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Electrons and Phonons in Semiconductor Multilayers
2nd Edition

半导体多层膜中的电子和声子
第二版

（影印版）

〔英〕里德利（B. K. Ridley）著

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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

ELECTRONS AND PHONONS IN SEMICONDUCTOR MULTILAYERS

Second Edition

B. K. RIDLEY

University of Essex

CAMBRIDGE
UNIVERSITY PRESS

Preface

A Second Edition has given me several opportunities, which I have grasped with some eagerness. The first involved a matter of house-keeping – the correction of typos and an equation (Eq. (11.31)) in the First Edition. The second has allowed me to add the theory of the elasticity of optical modes, which became formulated too late to be included in the First Edition, but which resolved some uncertainties regarding mechanical boundary conditions. Given the current interest in hot phonons in high-power devices, I have updated the section on phonon lifetime. But the greatest opportunity was to expand the book to include some of the topics that grew in significance during the decade following the writing of the First Edition. Four new chapters focus on spin relaxation, the III–V nitrides, and the generation of terahertz radiation. In the burgeoning technology of spintronics, the rate of decay of the spin-polarization of the electron gas is a crucial parameter, and I have reviewed the mechanisms for this in both bulk and low-dimensional material. The advance of growth techniques and the technological need for higher-powered devices and for visible LEDs have thrust AlN, GaN, and InN and their alloys into the forefront of semiconductor physics. New properties associated with the hexagonal lattice have presented a challenge, and these are described in the chapter on electrons and phonons in the wurtzite lattice, and their role in heterostructures and multilayers is reviewed in a further chapter. Considerable effort is being made to close the gap in the electromagnetic spectrum, roughly between 300GHz and 30THz, in the emission spectrum of sources of radiation. The final chapter focuses on some of the physical mechanisms that are used or proposed to fill this gap. Terahertz radiation has applications in astrophysics, study of the atmosphere, biology, medicine, security screening, illicit material detection, non-destructive analysis, communications, and ultra-fast spectroscopy. The development of a compact, coherent continuous-wave, solid-state source is therefore of considerable technological importance.

It was timely, therefore, that John Fowler of CUP suggested I tackle a second edition of my book. His efforts and those of his CUP colleagues, Dawn Preston, Lindsay Barnes and Anne Rix, in gently guiding an author, only partly computer literate, through the mysteries of electronic publishing, were much appreciated. I was also much delighted by Ann Ridley's cover design of the wurtzite lattice that has captured some of its quantum mystery.

In preparing this new edition I have been generously helped by friends, who also happen to be colleagues. My warm thanks go to Angela Dyson, Ceyhun Bulutay, Martin Vaughan, and Alan Brannick for much practical assistance, and to Nic Zakhlenuik for his attempts (not always successful) to curb what passes for intuition in favour of formal proof. But my timeless gratitude is for my wife, Sylvia, who has borne the frequent fate over the last few months of book-widowhood with unfailing good nature.

Thorpe-le-Soken BKR

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Introduction

It is the intellect's ambition to seem
no longer to belong to an individual.
Human, All Too Human, *F. Nietzsche*

If one tells the truth, one is sure, sooner or later, to be found out.
(Phrases and Philosophies for the Use of the Young, *O. Wilde*)

This book has grown out of my own research interests in semiconductor multilayers, which date from 1980. It therefore runs the risk of being far too limited in scope, of prime interest only to the author, his colleagues and his research students. I hope that this is not the case, and of course I believe that it will be found useful by a large number of people in the field; otherwise I would not have written it. Nevertheless, knowledgeable readers will remark on the lack of such fashionable topics as the quantum-Hall effect, Coulomb blockade, quantized resistance, quantum tunnelling and any physical process that can be studied only in the millikelvin regime of temperature. This has more to do with my own ignorance than any lack of feeling that these phenomena are important. My research interests have not lain there. My priorities have always been to try to understand what goes on in practical devices, and as these work more or less at room temperature, the tendency has been for my interest to cool as the temperature drops. The essential entities in semiconductor multilayers are electrons and phonons, and it has seemed to me fundamental to the study and exploitation of these systems that the effect of confinement on these particles and their interactions be fully understood. This book is an attempt to discuss what understanding has been achieved and to discover where it is weak or missing. Inevitably it emphasizes concepts over qualitative description, and experimentalists may find the paucity of experimental detail regrettable. I hope not, though I would appreciate their point, but the book is long enough as it is, and there are excellent review articles in the literature.

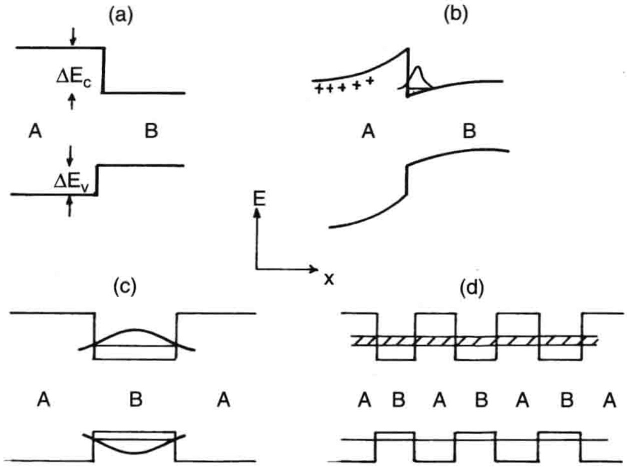

Fig. 1 Types of multilayered structures: (a) Single heterojunction, (b) Modulation-doped heterojunction, (c) Quantum well, (d) Superlattice.

At the risk of being boring, let me remind the reader what a semiconductor multilayer is about. There are several kinds of layered structure, of which those shown in Fig. 1 are the most common. They are interesting only insofar as they have a dimension that is smaller than the coherence length of an electron, in which case the electron becomes quantum confined between two potential steps. The free motion of the electron is then confined to a plane and many of its properties stem from this two-dimensional (2D) space. Electrons are not 2D objects and never could be, but for brevity they are usually referred to as 2D electrons when they are in the sort of layered structure shown in Fig. 1. The most striking effects are the quantization of energy into subbands, as depicted in Fig. 2 and Fig. 3, and the consequent transformation of the density-of-states function as shown in Fig. 4 for 3D, 2D, 1D and 0D electrons. Scattering events must now be classified into intrasubband, intersubband and capture processes, as indicated in Fig. 3. All of this is qualitatively well understood. The real problem here concerns the description of the confined-electron wavefunction (Fig. 5), which involves solving the Schrödinger equation in an inhomogeneous system. This problem is as basic as one can get in a multilayer system and calls for a comprehensive pseudopotential band structure computation. But for me, and anyone interested in further describing scattering events, this approach is too computer-intensive and inflexible, though in some cases there may be little alternative. An attractive (because simple) approximation is to take as known and unchanged the Bloch functions in each bulk medium and connect them at the interface, satisfying the