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半导体纳米结构

（影印版）

〔德〕宾贝格（D. Bimberg） 主编

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序　言

物理学是研究物质、能量以及它们之间相互作用的科学。她不仅是化学、生命、材料、信息、能源和环境等相关学科的基础，同时还是许多新兴学科和交叉学科的前沿。在科技发展日新月异和国际竞争日趋激烈的今天，物理学不仅囿于基础科学和技术应用研究的范畴，而且在社会发展与人类进步的历史进程中发挥着越来越关键的作用。

我们欣喜地看到，改革开放三十多年来，随着中国政治、经济、教育、文化等领域各项事业的持续稳定发展，我国物理学取得了跨越式的进步，做出了很多为世界瞩目的研究成果。今日的中国物理正在经历一个历史上少有的黄金时代。

在我国物理学科快速发展的背景下，近年来物理学相关书籍也呈现百花齐放的良好态势，在知识传承、学术交流、人才培养等方面发挥着无可替代的作用。从另一方面看，尽管国内各出版社相继推出了一些质量很高的物理教材和图书，但系统总结物理学各门类知识和发展，深入浅出地介绍其与现代科学技术之间的渊源，并针对不同层次的读者提供有价值的教材和研究参考，仍是我国科学传播与出版界面临的一个极富挑战性的课题。

为有力推动我国物理学研究、加快相关学科的建设与发展，特别是展现近年来中国物理学者的研究水平和成果，北京大学出版社在国家出版基金的支持下推出了“中外物理学精品书系”，试图对以上难题进行大胆的尝试和探索。该书系编委会集结了数十位来自内地和香港顶尖高校及科研院所的知名专家学者。他们都是目前该领域十分活跃的专家，确保了整套丛书的权威性和前瞻性。

这套书系内容丰富，涵盖面广，可读性强，其中既有对我国传统物理学发展的梳理和总结，也有对正在蓬勃发展的物理学前沿的全面展示；既引进和介绍了世界物理学研究的发展动态，也面向国际主流领域传播中国物理的优秀专著。可以说，“中外物理学精品书系”力图完整呈现近现代世界和中国物理

科学发展的全貌，是一部目前国内为数不多的兼具学术价值和阅读乐趣的经典物理丛书。

“中外物理学精品书系”另一个突出特点是，在把西方物理的精华要义“请进来”的同时，也将我国近现代物理的优秀成果“送出去”。物理学科在世界范围内的重要性不言而喻，引进和翻译世界物理的经典著作和前沿动态，可以满足当前国内物理教学和科研工作的迫切需求。另一方面，改革开放几十年来，我国的物理学研究取得了长足发展，一大批具有较高学术价值的著作相继问世。这套丛书首次将一些中国物理学者的优秀论著以英文版的形式直接推向国际相关研究的主流领域，使世界对中国物理学的过去和现状有更多的深入了解，不仅充分展示出中国物理学研究和积累的“硬实力”，也向世界主动传播我国科技文化领域不断创新的“软实力”，对全面提升中国科学、教育和文化领域的国际形象起到重要的促进作用。

值得一提的是，“中外物理学精品书系”还对中国近现代物理学科的经典著作进行了全面收录。20 世纪以来，中国物理界诞生了很多经典作品，但当时大都分散出版，如今很多代表性的作品已经淹没在浩瀚的图书海洋中，读者们对这些论著也都是“只闻其声，未见其真”。该书系的编者们在这方面下了很大工夫，对中国物理学科不同时期、不同分支的经典著作进行了系统的整理和收录。这项工作具有非常重要的学术意义和社会价值，不仅可以很好地保护和传承我国物理学的经典文献，充分发挥其应有的传世育人的作用，更能使广大物理学人和青年学子切身体会我国物理学研究的发展脉络和优良传统，真正领悟到老一辈科学家严谨求实、追求卓越、博大精深的治学之美。

温家宝总理在 2006 年中国科学技术大会上指出，“加强基础研究是提升国家创新能力、积累智力资本的重要途径，是我国跻身世界科技强国的必要条件”。中国的发展在于创新，而基础研究正是一切创新的根本和源泉。我相信，这套“中外物理学精品书系”的出版，不仅可以使所有热爱和研究物理学的人们从中获取思维的启迪、智力的挑战和阅读的乐趣，也将进一步推动其他相关基础科学更好更快地发展，为我国今后的科技创新和社会进步做出应有的贡献。

“中外物理学精品书系”编委会 主任

中国科学院院士，北京大学教授

王恩哥

2010 年 5 月于燕园

Dieter Bimberg (Ed.)

Semiconductor Nanostructures

With 245 Figures

Springer

Preface

Let me start by defining the subject of this book, semiconductor nanostructures, using a strictly physical argument.

If the geometrical extent of a semiconductor, typically embedded in the matrix of another semiconductor, is reduced in one, two or three directions of space below the size of the "de Broglie wavelength" of a charge carrier—in other words, if it is reduced in size to only a few nanometers—it is a nanostructure. Reduction of dimensionality in one, two or three directions leads to quantum wells, wires or dots, respectively. The focus here is mainly on the ultimate limit, quantum dots.

