Topics in Applied Physics

Volume 8

Light Scattering in Solids I

Introductory Concepts

Second Edition

Editor: M. Cardona

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Light Scattering in Solids I

Introductory Concepts

Edited by M. Cardona

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Second Corrected and Updated Edition

With 111 Figures

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Preface to the Second Edition

The first edition of this book appeared in 1975. Five years later I decided to edit, in collaboration with G. Güntherodt, another volume on light scattering in solids. In the meantime light scattering spectroscopy had become a standard, well established technique with most of the necessary equipment commercially available. Results have been appearing in the literature at an increasing pace and, while the basic principles of the phenomenon were covered in the first volume, we felt that the wealth of new information available warranted issuing a new volume of the Topics in Applied Physics series. The originally planned volume exploded as the authors overran their page allotments and a few more authors were added. Thus, by the time this second edition appears, instead of a new additional volume we shall have three (including this one) and a further volume is still forthcoming.

This paperback edition is essential identical to the original hardcover one, except that Chapter 7 has been supplemented with new results and a new chapter (Chap. 8) has been added. This new chapter outlines the current status of light-scattering spectroscopy applied to the study of solids and provides numerous new references. A few typographical errors in the original edition were corrected.

Because of limitation of space, we can do little more in Chapter 8 than point out to the reader the latest literature as well as to the now completed treatment of *Light Scattering in Solids I–IV*, published in the Topics in Applied Physics series (Vols. 8, 50, 51, and 54). For convenient, cross-referencing we have added the Roman numeral one to the title of this second edition, and supplemented its various chapters with references to related work covered in other volumes of this series: their contents have been listed on pages 335–347. A few relevant references to recent work have also been included. Completeness has not been attempted in the compilation of these references. Instead we have tried to give a sampling of the current works by some of the most representative groups.

Stuttgart, July 1982 MANUEL CARDONA

Preface to the First Edition

This book is devoted to the problem of inelastic light scattering in semiconductors, i.e., to processes in which a photon impinges upon a semiconductor, creating or anihilating one or several quasi-particles, and then emerges with an energy somewhat different from that of the incident photon. In light scattering spectroscopy the incident photons are monochromatic; one measures the energy distribution of the scattered photons with a spectrometer. Because of its monochromaticity, power, and collimation, lasers are ideal sources for light scattering spectroscopy. Consequently, developments in the field of light scattering have followed, in recent years, the developments in laser technology. The scattering efficiencies are usually weak and thus light scattering spectroscopy requires sophisticated double and triple monochromators with high stray light rejection ratio. Both, powerful lasers and good monochromators are specially important for studying the scattering of light to which the samples of interest are opaque, as is the case in most semiconductors. This explains why these materials are relatively latecomers to the field of light scattering.

In spite of these difficulties, the field of light scattering in semiconductors has experienced a boom in recent years, and reached a certain degree of maturity. Because of space limitations, the editor was faced with the necessity of making a choice in the subjects to be included. In spite of the natural bias towards his own research interests he hopes to have gathered a number of articles representative of present-day research in the field.

Chapter 1 contains a historical survey of the field of light scattering in general and of the bibliography in the fields of light scattering by one and two phonons, including resonant Raman scattering, i.e., scattering of phonons whose energy lies in the neighborhood of strong electronic structure in the optical constants.

Chapter 2 discusses the fundamentals of light scattering, its phenomenological description, kinematics and selection rules. It also contains an introduction to the microscopic theory.

Chapter 3 describes in detail the phenomenon of resonant Raman scattering which, in isolating the electronic states which participate

in the resonance, yields very detailed information about the scattering mechanism and the electron-phonon interaction. Several models are considered quantitatively in order to give a feeling for the interpretation of observed resonances.

Chapter 4 treats scattering by electronic excitations in semiconductors, a field of considerable technological interest. It includes scattering by free particles, plasmons and excitations between impurity levels. In all cases the specific effects of the intricacies of constant-energy surfaces in semiconductors are taken into account.

Chapter 5 discusses Raman scattering by amorphous semiconductors. This field which has received considerable attention since the discovery by the contributor and his coworkers that the observed first-order spectra often contain information about the density of one-phonon states in alotropic crystalline materials. A discussion of the implications of the observed spectra with respect to short-range order and chemical bonding is included.

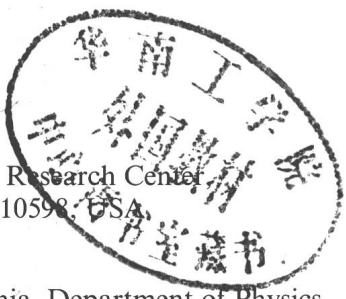
Chapter 6 describes the fundamentals of Brillouin scattering in semiconductors, and the spontaneous and stimulated processes which can be observed when phonons are generated in polar materials by means of the acousto-electric effect.

