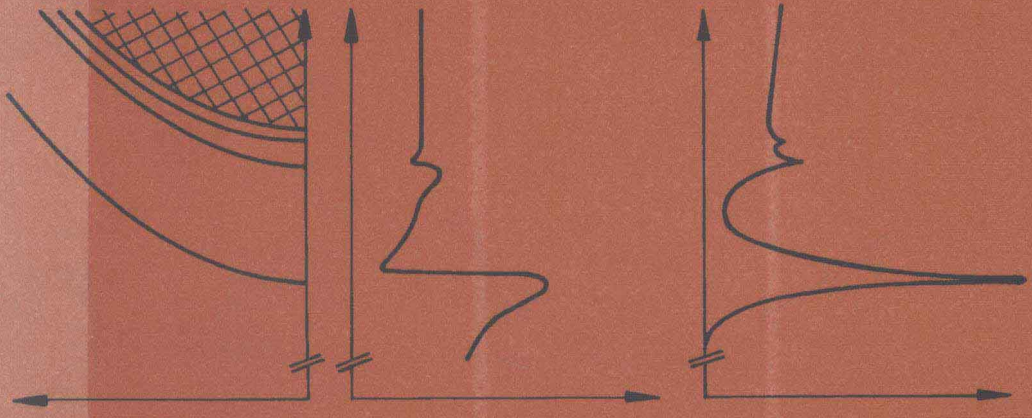
C. Klingshirn

Semiconductor Optics

Second Edition



Springer

Claus Klingshirn

Semiconductor Optics

Second Edition

With 380 Figures and 20 Tables

Springer

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Semiconductor Optics

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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.

Just as an illustration of the above statement, the attention of the author has been drawn to the fact, that the same statement has been reported even in German language also from NIELS BOHR. See Steven Weinberg, Dreams of a Final Theory, Vintage Books, New York (1994) p. 74.

Preface to the Second Edition

The book on Semiconductor Optics has been favourably received by the students and the scientific community worldwide. After the first edition, which appeared in 1995 several reprints became necessary starting from 1997, one of them for the Chinese market. They contained only rather limited updates of the material and corrections.

In the meantime scientific progress brought a lot of new results, which necessitate a new, seriously revised edition. This progress includes bulk semiconductors, but especially structures of reduced dimensionality. These new trends and results are partly included in existing chapters e.g. for phonons or for time-resolved spectroscopy, partly new chapters have been introduced like the ones on cavity polaritons and photonic structures.

We based the description of the optical properties again on the simple and intuitively clear model of the Lorentz-oscillators and the concept of polaritons as the quanta of light in matter. But since there is presently a trend to describe at least the optical properties of the electronic system of semiconductors by the optical or the semiconductor Bloch equations, a chapter has been added on this topic written by Prof. Dr. R. v. Baltz (Karlsruhe) to familiarize the reader with this concept, too, which needs a bit more quantum mechanics compared the approach used here. The chapter on group theory has been revised by Prof.Dr. K. Hümmer (Karlsruhe/Forchheim)

Karlsruhe,
September 2004

C.F. Klingshirn

Preface to the First Edition

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), J.C. Maxwell (1831–1879), M. Planck (1858–1947), A. Einstein (1879–1955), N. Bohr (1885–1962), and W. Heisenberg (1901–1976).

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 [85Q1]. 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. Teich-

mann [88T1]. 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 Gottingen.

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 [77B1,84M1,88H1]. The present author considers himself a scientific grandson of Pohl, with E. Mollwo (1909–1993), F. Stöckmann (1918–1998) and W. Martienssen (*1926) 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 [50I1] and on Luminescence [81I1] or on Non-linear Optics and Excitation Kinetics [87N1]. 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, laser printers and laser scanners or solar cells.

Karlsruhe,
February 1995

C.F. Klingshirn

References

[50I1] 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

a. 12th ICPS, Stuttgart (1974), ed. by M.H. Pilkuhn (Teubner, Stuttgart 1974)
b. 13th ICPS, Rome (1976), ed. by F.G. Fumi (Tipographia Marves, Rome 1976)
c. 14th ICPS, Edinburgh (1978), ed. by B.L.H. Wilson (The Institute of Physics, Bristol 1979)
d. 15th ICPS, Kyoto (1980), ed. by S. Tanaka, Y. Toyozawa: J. Phys. Soc. Jpn. **49**, Suppl. A (1980)
e. 16th ICPS, Montpellier (1982), ed. by M. Averous: Physica B 117 + 118 (1983)
f. 17th ICPS, San Francisco (1984), ed. by J.M. Chadi, W.A. Harrison (Springer, Berlin, Heidelberg 1984)
g. 18th ICPS, Stockholm (1986), ed. by O. Engstrom (World Scientific, Singapore 1987)
h. 19th ICPS, Warsaw (1988), ed. by W. Zawadzki (The Institute of Physics, Polish Academy of Sciences, 1988)

