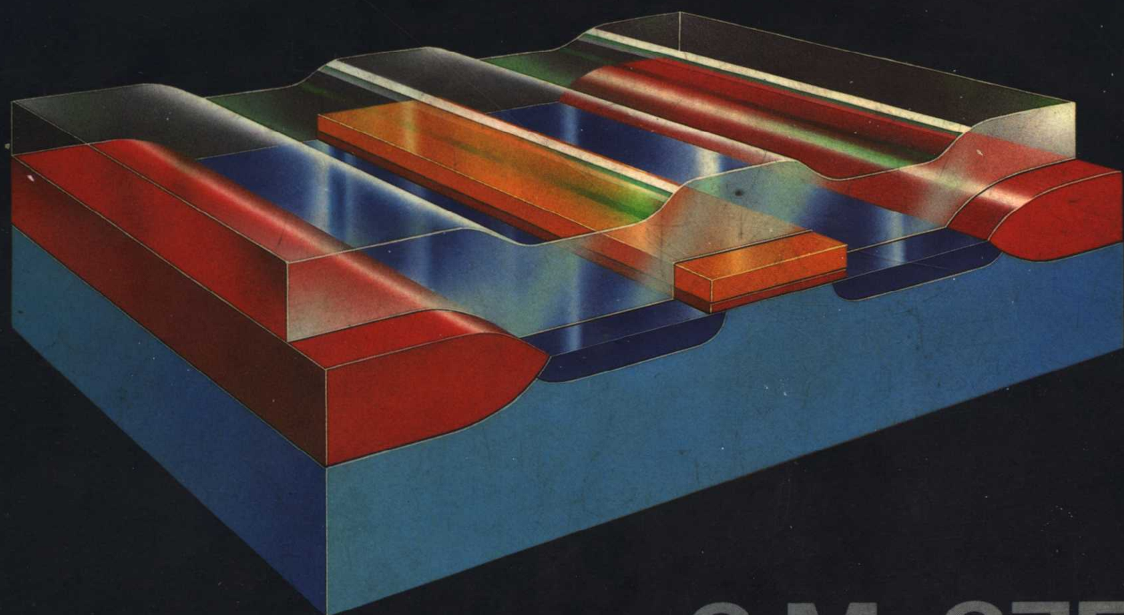
SEMICONDUCTOR DEVICES

Physics and Technology



S.M. SZE

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Physics and Technology

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SEMICONDUCTOR DEVICES
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To Therese, Raymond and Julia

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Preface

This book is an introduction to the physical principles of semiconductor devices and their fabrication technology. It is intended as a textbook for undergraduate students in applied physics, electrical 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.

The text is organized into three parts. The first part, Chapters 1 and 2, 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 second part, Chapters 3 through 7, considers the physics and characteristics of semiconductor devices. We begin with the p–n junction, which is the building block of most semiconductor devices; we proceed to bipolar and unipolar devices and then cover special microwave and photonic devices. The third part, Chapters 8 through 12, deals with processing technology from crystal growth to lithographic pattern transfer. We present the theoretical and practical aspects of the major steps in device fabrication with an emphasis on integrated devices. Although each chapter is more or less independent of the other chapters, it is recommended that instructors follow the sequence of topics from Chapter 1 to Chapter 12 for a logical and coherent presentation. The problems at the end of each chapter form an integral part of the development of the topics.

Many people have assisted me in writing the book. I would first like to express my deep appreciation to the management of AT&T Bell Laboratories for their support of this project. I have benefited significantly from suggestions made by the reviewers Drs. A.C. Adams, J. Agraz-Guerena, J.R. Brews, J.H. Bruning, D.I. Caplan, A.Y. Cho, C.M. Drum, W. Fichtner, D.B. Fraser, W.D. Johnston, L.E. Katz, T.P. Lee, M.P. Lepselter, S. Luryi, W.T. Lynch, D.A. McGillis, C.J. Mogab, K.K. Ng, M.B. Panish, L.C. Parrillo, C.W. Pearce, T.P. Pearsall, T.E. Seidel, T.T. Sheng, G.E. Smith, G.W. Taylor, and J.C.C. Tsai of AT&T Bell Laboratories; and Professors C.Y. Chang, the National Cheng Kung University, C.R. Crowell, University of Southern California, H. Melchior, Swiss Federal Institute of Technology, and H.W. Thim, Technical University of Vienna.

