

H. Kalt
M. Hetterich (Eds.)

Optics of Semiconductors and Their Nanostructures



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Heinz Kalt Michael Hetterich (Eds.)

Optics of Semiconductors and Their Nanostructures

With 164 Figures

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Preface

The history of semiconductor optics started with the first experimental observations of light emission in the 19th century. Einstein developed his quantum description of the interaction of light with matter in the early 20th century and the famous Elliott formula for the optical response of the exciton was published in the 1960s. The solar cell celebrates its 50th birthday this year and the laser diode will turn 35 in 2005. Semiconductor optical devices are nowadays found in every household and are the goods of a multi-billion dollar market. Hence one might expect that semiconductor optics has reached a quite mature state. However, in particular the decade around the transition from the 20th to the 21st century has demonstrated that the latter is still a highly active field constantly bringing up new, surprising breakthroughs and even technical revolutions.

The reasons for this development are manifold and it is the aim of this book to highlight some of the most important ones. Firstly, there is the evolution of new experimental techniques to uncover the microscopic basics of semiconductor optics as well as new concepts to manipulate these processes for novel applications. The theory of semiconductor optics follows new paths to describe or predict such phenomena. The progress in nanotechnology brings along a wealth of new physics resulting from confinement and quantization of both light and carriers. Finally, the advent of new semiconductor materials and the enormous advance in the epitaxial growth of well known compounds extends the applications of semiconductor optics from the ultraviolet through the whole visible range to the near infrared.

To be more specific, ultrafast optical spectroscopy now explores the timescale of, and even before, the first scattering processes of optically excited carriers with their environment. This can be ultimately extended to the timescale of one cycle of light leading to effects of extreme nonlinear optics. Ultrafast laser spectroscopy utilizes and tests the coherent nature of the optical excitations via methods of coherent spectroscopy such as four-wave mixing, quantum-beat spectroscopy, and coherent control. These as well as resonant light scattering (both time-resolved and continuous wave) including the analysis of speckle reveal the coherent contributions to the optical response and the processes of dephasing. Such studies now increasingly focus also on the coherence of spin states in semiconductors. The studies

in the traditional frequency range of optics are supplemented by terahertz spectroscopy exploring the intersubband transitions of excitonic or carrier excitations. New approaches in near-field and confocal microscopy give access to a length scale well below the wavelength of light which is governed by quasi-ballistic transport of carriers and excitons. Temporally and spatially resolved phonon-sideband spectroscopy directly monitors exciton populations and their spatio-temporal dynamics.

This evolution of experimental techniques is accompanied by the elaboration of new theoretical concepts. Quantum kinetics theory, which describes e.g. the temporal build-up of correlation effects and screening, has to include memory terms to describe the optical response on a timescale where collisions between carriers can not be viewed as instantaneous. The standard semiconductor Bloch equations are extended to include correlation terms which requires an intelligent truncation of the hierarchy of higher-order effects in a self-consistent way. Including the quantization of the light field, which is obviously necessary for the description of systems with strong carrier-photon coupling like microcavities, also leads to a new interpretation of the optical spectra of excitons and the electron-hole plasma in semiconductors with slow carrier relaxation and weak excitonic binding like (Ga,In)As. Finally, effects related to localization find an elegant description by treating the excitonic center-of-mass motion in a fluctuating potential.

Semiconductor optics has gained enormous momentum from the development of nanostructure technology. One finds atom-like properties in self-organized quantum islands and dots, namely discrete states rather than bands which are unperturbed by inhomogeneous broadening. New fundamental excitations of the semiconductor such as trions are found and multi-particle states like the biexciton are strongly enhanced due to confinement. These novel properties are currently being transferred into applications such as quantum-dot lasers and optical amplifiers. They are also hot candidates for the realization of quantum computing.

New concepts for optoelectronic applications arise from the combination of semiconductors with photonic structures. An illustrative example is the normal-mode coupling, i.e. the splitting of modes due to a coupling between exciton and photon modes, established in microcavities. The ultimate goal is to place a single quantum dot in a photonic nanocavity providing entanglement or single photons on demand. No less innovative is the emerging field of spintronics which uses the spin rather than the charge of carriers for information technology. Experiments triggered by theoretical predictions show that quantum interference of transition amplitudes of one and two-photon absorption can be used to control independently spin and charge currents. And even in the relatively mature field of photovoltaics there is still room for optimization, as is shown by rigorous thermodynamical considerations.

Finally, the last decade has seen a major breakthrough in commercial optoelectronics including lighting, displays, data storage, as well as optical

sensing in chemistry and biology. This breakthrough was caused by the development of efficient blue and white light-emitting diodes (LEDs) and the blue diode laser on the basis of group-III nitrides. Alternative wide-gap semiconductors for optoelectronics in the ultraviolet and blue are diamond and even more important ZnO. In the field of telecommunications new infrared emitters based on GaInNAs have been realized with a performance superior to existing technology and unusual physical properties related to the band structure. The development of such materials as standard components of mass-produced devices requires an elaborate optical characterization including the identification of dopant states or the revelation of band structure details.

This long list of highlights in recent years shows that the field of semiconductor optics is more vibrant than ever. The topics under investigation have gone far beyond the level that is described in standard textbooks like the one written by Claus Klingshirn [C.F. Klingshirn: *Semiconductor Optics*, 2nd corr. printing (Springer, Berlin Heidelberg New York 1997)], which gives one of the best introductions to the field. This present compilation of recent research activities appears on the occasion of C. Klingshirn's 60th birthday in honor of his outstanding contributions to the science and teaching in semiconductor optics. The contributors include some of his former students as well as close collaborators and longstanding scientific colleagues. We know that C. Klingshirn is very pleased by the fact that some of the topics and materials (like ZnO and GaN) which were "modern" at the time of his doctoral studies, have recently gained renewed attention in the quest for advanced concepts in semiconductor optics and its applications.

Karlsruhe,
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