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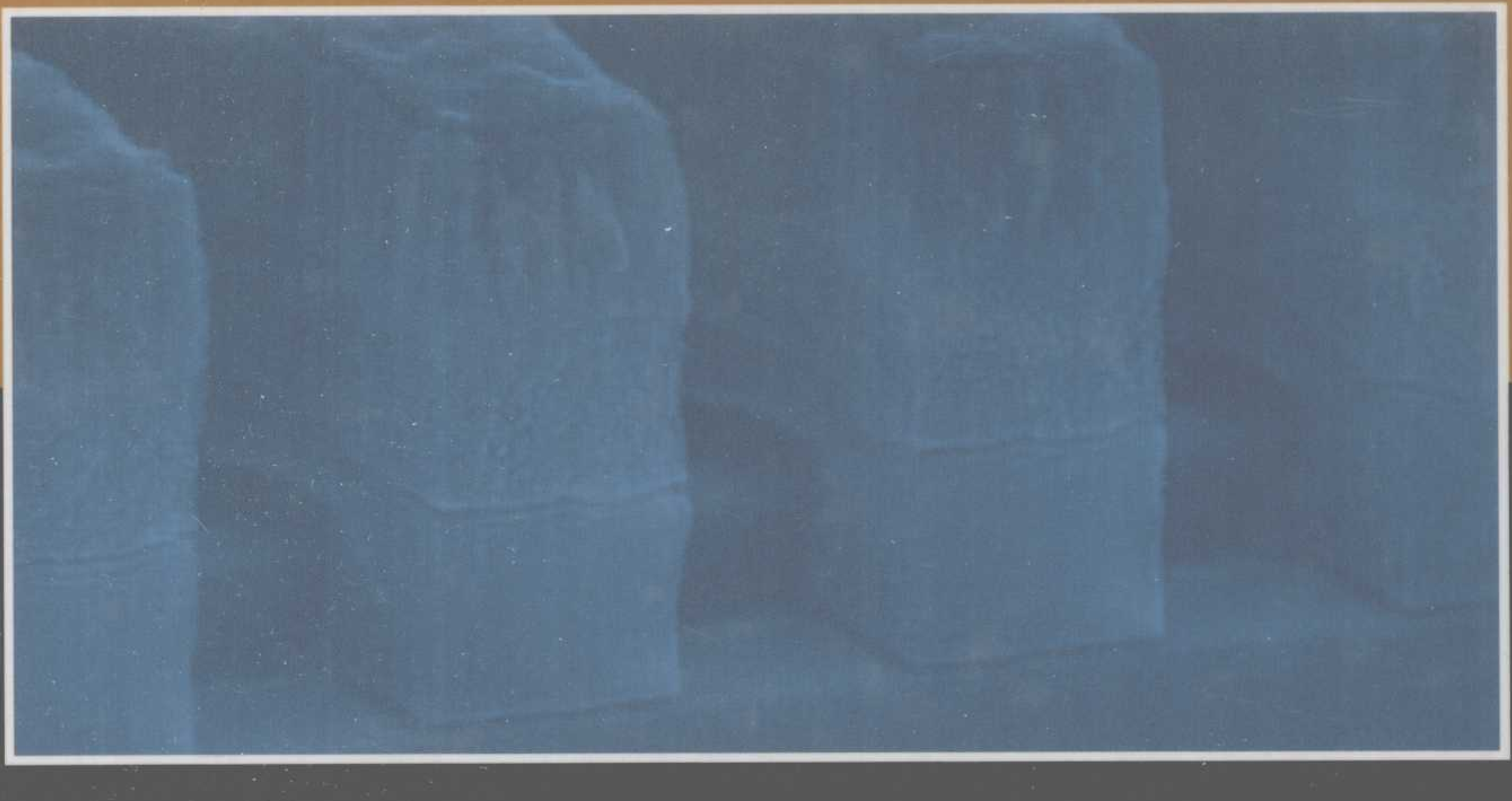
PHYSICS OF SEMICONDUCTOR DEVICES



THIRD EDITION

S. M. SZE

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Physics of Semiconductor Devices

Third Edition

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Description of cover photograph:

A scanning electron micrograph of an array of the floating-gate nonvolatile semiconductor memory (NVSM) magnified 100,000 times. NVSM was invented at Bell Telephone Laboratories in 1967. There are more NVSM cells produced annually in the world than any other semiconductor device and, for that matter, any other human-made item. For a discussion of this device, see Chapter 6. Photo courtesy of Macronix International Company, Hsinchu, Taiwan, ROC.

