Physics of Semiconductor Devices

SECOND EDITION

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Bell Laboratories, Incorporated
Murray Hill, New Jersey

A WILEY-INTERSCIENCE PUBLICATION

JOHN WILEY & SONS

New York • Chichester • Brisbane • Toronto • Singapore

Library of Congress Cataloging in Publication Data:

Sze, S. M., 1936-
Physics of semiconductor devices.

"A Wiley-Interscience publication."
Includes index.
1. Semiconductors. I. Title.

TK7871.85.S988 1981 537.6'22 81-213
ISBN 0-471-05661-8 AACR2

Printed in the United States of America

10 9 8 7 6 5 4 3

Preface

Since the invention of the bipolar transistor in 1947, the semiconductor device field has grown rapidly. Coincident with this growth, semiconductor-device literature has also burgeoned and diversified. For access to this massive amount of information, there is a need for a book giving a comprehensive introductory account of device physics and operational principles, with references. In 1969, the first edition of *Physics of Semiconductor Devices* was published with the intention of meeting such a need. It is perhaps somewhat surprising that the book has so long held its place as one of the main textbooks for advanced undergraduate and graduate courses, and as a major reference for scientists in semiconductor-device research and development.

In the last decade, more than 40,000 papers on semiconductor devices have been published, with numerous breakthroughs in device concepts and performance. The book clearly needed substantial revision if it were to continue to serve its purpose. In the second edition of *Physics of Semiconductor Devices*, 80 percent of the material has been revised or updated, and the material has been totally reorganized. About 1,000 references have been cited, of which 70 percent were published in the last decade, and over 600 technical illustrations are included, of which 65 percent are new.

Most of the important semiconductor devices are included, and they are divided into four groups: bipolar, unipolar, microwave, and photonic devices. A brief historical review is given in the introduction to each chapter. Subsequent sections present the physics and mathematical formulations of the devices. The sections are arranged in a logical sequence without heavy reliance on the original papers. Each chapter is more or less independent of the other chapters, so readers can use the book as a reference and instructors can rearrange the device chapters or select ones appropriate for their classes.

In the course of the writing many people have assisted me and offered their support. I would like, first, to express my appreciation to the management of Bell Laboratories for providing the environment in which I worked on the book; without their support this book could not have been

written. I have benefited significantly from the suggestions of the reviewers: Drs. J. M. Andrews, D. E. Aspnes, W. E. Beadle, J. R. Brews, H. J. Boll, C. C. Chen, W. Fichtner, H. Fukui, H. K. Gummel, D. Kahng, T. P. Lee, M. P. Lepselter, E. H. Nicollian, W. C. Niehaus, P. T. Panousis, T. Paoli, R. M. Ryder, M. Shoji, G. E. Smith, K. K. Thornber, and S. H. Wemple of Bell Laboratories; Professors H. C. Casey, Duke University, C. R. Crowell, University of Southern California, W. S. Feng, National Taiwan University, S. K. Ghandhi, Rensselaer Polytechnic Institute, H. Kroemer, University of California, M. Lampert, Princeton University, H. Melchior, Swiss Federal Institute of Technology, R. H. Rediker, Massachusetts Institute of Technology, and H. W. Thim, Technical University of Vienna; and Drs. L. L. Chang, IBM Corporation, G. Gibbons, Plessey Research Limited, and R. N. Hall, General Electric Company.

I am further indebted to Ms. D. McGrew, Ms. J. Chee, Ms. K. R. Funk, and Mr. M. Lynch for technical editing of the entire manuscript, to Messrs. E. Labate, B. A. Stevens, and H. H. Teitelbaum for their literature searches, and to Ms. A. W. Talcott for providing more than five thousand technical papers on semiconductor devices cataloged at the Murray Hill Library of Bell Laboratories. Thanks are also due Mr. W. H. Shafer of the Center for Information and Numerical Data Analysis and Synthesis (CINDAS), Purdue University, for providing up-to-date references on semiconductor properties. I wish to thank Ms. J. T. McCarthy and Ms. V. J. Maye, who typed various sections of the book in its revision stage, and Mr. G. Holmfelt and members of the Drafting Department of Bell Laboratories, who furnished hundreds of technical illustrations used in this book. In each case where an illustration was used from another published source, I have applied for and received permission from the copyright holder even though all illustrations were then adapted and redrawn. I appreciate being granted these permissions. At my publishers, John Wiley and Sons, I want to acknowledge Mr. G. Novotny who encouraged me to undertake this new edition, and Ms. V. Aldzeris, Ms. R. Farkas and Mr. R. Fletcher who handled the production of this book. Finally, I wish especially to thank my wife Therese Ling-yi, my son Raymond, and my daughter Julia for their assistance in many ways, including typing the first draft and preparing the final manuscript.