Finally, Chapter 7 is devoted to stimulated Raman scattering, another subject of considerable technological importance because of the tunable spin-flip lasers and the recently developed spectroscopical technique referred to as CARS (coherent antistokes Raman spectroscopy).

The editor, a relatively new comer to the field of light scattering, has profited from his collaboration in this field with a large number of scientists, graduate students, colleagues at Brown University and at the Max Planck Institute and other institutions. It would be cumbersome to name them all here. Most of their names appear in the literature referenced throughout this tract. Last but not least thanks are due to all the contributors for keeping the deadlines as well as they could in spite of numerous other commitments and for their patient consideration of the editor's suggestions.

Stuttgart, May 1975 MANUEL CARDONA

Contributors



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Amorphous Semiconductors

Editor: M. H. Brodsky
1979. 181 figures, 5 tables. XVI, 337 pages.
(Topics in Applied Physices. Volume 36)
ISBN 3-540-09496-2

Contents: *M. H. Brodsky:* Introduction. – *B. Kramer, D. Weaire:* Theory of Electronic States in Amorphous Semiconductors. – *E. A. Davis:* States in the Gap and Defects in Amorphous Semiconductors. – *G. A. E. Conell:* Optical Properties of Amorphous Semiconductors. – *P. Nagels:* Electronic Transport in Amorphous Semiconductors. – *R. Fischer:* Luminescence in Amorphous Semiconductors. – *I. Solomon:* Spin Effects in Amorphous Semiconductors. – *G. Lucovsky, T. M. Hayes:* Short-Range Order in Amorphous Semiconductors. – *P. G. LeComber, W. E. Spear:* Doped Amorphous Semiconductors. – *D. E. Carlson, C. R. Wronski:* Amorphous Silicon Solar Cells.

Fundamental Physics of Amorphous Semiconductors

Proceedings of the Kyoto Summer Institute, Kyoto, Japan, September 8–11, 1980

Editor: **F. Yonezawa**
1981. 91 figures. VIII, 181 pages. (Springer Series in Solid-State Sciences, Volume 25)
ISBN 3-540-10634-0

Contents: What are Non-Crystalline Semiconductors. – Defects in Covalent Amorphous Semiconductors. – Surface Effects and Transport Properties in Thin Films of Hydrogenated Silicon. – The Past, Present and Future of Amorphous Silicon. – The Effect of Hydrogen and Other Additives on the Electronic Properties of Amorphous Silicon. – New Insights on Amorphous Semiconductors from Studies of Hydrogenated a-Ge, a-Si, a-$SI_{1-x}Ge_x$ and a-GaAs. – Chemical Bonding of Alloy Atoms in Amorphous Semiconductors. –Theory of Electronic Properties of Amorphous Semiconductors. – Some Problems of the Electron Theory of Disordered Semiconductors. –The Anderson Localisation Problem. – Summary Talk. – Seminars Given During the KSI '80. – Photographs of the Participants of the KSI '80. – List of Participants.

Photoemission in Solids I

General Principles

Editors: **M. Cardona, L. Ley**
1978. 90 figures, 17 tables. XI, 290 pages.
(Topics in Applied Physics, Volume 26)
ISBN 3-540-08685-4

Contents: *M. Cardona, L. Ley:* Introduction. – *W. L. Schaich:* Theory of Photoemission: Independent Particle Model. – *S. T. Manson:* The Calculation of Photoionization Cross Sections: An Atomic View. – *D. A. Shirley:* Many-Electron and Final-State Effects: Beyond the One-Electron Picture. – *G. K. Wertheim, P. H. Citrin:* Fermi Surface Excitations in X-Ray Photoemission Line Shapes from Metals. – *N. V. Smith:* Angular Dependent Photoemission. – Appendix.

Photoemission in Solids II

Case Studies

Editors: **L. Ley, M. Cardona**
1979. 214 figures, 26 tables. XVIII, 401 pages.
(Topics in Applied Physics, Volume 27).
ISBN 3-540-09202-1

Contents: *L. Ley, M. Cardona:* Introduction. – *L. Ley, M. Cardona, R. A. Pollak:* Photoemission in Semiconductors. – *S. Hüfner:* Unifilled Inner Shells: Transition Metals and Compounds. – *M. Campagna, G. K. Wertheim, Y. Baer:* Unfilled Inner Shells: Rare Earths and Their Compounds. – *W. D. Grobman, E. E. Koch:* Photoemission from Organic Molecular Crystals. – *C. Kunz:* Synchrotron Radiation: Overview. – *P. Steiner, H. Höchst, S. Hüfner:* Simple Metals. – Appendix: Table of Core-Level Binding Energies. – Additional References with Titles. – Subject Index.