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I wish to thank Mr. M.G. Floyd and Mr. G.V. Novotny of John Wiley and Sons, who encouraged me to undertake this project. My sincere appreciation is also extended to Mr. Ranjit S. Mand, a doctoral student at the University of Bradford, for his contribution in improving the content of the text and for preparation of the problem solutions. Finally, I am grateful to my wife and children for their assistance in many ways, including typing the entire first draft and preparing the illustrations, appendixes, and index.

Murray Hill, New Jersey
January 1985

S.M. Sze

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1

Energy Bands and Carrier Concentration

In this chapter we consider some basic properties of semiconductors. We begin with a discussion of crystal structure, which is the arrangement of atoms in a semiconductor. We then present the concepts of valence bonds and energy bands, which relate to conduction in semiconductors. Finally, we discuss the concept of carrier concentration under thermal equilibrium. These concepts will be used throughout this book.

1.1 SEMICONDUCTOR MATERIALS

Solid-state materials can be grouped into three classes—insulators, semiconductors, and conductors. Figure 1 shows the electrical conductivities σ (and the corresponding resistivities $\rho \equiv 1/\sigma$)* associated with some important

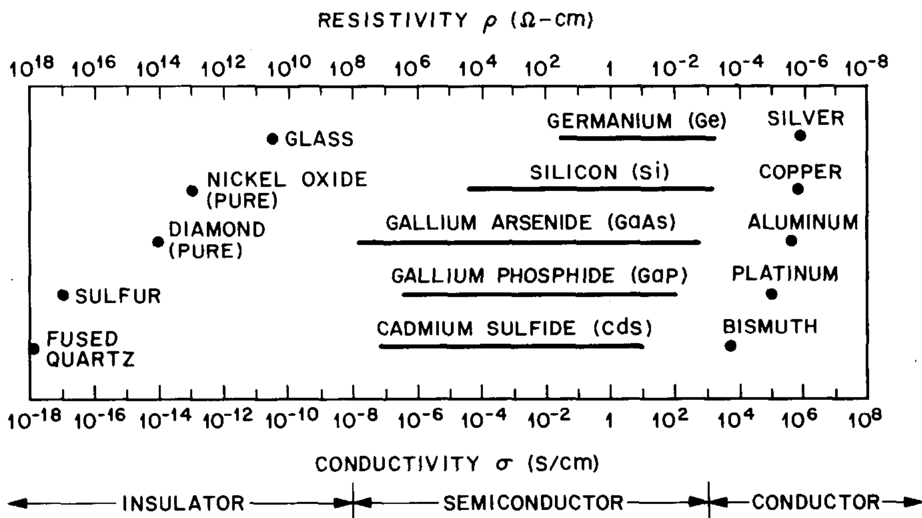

Fig. 1 Typical range of conductivities for insulators, semiconductors, and conductors.

* A list of symbols is given in Appendix A.

materials in each of the three classes. Insulators such as fused quartz and glass have very low conductivities, in the order of 10^{-18} to 10^{-8} S/cm; and conductors such as aluminum and silver have high conductivities, typically from 10^4 to 10^6 S/cm.† Semiconductors have conductivities between those of insulators and those of conductors. The conductivity of a semiconductor is generally sensitive to temperature, illumination, magnetic field, and minute amount of impurity atoms. This sensitivity in conductivity makes the semiconductor one of the most important materials for electronic applications.

The study of semiconductor materials began in the early nineteenth century.[1] Over the years many semiconductors have been investigated. Table 1 shows a portion of the periodic table related to semiconductors. The element semiconductors, those composed of single species of atoms, such as silicon (Si) and germanium (Ge), can be found in Column IV. However, numerous compound semiconductors are composed of two or more elements. For example, gallium arsenide (GaAs) is a III–V compound that is a combination of gallium (Ga) from Column III and arsenic (As) from Column V. Table 2 lists some of the element and compound semiconductors.

