电子科学与技术专业英语

微电子技术分册

总主编　张爱红

主　编　陈伟平　田丽

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# 内 容 简 介

本书由半导体物理、半导体器件、半导体与集成电路工艺、集成电路设计、微电子机械系统和科技文献范例六部分组成。全书涵盖了微电子技术领域的基本内容,同时又介绍了该领域的一些较新的发展。

本书可作为电子科学与技术专业微电子技术方向的三、四年级本科生的专业英语教材,也可供相关专业的本科生和从事该专业领域的工程技术人员使用。

# 前　言

　　21世纪是国际化的高科技时代,国际化的信息时代,作为国际间交流的重要载体——英语,其作用显得更为重要。专业英语是大学外语教学的重要组成部分,其目的是强化巩固基础英语并进行实践应用,从而掌握科技英语技能,使学生能够熟练阅读国外相关文献,掌握国内外本专业发展前沿的最新动态,并具有一定的科技写作能力。为此我们编写这套专业英语教材,以满足高等院校电子科学与技术和电子信息科学与技术专业及相关专业的本科生专业英语教学的需要以及从事上述专业的工程技术人员学习英语的要求。全套教材分三册,包括光电子技术分册、微电子技术分册和光电信息技术分册。

　　本书是微电子技术分册,由陈伟平副教授担任主编,参编人员有田丽、王东红、叶水驰、王进祥、来逢昌。刘晓为教授担任主审。

　　本分册内容分为五部分:第一部分为半导体物理的基本理论。主要内容包括:半导体、晶格、能带、载流子等基本概念;硅及砷化镓物理学特性;P-N结及其特性。第二部分为半导体器件。主要内容包括:双极型器件;MOS器件;微波与光电子器件。第三部分为半导体工艺。主要内容包括晶体生长、薄膜生长、光刻、腐蚀、扩散、注入等基本半导体工艺;双极型集成电路工艺;MOS集成电路工艺。第四部分为集成电路设计。主要内容包括:设计方法;综合与仿真。第五部分为MEMS。主要内容包括:MEMS概念与特点;MEMS工艺、器件与材料等。第六部分为科技文献范例。主要介绍微电子技术的现状与未来发展。

　　书中内容选材精良,但考虑到篇幅的限制及上下文的连惯性,对所选内容的图表及文字进行了部分删减和改动。为了有利于教

学和阅读理解,帮助学生更好地理解原文,每章后面给出了主要专业词汇及难句注释,并在每部分后面列出了有关参考文献。

本书是根据编者在专业英语方面的长期教学经验和体会编写而成的,内容较多,教师可以根据实际教学时数和需要选取合适的章节作为课堂教学内容,其他部分可作为学生课后阅读材料。对于其他专业的读者,也可通过阅读本书对微电子学原理及其应用有一定的了解和认识,既学习了英语,又开阔了视野。

本书在编写过程中得到电子科学与技术系的许多老师和学生的大力支持,在此一并表示诚挚的感谢。由于编者水平有限,书中难免还存在一些缺点和疏漏,殷切希望广大读者批评指正。

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# Chapter 1

# Semiconductors Physics

## 1.1 Energy Bands and Carrier Concentration

### 1.1.1 Semiconductor Materials

Solid-state materials can be grouped into three classes—insulators, semiconductors, and conductors. Figure 1 – 1 shows the electrical conductivities $\sigma$ ( and the corresponding resis - tivities $\rho \equiv 1/\sigma$ ) associated with some important materials in each of the three classes. Insulators such as fused quartz and glass have very low conductivities, in the order of 1E-18 to 1E-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. 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.

RESISTIVITY $\rho(\Omega - cm)$

$10^{18}$ $10^{16}$ $10^{14}$ $10^{12}$ $10^{10}$ $10^8$ $10^6$ $10^4$ $10^2$ $1$ $10^{-2}$ $10^{-4}$ $10^{-6}$ $10^{-8}$

• GLASS

GERMANIUM (Ge)    SILVER •

• NICKEL OXIDE (PURE)

SILICON (Si)    COPPER •

• DIAMOND (PURE)

GALLIUM ARSENIDE (GaAs)    ALUMINUM •

• SULFUR

GALLIUM PHOSPHIDE (GaP)    PLATINUM •

FUSED QUARTZ •

CADMIUM SULFIDE (cds)    BISMUTH •

$10^{-18}$ $10^{-16}$ $10^{-14}$ $10^{-12}$ $10^{-10}$ $10^{-8}$ $10^{-6}$ $10^{-4}$ $10^{-2}$ $1$ $10^2$ $10^4$ $10^6$ $10^8$

CONDUCTIVITY $\sigma$ (S/cm)

◄── INSULATOR ──►│◄── SEMICONDUCTOR ──►│◄ CONDUCTOR ►

Figure 1 – 1    Typical range of conductivities for insulators, semiconductors, and conductors

**Table 1 – 1    Portion of the Periodic Table Related to Semiconductors**

| Period | Column I | 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 | | |

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 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.

