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国外物理名著系列 30

（影印版）

Semiconductor Optics and Transport Phenomena

半导体光学和输运现象

W. Schäfer M. Wegener

科学出版社

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国外物理名著系列序言

对于国内的物理学工作者和青年学生来讲，研读国外优秀的物理学著作是系统掌握物理学知识的一个重要手段。但是，在国内并不能及时、方便地买到国外的图书，且国外图书不菲的价格往往令国内的读者却步，因此，把国外的优秀物理原著引进到国内，让国内的读者能够方便地以较低的价格购买是一项意义深远的工作，将有助于国内物理学工作者和青年学生掌握国际物理学的前沿知识，进而推动我国物理学科研和教学的发展。

为了满足国内读者对国外优秀物理学著作的需求，科学出版社启动了引进国外优秀著作的工作，出版社的这一举措得到了国内物理学界的积极响应和支持，很快成立了专家委员会，开展了选题的推荐和筛选工作，在出版社初选的书单基础上确定了第一批引进的项目，这些图书几乎涉及了近代物理学的所有领域，既有阐述学科基本理论的经典名著，也有反映某一学科专题前沿的专著。在选择图书时，专家委员会遵循了以下原则：基础理论方面的图书强调“经典”，选择了那些经得起时间检验、对物理学的发展产生重要影响、现在还不“过时”的著作（如狄拉克的《量子力学原理》）。反映物理学某一领域进展的著作强调“前沿”和“热点”，根据国内物理学研究发展的实际情况，选择了能够体现相关学科最新进展，对有关方向的科研人员和研究生有重要参考价值的图书。这些图书都是最新版的，多数图书都是2000年以后出版的，还有相当一部分是当年出版的新书。因此，这套丛书具有权威性、前瞻性和应用性强的特点。由于国外出版社的要求，科学出版社对部分图书进行了少量的翻译和注释（主要是目录标题和练习题），但这并不会影响图书“原汁原味”的感觉，可能还会方便国内读者的阅读和理解。

“他山之石，可以攻玉”，希望这套丛书的出版能够为国内物理学工作者和青年学生的工作和学习提供参考，也希望国内更多专家参与到这一工作中来，推荐更多的好书。

杨国桢
中国科学院院士
中国物理学会理事长

Preface

Whenever a physicist visits the physics faculty in Dortmund, he/she is bound to hear the success story of the so-called integrated course, a four-semester introduction to physics. These lectures are given by two professors simultaneously, one experimentalist and one theorist. After having asked the common question, "How many professors have killed each other?", the visitor usually realizes that this is an excellent way of presenting a coherent introduction to both experimental and theoretical physics. We decided to try this concept in an advanced course on semiconductor physics. At that point the typical student has already had an introductory course in solid-state physics and solid-state theory. The aim of the lectures was to repeat some of the most important, well-known classics of semiconductor optics and transport and eventually guide the students to topics of current interest in research. When preparing the lectures, we did not find a textbook addressing all these aspects: experiment *and* theory in semiconductor optics *and* transport – which made us write this book. This book presents the phenomenology and a simple, intuitive understanding of many effects and, in addition, attempts to explain the underlying physics on a consistent theoretical footing. Calculations are presented such that a student should be able to follow them with a pencil and a piece of paper. It is our hope that this synthesis of experiment and theory will help to prepare young scientists to contribute something new at the current frontiers of semiconductor physics. After all, the optical and transport properties of semiconductors are among the most important aspects of this particular class of solids for the purposes of their applications – and there are many such applications in everyday life.

This book is organized as follows. A brief introduction to the material systems, we are concerned with in this book is given in Chap. 1. A reader familiar with the general aspects of semiconductor physics and with a basic knowledge of solid-state theory may easily skip Chaps. 2 and 3 without problems. These chapters are merely intended as a reminder of our basic knowledge of electrodynamics, quantum mechanics, statistical physics, and solid-state physics. In addition, they define our nomenclature. We then start discussing the optical properties of semiconductors in Chap. 4, where the important Coulomb correlations are neglected. Nevertheless, this allows us to understand basic experimental techniques, semiconductor photodetectors, and lasers. In Chaps. 5 and 6, Coulomb correlations are treated to first order, such that two-particle correlations are taken into account. This treatment constitutes the semiconductor Bloch equations and modifies the physics of Chap. 4. The dependence on static external fields is discussed in Chaps. 7 and 8, which enables us to understand most types of electro-optic modulators.