Prior to the invention of the bipolar transistor in 1947, semiconductors were used only as two-terminal devices, such as rectifiers and photodiodes. In the early 1950s, germanium was the major semiconductor material. However, germanium proved unsuitable in many applications because germanium devices exhibited high leakage currents at only moderately elevated temperatures. In addition, germanium oxide is water soluble and unsuited for device fabrication. Since the early 1960s silicon has become a practical substitute and has now virtually supplanted germanium as a material for semiconductor fabrication. The main reasons we now use silicon are that silicon devices exhibit much lower leakage currents, and high-quality silicon dioxide can be grown thermally. There is also an economic consideration. Device grade silicon costs much less than any other semiconductor material. Silicon in the form of silica

Table 1 Portion of the Periodic Table Related to Semiconductors

Period	Column II	III	IV	V	VI
2		B Boron	C Carbon	N Nitrogen	
3	Mg Magnesium	Al Aluminum	Si Silicon	P Phosphorus	S Sulfur
4	Zn Zinc	Ga Gallium	Ge Germanium	As Arsenic	Se Selenium
5	Cd Cadmium	In Indium	Sn Tin	Sb Antimony	Te Tellurium
6	Hg Mercury		Pb Lead		

† The international system of units is presented in Appendix B.

Table 2 Element and Compound Semiconductors

Element	IV–IV Compounds	III–V Compounds	II–VI Compounds	IV–VI Compounds
Si	SiC	AlAs	CdS	PbS
Ge		AlSb	CdSe	PbTe
		BN	CdTe	
		GaAs	ZnS	
		GaP	ZnSe	
		GaSb	ZnTe	
		InAs		
		InP		
		InSb		

and silicates comprises 25% of the Earth's crust, and silicon is second only to oxygen in abundance. At present, silicon is one of the most studied elements in the periodic table; and silicon technology is by far the most advanced among all semiconductor technologies.

Many of the compound semiconductors have electrical and optical properties that are absent in silicon. These semiconductors, especially gallium arsenide (GaAs), are used mainly for microwave and photonic applications. Although we do not know as much about the technology of compound semiconductors as we do about that of silicon, compound semiconductor technology has advanced partly because of the advances in silicon technology. In this book we are concerned mainly with device physics and processing technology of silicon and gallium arsenide.

1.2 CRYSTAL STRUCTURE

The semiconductor materials we will study are single crystals, that is, the atoms are arranged in a three-dimensional periodic fashion. The periodic arrangement of atoms in a crystal is called a *lattice*. In a crystal, an atom never strays far from a single, fixed position. The thermal vibrations associated with the atom are centered about this position. For a given semiconductor, there is a *unit cell* that is representative of the entire lattice; by repeating the unit cell throughout the crystal, one can generate the entire lattice.

Figure 2 shows some basic cubic-crystal unit cells. Figure 2*a* shows a simple cubic crystal; each corner of the cubic lattice is occupied by an atom that has six equidistant nearest neighboring atoms. The dimension a is called the *lattice constant*. Only polonium is crystallized in the simple cubic lattice. Figure 2*b* is a body-centered cubic (bcc) crystal, where in addition to the eight corner atoms, an atom is located at the center of the cube. In a bcc lattice, each atom has eight nearest-neighboring atoms. Crystals exhibiting bcc lattices include those of sodium and tungsten. Figure 2*c* shows a face-centered

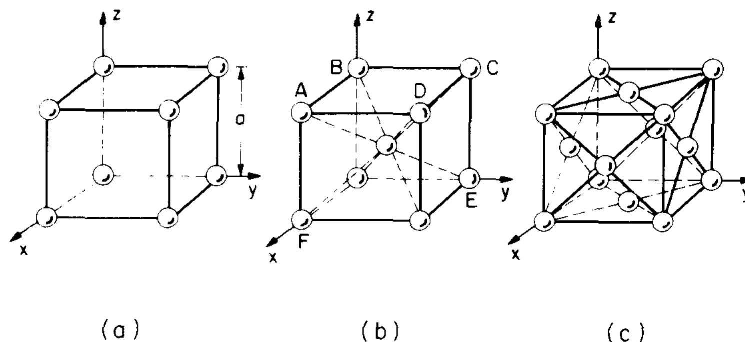

Fig. 2 Three cubic-crystal unit cells. (*a*) Simple cubic. (*b*) Body-centered cubic. (*c*) Face-centered cubic.