i. 20th ICPS, Thessaloniki (1990), ed. by E.M. Anastassakis, J.D. Joannopoulos (World Scientific, Singapore 1990)
j. 21st ICPS, Beijing (1992), ed. by Ping Jiang, Hou-Zhi Zheng (World Scientific, Singapore 1993)
k. 22nd ICPS, Vancouver (1994) D.J. Loockwood ed. (World Scientific, Singapore, 1995)
l. 23rd ICPS, Berlin (1996), M. Scheffler and R. Zimmermann (eds.), World Scientific, Singapore (1996)
m. 24th ICPS, Jerusalem (1998), D. Gershoni (ed.), World Scientific, Singapore (1999)
n. 25th ICPS, Osaka (2000), N. Miura and T. Ando (eds.), Springer Proc. In Physics **87**, Springer, Berlin (2001)
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p. 27th ICPS, Flagstaff (2004)

[77B1] A.D. Beyerchen: *Scientists under Hitler,* (Yale Univ. Press, New Haven 1977)
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[85Q1] H.-J. Queisser: *Kristallene Krisen* (Piper, München 1985)
[88H1] F. Hund, H. Maier-Leibnitz, E. Mollwo: Eur. J. Phys. **9**, 188 (1988)
[88T1] J. Teichmann: *Zur Geschichte der Festkorperphysik-Farbzentrenforschung bis 1940* (Steiner, Wiesbaden 1988)
[81I1] The proceedings of the Series of Int'l Conferences of Luminescence (ICL) are published in J. Lumin. The more recent ones were
a. ICL, Berlin (1981), ed. by I. Broser, H.-E. Gumlich, R. Broser: J. Lumi. **24/25** (1981)
b. ICL, Madison (1984), ed. by W.M. Yen, J.C. Wright: J. Lumin. **31/32** (1984)
c. ICL, Beijing (1987), ed. by Xu Xurong: J. Lumin. **40/41** (1987)
d. ICL, Lisbon (1990), ed. by S.J. Formosinho, M.D. Sturge: J. Lumin. **48/49** (1990)
e. ICL, Storrs (1993) ed. by D.S. Hamilton, R.S. Meltzer and M.D. Sturge: J. Lumi. **60/61** (1995)
f. ICL, Prague (1996) ed. J. Hala, P. Reinecker, J. Lumin. **72–74** (1997)
g. ICL, Osaka (1999) ed by K. Cho, J. Lumin **87–89** (2000)
h. ICL Budapest (2002), ed by S. Speiser, J. Lumin **102–103** (2003)

[87N1] The Series of International conferences/workshops on Nonlinear Optics and Excitation Kinetics (NOEKS) has been started in the former German Democratic Republic (DDR) and continued successfully after the reunification of Germany. The proceedings have so far been published in
a. NOEKS I Nov. 1987, Bad Stuer phys. stat. sol. (b) **146** and **147** (1988)
b. NOEKS II Dez. 1989, Bad Stuer phys. stat. sol. (b) **159** (1) (1990)
c. NOEKS III Mai 1992, Bad Honnef phys. stat. sol. (b) **173** (1) (1992)
d. NOEKS IV Nov. 1994, Gosen phys. stat. sol. (b) **188** (1) (1995)
e. NOEKS V Sept. 1997, Graal-Müritz phys. stat. sol. (b) **206** (1) (1998)
f. NOEKS VI April 2000, Marburg phys. stat. sol. (b) **221** (1) (2000)
g. NOEKS VII Feb. 2003, Karlsruhe phys. stat. sol. (c) **0** (5) (2003)

Acknowledgements

This book is based on various lectures given by the author at the Universities of Karlsruhe, Frankfurt am Main and Kaiserslautern, at Harvard University and the University of Metz and on contributions given at several of the Summer Schools on Atomic and Molecular Spectroscopy organised by Prof. Dr. B. Di Bartolo in Erice, Sicily.

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 during my studies and PhD work at the University of Erlangen, my post-doc time at the Laboratoire de Spéctroscopie et d'Optique du Corps Soilide in Strasbourg and my Habilitation at the University of Karlsruhe, and later on from fruitful discussions with many collegues and co-workers at the places where I was or still am as Professor (Frankfurt am Main, Kaiserslautern and Karlsruhe) and abroad including guest scientists in my group. Without trying to be complete, I should like to mention my academic teachers Profs. Drs. R. Fleischmann (†), H. Volz (†), E. Mollow (†), R. Helbig and K. Hümmer (Erlangen) and F. Stöckmann (†), W. Ruppel and W. Stößel (Karlsruhe).

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