SOLID-STATE SCIENCES

H. Kalt
M. Hetterich (Eds.)

Optics of Semiconductors and Their Nanostructures

Springer

Heinz Kalt Michael Hetterich (Eds.)

Optics of Semiconductors and Their Nanostructures

With 164 Figures

Springer

Professor Dr. Heinz Kalt
Dr. Michael Hetterich
Institut für Angewandte Physik and
DFG-Center for Functional Nanostructures
Universität Karlsruhe (TH)
76128 Karlsruhe, Germany
E-mail: Heinz.Kalt@physik.uni-karlsruhe.de
michael.hetterich@physik.uni-karlsruhe.de

Series Editors:

ISSN 0171-1873

ISBN 3-540-22068-2 Springer Berlin Heidelberg New York

Library of Congress Control Number: 2004105248

Springer is a part of Springer Science+Business Media
springeronline.com

Typesetting by the editor/authors
Cover concept: eStudio Calamar Steinen
Cover production: *design & production* GmbH, Heidelberg

Printed on acid-free paper SPIN: 10953136 57/3141/ba - 5 4 3 2 1 0

Springer Series in
SOLID-STATE SCIENCES 146

Springer Series in
SOLID-STATE SCIENCES

The Springer Series in Solid-State Sciences consists of fundamental scientific books prepared by leading researchers in the field. They strive to communicate, in a systematic and comprehensive way, the basic principles as well as new developments in theoretical and experimental solid-state physics.

126 **Physical Properties of Quasicrystals**
Editor: Z.M. Stadnik

127 **Positron Annihilation in Semiconductors**
Defect Studies. By R. Krause-Rehberg and H.S. Leipner

128 **Magneto-Optics**
Editors: S. Sugano and N. Kojima

129 **Computational Materials Science**
From Ab Initio to Monte Carlo Methods. By K. Ohno, K. Esfarjani, and Y. Kawazoe

130 **Contact, Adhesion and Rupture of Elastic Solids**
By D. Maugis

131 **Field Theories for Low-Dimensional Condensed Matter Systems**
Spin Systems and Strongly Correlated Electrons. By G. Morandi, P. Sodano, A. Tagliacozzo, and V. Tognetti

132 **Vortices in Unconventional Superconductors and Superfluids**
Editors: R.P. Huebener, N. Schopohl, and G.E. Volovik

133 **The Quantum Hall Effect**
By D. Yoshioka

134 **Magnetism in the Solid State**
By P. Mohn

135 **Electrodynamics of Magnetoactive Media**
By I. Vagner, B.I. Lembrikov, and P. Wyder

136 **Nanoscale Phase Separation and Colossal Magnetoresistance**
The Physics of Manganites and Related Compounds
By E. Dagotto

137 **Quantum Transport in Submicron Devices**
A Theoretical Introduction
By W. Magnus and W. Schoenmaker

138 **Phase Separation in Soft Matter Physics**
Micellar Solutions, Microemulsions, Critical Phenomena
By P.K. Khabibullaev and A.A. Saidov

139 **Optical Response of Nanostructures**
Microscopic Nonlocal Theory
By K. Cho

140 **Fractal Concepts in Condensed Matter Physics**
By T. Nakayama and K. Yakubo

141 **Excitons in Low-Dimensional Semiconductors**
Theory, Numerical Methods, Applications By S. Glutsch

142 **Two-Dimensional Coulomb Liquids and Solids**
By Y. Monarkha and K. Kono

143 **X-Ray Multiple-Wave Diffraction**
Theory and Application
By S.-L. Chang

144 **Physics of Transition Metal Oxides**
By S. Maekawa, T. Tohyama, S.E. Barnes, S. Ishihara, W. Koshibae, and G. Khaliullin

145 **Point-Contact Spectroscopy**
By Y. Naidyuk and I.K. Yanson

146 **Optics of Semiconductors and Their Nanostructures**
Editors: H. Kalt and M. Hetterich

147 **Electron Scattering in Solid Matter**
A Theoretical and Computational Treatise By J. Zabloudil, R. Hammerling, L. Szunyogh, and P. Weinberger

Volumes 1–125 are listed at the end of the book.