cubic (fcc) crystal that has one atom at each of the six cubic faces in addition to the eight corner atoms. In an fcc lattice, each atom has 12 nearest-neighboring atoms. A large number of elements exhibit the fcc lattice form, including aluminum, copper, gold, and platinum.

Problem

If we pack hard spheres in a bcc lattice such that the atom in the center just touches the atoms at the corners of the cube, find the fraction of the bcc unit cell volume filled with hard spheres.

Solution

Each corner sphere in a bcc unit cell is shared among eight neighboring cells; thus, each unit cell contains one eighth of a sphere at each of the eight corners for a total of one sphere. In addition, each unit cell contains one central sphere. We have

Spheres (atoms) per unit cell = 1 (corner) + 1 (center) = 2

Nearest-neighbor distance (along the diagonal AE in Fig. 2*b*) = $a\sqrt{3}/2$

Radius of each sphere = $a\sqrt{3}/4$

Volume of each sphere = $\frac{4}{3}\pi(a\sqrt{3}/4)^3 = \frac{\pi a^3\sqrt{3}}{16}$

Maximum fraction of unit cell filled

$$= \frac{\text{number of spheres} \times \text{volume of each sphere}}{\text{total volume of unit cell}}$$

$$= \frac{2 \times \pi a^3\sqrt{3}/16}{a^3} = \pi\sqrt{3}/8 = 0.68\,.$$

Therefore, 68% of the bcc unit cell volume is filled with hard spheres, and 32% of the volume is empty.

The element semiconductors, silicon and germanium, have a *diamond lattice* structure as shown in Fig. 3*a*. This structure also belongs to the cubic-crystal family and can be seen as two interpenetrating fcc sublattices with one sublattice displaced from the other by one quarter of the distance along a diagonal of the cube (i.e., a displacement of $a\sqrt{3}/4$). All atoms are identical

