molecular beam epitaxy	Cho	44
1971	Microprocessor (4004)	Hoff et al.	45
1982	Trench isolation	Rung, Momose, and Nagakubo	46
1989	Chemical mechanical polishing	Davari et al.	47
1993	Copper interconnect	Paraszczak et al.	48

[a] CVD, chemical vapor deposition; CMOS, complementary metal-oxide-semiconductor field-effect transistor; DRAM, dynamic random access memory; MOCVD, metalorganic CVD.

The oxide masking method was developed by Frosch and Derrick[33] in 1957. They found that an oxide layer can prevent most impurity atoms from diffusing through it. In the same year, the epitaxial growth process based on chemical vapor deposition technique was developed by Sheftal et al.[34] Epitaxy, derived from the Greek word epi, meaning on, and taxis, meaning arrangement, describes a technique of crystal growth to form a thin layer of semiconductor materials on the surface of a crystal that has a lattice structure identical to that of the crystal. This method is important for the improvement of device performance and the creation of novel device structures.

In 1958, Shockley[35] proposed the method of using ion implantation to dope the semiconductors. Ion implantation has the capability of precisely controlling the number of implanted dopant atoms. Diffusion and ion implantation can complement each other for impurity doping. For example, diffusion can be used for high-temperature, deep-junction processes, whereas ion implantation can be used for lower-temperature, shallow-junction processes.

In 1959, a rudimentary integrated circuit (IC) was made by Kilby.[36] It contained one bipolar transistor, three resistors, and one capacitor, all made in germanium and connected by wire bonding—a hybrid circuit. Also in 1959, Noyce[37] proposed the monolithic IC by fabricating all devices in a single semiconductor substrate (monolith means single stone) and connecting the devices by aluminum metallization. Figure 6 shows the first monolithic IC of a flip-flop circuit containing six devices. The aluminum interconnection lines were obtained by etching evaporated aluminum layer over the entire oxide surface using the lithographic technique. These inventions laid the foundation for the rapid growth of the microelectronics industry.