TURING 图灵原版电子与电气工程系列

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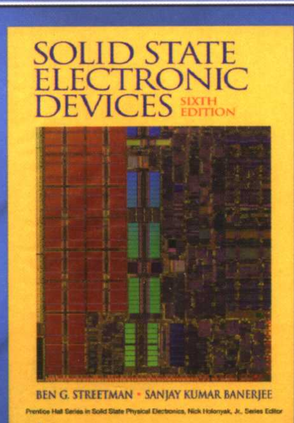
Solid State Electronic Devices (Sixth Edition)

固态电子器件

（英文版 · 第6版）

[美] Ben G. Streetman
Sanjay Kumar Banerjee 著



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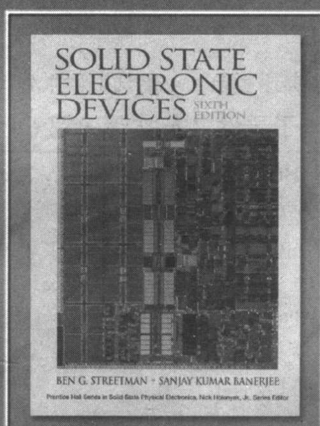

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内 容 提 要

本书是介绍半导体器件工作原理的经典入门教材，其主要内容包括固体物理基础和半导体器件物理两大部分，同时也涵盖半导体晶体结构与材料生长技术、集成电路原理与制造工艺以及光电子器件与高频大功率器件等相关内容。

本书注重基本物理概念，强调理论联系实际，可作为高等院校电子信息类专业“固态器件与电路”专业基础课的教材，也可供相关领域的研究人员和技术人员参考。

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前　言

本书旨在向电子工程专业的大学本科生以及其他专业有兴趣的学生介绍有关半导体器件的基本知识，同时本书也为从事实际工作的各类工程和科研人员提供了一个更新其现代电子学知识的途径。通过学习本书内容，大学生们可以从只具备大学二年级物理知识的程度，达到能够阅读并理解当前大多数论述有关各种新型电子器件及其应用技术方面专业文献的水平。

目标

一门有关电子器件方面的本科生课程通常具有以下两个基本目的：一是给大学生们建立一个牢固的关于目前各类常见电子器件的知识基础，以使他们能够更好地学习和理解后续的电子线路与系统课程；二是引导和帮助大学生们学习并掌握那些基本的分析方法和技能，以使他们今后能够将其应用于各种新型电子器件的研究、开发与应用工作中。从长远发展的角度来看，上述两个目标中的第二个可能具有更重要的意义，原因是显而易见的，因为这些未来将要处理各种电子学问题的工程和科研人员今后还需要不断地学习和掌握各种新型电子器件及其物理机理。有鉴于此，我们在本教材中将尝试着把有关半导体材料的基础知识以及固体材料的导电机理等内容一并包含进来，因为这些知识在今后讨论和分析各种新型电子器件原理的文献中将会反复出现。在一些概论性的电子器件课程中，一般认为要理解和掌握半导体PN结和晶体管的基本原理，并不需要详细了解这些固体材料方面的内容，因此上述这些基本知识的某些部分往往被省略了。但是我们认为这种观点完全忽视了一个重要的培养目标，即训练学生通过独立阅读最新专业文献而理解并掌握一种新型电子器件工作原理的能力。因此在本教材中我们尽可能包含了大多数常用的半导体物理方面的基本概念和基本原理，并力图将其应用于各种不同类型半导体器件的分析工作中。

阅读书目

为了更好地发展学生的自学能力，本书在每一章的最后都给出了包含部分专业文献的阅读书目，学生们在学习本书的过程中可以自由选读这些专业文献。我们

并不期望学生们会读完阅读书目中所推荐的全部专业文献，但是我们认为能够经常不断地受到这些学术期刊的熏陶，对于学生们今后为其职业生涯打下一个不断进行知识更新和自我继续教育的基础则是非常有用的。另外，每一章的最后还给出了关于本章内容中关键概念的总结。

习题

能够比较成功地学好并牢固掌握本书内容的关键方法之一就是通过分析求解各种练习题来加深对基本概念的理解。本书每一章后面所附的练习题都是经过精心设计的，以便帮助学生更好地消化书中的内容。只有很少的练习题属于那种简单地直接“代入公式”就可以求解的，而绝大多数练习题都是用来强化或拓展书中所学内容的。此外，我们在每一章的最后还增加了“自我测验题”，以供学生们自我检查对该章基本内容的理解和掌握情况。

单位制

为了实现上述教学目标，书中所有的例题和练习题都是采用与半导体专业文献相一致的单位制形式来陈述的。尽管长度单位大多采用的是传统的厘米（cm），但是基本的单位制仍然是统一的米·千克·秒（MKS）制。与此类似，在表示电子能量时通常采用的单位是电子伏特（eV），而不是采用焦耳（J）为单位。附录I和附录II给出了不同物理量的常用单位。