## 1.1.2 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 1 – 2 shows some basic cubic-crystal unit cells. Figure 1 – 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 1 – 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 1 – 2(c) shows a face-centered 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.

The element semiconductors, silicon and germanium, have a *diamond lattice* structure. This structure also belongs to the cubic- crystal family and can be seen as two interpenetrating fcc

· 4 ·

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 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. Most of the III-V compound semiconductors ( e. g. , GaAs) have a *zincblende lattice*, 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).
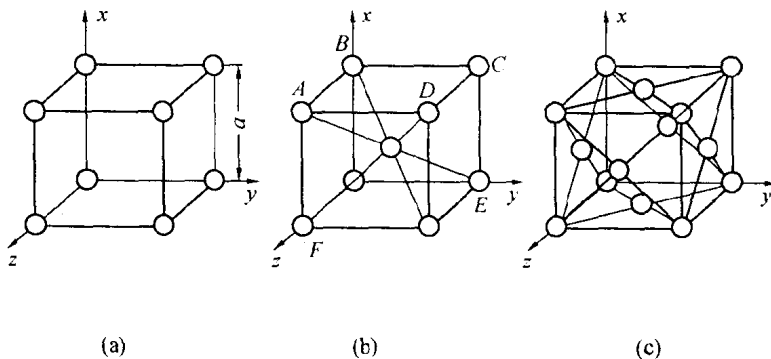


(a)         (b)         (c)

Figure 1 – 2    Three cubic-crystal unit celss

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*. 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.

Some conventions are given as follows:

$(hkl)$: 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 $(100)$, $(010)$, $(001)$, $(\bar{1}00)$, $(010)$, and $(00\bar{1})$ in cubic symmetry.

$[hkl]$: For a crystal direction, such as $[100]$ for the $x$-axis. Thus, the $[100]$-direction is perpendicular to $(100)$-plane, and the $[111]$-direction is perpendicular to the $(111)$-plane.

$<hkl>$: For a full set of equivalent directions-such as $<100>$ for $[100]$, $[010]$, $[001]$, $[\bar{1}00]$, $[0\bar{1}0]$, and $[00\bar{1}]$.

### 1.1.3 Valence Bonds

As discussed in Section 1.1.2, each atom in a diamond lattice is surrounded by four nearest neighbors. Each atom has four electrons in the outer orbit, and each atom shares these <u>valence electrons</u> with its four neighbors. This sharing of electrons is known as <u>*covalent bonding*</u>; each electron pair constitutes a covalent bond. Covalent bonding occurs between atoms of the same element, or between atoms of different elements that have similar outer-shell electron configurations. Each electron spends an equal amount of time with each nucleus. However, both electrons spend most of their time between the two nuclei. The force of attraction for the electrons by both nuclei holds the two atoms together. For a zincblende lattice such as gallium arsenide, the major bonding force is from the covalent bonds. However, gallium arsenide has a slight ionic bonding force that is an

electrostatic attractive force between each Ga⁻ ion and its four neighboring As⁺ ions, or between each As⁺ ion and its four neighboring Ga⁻ ions.

At low temperatures, the electrons are bound in their respective tetrahedron lattice; consequently, they are not available for conduction. At higher temperatures, thermal vibrations may break the covalent bonds. When a bond is broken, a free electron results that can participate in current conduction. An electron deficiency is left in the covalent bond. This deficiency may be filled by one of the neighboring electrons, which results in a shift of the deficiency location, as from location A to location B. We may therefore consider this deficiency as a particle similar to an electron. This fictitious particle is called a _hole_. It carries a positive charge and moves, under the influence of an applied electric field, in the direction opposite to that of an electron. The concept of a hole is analogous to that of a bubble in a liquid. Although it is actually the liquid that moves, it is much easier to talk about the motion of the bubble in the opposite direction.

## 1.1.4 Energy Bands

For an isolated atom, the electrons of the atom can have onlydiscrete _energy levels_. For example, the energy levels for an isolated hydrogen atom are given by the Bohr model

$$E_h = - m_0 q^4 / (8\varepsilon_0^2 h^2 n^2) = - 13.6 / n^2 \text{ eV}$$

where $m_0$ is the free-electron mass, q is the electronic charge, $\varepsilon_0$ is the free- space permittivity, h is the Planck constant, and n is a positive integer called the principal quantum number. The discrete energies are $- 13.6$ eV for the ground level ( $n = 1$ ), $- 3.4$ eV for the first excited level( $n = 2$ ), etc

We now consider two identical atoms. When they are far apart, the allowed energy levels for a given principal quantum number (e. g., $n = 1$) consist of one doubly degenerate level, that is, each atom has exactly the same energy (e.g., $-13.6$ eV for $n = 1$). As the two atoms approach one another, the doubly degenerate energy level will split into two levels by the interaction between the atoms. When we bring $N$ atoms together to form a crystal, the $N$-fold degenerate energy level will split into $N$ separate but closely spaced levels due to atomic interaction. This results in an essentially continuous band of energy.