A method to include higher order correlations, in particular the formation of four-particle bound states, is introduced in Chap. 9. In order to take care also of other important many-particle interaction processes, such as scattering or screening, we head towards the quantum kinetic equations. The necessary mathematical background is derived in Chap. 10 and extended in Chap. 11 to include scattering from phonons. On a first reading, Chap. 10 (which contains some fairly spicy mathematics) might be skipped. A survey of basic experimental facts and of applications of the theory is presented in Chap. 12. The physics of semiconductor lasers is a nice example where semiconductor optics and transport merge. The physics of these technologically important devices is discussed in Chap. 13.

Classical transport (Chap. 14) is nothing but the strong-scattering limit of the Boltzmann equation. This limit is contrasted with the weak-scattering limit of transport, which is realized in mesoscopic systems. An introduction to this issue is given in Chaps. 15 and 16. Current topics, such as for example, single-electron charging effects, the fractional quantum Hall effect, and magnetotransport through dot and antidot lattices, are dealt with.

We use SI units consistently throughout this book. Nevertheless, a few reminders of fundamental constants in SI units are included in Chaps. 2 and 3 for those using other systems.

Jülich,
Karlsruhe
December 2001

Wilfried Schäfer
Martin Wegener

Contents

1. Some Basic Facts on Semiconductors

Semiconductors have entered our everyday life to such a degree that the notion of a "silicon age" has been employed. Silicon is in fact the most important material as far as commercial applications of semiconductors are concerned. However, while silicon satisfies most of our current needs for electronics, it is only of limited use for optoelectronic applications. Semiconductor lasers, which are at the heart of compact disc players (present in most households), laser printers, and light modulators, the key to today's telecommunication systems, require a direct band gap. Hence, many other semiconductor materials are subjects of current interest. Moreover, today's scientists are no longer satisfied with the variety of bulk materials provided by nature, but have become artists who design semiconductor heterostructures and mesoscopic semiconductor devices corresponding to their needs and interests. This often results in surprising and quite remarkable material properties. Many of these structures, and their optical and transport properties will be discussed in this book.

Semiconductors at room temperature are neither good conductors nor good insulators. They are defined by the presence of an energy gap E_g (throughout the entire Brillouin zone) between the lowest fully occupied bands (at $T = 0$ K), the *valence bands*, and the higher-energy empty bands, the *conduction bands*. It is this gap which makes semiconductors so different from metals. Figure 1.1 shows the computed band structure of gallium arsenide (GaAs). If the extrema of the bands are located at the same point in reciprocal space, the material is referred to as a *direct-gap semiconductor*; if they occur at different points, the term *indirect-gap semiconductor* is used. Silicon is an example of an indirect-gap and GaAs an example of a direct-gap semiconductor. Ideal semiconductors at zero temperature are perfect insulators, materials with large band-gap energies are insulating even at room temperature. Hence, crystals with a room-temperature conductivity less than 10^{-10} $(\Omega\ \mathrm{cm})^{-1}$ are not considered to be semiconductors, but rather *insulators*.

Besides the well-known elementary group IV semiconductor materials Si and Ge (with covalent bonding), a rich variety of binary, ternary, and quaternary semiconductors can be realized. Combinations of, for example, Ga with As (from groups III and V, respectively), Cd with S (from groups II