讲述方式

在向本科生们讲授本书内容的时候，授课教师肯定会预见到在很多情况下需要经常采用“可以证明……”这样的说法，这是一件令人感到非常沮丧和遗憾的事情。当然另外一种变通的办法就是将“固态电子器件”课程的教学内容推迟到研究生阶段再向学生们传授，那时学生们将已经学过了统计力学、量子理论以及其他高层次的背景知识。经过这样的推迟之后，课程中很多内容的教学处理就会变得更加得体和合乎逻辑，但是这样一来，就无法使本科生们享受学习那些奇妙的电子器件的乐趣。

为了充分反映化合物半导体材料在光电子器件和超高速电子器件应用领域中日益增长的重要性，本书所讨论的内容既包括了硅器件，也包括了多种化合物半导体器件。诸如半导体异质结、采用三元或四元合金实现的晶格匹配、带隙宽度随着合金组分的改变以及量子阱的特性等这样一些论题大大拓宽了本书所讨论的视野。但是硅基器件也并没有完全被化合物半导体器件所超越，与之相反，它们继续演绎着更加辉煌的成就。本书中有关各类场效应晶体管结构和硅集成电路的讨论就是对这些成就的最好反映。我们的目标并不是要在本书中包含所有最新的电

子器件，这种工作只有通过期刊杂志和会议论文集才可能真正实现。本书中选择讨论的几种电子器件都是为了能够最大限度地说明那些重要的基本原理。

本书前4章给出了有关半导体基本特性以及固体材料导电机理的背景知识，其中第2章包含了对量子理论的一个简要介绍，这为那些没有学过这方面内容的同学提供了很好的背景知识。第5章介绍了PN结理论及它的某些应用。第6章和第7章则集中讨论了晶体管的工作原理。第8章和第9章分别包含了光电子学和集成电路的相关内容。第10章则将PN结理论和半导体的导电机理应用于微波器件和功率器件。书中讨论的所有器件都是当今电子学领域的重要器件，而且我们相信学习和研究这些电子器件是令人非常愉快和有意义的经历。同时我们也希望本书能够给读者带来这种快乐的体验。

致谢

最新第6版在很大程度上受益于使用本书前5版作为教材的老师和同学们给我们提出的大量宝贵的意见和建议。本书的很多读者也为我们进一步完善目前这个版本而慷慨地提供了许多建设性的意见。此外我们对于那些在本书前5个版本的前言中已经提到过的各位人士也仍然心存感激之情，因为他们同样也为本书的编辑、出版和发行工作做出了巨大的贡献。其中特别要提到的是Nick Holonyak，他一直为本书所有6个版本的编写和出版工作提供了持续不断的信息来源和创作灵感。我们还要感谢美国得克萨斯大学奥斯汀分校的同事们，特别是Joe Campbell、Leonard Frank Register、Ray Chen、Archie Holmes、Dim-Lee Kwong、Jack Lee以及Dean Neikirk，他们为我们顺利地完成本书提供了特别的帮助。另外，Lisa Weltzer协助我们录入了本书各章后面所附练习题的解答。我们还要感谢很多公司和有关的研究机构，它们非常慷慨地提供了本书中所介绍的各种半导体器件及其制造工艺的大量实际照片，这一点在书中相关照片的说明中都有标注。其中特别要说明的是，Bill Dunnigan、Naras Iyengar、美国飞思卡尔（Freescale）公司的Pradipto Mukherjee、美国德州仪器（TI）公司的Peter Rickert和Puneet Kohli、美国美光科技（Micron）公司的Chandra Mouli和Dan Spangler、美国应用材料（Applied Materials）公司的Majeed Foad以及美国休斯电子材料（MEMC）公司的Tim Sater为我们提供了这一版教材中的许多新照片。最后我们还要说明的是，对于已故的Al Tasch，一位永远令我们尊敬的同事和朋友，我们经常怀着感激的心情回忆起多年来和他在一起合作的情景。

Ben G. Streetman

Sanjay Kumar Banerjee

CONTENTS

Chapter 1

Crystal Properties and Growth of Semiconductors

OBJECTIVES

1. Describe what a semiconductor is
2. Perform simple calculations about crystals
3. Understand what is involved in bulk Czochralski and thin-film epitaxial crystal growth
4. Learn about crystal defects

In studying solid state electronic devices we are interested primarily in the electrical behavior of solids. However, we shall see in later chapters that the transport of charge through a metal or a semiconductor depends not only on the properties of the electron but also on the arrangement of atoms in the solid. In the first chapter we shall discuss some of the physical properties of semiconductors compared with other solids, the atomic arrangements of various materials, and some methods of growing semiconductor crystals. Topics such as crystal structure and crystal growth technology are often the subjects of books rather than introductory chapters; thus we shall consider only a few of the more important and fundamental ideas that form the basis for understanding electronic properties of semiconductors and device fabrication.

1.1 SEMICONDUCTOR MATERIALS

Semiconductors are a group of materials having electrical conductivities intermediate between metals and insulators. It is significant that the conductivity of these materials can be varied over orders of magnitude by changes in temperature, optical excitation, and impurity content. This variability of electrical properties makes the semiconductor materials natural choices for electronic device investigations.

