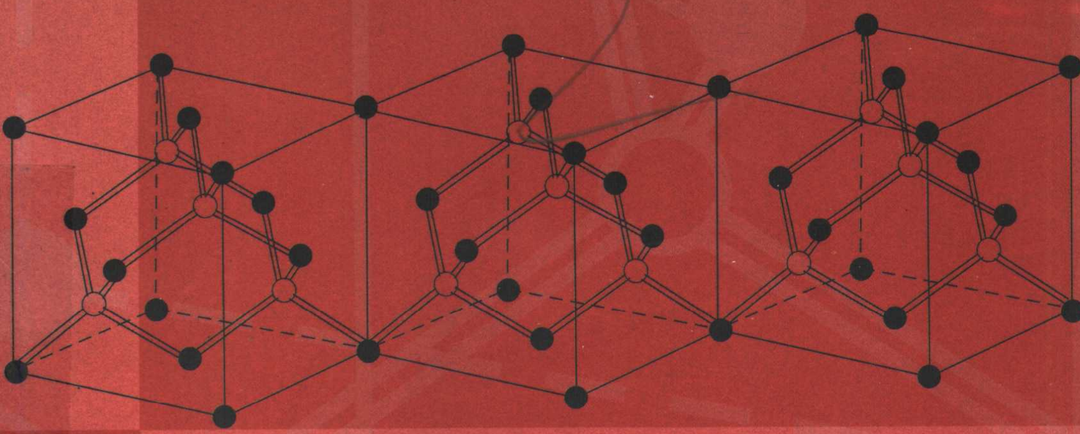
Peter Y. Yu
Manuel Cardona

Fundamentals of Semiconductors

Physics and Materials Properties

半导体基础 第3版

Third Edition



Springer

世界图书出版公司
www.wpcbj.com.cn

Peter Y. Yu   Manuel Cardona

Fundamentals of Semiconductors

Physics and Materials Properties

Third, Revised and Enlarged Edition
With 250 Two-Color Figures,
52 Tables and 116 Problems

Springer
世界图书出版公司

Professor Dr. Peter Y. Yu

University of California, Department of Physics
CA 94720-7300 Berkeley, USA
email: pyyu@lbl.gov

Professor Dr., Dres. h.c. Manuel Cardona

Max-Planck-Institut für Festkörperforschung, Heisenbergstrasse 1
70569 Stuttgart, Germany
email: cardona@cardix.mpi-stuttgart.mpg.de

2nd, Corrected Printing 2003

ISBN 3-540-41323-5 3rd Edition
Springer-Verlag Berlin Heidelberg New York

ISBN 3-540-65352-X 2nd Edition
Springer-Verlag Berlin Heidelberg New York

Library of Congress Cataloging-in-Publication Data.
Yu, Peter Y., 1944 –. Fundamentals of semiconductors: physics and materials properties /Peter Y. Yu, Manuel Cardona. – 3rd, rev. and enlarged ed. p. cm. Includes bibliographical references and index. ISBN 3540413235 (alk. paper) 1. Semiconductors. 2. Semiconductors–Materials. I. Cardona, Manuel, 1934 –. QC611.Y88 2001 537.6'22–dc21 2001020462

Springer-Verlag Berlin Heidelberg New York
a member of BertelsmannSpringer Science + Business Media GmbH

http://www.springer.de

Cover picture: The crystal structure drawn on the book cover is a "wallpaper stereogram". Such stereograms are based on repeating, but offset, patterns that resolve themselves into different levels of depth when viewed properly. They were first described by the English physicist Brewster more than 100 years ago. See: *Superstereograms* (Cadence Books, San Francisco, CA, 1994)

Preface to the Third Edition

The support for our book has remained high and compliments from readers and colleagues have been most heart-warming. We would like to thank all of you, especially the many students who have continued to send us their comments and suggestions. We are also pleased to report that a Japanese translation appeared in 1999 (more details can be obtained from a link on our Web site: **http://pauline.berkeley.edu/textbook**). Chinese[a)] and Russian translations are in preparation.