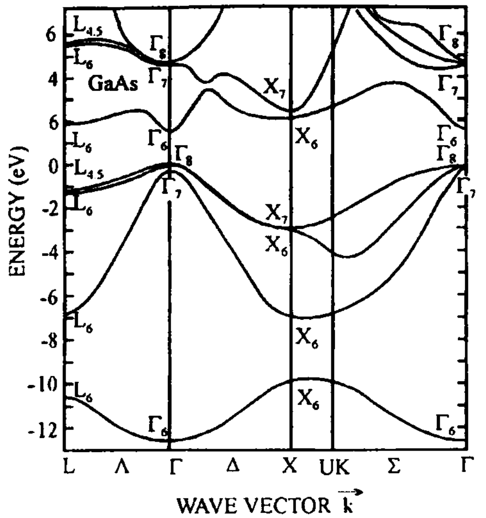

Fig. 1.1. Calculated band structure of the direct-gap semiconductor GaAs. Taken from [1]

and VI), or Cu with Cl (from groups I and VII) yield a rather similar electronic configuration. In the usual jargon, one speaks of III–V, II–VI, and I–VII semiconductors. Similarly, a combination of three elements such as Ga, Al, and As makes a ternary compound and a combination of four elements such as In, Ga, Al, and As constitutes a quaternary compound.

1.1 Semiconductor Heterostructures

One attractive feature of these ternaries and quaternaries is that the band-gap energy can be tailored by choice of the composition. The resulting range of accessible band-gap energies is shown in Fig. 1.2. It is usually a good first-order approximation to interpolate linearly between different materials, i.e. to write for the band gap of a material $A_{1-x}B_xC$ (with x ranging from 0 to 1) $E_g(A_{1-x}B_xC) = (1-x)\,E_g(AC) + xE_g(BC)$. If two semiconductor materials are to be grown on top of each other in the form of a single crystal, *a semiconductor heterostructure* (Fig. 1.3), the respective lattice constants have to be equal or closely similar in order for an unstrained single crystal to be obtained. Still, there is a lot of freedom of choice, as can be seen from Fig. 1.2. One of the most frequently investigated material systems is GaAs/$Al_{1-x}Ga_xAs$ because of the almost perfect lattice matching for any choice of x. The semiconductor lasers in most of today's CD players are made from this particular type of heterostructure. A transmission electron micrograph (TEM) (Fig. 1.4) reveals the position of individual atoms and demonstrates the amazing level of perfection to which epitaxial growth has advanced in this material system, and in several others also.

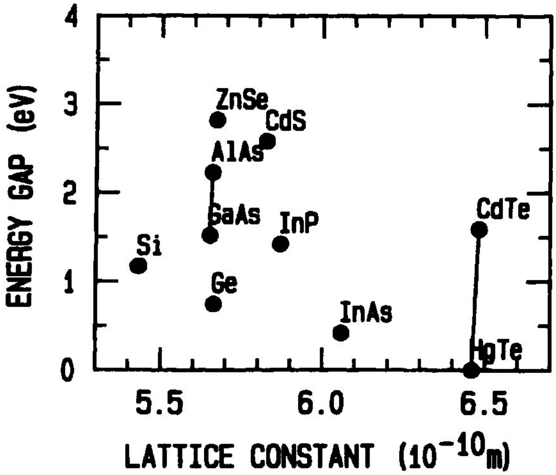

Fig. 1.2. Energy gap (lowest) versus lattice constant for a number of semiconductor materials at low temperature, $T \leq 4.4$ K. HgTe is a semimetal. Numbers taken from [2]

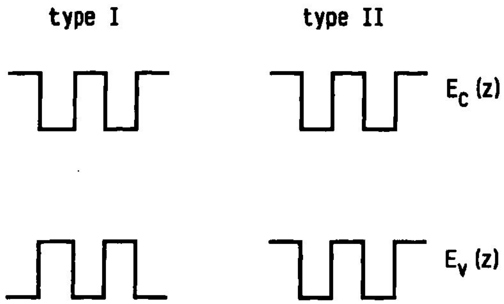

Fig. 1.3. Schematic illustration of the conduction band edge and the valence band edge as a function of the growth direction z in a type I and a type II heterostructure