S. M. SZE

Murray Hill, New Jersey
May 1981

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Introduction

The book is divided into five parts:

Part 1: résumé of physics and properties of semiconductors
Part 2: bipolar devices
Part 3: unipolar devices
Part 4: microwave devices
Part 5: photonic devices

Part 1, Chapter 1, is intended as a summary of materials properties, to be used throughout the book as a basis for understanding and calculating device characteristics. Energy-band, carrier distribution, and transport properties are briefly surveyed, with emphasis on the three most important semiconductors: germanium (Ge), silicon (Si), and gallium arsenide (GaAs). A compilation of the recommended or the most accurate values for these semiconductors is given in the illustrations of Chapter 1 and in the appendixes for convenient reference.

Part 2, Chapters 2 through 4, treats bipolar devices in which both electrons and holes are involved in the transport processes. The basic device technology and *p-n* junction characteristics are considered in Chapter 2. Because the *p-n* junction is the building block of most semiconductor devices, the *p-n* junction theory serves as the foundation of the physics of semiconductor devices. Chapter 3 treats the bipolar transistor, that is, the interaction between two closely coupled *p-n* junctions. The bipolar transistor is one of the most important semiconductor devices. The invention of the bipolar transistor in 1947 was the beginning of the modern electronics era. The thyristor, which is basically three closely coupled *p-n* junctions in the form of a *p-n-p-n* structure, is discussed in Chapter 4. Thyristors have a wide range of power-handling capability; they can handle currents from a few milliamperes to thousands of amperes and voltages extending above 5000 V.

Part 3, Chapters 5 through 8, deals with unipolar devices in which only one type of carrier predominantly participates in the conduction mechanism. The metal–semiconductor contact, in Chapter 5, is electrically similar to a one-sided abrupt *p-n* junction, yet it can be operated as a majority-carrier device with inherent fast response. The metal–semiconductor contact on heavily doped semiconductors constitutes the most important form of ohmic contacts. The junction field-effect transistor (JFET) and metal–semiconductor field-effect transistor (MESFET), described in Chapter 6, are generically similar devices. Both utilize the electric field to control a current flow that is parallel to the junction rather than perpendicular to it. The surface physics and metal–oxide–semiconductor (MOS) devices are considered in Chapters 7 and 8. A knowledge of the 'interface traps" associated with these devices is important not only because of the devices themselves but also because of their relevance to the stability and reliability of all other semiconductor devices. The charge-coupled device (CCD), which is especially useful for signal processing and image sensing, is formed using closely coupled MOS capacitors. The metal–oxide–semiconductor field-effect transistor (MOSFET), discussed in Chapter 8, is the most important device for very-large-scale integrated (VLSI) circuits. MOSFETs are used extensively in semiconductor memories and microprocessors having thousands of individual components per chip.

Part 4, Chapters 9 through 11, considers some special microwave devices. When a *p-n* junction is doped so heavily on both sides that the field becomes sufficiently high for quantum-mechanical tunneling, the interesting features of tunnel diode behavior are seen (Chapter 9). When a *p-n* junction or a metal–semiconductor contact is operated in avalanche breakdown, under proper conditions we have an IMPATT diode that can generate microwave radiation. The operational characteristics of IMPATT diodes and some related devices are presented in Chapter 10. Microwave oscillation can be generated by the mechanism of electron transfer from a high-mobility lower-energy valley in the conduction band to a low-mobility higher-energy valley. The transferred-electron device is considered in Chapter 11.

Part 5, Chapters 12 through 14, deals with photonic devices that can detect, generate, and convert optical energy to electric energy, or vice versa. The light-emitting diode (LED) and semiconductor laser are discussed in Chapter 12. Both devices are important sources for optical-fiber communication systems. Various photodetectors with high quantum efficiency and high response speed are discussed in Chapter 13. As the worldwide energy demand increases, there is a need to develop alternative energy sources. The solar cell is considered a major candidate because it can convert sunlight directly to electricity with high efficiency. Various configurations of solar cells and their operational characteristics are considered in Chapter 14.

A remark on notation: To keep the notation simple, it is necessary to use the simple symbols more than once, with different meanings for different devices. For example, the symbol α is used as the common-base current gain for a bipolar transistor, as the optical absorption coefficient for a photodetector, and as the impact ionization coefficient for an IMPATT diode. This usage is considered preferable to the alternative, which would be to use alpha only once and then be forced to find more complicated symbols for the other uses. Within each chapter, however, each symbol is used with only one meaning and is defined the first time it appears. Many symbols do have the same or similar meanings consistently throughout this book; they are summarized in Appendix A for convenient reference.

