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集成电路中的现代半导体器件

Modern Semiconductor Devices for Integrated Circuits

（英文版）

[美] Chenming Calvin Hu　著

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内 容 简 介

本书主要介绍与集成电路相关的主流半导体器件的基本原理，包括PN结二极管、MOSFET器件和双极型晶体管（BJT），同时介绍了与这些半导体器件相关的集成工艺制造技术。本书作者是美国工程院院士、中国科学院外籍院士，多年从事半导体器件与集成电路领域的前沿性研究工作。本书内容简明扼要，重点突出，深度掌握适宜，讲解深入浅出，理论联系实际。本书可作为微电子及相关专业本科生教材，也可以作为微电子及相关领域工程技术人员的参考书。

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Preface

Modern Semiconductor Devices for Integrated Circuits is primarily intended for use by undergraduate students, although it is also suitable for graduate students and practicing engineers and scientists.

The manuscript of this book has been used very successfully at the University of California, Berkeley, as the text of a one-semester course. It can also serve as the text of a course taught over two quarters. It has been well received by students with interests in fields such as semiconductor technology, IC design, MEMS, optical devices, nanotechnology, and materials science.

Readers should have had an introduction to elementary differential equations, modern physics, and electronics. From that background, this book develops a deep understanding of modern device theory and practice to help prepare students for further studies or professional careers. It presents more information on modern transistors and their impact on circuit design than typical texts in this field. In so doing, it aims to provide a strong foundation for understanding future issues of devices and design.

Modern Semiconductor Devices for Integrated Circuits emphasizes the commonality among devices by avoiding the usual compartmental organization along the lines of electronic, optical, microwave devices, and so on. The strong focus on a few basic devices, PN junction, metal–semiconductor contact, bipolar transistor, and especially MOSFET achieves the desired depth of treatment. These devices provide the theoretical background and chapter homes for introducing other important devices such as solar cell, LED, diode laser, CCD, CMOS imager, HEMT, and memory devices. The goal is to achieve depth and breadth in a more concise, integrated, and hopefully interesting way.

An Instructor's Manual, art PowerPoints, and lecture PowerPoint slides are available to professors only. The lecture slides have been developed through several years of classroom use.

I would like to thank many people who have helped to bring this book to fruition. Bingliang Yang, Hyuck Choo, and Vivian Lin helped to type the text and prepare the figures and the solutions manual. Jemin Park, Kanghoon Jeon, Chung-Hsun Lin, and especially Babak Heydari contributed substantive materials. Many students including Anupama Bowonder, Pratik Patel, and Darsen Lu helped to proofread the manuscript. Grateful acknowledgment is made to the panel of reviewers: John Beresford, Brown University; Tim Dallas, Texas Tech University; Todd J. Kaiser, Montana State University; Long Que, Louisiana Tech University; Pritpal Singh, Villanova University; Nina Telang, University of Texas at Austin; Pouya Valizadeh, Concordia University; and Joshua M. O. Zide, University of Delaware.

Thanks are due to the staff at Pearson Prentice Hall, especially to Jane Bonnell, who guided the production expertly. I give special thanks to my wife, Margaret, and my sons, Jason and Raymond, for their understanding and support when I extracted myself from their lives for long hours spent writing this book.

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1

Electrons and Holes in Semiconductors

CHAPTER OBJECTIVES

This chapter provides the basic concepts and terminology for understanding semiconductors. Of particular importance are the concepts of energy band, the two kinds of electrical charge carriers called electrons and holes, and how the carrier concentrations can be controlled with the addition of dopants. Another group of valuable facts and tools is the Fermi distribution function and the concept of the Fermi level. The electron and hole concentrations are closely linked to the Fermi level. The materials introduced in this chapter will be used repeatedly as each new device topic is introduced in the subsequent chapters. When studying this chapter, please pay attention to (1) concepts, (2) terminology, (3) typical values for Si, and (4) all boxed equations such as Eq. (1.7.1).

The title and many of the ideas of this chapter come from a pioneering book, *Electrons and Holes in Semiconductors* by William Shockley [1], published in 1950, two years after the invention of the transistor. In 1956, Shockley shared the Nobel Prize in physics for the invention of the transistor with Brattain and Bardeen (Fig. 1–1).

