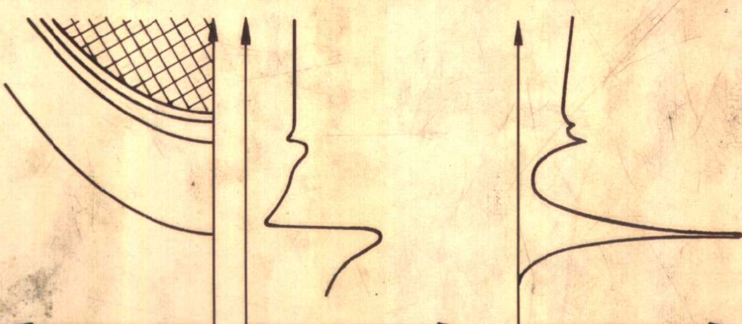
C. F. Klingshirn

Semiconductor Optics



Springer

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With 270 Figures

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To my parents, my wife and my children

Wahrheit und Klarheit sind komplementär.

E. MOLLWO

This aphorism was coined in the nineteen-fifties by E. MOLLWO, Professor of Physics at the Institut für Angewandte Physik of the Universität Erlangen during a discussion with W. HEISENBERG. The author hopes that, with respect to his book, the deviations from exact scientific truth (Wahrheit) and perfect understandability (Klarheit) are in a reasonable balance.

Preface

One of the most prominent senses of many animals and, of course, of human beings is sight or vision. As a consequence, all phenomena which are connected with light and color, or with the optical properties of matter, have been focal points of interest throughout the history of mankind. Natural light sources such as the Sun, the Moon and stars, or fire, were worshipped as gods or godesses in many ancient religions. Fire, which gives light and heat, was for many centuries thought to be one of the four elements – together with earth, water, and air. In alchemy, which marks the dawn of our modern science, the Sun and the Moon appeared as symbols of gold and silver, respectively, and many people tried to produce these metals artificially. Some time later, Johann Wolfgang von Goethe (1749–1832) considered his "Farbenlehre" as more important than his poetry. In the last two centuries a considerable fraction of modern science has been devoted to the investigation and understanding of light and the optical properties of matter. Many scientists all over the world have added to our understanding of this topic. As representatives of the many we should like to mention here only a few of them: I. Newton (1643–1727), Maxwell (1831–1879), M. Planck (1858–1947), A. Einstein (1879–1955), N. Bohr (1885–1962), and W. Heisenberg (1901–1967).

The aim of this book is more modest. It seeks to elucidate one of the numerous aspects in the field of light and the optical properties of matter, namely the interaction of light with semiconductors, i.e., semiconductor optics. The investigation of the properties of semiconductors has, in turn, its own history, which has been summarized recently by H.J. Queisser[1]. In Queisser's book one can find early examples of semiconductor optics, namely the observation of artificially created luminescence by V. Cascariolo in Bologna at the beginning of the 17th century, or by K.F. Braun (1850–1918), inventor of the "Braun'sche Röhre" (Braun's tube) now usually called CRT (cathode ray tube), at the beginning of this century.

Another root of semiconductor optics comes from the investigation of the optical properties of insulators, especially of the color (Farb- or F-) centers in alkali halides. This story has been written down recently by J. Teichmann[2]. It is inseparably connected with names such as Sir Nelville Mott and A. Smakula, but especially with R.W. Pohl (1884–1976) and his school in Göttingen.

Together with J. Franck (1882–1964) and M. Born (1882–1970) R.W. Pohl was one of the outstanding physicists of the "golden years of physics" at Göttingen before 1933[3]. The present author considers himself a scientific grandson of Pohl, with E. Mollwo (1909–1993), F. Stöckmann and W. Martienssen as the intermediate generation, and he owes to them a large part of his scientific education.

Scientific interest in semiconductor optics comprises both fundamental and applied research. It has been an extremely lively, rapidly developing area of research for the last five decades and more, as can be seen from the contributions to the series of International Conferences on the Physics of Semiconductors[4] and on the Physics of Luminescence[5]. It does not need much of a prophetic gift to predict that semiconductor optics will continue to be a major topic of solid state physics far into the next century. Many applications of semiconductor optics are known from everyday life such as light-emitting diodes (LED) in displays, laser diodes in compact-disk (CD) players, and laser printers.