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 selforganized 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, *Heinz Kalt*
March 2004 *Michael Hetterich*

List of Contributors

Tommy W. Berg
Research Center COM
Technical University of Denmark
Ørsteds Plads 345V
2800 Lyngby, Denmark
twb@com.dtu.dk

Ravi D.R. Bhat
Department of Physics
University of Toronto
60 St. George Street
Toronto, Ontario, Canada M5S 1A7
rbhat@physics.utoronto.ca

Hans-Georg Breunig
Institut für Festkörperphysik
Universität Bremen
Postfach 330440
28334 Bremen, Germany
breunig@staff.uni-marburg.de

Hyatt M. Gibbs
Optical Sciences Center
The University of Arizona
Tucson, AZ 85721, USA
hyattgibbs@att.net

Jürgen Gutowski
Institut für Festkörperphysik
Universität Bremen
Postfach 330440
28334 Bremen, Germany
gutowski@ifp.uni-bremen.de

Hartmut Haug
J.W. Goethe-Universität Frankfurt
Institut für Theoretische Physik,
Robert-Mayer-Str. 8
60054 Frankfurt am Main, Germany
Haug@itp.uni-frankfurt.de

Michael Hetterich
Institut für Angewandte Physik
Universität Karlsruhe (TH)
Wolfgang-Gaede-Straße 1
76131 Karlsruhe, Germany
michael.hetterich@physik.
uni-karlsruhe.de

Jørn M. Hvam
Research Center COM
Technical University of Denmark
Ørsteds Plads 345V
2800 Lyngby, Denmark
hvam@com.dtu.dk

Heinz Kalt
Institut für Angewandte Physik
Universität Karlsruhe (TH)
Wolfgang-Gaede-Straße 1
76131 Karlsruhe, Germany
heinz.kalt@physik.
uni-karlsruhe.de

Mackillo Kira
Fachbereich Physik und
Wiss. Zentrum
für Materialwissenschaften
Philipps-Universität Marburg
Renthof 5
35032 Marburg, Germany
mackillo.kira@physik.
uni-marburg.de

Stephan W. Koch
Fachbereich Physik und
Wiss. Zentrum für
Materialwissenschaften
Philipps-Universität Marburg
Renthof 5
35032 Marburg, Germany
stephan.w.koch@physik.
uni-marburg.de

Gerrit Kocherscheidt
Experimentelle Physik IIb
Universität Dortmund
Otto-Hahn-Str. 4
44227 Dortmund, Germany
gerrit.kocherscheidt@gmx.de

Martin Kuball
H.H. Wills Physics Laboratory
University of Bristol
Tyndall Avenue
Bristol BS8 1TL, UK
martin.kuball@bristol.ac.uk

Wolfgang Langbein
Experimentelle Physik IIb
Universität Dortmund
Otto-Hahn-Str. 4
44227 Dortmund, Germany
wolfgang.langbein@
uni-dortmund.de

Ali Najmaie
Department of Physics
University of Toronto
60 St. George Street
Toronto, Ontario, Canada M5S 1A7
anajmaie@physics.utoronto.ca

Rolf Sauer
Abteilung Halbleiterphysik
Universität Ulm
Albert-Einstein-Allee 45
89069 Ulm, Germany
rolf.sauer@physik.uni-ulm.de

John E. Sipe
Department of Physics
University of Toronto
60 St. George Street
Toronto, Ontario, Canada M5S 1A7

Arthur L. Smirl
Laboratory for Photonics
& Quantum Electronics
138 IATL
University of Iowa
Iowa City, Iowa 52242, USA
art-smirl@uiowa.edu

Martin J. Stevens
Laboratory for Photonics
& Quantum Electronics
138 IATL
University of Iowa
Iowa City, Iowa 52242, USA
martin-stevens@uiowa.edu

Klaus Thonke
Abteilung Halbleiterphysik
Universität Ulm
Albert-Einstein-Allee 45
89069 Ulm, Germany
klaus.thonke@physik.uni-ulm.de

Henry M. van Driel
Department of Physics
University of Toronto
60 St. George Street
Toronto, Ontario, Canada M5S 1A7
vandriel@physics.utoronto.ca

Tobias Voss
Institut für Festkörperphysik
Universität Bremen
Postfach 330440
28334 Bremen, Germany
tvoss@ifp.uni-bremen.de

Martin Wegener
Institut für Angewandte Physik
Universität Karlsruhe (TH)
Wolfgang-Gaede-Straße 1
76131 Karlsruhe, Germany
martin.wegener@physik.
uni-karlsruhe.de

Ulrike Woggon
Experimentelle Physik IIb
Universität Dortmund
Otto-Hahn-Str. 4
44227 Dortmund, Germany
ulrike.woggon@uni-dortmund.de

Peter Würfel
Institut für Angewandte Physik
Universität Karlsruhe (TH)
Wolfgang-Gaede-Straße 1
76131 Karlsruhe, Germany
peter.wuerfel@physik.
uni-karlsruhe.de

Hui Zhao
Laboratory for Photonics
& Quantum Electronics
138 IATL
University of Iowa
Iowa City, Iowa 52242, USA
hui-zhao@uiowa.edu