The materials to be presented in this and the next chapter have been found over the years to be useful and necessary for gaining a deep understanding of a large variety of semiconductor devices. Mastery of the terms, concepts, and models presented here will prepare you for understanding not only the many semiconductor devices that are in existence today but also many more that will be invented in the future. It will also enable you to communicate knowledgeably with others working in the field of semiconductor devices.

1.1 • SILICON CRYSTAL STRUCTURE •

A crystalline solid consists of atoms arranged in a repetitive structure. The periodic structure can be determined by means of X-ray diffraction and electron microscopy. The large cubic unit shown in Fig. 1–2 is the **unit cell** of the silicon

Inventors of the Transistor

Born on three different continents (Brattain in Amoy, China; Bardeen in Madison, Wisconsin, USA; and Shockley in London, England), they all grew up in the United States and invented the transistor in 1947–1948 at Bell Telephone Laboratories. Brattain was an experimentalist while Bardeen and Shockley contributed more to the concepts and theories. Their reflections on that historic event:

"... after fourteen years of work, I was beginning to give up ..."

—Walter H. Brattain (1902–1987)

"Experiments that led to the invention of the point-contact transistor by Walter Brattain and me were done in November and December, 1947, followed closely by the invention of the junction transistor by Shockley."

—John Bardeen (1908–1991)

"All of us who were involved had no doubt that we had opened a door to a new important technology."

—William B. Shockley (1910–1988)

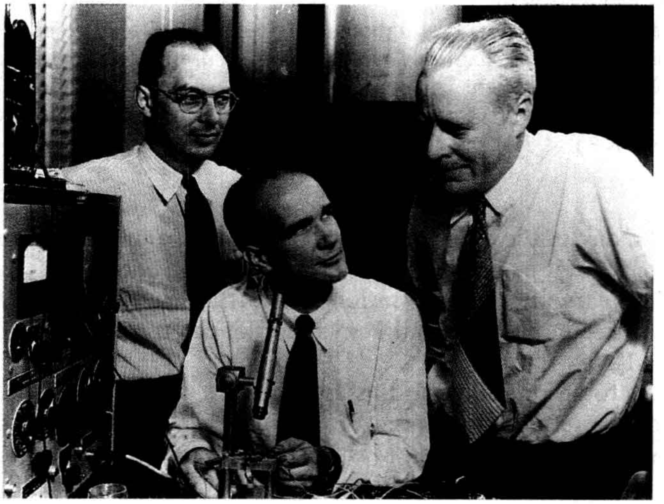

FIGURE 1–1 Transistor inventors John Bardeen, William Shockley, and Walter Brattain (left to right) at Bell Telephone Laboratories. (Courtesy of Corbis/Bettmann.)

crystal. Each sphere represents a silicon atom. This unit cell is repeated in all three directions many times to form a silicon crystal. The length of the unit cell, e.g., 5.43 Å in Fig. 1–2, is called the **lattice constant**.

The most important information from Fig. 1–2 is the simple fact that *each and every silicon atom has four other silicon atoms as its nearest neighbor atoms.* This fact is illustrated in Fig. 1–2 with the darkened cluster of a center atom having four neighboring atoms. This cluster is called the **primitive cell**. Silicon is a group IV element in the periodic table and has four valence electrons. These four electrons are shared with the nearest neighbors so that eight covalent electrons are associated

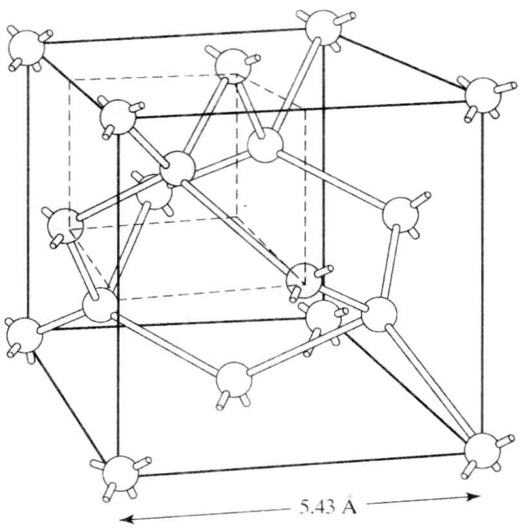

FIGURE 1–2 The unit cell of the silicon crystal. Each sphere is a Si atom. Each Si atom has four nearest neighbors as illustrated in the small cube with darkened atoms. (Adapted from Shockley [1].) For an interactive model of the unit cell, see http://jas.eng.buffalo.edu/

with each atom. The structure shown in Fig. 1–2 is known as the **diamond structure** because it is also the unit cell of the diamond crystal with each sphere representing a carbon atom. Germanium, the semiconductor with which the first transistor was made, also has the diamond crystal structure.