The electronic—and to a lesser extent the vibronic—properties of low-dimensional structures (including their interactions such as electron–electron, electron–hole and electron–phonon interaction) depend qualitatively on the dimensionality of the structure and quantitatively on details of the geometry of the structure (its size and shape) and of the distribution of atoms inside. The electronic properties in turn control the linear and nonlinear optical and transport properties. Thus "geometrical architecture" opens enormous opportunities for designing completely novel materials or heterostructures. These opportunities extend far beyond the well-known "chemical architecture", where properties are modified by varying the chemical composition. Radically different from three-, two-, and one-dimensional structures in their electronic properties are zero-dimensional structures: quantum dots. Their "density of electronic states" is described by delta-functions and they show no dispersion of energy, thus resembling an atom in a dielectric matrix instead of a classical semiconductor. The Hamilton and momentum operators of quantum dots do not commute, leading again to novel physical properties. Figure 1 shows the variation of the density of states in structures of varying dimensionality.

The geometrical properties of quantum dots are controlled by the thermodynamic and kinetic parameters of the growth of strongly strained heterostructures, as long as we focus on the various fully epitaxial modes of their fabrication. Such

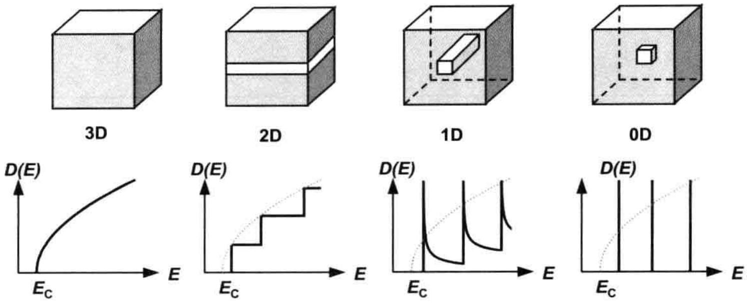

Fig. 1. Top: Schematic representations of three-, two-, one- and zero-dimensional heterostructures. Bottom: Densities of electronic states for the given case of dimensionality

growth modes lead to completely defect-free structures and interfaces. Fabrication of "classical" defect-free semiconductor heterostructures is based on the few existing lattice-matched or close to lattice-matched pseudomorphic structure families like GaAs/AlAs, or InP/InGaAsP. In contrast, quantum dot growth inverts this paradigm because a minimum difference of lattice constants is necessary to initiate self-organization effects, suddenly yielding an enormous wealth of "possible" combinations of material systems, complementary to the "classical" case.

Theoretical and experimental studies of growth mechanisms leading to the formation of nanostructures on different types of surfaces and for different semiconductors were one of the goals of the "Sonderforschungsbereich (SFB)" on "Growth Related Properties of Semiconductor Nanostructures", a "Center of Excellence", using a nonliteral translation, of the Deutsche Forschungsgemeinschaft (DFG), the German National Science Foundation. Self-ordering and self-organization effects play a decisive role for these newly discovered growth modes. Experimental investigations of nanostructures by structural, optical and transport methods, in addition to theoretical modeling of their electronic, linear and nonlinear optical properties were another objective. Novel experimental methods, like cathodoluminescence, cross-section tunneling microscopy, calorimetric absorption spectroscopy, near-field microscopy, to mention a few, had to be developed to meet the experimental challenges of gathering information on such ultra small structures. Discovery of many absolutely unique properties of nanostructures turned out to be of fundamental importance and present the starting point for a novel generation of photonic and electronic devices.

The reunification of Berlin brought together the members of this SFB, centered at the Technical University of Berlin. The principal scientists of the SFB came in almost equal numbers from some of the strongest research groups of the former West Berlin—the TU Berlin and the Fritz-Haber-Institute of the Max-Planck-Society—and from the former East-Berlin—the Humboldt University, the Paul-Drude-Institute and the Max-Born-Institute. In addition, guest scientists from all over the world contributed to its success, in particular those from the Ioffe Institute of the Russian Academy of Sciences.

The start of the SFB in the summer of 1994, after more than two years of preparation, was just in time. The international nano-wave then began to roll, triggered partly by the work of the SFB. After more than 12 years of operation, the papers published in 2006 by its researchers in international journals and at international conferences led them to the "top of the chart". The international citation index shows that many of the publications from the SFB belong to the most cited ones of the world in this area.

Three books [1–3] published in 1999, 2002 and 2004 summarize the initial worldwide fundamental work on quantum dots [1], aspects of epitaxial growth [2] and applications of quantum dots for novel nano-optoelectronics [3]. This new book summarizes what we believe represents the best, most important works on nanostructures of the last years, presented to the scientific community in a compact thus readable manner. Chapters 1–6 cover theoretical and experimental aspects of growth and structural studies. Chapters 7–10 are devoted to the theory of electronic and optical properties of quantum dots. Sections 11–16 finally focus on experimental studies of optical properties of nanostructures including ultra-high magnetic fields, ultra fast spectroscopy and emerging applications for novel nano-memories, quantum computing and cryptography. The authors of the contributions are the work package leaders of the SFB (Chaps. 1, 3–6, 8–10, 12, 13, 15 and 16) and of some of my coworkers (Chaps. 1, 2, 7, 11 and 14).

I thank my colleagues for the joy of working together for one and a half decades, lending me their support as a chairman of the SFB. I also thank the many reviewers for their constructive advice all along our way; the staff of the DFG for their never-ending patience and always-positive thinking; Claus Ascheron and the staff of Springer for their enthusiasm; Doreen Nitzsche for her energy reminding everybody to deliver and for completing the technical part of the book; and to my wife, Sigrun, for her patience when I looked overworked.

Berlin, March 2008 Dieter Bimberg

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