Roland Zimmermann
Institut für Physik der
Humboldt-Universität zu Berlin
Newtonstr. 15
12489 Berlin, Germany
zim@physik.hu-berlin.de

Springer Series in Solid-State Sciences

Editors: M. Cardona P. Fulde K. von Klitzing H.-J. Queisser

1 **Principles of Magnetic Resonance** 3rd Edition By C. P. Slichter
2 **Introduction to Solid-State Theory** By O. Madelung
3 **Dynamical Scattering of X-Rays in Crystals** By Z. G. Pinsker
4 **Inelastic Electron Tunneling Spectroscopy** Editor: T. Wolfram
5 **Fundamentals of Crystal Growth I** Macroscopic Equilibrium and Transport Concepts By F. E. Rosenberger
6 **Magnetic Flux Structures in Superconductors** 2nd Edition By R. P. Huebener
7 **Green's Functions in Quantum Physics** 2nd Edition By E. N. Economou
8 **Solitons and Condensed Matter Physics** Editors: A. R. Bishop and T. Schneider
9 **Photoferroelectrics** By V. M. Fridkin
10 **Phonon Dispersion Relations in Insulators** By H. Bilz and W. Kress
11 **Electron Transport in Compound Semiconductors** By B. R. Nag
12 **The Physics of Elementary Excitations** By S. Nakajima, Y. Toyozawa, and R. Abe
13 **The Physics of Selenium and Tellurium** Editors: E. Gerlach and P. Grosse
14 **Magnetic Bubble Technology** 2nd Edition By A. H. Eschenfelder
15 **Modern Crystallography I** Fundamentals of Crystals Symmetry, and Methods of Structural Crystallography 2nd Edition By B. K. Vainshtein
16 **Organic Molecular Crystals** Their Electronic States By E. A. Silinsh
17 **The Theory of Magnetism I** Statics and Dynamics By D. C. Mattis
18 **Relaxation of Elementary Excitations** Editors: R. Kubo and E. Hanamura
19 **Solitons** Mathematical Methods for Physicists By. G. Eilenberger
20 **Theory of Nonlinear Lattices** 2nd Edition By M. Toda
21 **Modern Crystallography II** Structure of Crystals 2nd Edition By B. K. Vainshtein, V. L. Indenbom, and V. M. Fridkin
22 **Point Defects in Semiconductors I** Theoretical Aspects By M. Lannoo and J. Bourgoin
23 **Physics in One Dimension** Editors: J. Bernasconi and T. Schneider
24 **Physics in High Magnetics Fields** Editors: S. Chikazumi and N. Miura
25 **Fundamental Physics of Amorphous Semiconductors** Editor: F. Yonezawa
26 **Elastic Media with Microstructure I** One-Dimensional Models By I. A. Kunin
27 **Superconductivity of Transition Metals** Their Alloys and Compounds By S. V. Vonsovsky, Yu. A. Izyumov, and E. Z. Kurmaev
28 **The Structure and Properties of Matter** Editor: T. Matsubara
29 **Electron Correlation and Magnetism in Narrow-Band Systems** Editor: T. Moriya
30 **Statistical Physics I** Equilibrium Statistical Mechanics 2nd Edition By M. Toda, R. Kubo, N. Saito
31 **Statistical Physics II** Nonequilibrium Statistical Mechanics 2nd Edition By R. Kubo, M. Toda, N. Hashitsume
32 **Quantum Theory of Magnetism** 2nd Edition By R. M. White
33 **Mixed Crystals** By A. I. Kitaigorodsky
34 **Phonons: Theory and Experiments I** Lattice Dynamics and Models of Interatomic Forces By P. Brüesch
35 **Point Defects in Semiconductors II** Experimental Aspects By J. Bourgoin and M. Lannoo
36 **Modern Crystallography III** Crystal Growth By A. A. Chernov
37 **Modern Chrystallography IV** Physical Properties of Crystals Editor: L. A. Shuvalov
38 **Physics of Intercalation Compounds** Editors: L. Pietronero and E. Tosatti
39 **Anderson Localization** Editors: Y. Nagaoka and H. Fukuyama
40 **Semiconductor Physics** An Introduction 6th Edition By K. Seeger
41 **The LMTO Method** Muffin-Tin Orbitals and Electronic Structure By H. L. Skriver
42 **Crystal Optics with Spatial Dispersion, and Excitons** 2nd Edition By V. M. Agranovich and V. L. Ginzburg
43 **Structure Analysis of Point Defects in Solids** An Introduction to Multiple Magnetic Resonance Spectroscopy By J.-M. Spaeth, J. R. Niklas, and R. H. Bartram
44 **Elastic Media with Microstructure II** Three-Dimensional Models By I. A. Kunin
45 **Electronic Properties of Doped Semiconductors** By B. I. Shklovskii and A. L. Efros
46 **Topological Disorder in Condensed Matter** Editors: F. Yonezawa and T. Ninomiya