Figure 1–3 introduces a useful system of denoting the orientation of the silicon crystal. The cube in Fig. 1–3a represents the Si unit cell shown in Fig. 1–2 and each darkened surface is a crystal plane. The (100) crystal plane in the leftmost drawing in Fig. 1–3a, for example, is simply the plane in Fig. 1–2 closest to the reader. It intersects the x axis at 1 lattice constant and the y and z axes at infinity. One might refer to this plane as the 1 ∞ plane. However, it is standard practice to refer to it as the $(1/1\ 1/\infty\ 1/\infty)$, or the (100), plane. In general, the (abc) plane intersects the x, y, and z axes at $1/a$, $1/b$, and $1/c$ lattice constants. For example, the (011) plane in the middle drawing in Fig. 1–3a intersects the x axis at infinity and the y and z axes at 1 lattice constant. The numerals in the parentheses are called the **Miller indices**. The related symbol $[abc]$ indicates the direction in the crystal normal to the (abc) plane. For example, when an electron travels in the [100] direction, it travels perpendicular to the (100) plane, i.e., along the x axis.

Figure 1–3b shows that the silicon wafers are usually cut along the (100) plane to obtain uniformity and good device performance. A flat or a notch is cut along the (011) plane in order to precisely and consistently orient the wafer as desired during device fabrication. Different surface orientations have different properties such as the rate of oxidation and the electronic quality of the oxide/semiconductor interface. Both the surface orientation and the direction of current flow along the surface affect the speed performance of a surface-base device such as metal-oxide-semiconductor field-effect transistor (MOSFET, see Section 6.3.1). The most important semiconductor materials used in microelectronics are crystalline. However, most everyday solids are not single crystals as explained in the sidebar in Section 3.7.

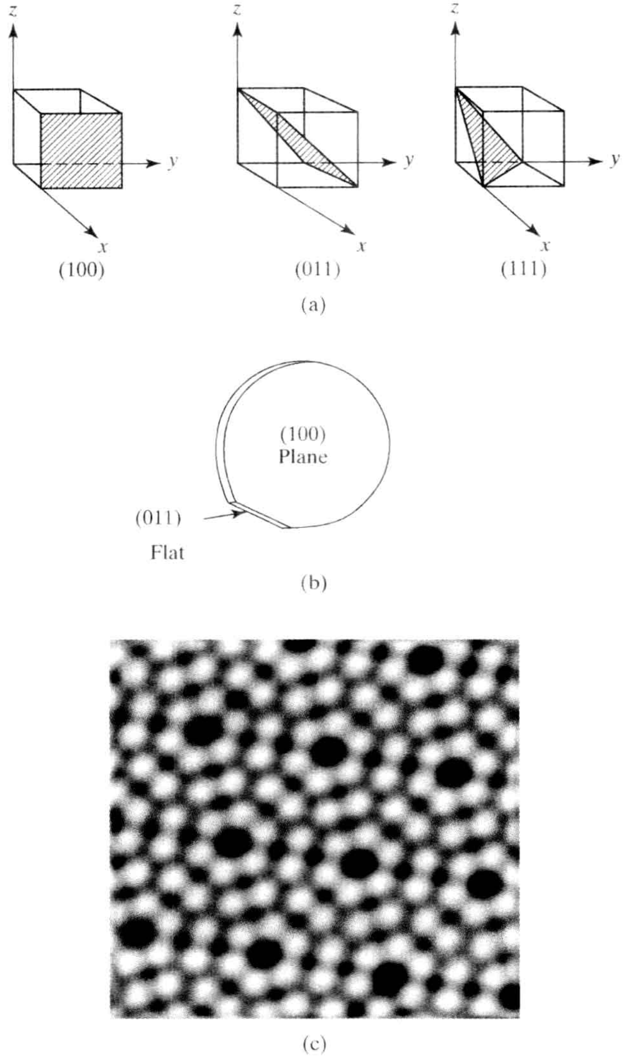

FIGURE 1–3 (a) A system for describing the crystal planes. Each cube represents the unit cell in Fig. 1–2. (b) Silicon wafers are usually cut along the (100) plane. This sample has a (011) flat to identify wafer orientation during device fabrication. (c) Scanning tunneling microscope view of the individual atoms of silicon (111) plane.