Semiconductor materials are found in column IV and neighboring columns of the periodic table (Table 1–1). The column IV semiconductors, silicon and germanium, are called *elemental* semiconductors because they are composed of single species of atoms. In addition to the elemental materials, compounds of column III and column V atoms, as well as certain combinations from II and VI, and from IV, make up the *compound* semiconductors.

As Table 1-1 indicates, there are numerous semiconductor materials. As we shall see, the wide variety of electronic and optical properties of these semiconductors provides the device engineer with great flexibility in the design of electronic and optoelectronic functions. The elemental semiconductor Ge was widely used in the early days of semiconductor development for transistors and diodes. Silicon is now used for the majority of rectifiers, transistors, and integrated circuits. However, the compounds are widely used in high-speed devices and devices requiring the emission or absorption of light. The two-element (*binary*) III–V compounds such as GaN, GaP, and GaAs are common in light-emitting diodes (LEDs). As discussed in Section 1.2.4, three-element (*ternary*) compounds such as GaAsP and four-element (*quaternary*) compounds such as InGaAsP can be grown to provide added flexibility in choosing materials properties.

Fluorescent materials such as those used in television screens usually are II–VI compound semiconductors such as ZnS. Light detectors are commonly made with InSb, CdSe, or other compounds such as PbTe and HgCdTe. Si and Ge are also widely used as infrared and nuclear radiation detectors. An important microwave device, the Gunn diode, is usually made of GaAs or InP. Semiconductor lasers are made using GaAs, AlGaAs, and other ternary and quaternary compounds.

One of the most important characteristics of a semiconductor, which distinguishes it from metals and insulators, is its *energy band gap*. This property, which we will discuss in detail in Chapter 3, determines among other things the wavelengths of light that can be absorbed or emitted by the semiconductor. For example, the band gap of GaAs is about 1.43 electron volts (eV), which corresponds to light wavelengths in the near infrared. In contrast,

Table 1–1. Common semiconductor materials: (a) the portion of the periodic table where semiconductors occur; (b) elemental and compound semiconductors.

(a)	II	III	IV	V	VI
		B	C	N	
		Al	Si	P	S
	Zn	Ga	Ge	As	Se
	Cd	In		Sb	Te

(b)	Elemental	IV compounds	Binary III–V compounds	Binary II–VI compounds
	Si	SiC	AlP	ZnS
	Ge	SiGe	AlAs	ZnSe
			AlSb	ZnTe
			GaN	CdS
			GaP	CdSe
			GaAs	CdTe
			GaSb	
			InP	
			InAs	
			InSb	

GaP has a band gap of about 2.3 eV, corresponding to wavelengths in the green portion of the spectrum.[1] The band gap E_g for various semiconductor materials is listed along with other properties in Appendix III. As a result of the wide variety of semiconductor band gaps, light-emitting diodes and lasers can be constructed with wavelengths over a broad range of the infrared and visible portions of the spectrum.

The electronic and optical properties of semiconductor materials are strongly affected by impurities, which may be added in precisely controlled amounts. Such impurities are used to vary the conductivities of semiconductors over wide ranges and even to alter the nature of the conduction processes from conduction by negative charge carriers to positive charge carriers. For example, an impurity concentration of one part per million can change a sample of Si from a poor conductor to a good conductor of electric current. This process of controlled addition of impurities, called *doping*, will be discussed in detail in subsequent chapters.

To investigate these useful properties of semiconductors, it is necessary to understand the atomic arrangements in the materials. Obviously, if slight alterations in purity of the original material can produce such dramatic changes in electrical properties, then the nature and specific arrangement of atoms in each semiconductor must be of critical importance. Therefore, we begin our study of semiconductors with a brief introduction to crystal structure.

1.2 CRYSTAL LATTICES

In this section we discuss the arrangements of atoms in various solids. We shall distinguish between single crystals and other forms of materials and then investigate the periodicity of crystal lattices. Certain important crystallographic terms will be defined and illustrated in reference to crystals having a basic cubic structure. These definitions will allow us to refer to certain planes and directions within a lattice. Finally, we shall investigate the diamond lattice; this structure, with some variations, is typical of most of the semiconductor materials used in electronic devices.

1.2.1 Periodic Structures

A crystalline solid is distinguished by the fact that the atoms making up the crystal are arranged in a periodic fashion. That is, there is some basic arrangement of atoms that is repeated throughout the entire solid. Thus the crystal appears exactly the same at one point as it does at a series of other equivalent points, once the basic periodicity is discovered. However, not all solids are crystals (Fig. 1-1); some have no periodic structure at all (*amorphous* solids), and others are composed of many small regions of single-crystal material (*polycrystalline* solids). The high-resolution micrograph shown in Fig. 6-33 illustrates the periodic array of atoms in the single-crystal silicon of a transistor channel compared with the amorphous SiO_2 (glass) of the oxide layer.

[1]The conversion between the energy E of a photon of light (eV) and its wavelength $\lambda(\mu m)$ is $\lambda = 1.24/E$. For GaAs, $\lambda = 1.24/1.43 = 0.87\ \mu m$.