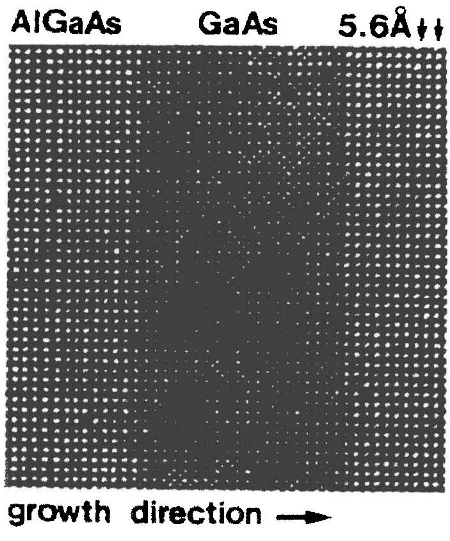

Fig. 1.4. Chemical lattice image, a technique based on transmission electron microscopy, of a GaAs/AlGaAs heterostructure, revealing the positions of individual atoms of the various elements. Taken from [3]

A sequence of layers of different semiconductor materials results in a spatially varying band-gap energy, and hence can be described by a spatially varying potential for the electrons and holes within the structure. This approximation remains reasonable even down to layer thicknesses of the order of a few atomic monolayers. If the resulting minima, *quantum wells*, of this potential for electrons and holes are located within the same material we have a *type I* heterostructure; if they are in different spatial positions, we have a *type II* heterostructure.

The physics of semiconductor optics has benefited tremendously from the availability of such high-quality semiconductor heterostructures.

1.2 Doped and Modulation-Doped Semiconductors

In many situations, the poor conductivity of semiconductors is undesired and one would like to introduce additional electrons (or holes) into the conduction (or valence) band. In Si or Ge this is easily achieved by introducing a group V (or group III) element into the melt. Technically relevant dopants at low concentrations are well described by shallow, bound donor (or acceptor) energy levels below (or above) the corresponding band. At very low temperatures the electrons (or holes) are trapped in these levels, and are thermally activated only at elevated temperatures. This picture, however, breaks down at higher doping concentrations (e.g. $\approx 10^{16}$ cm^{-3} in Sb-doped Ge), and impurity bands are formed as the impurity wavefunctions exhibit increasing overlap. Owing to the resulting mobility, the conductivity is finite even at very low temperatures, a behavior that is well established as the Mott transition. Eventually, at yet higher doping concentrations, the impurity bands can hybridize with the conduction (or valence) bands.

An obvious disadvantage of doping is the inherent concentration of impurities, which serve as rather undesired scattering centers. This problem, which is unavoidable in bulk semiconductors, can be elegantly circumvented in semiconductor heterostructures. Here certain regions of the structure can be doped selectively in different ways, one example can be seen in Fig. 1.5.

The electrons in such structures originate from the doped, large-band-gap AlGaAs region and are located in the triangular-shaped energy minimum within the low-band-gap material (GaAs). It is clear that the steady-state solution (without additional bias) depicted is defined by a spatially and temporally constant electron chemical potential μ_e; details will be discussed in Chap. 15. Most importantly, electrons are now spatially separated from the impurities, hence reducing the scattering by orders of magnitude. Additionally, the electrons are confined to a region comparable to their de Broglie wavelength, resulting in a (quasi-) two-dimensional electron gas.

The physics of transport in semiconductors has greatly benefited from this concept of *modulation doping*.

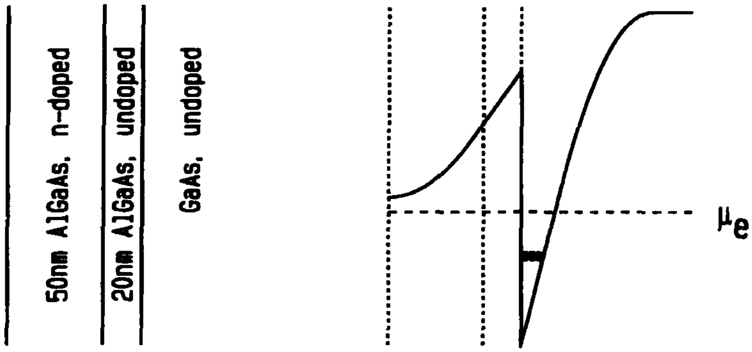

Fig. 1.5. Schematic illustration of a semiconductor heterojunction with a typical layer sequence (*left*) and the conduction band edge as a function of the growth direction (*right*). The carriers confined to the triangular-shaped potential minimum give rise to a highly mobile two-dimensional electron gas