Semiconductor physics and material science have continued to prosper and to break new ground. For example, in the years since the publication of the first edition of this book, the large band gap semiconductor GaN and related alloys, such as the GaInN and AlGaN systems, have all become important materials for light emitting diodes (LED) and laser diodes. The large scale production of bright and energy-efficient white-light LED may one day change the way we light our homes and workplaces. This development may even impact our environment by decreasing the amount of fossil fuel used to produce electricity. In response to this huge rise in interest in the nitrides we have added, in appropriate places throughout the book, new information on GaN and its alloys. New techniques, such as Raman scattering of x-rays, have given detailed information about the vibrational spectra of the nitrides, available only as thin films or as very small single crystals. An example of the progress in semiconductor physics is our understanding of the class of deep defect centers known as the DX centers. During the preparation of the first edition, the physics behind these centers was not universally accepted and not all its predicted properties had been verified experimentally. In the intervening years additional experiments have verified all the remaining theoretical predictions so that these deep centers are now regarded as some of the best understood defects. It is now time to introduce readers to the rich physics behind this important class of defects.

The progress in semiconductor physics has been so fast that one problem we face in this new edition is how to balance the new information with the old material. In order to include the new information we had either to expand the size of the book, while increasing its price, or to replace some of the existing material by new sections. We find either approach undesirable. Thus we have come up with the following solution, taking advantage of the Internet in this

---

[a] The Chinese version was published in 2002 by Lanzhou University Press (see **www.onbook.com.cn**)

new information age. We assume that most of our readers, possibly all, are "internet-literate" so that they can download information from our Web site. Throughout this new edition we have added the address of Web pages where additional information can be obtained, be this new problems or appendices on new topics. With this solution we have been able to add new information while keeping the size of the book more or less unchanged. We are sure the owners of the older editions will also welcome this solution since they can update their copies at almost no cost.

Errors seem to decay exponentially with time. We thought that in the second edition we had already fixed most of the errors in the original edition. Unfortunately, we have become keenly aware of the truth contained in this timeless saying: "to err is human". It is true that the number of errors discovered by ourselves or reported to us by readers has dropped off greatly since the publication of the second edition. However, many serious errors still remained, such as those in Table 2.25. In addition to correcting these errors in this new edition, we have also made small changes throughout the book to improve the clarity of our discussions on difficult issues.

Another improvement we have made in this new edition is to add many more material parameters and a Periodic Table revealing the most common elements used for the growth of semiconductors. We hope this book will be not only a handy source for information on topics in semiconductor physics but also a handbook for looking up material parameters for a wide range of semiconductors. We have made the book easier to use for many readers who are more familiar with the SI system of units. Whenever an equation is different when expressed in the cgs and SI units, we have indicated in red the difference. In most cases this involves the multiplication of the cgs unit equation by $(4\pi\varepsilon_0)^{-1}$ where ε_0 is the permittivity of free space, or the omission of a factor of $(1/c)$ where c is the speed of light.

Last but not least, we are delighted to report that the Nobel Prize in Physics for the year 2000 has been awarded to two semiconductor physicists, Zhores I. Alferov and Herbert Kroemer ("for developing semiconductor heterostructures used in high-speed- and opto-electronics") and a semiconductor device engineer, Jack S. Kilby ("for his part in the invention of the integrated circuit").

Stuttgart and Berkeley,
January 2001

Peter Y. Yu
Manuel Cardona

Preface to the Second Edition

We have so far received many comments and feedback on our book from all quarters including students, instructors and, of course, many friends. We are most grateful to them not only for their compliments but also for their valuable criticism. We also received many requests for an instructor manual and solutions to the problems at the end of each chapter. We realize that semiconductor physics has continued to evolve since the publication of this book and there is a need to continue to update its content. To keep our readers informed of the latest developments we have created a Web Page for this book. Its address (as of the writing of this preface) is: **http://pauline.berkeley.edu/textbook**. At this point this Web Page displays the following information:

1) Content, outline and an excerpt of the book.
2) Reviews of the book in various magazines and journals.
3) Errata to both first and second printing (most have been corrected in the second edition as of this date).
4) Solutions to selected problems.
5) Additional supplementary problems.