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Preface

Since the mid-20th Century the electronics industry has enjoyed phenomenal growth and is now the largest industry in the world. The foundation of the electronics industry is the *semiconductor device.* To meet the tremendous demand of this industry, the semiconductor-device field has also grown rapidly. Coincident with this growth, the semiconductor-device literature has expanded 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 the intention of meeting such a need, the First Edition and the Second Edition of *Physics of Semiconductor Devices* were published in 1969 and 1981, respectively. 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 students in applied physics, electrical and electronics engineering, and materials science. Because the book includes much useful information on material parameters and device physics, it is also a major reference for engineers and scientists in semiconductor-device research and development. To date, the book is one of the most, if not *the* most, cited works in contemporary engineering and applied science with over 15,000 citations (ISI, Thomson Scientific).

Since 1981, more than 250,000 papers on semiconductor devices have been published, with numerous breakthroughs in device concepts and performances. The book clearly needed another major revision if it were to continue to serve its purpose. In this Third Edition of *Physics of Semiconductor Devices*, over 50% of the material has been revised or updated, and the material has been totally reorganized. We have retained the basic physics of classic devices and added many sections that are of contemporary interest such as the three-dimensional MOSFETs, nonvolatile memory, modulation-doped field-effect transistor, single-electron transistor, resonant-tunneling diode, insulated-gate bipolar transistor, quantum cascade laser, semiconductor sensors, and so on. On the other hand, we have omitted or reduced sections of less-important topics to maintain the overall book length.

We have added a problem set at the end of each chapter. The problem set forms an integral part of the development of the topics, and some problems can be used as worked examples in the classroom. A complete set of detailed solutions to all end-of-chapter problems has been prepared. The solution manuals are available free to all adopting faculties. The figures and tables used in the text are also 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/interscience/sze*.

In the course of writing this text, we had the fortune of help and support of many people. First we express our gratitude to the management of our academic and industrial institutions, the National Chiao Tung University, the National Nano Device Laboratories, Agere Systems, and MVC, without whose support this book could not have been written. We wish to thank the Spring Foundation of the National Chiao Tung University for the financial support. One of us (K. Ng) would like to thank J. Hwang and B. Leung for their continued encouragement and personal help.

We have benefited greatly from suggestions made by our reviewers who took their time from their busy schedule. Credits are due to the following scholars: A. Alam, W. Anderson, S. Banerjee, J. Brews, H. C. Casey, Jr., P. Chow, N. de Rooij, H. Eisele, E. Kasper, S. Luryi, D. Monroe, P. Panayotatos, S. Pearton, E. F. Schubert, A. Seabaugh, M. Shur, Y. Taur, M. Teich, Y. Tsividis, R. Tung, E. Yang, and A. Zaslavsky. We also appreciate the permission granted to us from the respective journals and authors to reproduce their original figures cited in this work.

It is our pleasure to acknowledge the help of many family members in preparing the manuscript in electronic format; Kyle Eng and Valerie Eng in scanning and importing text from the Second Edition, Vivian Eng in typing the equations, and Jennifer Tao in preparing the figures which have all been redrawn. We are further thankful to Norman Erdos for technical editing of the entire manuscript, and to Iris Lin and Nai-Hua Chang for preparing the problem sets and solution manual. At John Wiley and Sons, we wish to thank George Telecki who encouraged us to undertake the project. Finally, we are grateful to our wives, Therese Sze and Linda Ng, for their support and assistance during the course of the book project.

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Part I Semiconductor Physics

Part II Device Building Blocks

Part III Transistors

Part IV Negative-Resistance and Power Devices

Part V Photonic Devices and Sensors

Introduction

The book is organized into five parts:

Part I: Semiconductor Physics
Part II: Device Building Blocks
Part III: Transistors
Part IV: Negative-Resistance and Power Devices
Part V: Photonic Devices and Sensors

Part I, Chapter 1, is a summary of semiconductor properties that are used throughout the book as a basis for understanding and calculating device characteristics. Energy band, carrier concentration, and transport properties are briefly surveyed, with emphasis on the two most-important semiconductors: silicon (Si) and gallium arsenide (GaAs). A compilation of the recommended or most-accurate values for these semiconductors is given in the illustrations of Chapter 1 and in the Appendixes for convenient reference.