Springer Series in Solid-State Sciences

Editors: M. Cardona P. Fulde K. von Klitzing H.-J. Queisser

Springer Series in Solid-State Sciences

Editors: M. Cardona P. Fulde K. von Klitzing H.-J. Queisser

---

90 **Earlier and Recent Aspects of Superconductivity**
Editors: J. G. Bednorz and K. A. Müller

91 **Electronic Properties of Conjugated Polymers III** Basic Models and Applications
Editors: H. Kuzmany, M. Mehring, and S. Roth

92 **Physics and Engineering Applications of Magnetism** Editors: Y. Ishikawa and N. Miura

93 **Quasicrystals** Editors: T. Fujiwara and T. Ogawa

94 **Electronic Conduction in Oxides** 2nd Edition
By N. Tsuda, K. Nasu, F. Atsushi, and K. Siratori

95 **Electronic Materials**
A New Era in Materials Science
Editors: J. R. Chelikowsky and A. Franciosi

96 **Electron Liquids** 2nd Edition By A. Isihara

97 **Localization and Confinement of Electrons in Semiconductors**
Editors: F. Kuchar, H. Heinrich, and G. Bauer

98 **Magnetism and the Electronic Structure of Crystals** By V.A. Gubanov, A.I. Liechtenstein, and A.V. Postnikov

99 **Electronic Properties of High-T_c Superconductors and Related Compounds**
Editors: H. Kuzmany, M. Mehring, and J. Fink

100 **Electron Correlations in Molecules and Solids** 3rd Edition By P. Fulde

101 **High Magnetic Fields in Semiconductor Physics III** Quantum Hall Effect, Transport and Optics By G. Landwehr

102 **Conjugated Conducting Polymers**
Editor: H. Kiess

103 **Molecular Dynamics Simulations**
Editor: F. Yonezawa

104 **Products of Random Matrices** in Statistical Physics By A. Crisanti, G. Paladin, and A. Vulpiani

105 **Self-Trapped Excitons**
2nd Edition By K. S. Song and R. T. Williams

106 **Physics of High-Temperature Superconductors**
Editors: S. Maekawa and M. Sato

107 **Electronic Properties of Polymers**
Orientation and Dimensionality of Conjugated Systems Editors: H. Kuzmany, M. Mehring, and S. Roth

108 **Site Symmetry in Crystals**
Theory and Applications 2nd Edition
By R. A. Evarestov and V. P. Smirnov

109 **Transport Phenomena in Mesoscopic Systems** Editors: H. Fukuyama and T. Ando

110 **Superlattices and Other Heterostructures**
Symmetry and Optical Phenomena 2nd Edition
By E. L. Ivchenko and G. E. Pikus

111 **Low-Dimensional Electronic Systems**
New Concepts
Editors: G. Bauer, F. Kuchar, and H. Heinrich

112 **Phonon Scattering in Condensed Matter VII**
Editors: M. Meissner and R. O. Pohl

113 **Electronic Properties of High-T_c Superconductors**
Editors: H. Kuzmany, M. Mehring, and J. Fink

114 **Interatomic Potential and Structural Stability**
Editors: K. Terakura and H. Akai

115 **Ultrafast Spectroscopy of Semiconductors and Semiconductor Nanostructures**
2nd Edition By J. Shah

116 **Electron Spectrum of Gapless Semiconductors**
By J. M. Tsidilkovski

117 **Electronic Properties of Fullerenes**
Editors: H. Kuzmany, J. Fink, M. Mehring, and S. Roth

118 **Correlation Effects in Low-Dimensional Electron Systems**
Editors: A. Okiji and N. Kawakami

119 **Spectroscopy of Mott Insulators and Correlated Metals**
Editors: A. Fujimori and Y. Tokura

120 **Optical Properties of III–V Semiconductors**
The Influence of Multi-Valley Band Structures
By H. Kalt

121 **Elementary Processes in Excitations and Reactions on Solid Surfaces**
Editors: A. Okiji, H. Kasai, and K. Makoshi

122 **Theory of Magnetism**
By K. Yosida

123 **Quantum Kinetics in Transport and Optics of Semiconductors**
By H. Haug and A.-P. Jauho

124 **Relaxations of Excited States and Photo-Induced Structural Phase Transitions**
Editor: K. Nasu

125 **Physics and Chemistry of Transition-Metal Oxides**
Editors: H. Fukuyama and N. Nagaosa

Contents