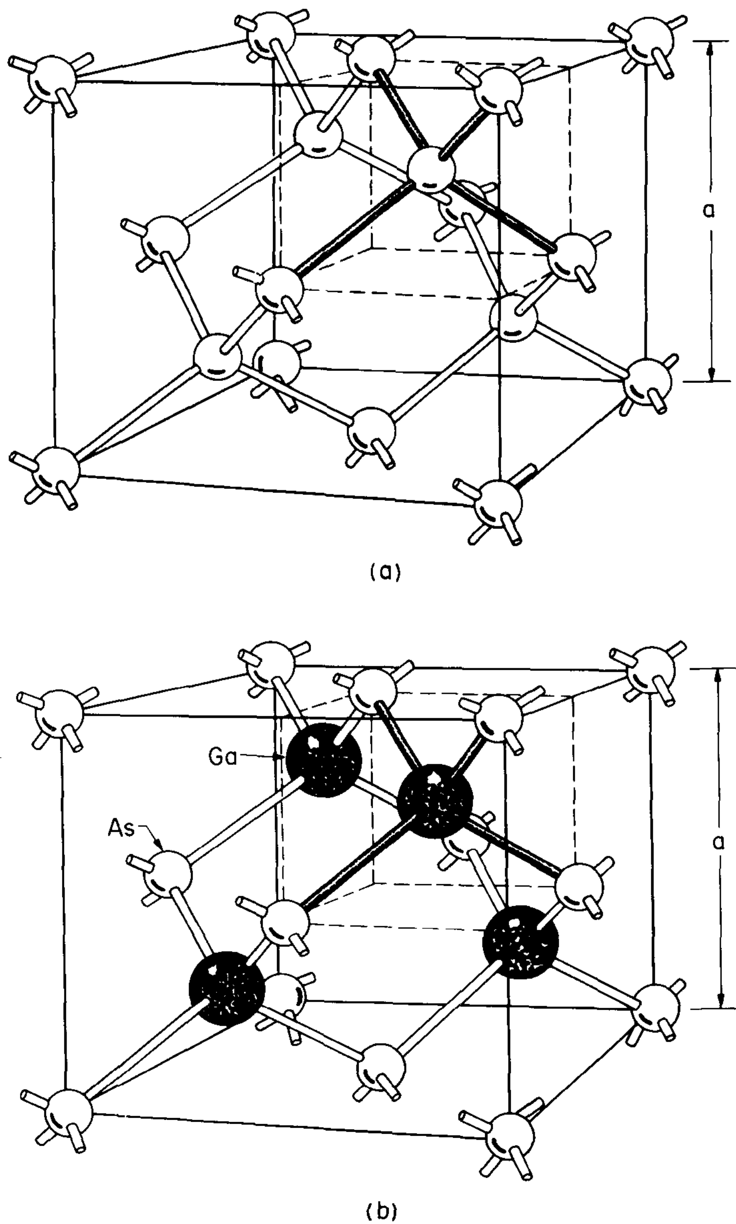

Fig. 3 (*a*) Diamond lattice. (*b*) Zincblende lattice.

in a diamond lattice, and each atom in the diamond lattice is surrounded by four equidistant nearest neighbors that lie at the corners of a tetrahedron (refer to the spheres connected by darkened bars in Fig. 3*a*). Most of the III–V compound semiconductors (e.g., GaAs) have a *zincblende lattice*, shown in Fig. 3*b*, which is identical to a diamond lattice except that one fcc sublattice

has Column III atoms (Ga) and the other has Column V atoms (As). Appendix F gives a summary of the lattice constants and other properties of important semiconductors.

Problem

At 300 K the lattice constant for silicon is 5.43 Å. Calculate the number of silicon atoms per cubic centimeter and the density of silicon at room temperature.

Solution

There are eight atoms per unit cell. Therefore,

$$\frac{8}{a^3} = \frac{8}{(5.43 \times 10^{-8})^3} = 5 \times 10^{22} \text{ atoms/cm}^3$$

$$\text{Density} = \frac{\text{no. of atoms/cm}^3 \times \text{atomic weight}}{\text{Avogadro constant}}$$

$$= \frac{5 \times 10^{22}\ (\text{atoms/cm}^3) \times 28.09\ (\text{g/mole})}{6.02 \times 10^{23}\ (\text{atoms/mole})} = 2.33 \text{ g/cm}^3 .$$

In Fig. 2*b* we note that there are four atoms in the ABCD plane and five atoms in the ACEF plane (four atoms from the corners and one from the center) and that the atomic spacings are different for the two planes. Therefore, the crystal properties along different planes are different, and the electrical and other device characteristics are dependent on the crystal orientation. A convenient method of defining the various planes in a crystal is to use *Miller indices*.[2] These indices are obtained using the following steps:

(1) Find the intercepts of the plane on the three Cartesian coordinates in terms of the lattice constant.

(2) Take the reciprocals of these numbers and reduce them to the smallest three integers having the same ratio.

(3) Enclose the result in parentheses (hkl) as the Miller indices for a single plane.

Example

As shown in Fig. 4, the plane has intercepts at a, $2a$, and $2a$ along the three coordinates. Taking the reciprocals of these intercepts, we get 1, ½, and ½. The smallest three integers having the same ratio are 2, 1, and 1 (obtained by multiplying each fraction by 2). Thus, the plane is referred to as a (211)-plane.

Figure 5 shows the Miller indices of important planes in a cubic crystal. Some other conventions are given as follows:

$(\bar{h}kl)$: For a plane that intercepts the x-axis on the negative side of the origin, such as $(\bar{1}00)$.

$\{hkl\}$: For planes of equivalent symmetry—such as {100} for (100), (010), (001), $(\bar{1}00)$, $(0\bar{1}0)$, and $(00\bar{1})$ in cubic symmetry.

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