Part II, Chapters 2 through 4, treats the basic device building blocks from which all semiconductor devices can be constructed. Chapter 2 considers the *p-n* junction characteristics. Because the *p-n* junction is the building block of most semiconductor devices, *p-n* junction theory serves as the foundation of the physics of semiconductor devices. Chapter 2 also considers the heterojunction, that is a junction formed between two dissimilar semiconductors. For example, we can use gallium arsenide (GaAs) and aluminum arsenide (AlAs) to form a heterojunction. The heterojunction is a key building block for high-speed and photonic devices. Chapter 3 treats the metal-semiconductor contact, which is an intimate contact between a metal and a semiconductor. The contact can be rectifying similar to a *p-n* junction if the semiconductor is moderately doped and becomes ohmic if the semiconductor is very heavily doped. An ohmic contact can pass current in either direction with a negligible voltage drop and can provide the necessary connections between devices and the outside world. Chapter 4 considers the metal-insulator-semiconductor (MIS) capacitor of which the Si-based metal-oxide-semiconductor (MOS) structure is the dominant member. Knowledge of the surface physics associated with the MOS capacitor is important, not only for understanding MOS-related devices such as the MOSFET and the floating-gate nonvolatile memory but also because of its relevance to the stability and reliability of all other semiconductor devices in their surface and isolation areas.

Part III, Chapters 5 through 7, deals with the transistor family. Chapter 5 treats the bipolar transistor, that is, the interaction between two closely coupled *p-n* junctions. The bipolar transistor is one of the most-important original semiconductor devices. The invention of the bipolar transistor in 1947 ushered in the modern electronic era. Chapter 6 considers the MOSFET (MOS field-effect transistor). The distinction between a field-effect transistor and a potential-effect transistor (such as the bipolar transistor) is that in the former, the channel is modulated by the gate through a capacitor whereas in the latter, the channel is controlled by a direct contact to the channel region.[1] The MOSFET is the most-important device for advanced integrated circuits, and is used extensively in microprocessors and DRAMs (dynamic random access memories). Chapter 6 also treats the nonvolatile semiconductor memory which is the dominant memory for portable electronic systems such as the cellular phone, notebook computer, digital camera, audio and video players, and global positioning system (GPS). Chapter 7 considers three other field-effect transistors; the JFET (junction field-effect-transistor), MESFET (metal-semiconductor field-effect transistor), and MODFET (modulation-doped field-effect transistor). The JFET is an older member and now used mainly as power devices, whereas the MESFET and MODFET are used in high-speed, high-input-impedance amplifiers and monolithic microwave integrated circuits.

Part IV, Chapters 8 through 11, considers negative-resistance and power devices. In Chapter 8, we discuss the tunnel diode (a heavily doped *p-n* junction) and the resonant-tunneling diode (a double-barrier structure formed by multiple heterojunctions). These devices show negative differential resistances due to quantum-mechanical tunneling. They can generate microwaves or serve as functional devices, that is, they can perform a given circuit function with a greatly reduced number of components. Chapter 9 discusses the transit-time devices. When a *p-n* junction or a metal-semiconductor junction is operated in avalanche breakdown, under proper conditions we have an IMPATT diode that can generate the highest CW (continuous wave) power output of all solid-state devices at millimeter-wave frequencies (i.e., above 30 GHz). The operational characteristics of the related BARITT and TUNNETT diodes are also presented. The transferred-electron device (TED) is considered 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 (in momentum space), the transferred-electron effect. Also presented are the real-space-transfer devices which are similar to TED but the electron transfer occurs between a narrow-bandgap material to an adjacent wide-bandgap material in real space as opposed to momentum space. 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 11. Also considered are the MOS-controlled thyristor (a combination of MOSFET with a conventional thyristor) and the insulated-gate bipolar transistor (IGBT, a combination of MOSFET with a conventional bipolar transistor). These devices have a wide range of power-handling and switching capability; they can handle currents from a few milliamperes to thousands of amperes and voltages above 5000 V.

Part V, Chapters 12 through 14, treats photonic devices and sensors. Photonic devices can detect, generate, and convert optical energy to electric energy, or vice versa. The semiconductor light sources—light-emitting diode (LED) and laser, are discussed in Chapter 12. The LEDs have a multitude of applications as display devices such as in electronic equipment and traffic lights, and as illuminating devices such as flashlights and automobile headlights. Semiconductor lasers are used in optical-fiber communication, video players, and high-speed laser printing. Various photodetectors with high quantum efficiency and high response speed are discussed in Chapter 13. The chapter also considers the solar cell which converts optical energy to electrical energy similar to a photodetector but with different emphasis and device configuration. As the worldwide energy demand increases and the fossil-fuel supply will be exhausted soon, there is an urgent need to develop alternative energy sources. The solar cell is considered a major candidate because it can convert sunlight directly to electricity with good conversion efficiency, can provide practically everlasting power at low operating cost, and is virtually nonpolluting. Chapter 14 considers important semiconductor sensors. A sensor is defined as a device that can detect or measure an external signal. There are basically six types of signals: electrical, optical, thermal, mechanical, magnetic, and chemical. The sensors can provide us with informations about these signals which could not otherwise be directly perceived by our senses. Based on the definition of sensors, all traditional semiconductor devices are sensors since they have inputs and outputs and both are in electrical forms. We have considered the sensors for electrical signals in Chapters 2 through 11, and the sensors for optical signals in Chapters 12 and 13. In Chapter 14, we are concerned with sensors for the remaining four types of signals, i.e., thermal, mechanical, magnetic, and chemical.