1.2 • BOND MODEL OF ELECTRONS AND HOLES •

Each silicon atom is surrounded by four nearest neighbors as illustrated by the shaded cluster in Fig. 1–2. We can represent the silicon crystal structure with the two-dimensional drawing shown in Fig. 1–4. An Si atom is connected to each neighbor with two dots representing the two shared electrons in the covalent bond. Figure 1–4 suggests that there are no free electrons to conduct electric current. This is strictly true

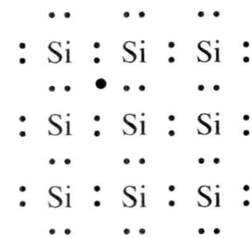

FIGURE 1–4 The silicon crystal structure in a two-dimensional representation.

only at the absolute zero temperature. At any other temperature, thermal energy will cause a small fraction of the covalent electrons to break loose and become **conduction electrons** as illustrated in Fig. 1–5a. Conduction electrons can move around in a crystal and therefore can carry electrical currents. For this reason, the conduction electrons are of more interest to the operation of devices than valence electrons.

An interesting thing happens when an electron breaks loose and becomes free. It leaves behind a void, or a **hole** indicated by the open circle in Fig. 1–5a. The hole can readily accept a new electron as shown in Fig. 1–5b. This provides another means for electrons to move about and conduct currents. An alternative way to think of this process is that the hole moves to a new location. It is much easier to think of this second means of current conduction as the motion of a positive hole than the motion of negative electrons moving in the opposite direction just as it is much easier to think about the motion of a bubble in liquid than the liquid movement that creates the moving bubble.

In semiconductors, current conduction by holes is as important as electron conduction in general. *It is important to become familiar with thinking of the holes as mobile particles carrying positive charge, just as real as conduction electrons are mobile particles carrying negative charge.* It takes about 1.1 eV of energy to free a covalent electron to create a conduction electron and a hole. This energy can be determined, for example, from a photoconductivity experiment. When light shines on a Si sample, its conductivity increases because of the generation of mobile electrons and holes. The minimum photon energy required to induce photoconductivity is 1.1 eV.

The densities of thermally generated electrons and holes in semiconductors are generally very small at room temperature given that the thermal energy, kT, is 26 meV at room temperature. A much larger number of conduction electrons can be introduced if desired by introducing suitable impurity atoms—a process called **doping**

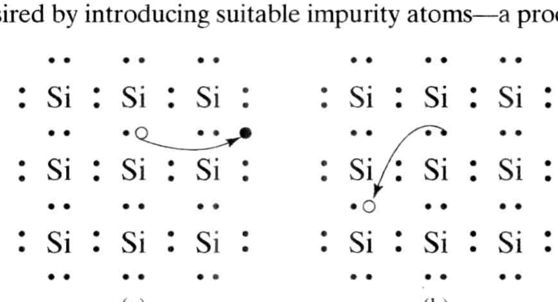

FIGURE 1–5 (a) When a covalent electron breaks loose, it becomes mobile and can conduct electrical current. It also creates a void or a hole represented by the open circle. The hole can also move about as indicated by the arrow in (b) and thus conduct electrical current.

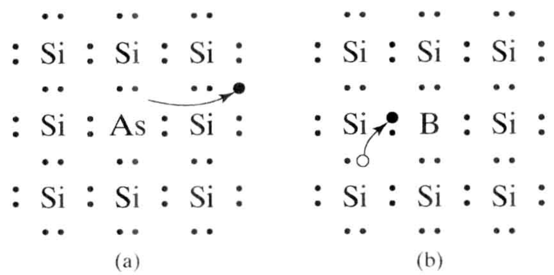

FIGURE 1–6 Doping of a semiconductor is illustrated with the bond model. (a) As is a donor. (b) B is an acceptor.

the semiconductor. For example, group V elements such as As shown in Fig. 1–6a bring five valence electrons with each atom. While four electrons are shared with the neighboring Si atoms, the fifth electron may escape to become a mobile electron, leaving behind a positive As ion. Such impurities are called **donors** for they *donate* electrons. Notice that in this case, no hole is created in conjunction with the creation of a conduction electron. Semiconductors containing many mobile electrons and few holes are called **N-type semiconductors** because electrons carry negative (N) charge. As and P are the most commonly used donors in Si.