Springer-Verlag Berlin Heidelberg New York

M. Lannoo, J. Bourgoin

Point Defects in Semiconductors

Theoretical Aspects

With a Foreword by J. Friedel
1981. 87 figures. XVII, 265 pages
(Springer Series in Solid-State Sciences, Volume 22)
ISBN 3-540-10518-2

Contents: Atomic Configuration of Point Defects. – Effective Mass Theory. – Simple Theory of Deep Levels in Semiconductors. – Many-Electron Effects and Sophisticated Theories of Deep Levels. – Vibrational Properties and Entropy. – Thermodynamics of Defects. – Defect Migration and Diffusion. – References. – Subject Index.

Thermally Stimulated Relaxation in Solids

Editor: **P. Bräunlich**

1979. 142 figures, 1 table. XII, 331 pages
(Topics in Applied Physics, Volume 37)
ISBN 09595-0

Contents: *P. Bräunlich:* Introduction and Basic Principles. – *P. Bräunlich, P. Kelly, J.-P. Fillard:* Thermally Stimulated Luminescence and Conductivity. – *D. V. Lang:* Space-Charge Spectroscopy in Semiconductors. – *J. Vanderschueren, J. Gasiot:* Field Induced Thermally Stimulated Currents. – *H. Glaefeke:* Exoemission. – *L. A. DeWerd:* Applications of Thermally Stimulated Luminescence.

D. C. Hanna, M. A. Yuratich, D. Cotter

Nonlinear Optics of Free Atoms and Molecules

1979. 89 figures, 10 tables. IX. 351 pages
(Springer Series in Optical Sciences, Volume 17)
ISBN 3-540-09628-0

"Here is a book, written in a style, that makes it more transparent, and therefore more suitable as an introduction to the field... The examples chosen are all very appropriate for this book and fit together very nicely. All the material is well-organized, thoroughly explored, and up-to-date. Citations to the original literature are extensive, and credit is fairly distributed... The notation is carefully explained and is consistent throughout. The printing is easily read and is of the excellent quality we have come to expect from the publisher, Springer-Verlag..." *J. Opt. Soc. Am.*

Structural Phase Transitions

Editors: **K. A. Müller, H. Thomas**

1981. 61 figures. IX, 190 pages
(Topics in Current Physics, Volume 23)
ISBN 3-540-10329-5

Contents: *K. A. Müller:* Introduction. – *P. A. Fleury, K. B. Lyons:* Optical Studies of Structural Phase Transformations. – *B. Dorner:* Investigation of Structural Phase Transformation by Inelastic Neutron Scattering. – *B. Lüthi, W. Rehwald:* Ultrasonic Studies Near Structural Phase Transitions.

W. Demtröder

Laser Spectroscopy

Basic Concepts and Intrumentation

2nd corrected printing. 1982.
431 figures. Approx. 710 pages
(Springer Series in Chemical Physics, Volume 5)
ISBN 3-540-10343-0

Springer-Verlag Berlin Heidelberg New York

Contents

1. Introduction

M. CARDONA

With 3 Figures

Licht, mehr Licht ...
J. W. GOETHE

Most of this volume is devoted to light scattering in semiconductors with special emphasis on Raman scattering by phonons, and, in particular, resonant Raman scattering. Among semiconductors, the family of tetrahedrally coordinated materials, including the structures of germanium, zincblende, wurtzite, ternary chalcopyrites, and others, form an excellent laboratory for light scattering experiments. They are simple, their band structures are well understood and offer an enormous variety. Also, considerable information is available about their phonon spectra. Besides, semiconductors muster a number of interesting many-body-type quasi-particle excitations such as excitons, plasmons, polarons, polaritons, exciton drops, excitons bound to impurities, etc. These quasi-particles can sometimes be excited in a light scattering process. They can also be studied indirectly by observing resonances in other scattering processes, when the frequency of the scattered light is in the neighborhood of the quasi-particle frequency. Recently, Cu_2O also became a one-material laboratory to test and analyze the mechanisms for Raman scattering processes. This material has, in contrast to zincblende, a large number of optical phonons at $\boldsymbol{k}=0$ and a forbidden direct edge with sharp excitons. This edge and excitons occur in a wavelength region very convenient for studies with tunable dye lasers.

1.1. Historical Remarks

The foundations of the light scattering process were established long ago. In 1922 BRILLOUIN [1.1] predicted the scattering of light by long wavelength elastic sound waves. SMEKAL [1.2] developed in 1923 the theory of light scattering by a system with two quantized energy levels; this theory contained the essential characteristics of the phenomena discovered by RAMAN [1.3] and, independently, by LANDSBERG and MANDELSTAM [1.4] in 1928. It was soon realized that the newly discovered effect constituted an excellent tool to study excitations of molecules and molecular structure. Such studies dominated the field until about 1940. In the 1940's emphasis shifted to systematic investigations of