We recommend that readers first study semiconductor physics (Part I) and the device building blocks (Part II) before moving to subsequent parts of the book. Each chapter in Parts III through V deals with a major device or a related device family, and is more or less independent of the other chapters. So, readers can use the book as a reference and instructors can select chapters appropriate for their classes and in their order of preference. We have a vast literature on semiconductor devices. To date, more than 300,000 papers have been published in this field, and the grand total may reach one million in the next decade. In this book, each chapter is presented in a clear and coherent fashion without heavy reliance on the original literature. However, we have an extensive listing of key papers at the end of each chapter for reference and for further reading.

REFERENCE

1. K. K. Ng, *Complete Guide to Semiconductor Devices*, 2nd Ed., Wiley, New York, 2002.

PART I

SEMICONDUCTOR PHYSICS

- **Chapter 1** **Physics and Properties of Semiconductors —A Review**

1

Physics and Properties of Semiconductors—A Review

1.1 INTRODUCTION

The physics of semiconductor devices is naturally dependent on the physics of semiconductor materials themselves. This chapter presents a summary and review of the basic 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] Smith.[5] Böer,[6] Seeger,[7] and Wang,[8] to name a few.

To condense a large amount of information into a single chapter, four tables (some in appendixes) and over 30 illustrations drawn from experimental data are compiled and presented here. This chapter emphasizes the two most-important semiconductors: silicon (Si) and gallium arsenide (GaAs). Silicon has been studied extensively and widely used in commercial electronics products. Gallium arsenide has been intensively investigated in recent years. Particular properties studied are its direct bandgap for photonic applications and its intervalley-carrier transport and higher mobility for generating microwaves.

1.2 CRYSTAL STRUCTURE

1.2.1 Primitive Cell and Crystal Plane

A crystal is characterized by having a well-structured periodic placement of atoms. The smallest assembly of atoms that can be repeated to form the entire crystal is called a primitive cell, with a dimension of lattice constant a. Figure 1 shows some important primitive cells.

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. The bond between two nearest neighbors is formed by two electrons with opposite spins. The diamond and the zincblende lattices can be considered as two interpenetrating face-centered cubic (fcc) lattices. For the diamond lattice, such as silicon (Fig. 1d), all the atoms are the same; whereas in a zincblende lattice, such as gallium arsenide (Fig. 1e), one sublattice is gallium and the other is arsenic. Gallium arsenide is a III-V compound, since it is formed from elements of groups III and V of the periodic table.

Most III-V compounds crystallize in the zincblende structure;[2,9] however, many semiconductors (including some III-V compounds) crystallize in the rock-salt or wurtzite structures. Figure 1f shows the rock-salt lattice, which again can be considered as two interpenetrating face-centered cubic lattices. In this rock-salt structure, each atom has six nearest neighbors. Figure 1g shows the wurtzite lattice, which can be considered as two interpenetrating hexagonal close-packed lattices (e.g., the sublattices of cadmium and sulfur). In this picture, for each sublattice (Cd or S), the two planes of adjacent layers are displaced horizontally such that the distance between these two planes are at a minimum (for a fixed distance between centers of two atoms), hence the name *close-packed*. The wurtzite structure has a tetrahedral arrangement of four equidistant nearest neighbors, similar to a zincblende structure.

Appendix F gives a summary of the lattice constants of important semiconductors, together with their crystal structures.[10,11] Note that some compounds, such as zinc sulfide and cadmium sulfide, can crystallize in either zincblende or wurtzite structures.

Since semiconductor devices are built on or near the semiconductor surface, the orientations and properties of the surface crystal planes are important. A convenient method of defining the various planes in a crystal is to use Miller indices. These indices are determined by first finding the intercepts of the plane with the three basis axes in terms of the lattice constants (or primitive cells), and then taking the reciprocals of these numbers and reducing them to the smallest three integers having the same ratio. The result is enclosed in parentheses (hkl) called the Miller indices for a single plane or a set of parallel planes $\{hkl\}$. Figure 2 shows the Miller indices of important planes in a cubic crystal. Some other conventions are given in Table 1. For