Similarly, when boron, a group III impurity, is introduced into Si as shown in Fig. 1–6b, each B atom can accept an extra electron to satisfy the covalent bonds, thus creating a hole. Such dopants are called **acceptors**, for they *accept* electrons. Semiconductors doped with acceptors have many holes and few mobile electrons, and are called **P type** because holes carry positive (P) charge. Boron is the most commonly used acceptor in Si. In and Al are occasionally used.

The energy required to ionize a donor atom (i.e., to free the extra electron and leave a positive ion behind) may be estimated by modifying the theory of the ionization energy of a hydrogen atom,

$$E_{ion} = \frac{m_0 q^4}{8\varepsilon_0^2 h^2} = 13.6 \text{ eV} \tag{1.2.1}$$

where m_0 is the free electron mass, ε_0 is the permittivity of free space, and h is Planck's constant. The modification involves replacing ε_0 with $12\varepsilon_0$ (where 12 is the relative permittivity of silicon) and replacing m_0 with an electron effective mass, m_n, which is a few times smaller than m_0 as explained later. The result is about 50 meV. Because donors have such small ionization energies, they are usually fully ionized at room temperature. For example, 10^{17}cm^{-3} of donor atoms would lead to 10^{17}cm^{-3} of conduction electrons. The same conclusion also applies to the acceptors.

• GaAs, III–V Compound Semiconductors and Their Dopants •

GaAs and similar **compound semiconductors**, such as InP and GaN, are dominant in optoelectronic devices such as light-emitting diodes and semiconductor lasers (see Sections 4.13 and 4.14). GaAs also plays a role in high-frequency electronics (see Sections 6.3.2 and 6.3.3). Its crystal structure is shown in Fig. 1–7 and Fig. 1–8. The similarity to the Si crystal is obvious. The shaded spheres represent As atoms and the light spheres represent Ga atoms. Each Ga atom has four As neighbors and each As atom has four Ga neighbors. The lattice constant is 5.65 Å. Ga is a group III element and As is a group V element. GaAs is known as a **III–V compound semiconductor**, as are GaP and A1As, which also have the same crystal structure as illustrated in Fig. 1–7.

It is probably obvious that group VI elements such as S and Se can replace the group V As and serve as donors in GaAs. Similarly, group II elements such as Zn can replace Ga and serve as acceptors.

But, are group IV elements such as Si and Ge donors or acceptors in GaAs? The answer is that they can be either donors or acceptors, depending on whether they substitute for Ga atoms (which have three valence electrons) or As atoms (which have five valence electrons). Such impurities are called **amphoteric dopants**. It turns out that Si is a donor and Ge is an acceptor in GaAs because it is energetically more favorable for the small Si atoms to substitute for the small Ga atoms and for the larger Ge to substitute for the larger As.

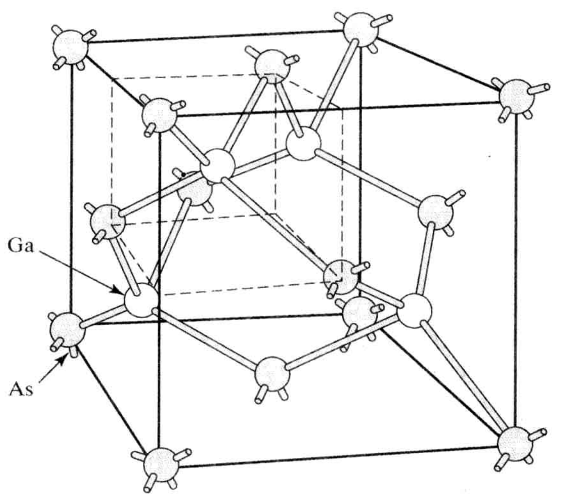

FIGURE 1–7 The GaAs crystal structure.

```
  ••    ••    ••
: Ga : As : Ga :
  ••    ••    ••
: As : Ga : As :
  ••    ••    ••
: Ga : As : Ga :
  ••    ••    ••
```

FIGURE 1–8 Bond model of GaAs.