Karlsruhe, February 1995 C.F. KLINGSHIRN

[1] H.-J. Queisser: *Kristallene Krisen* (Piper, München 1985)

[2] J. Teichmann: *Zur Geschichte der Festkörperphysik–Farbzentrenforschung bis 1940* (Steiner, Wiesbaden 1988)

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[4] The Series of Int'l Conferences on the Physics of Semiconductors (ICPS) was started in 1950 in Reading. Proceedings of the more recent ones are
12th ICPS, Stuttgart (1974), ed. by M.H. Pilkuhn (Teubner, Stuttgart 1974)
13th ICPS, Rome (1976), ed. by F.G. Fumi (Tipographia Marves, Rome 1976)
14th ICPS, Edinburgh (1978), ed. by B.L.H. Wilson (The Institute of Physics, Bristol 1979)
15th ICPS, Kyoto (1980), ed. by S. Tanaka, Y. Toyozawa: J. Phys. Soc. Jpn. **49**, Suppl. A (1980)
16th ICPS, Montpellier (1982), ed. by M. Averous: Physica B **117** + **118** (1983)
17th ICPS, San Francisco (1984), ed. by J.M. Chadi, W.A. Harrison (Springer, Berlin Heidelberg 1984)
18th ICPS, Stockholm (1986), ed. by O. Engström (World Scientific, Singapore 1987)
19th ICPS, Warsaw (1988), ed. by W. Zawadzki (The Institute of Physics, Polish Academy of Sciences, 1988)
20th ICPS, Thessaloniki (1990), ed. by E.M. Anastassakis, J.D. Joannopoulos (World Scientific, Singapore 1990)
21st ICPS, Beijing (1992), ed. by Ping Jiang, Hou-Zhi Zheng (World Scientific, Singapore 1993)
22st ICPS, vancouver (1994) to be published

[5]The proceedings of the Series of Int'l Conferences of Luminescence (ICL) are published in J. Lumin. The more recent ones were
ICL, Berlin (1981), ed. by I. Broser, H.-E. Gumlich, R. Broser: J. Lumi. **24/25** (1981)
ICL, Madison (1984), ed. by W.M. Yen, J.C. Wright: J. Lumin. **31/32** (1984)
ICL, Beijing (1987), ed. by Xu Xurong: J. Lumin. **40/41** (1987)
ICL, Lisbon (1990), ed. by S.J. Formosinho, M.D. Sturge: J. Lumi. **48/49** (1990)
ICL, Storrs (1993) ed. by D.S. Hamilton, R.S. Meltzer and M.D. Sturge: J. Lumi. **60/61** (1995)

Acknowledgements

This book is based on various lectures given by the author at the Universities of Karlsruhe, Frankfurt and Kaiserslautern and at some of the Summer Schools in Erice (1981, 1983, ..., 1993. See [1.7]). The sources of the scientific information presented here are partly the references given. Of equal importance, however, is the physics which I learned from my academic teachers and from many collegues and co-workers during fruitful discussions. Without trying to be complete, I should like to mention my academic teachers Prof. Dr. D. Fleischmann, Prof. Dr. H. Volz, Prof. Dr. E. Mollwo(†), Prof. Dr. R. Helbig, Prof. Dr. H. Hümmer (Erlangen) and Prof. Dr. F. Stöckmann and Prof. Dr. W. Ruppel (Karlsruhe). From the collegues I acknowledge with great pleasure fruitful and stimulating discussions with Prof. Dr. H. Haug, Prof. Dr. W. Martienssen, and Prof. Dr. E. Mohler and Dr. Banyai (Frankfurt/Main), Prof. Dr. U. Rössler (Regensburg). Prof. Dr. J.B. Grun, Prof. Dr. B. Hönerlage, and Dr. R. Lévy (Strasbourg), Prof. Dr. E. Göbel and Prof. Dr. S. Schmitt-Rink(†), (Marburg), Prof. Dr. D.S. Chemla (Berkeley), Prof. Dr. S.W. Koch (Marburg), Prof. Dr. I. Broser, Prof. Dr. R. Zimmermann, and Prof. Dr. F. Henneberger (Berlin), Dr. D.A.B. Miller (Holmdel), Dr. I. Bar-Joseph (Rehovot), Prof. Dr. B. Di Bartolo (Boston/Erice) and many others which I cannot mention here by name.