At present, the electronics field in general and the semiconductor-device field in particular are so dynamic and so fast-changing that today's concepts may be obsolete tomorrow. It is therefore important for us to understand the fundamental physical processes and to equip ourselves with sufficient background in physics and mathematics to digest, appreciate, and meet the challenge of these dynamic fields. It is important to point out that many of the devices, especially the unipolar devices and photonic devices, are still under intensive investigation.[1] Their ultimate performance is by no means fully understood at the present time. The material presented in this book is intended to serve as a foundation. The references listed at the end of each chapter can supply more information.

REFERENCE

1 S. M. Sze, "Semiconductor Device Development in the 1970s and 1980s—A Perspective," Proc. IEEE, *69*, 1121 (1981).

PART I

SEMICONDUCTOR PHYSICS

- Physics and Properties of Semiconductors—A Résumé

原书缺页

原书缺页

1

Physics and Properties of Semiconductors—A Résumé

- INTRODUCTION
- CRYSTAL STRUCTURE
- ENERGY BANDS
- CARRIER CONCENTRATION AT THERMAL EQUILIBRIUM
- CARRIER TRANSPORT PHENOMENA
- PHONON SPECTRA AND OPTICAL, THERMAL, AND HIGH-FIELD PROPERTIES OF SEMICONDUCTORS
- BASIC EQUATIONS FOR SEMICONDUCTOR-DEVICE OPERATION

1.1 INTRODUCTION

The physics of semiconductor devices is naturally dependent on the physics of semiconductors themselves. This chapter presents a summary of the physics and properties of semiconductors. It represents only a small cross section of the vast literature on semiconductors; only those subjects pertinent to device operations are included here.

For detailed consideration of semiconductor physics, the reader should consult the standard textbooks or reference works by Dunlap,[1] Madelung,[2] Moll,[3] Moss,[4] and Smith.[5]

To condense a large amount of information into a single chapter, three tables and over 30 illustrations drawn from experimental data are compiled and presented here. This chapter emphasizes the three most important semiconductors: germanium (Ge), silicon (Si), and gallium arsenide (GaAs).

Germanium and silicon have been studied extensively. Gallium arsenide has been intensively investigated in recent years. It has different properties than germanium and silicon; particular properties studied are its direct bandgap for photonic application and its intervalley-carrier transport and high mobility for generation of microwaves.

1.2 CRYSTAL STRUCTURE

Three primitive basis vectors, **a**, **b**, and **c**, describe a crystalline solid such that the crystal structure remains invariant under translation through any vector that is the sum of integral multiples of these basis vectors. In other words, the direct lattice sites can be defined by the set[6]

$$\mathbf{R} = m\mathbf{a} + n\mathbf{b} + p\mathbf{c} \tag{1}$$

where m, n, and p are integers.

Figure 1 shows some important unit cells (direct lattices). A great many important semiconductors have diamond or zincblende lattice structures which belong to the tetrahedral phases; that is, each atom is surrounded by four equidistant nearest neighbors which lie at the corners of a tetrahedron.

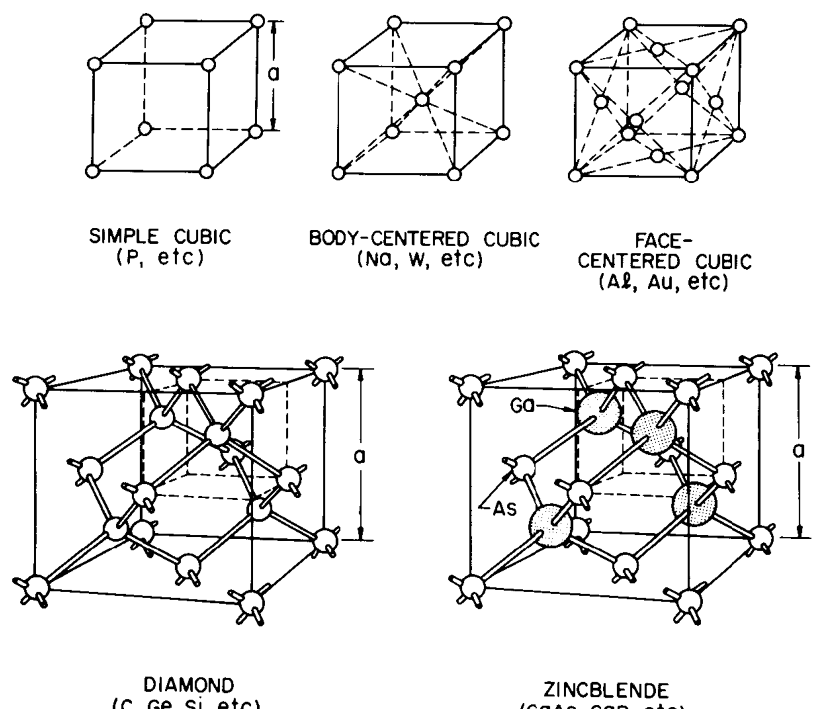

Fig. 1 Some important unit cells (direct lattices) and their representative elements or compounds; a is the lattice constant.