The detailed energy band structures of crystalline solids have been calculated using quantum mechanics. Figure $1-3$ is a schematic diagram of the formation of a diamond lattice crystal from isolated silicon atoms. Each isolated atom has its discrete energy levels (two levels are shown on the far right of the diagram). As the interatomic spacing decreases, each degenerate energy level splits to form a band. Further decrease in spacing causes the bands originating from different discrete levels to lose their identities and merge together, forming a single band. When the distance between atoms approaches the equilibrium interatomic spacing of the diamond lattice (with a lattice constant of 0.543 nm for silicon), this band splits again into two bands. These bands are separated by a region which designates energies that the electrons in the solid cannot possess. This region is called the forbidden gap, or bandgap $E_g$. The upper band is called the conduction band, while the lower band is called the valence band, as shown on the far left of Figure $1-3$.

Figure $1-4$ shows the energy band diagrams of three classes of solids—insulators, semiconductors, and conductors. In an

ELECTRON
ENERGY

Conduction
band
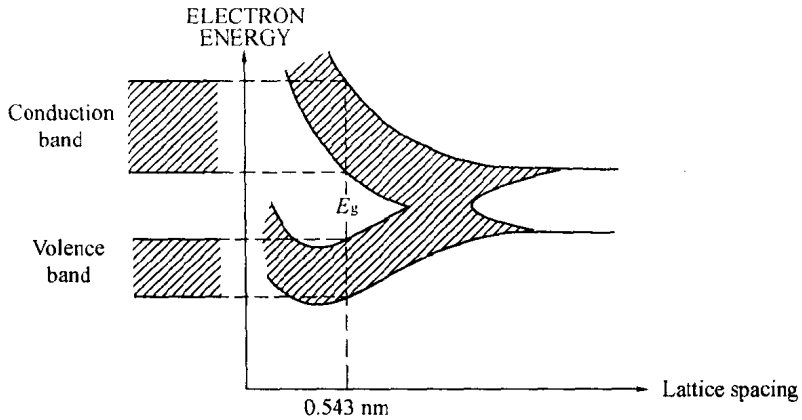
Volence
band

$E_g$

0.543 nm

Lattice spacing

Figure 1 – 3    Formation of energy bands

insulator such as silicon dioxide ($SiO_2$), the valence electrons form strong bonds between neighboring atoms. These bonds are difficult to break, and consequently there are no free electrons to participate in current conduction. As shown in the energy band diagram Figure 1 – 4(a), there is a large bandgap. Note that all energy levels in the valence band are occupied by electrons and all energy levels in the conduction band are empty. Thermal energy or an applied electric field cannot raise the uppermost electron in the valence band to the conduction band. Therefore, silicon dioxide is an insulator, which cannot conduct current.

As we discussed in Section 1.1.3, bonds between neighboring atoms in a semiconductor are only moderately strong. Therefore, thermal vibrations will break some bonds. When a bond is broken, a free electron along with a free hole result. Figure 1 – 4(b) shows that the bandgap of a semiconductor is not as large as that of an insulator (e.g., Si with a bandgap of 1.12 eV). Because of this, some electrons will be able to move from the valence band to the conduction band, leaving holes in the valence band. When an

electric field is applied, both the electrons in the conduction band and the holes in the valence band will gain <u>kinetic energy</u> and conduct electricity.
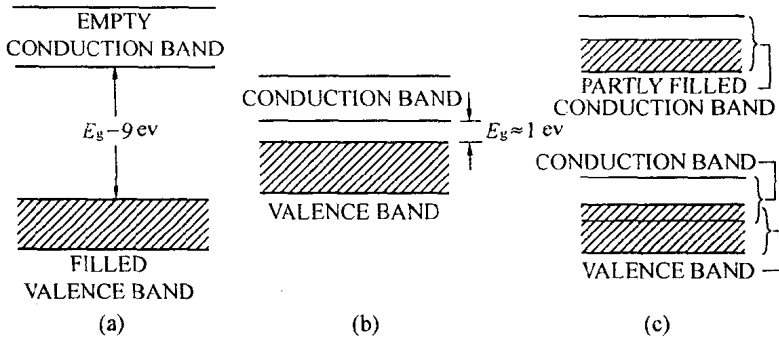


Figure 1 – 4　Schematic energy band representations

In conductors such as metals, Figure 1 – 4 ( c ), the conduction band either is partially filled or overlaps the valence band so that there is no bandgap. <u>As a consequence, the uppermost electrons in the partially filled band or electrons at the top of the valence band can move to the next-higher available energy level when they gain kinetic energy ( e. g. , from an applied electric field)</u>. Therefore, current conduction can readily occur in conductors.

The energy band diagrams shown in Figure1 – 4 indicate electron energies. When the energy of an electron is increased, the electron moves to a higher position in the band diagram. On the other hand, when the energy of a hole is increased, the hole moves downward in the valence band. (This is because a hole has a charge opposite that of an electron. )

As we discussed before, the separation between the energy of the lowest conduction band and that of the highest valence band is