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Contents

1 Introduction

This introductory chapter consists of an outline of the fundamental concepts and ideas on which the text is based, including the rather limited prerequisites so that the reader can follow it and, finally, some hints about its contents.

1.1 Aim and Concepts

The aim of this book is to explain the optical properties of semi-conductors, e.g., the spectra of transmission, reflection and luminescence, or of the complex dielectric function in the infrared, visible and near-ultraviolet part of the electromagnetic spectrum. We want to evoke in the reader a clear and intuitive understanding of the physical concepts and foundations of semiconductor optics and of some of their numerous applications. To this end, we try to keep the mathematical apparatus as simple and as limited as possible in order not to conceal the physics behind mathematics. We give ample references for those who want to enter more deeply into the mathematical concepts [1.1–3].

In this spirit, this present textbook is not only suitable for graduate and postgraduate students of physics, but also for students of neighboring disciplines, such as material science and electronics.

The prerequisites for the reader are an introductory or undergraduate course in general physics and some basic knowledge in atomic physics and quantum mechanics. The reader should know, for example, what the Schrödinger equation is, what the words eigen- (or proper-) state and eigen energy mean, and what quantum mechanics predicts about plane waves, the hydrogen atom or the harmonic oscillator, how to calculate transition probabilities e.g., by Fermi's golden rule. Some basic knowledge of solid state physics will facilitate reading of this book, although the basic concepts will always be outlined here.

At the end of every chapter we give several problems which can be solved with the information given in the text, combined with some basic knowledge of physics, some thinking and some creativity.

1.2 Outline

In the first part of this book (Chaps. 2–17) we shall present the linear optical properties of semiconductors. We start in Chap. 2 with Maxwell's equations and photons and introduce in Chap. 3 the basic concepts of the interaction of light with matter. In Chaps. 4–8 a model system of oscillators is treated with respect to the optical properties which can be expected for such a system. Chapters 9–12 are used to introduce the elementary excitations or quasiparticles in semiconductors, followed by a presentation of the linear optical properties resulting from the interaction of these quasiparticles with light in Chaps. 13–16. Chapter 17 gives a short résumé of the linear optical properties of semiconductors.

We include in Chaps. 9–16 modern concepts of semiconductor optics such as the properties of systems of reduced dimensionality, e.g., quantum wells, or disordered systems which lead to localization. At present, more than 600 different semiconductor materials are known. Many of them and their properties are listed in several volumes of Landolt-Börnstein [1.4]. We shall concentrate here on the most important ones. They are usually tetrahedrally coordinated and comprise, e.g., the group IV elements Si and Ge, the III–V compounds such as GaAs, the IIb–VI semiconductors such as CdS or ZnSe, and the Ib–VII materials such as the Cu halides.

Chapters 18–23 contain the main aspects of the nonlinear optical properties of semiconductors including optical bistability as an example for an application of nonlinear optical properties.

In Chaps. 24, 25, which can be considered as a kind of appendix, we shall outline some experimental techniques of semiconductor spectroscopy and some elements of group theory which are relevant for the description of semiconductor optics.

In the sections on the linear and on the nonlinear optical properties of semiconductors, the main emphasis is placed on those properties which are connected with excitations in the electronic system of semiconductors, since these aspects have obtained the widest interest both in fundamental and applied research as can be seen from an inspection of the conference series mentioned in the preface.

At the end of most chapters a selection of references will be given for further reading which penetrate deeper into the topic, consider some further aspects, or give a more detailed theoretical description. Since the number of original publications, conference proceedings or summer schools on the topics covered here is "close to infinite", it is definitely only possible to cite a very small fraction of them, the choice of which is partly arbitrary and determined by the author's research interest. Furthermore, we shall not give references at all for things which can be considered to belong to the "general education or culture" in physics but we give references to the sources of original data in the figures. These figures have all been redrawn and generally modified for the purpose of this textbook. We apologize for these deficiencies.

The present book thus complements the text books [1.5] and [1.6] which concentrate more on atomic and molecular spectroscopy and on solid state spectroscopy in general. A rather remarkable series of books on various aspects of optical properties of solids, with some emphasis on insulators results