The solutions in item (4) are usually incomplete. They are supposed to serve as helpful hints and guides only. The idea is that there will be enough left for the students to do to complete the problem. We hope that these solutions will satisfy the need of both instructors and students. We shall continue to add new materials to the Web Page. For example, a list of more recent references is planned. The readers are urged to visit this Web Page regularly to find out the latest information. Of course, they will be welcomed to use this Web Page to contact us.

While the present printing of this book was being prepared, the 1998 International Conference on the Physics of Semiconductors (ICPS) was being held in Jerusalem (Israel). It was the 24th in a biannual series that started in 1950 in Reading (U.K.), shortly after the discovery of the transistor by Shockley, Bardeen and Brattain in 1948. The ICPS conferences are sponsored by the International Union of Pure and Applied Physics (IUPAP). The proceedings of the ICPS's are an excellent historical record of the progress in the field and the key discoveries that have propelled it. Many of those proceedings appear in our list of references and, for easy identification, we have highlighted in red the corresponding entries at the end of the book. A complete list of all conferences held before 1974, as well as references to their proceedings, can be found in the volume devoted to the 1974 conference which was held in Stuttgart [M.H. Pilkuhn, editor (Teubner, Stuttgart, 1974) p. 1351]. The next ICPS is scheduled to take place in Osaka, Japan from Sept. 18 to 22 in the year 2000.

The Jerusalem ICPS had an attendance of nearly 800 researchers from 42 different countries. The subjects covered there represent the center of the current interests in a rapidly moving field. Some of them are already introduced in this volume but several are still rapidly developing and do not yet lend themselves to discussion in a general textbook. We mention a few keywords:

Fractional quantum Hall effect and composite fermions.
Mesoscopic effects, including weak localization.
Microcavities, quantum dots, and quantum dot lasers.
III–V nitrides and laser applications.
Transport and optical processes with femtosecond resolution.
Fullerites, C_{60}-based nanotubes.
Device physics: CMOS devices and their future.

Students interested in any of these subjects that are not covered here, will have to wait for the proceedings of the 24th ICPS. Several of these topics are also likely to find a place in the next edition of this book.

In the present edition we have corrected all errors known to us at this time and added a few references to publications which will help to clarify the subjects under discussion.

Stuttgart and Berkeley,
November 1998

Peter Y. Yu
Manuel Cardona

Preface to the First Edition

I, who one day was sand but am today a crystal
by virtue of a great fire
and submitted myself to the demanding rigor
of the abrasive cut,
today I have the power
to conjure the hot flame.
Likewise the poet, anxiety and word:
sand, fire, crystal, strophe, rhythm.
– woe is the poem that does not light a flame

David Jou, 1983
(translated from the Catalan original)

The evolution of this volume can be traced to the year 1970 when one of us (MC) gave a course on the optical properties of solids at Brown University while the other (PYY) took it as a student. Subsequently the lecture notes were expanded into a one-semester course on semiconductor physics offered at the Physics Department of the University of California at Berkeley. The composition of the students in this course is typically about 50 % from the Physics Department, whereas the rest are mostly from two departments in the School of Engineering (Electrical Engineering and Computer Science; Materials Science and Mineral Engineering). Since the background of the students was rather diverse, the prerequisites for this graduate-level course were kept to a minimum, namely, undergraduate quantum mechanics, electricity and magnetism and solid-state physics. The Physics Department already offers a two-semester graduate-level course on condensed matter physics, therefore it was decided to de-emphasize theoretical techniques and to concentrate on phenomenology. Since many of the students in the class were either growing or using semiconductors in device research, particular emphasis was placed on the relation between physical principles and device applications. However, to avoid competing with several existing courses on solid state electronics, discussions of device design and performance were kept to a minimum. This course has been reasonably successful in "walking this tight-rope", as shown by the fact that it is offered at semi-regular intervals (about every two years) as a result of demands by the students.

One problem encountered in teaching this course was the lack of an adequate textbook. Although semiconductor physics is covered to some extent in all advanced textbooks on condensed matter physics, the treatment rarely provides the level of detail satisfactory to research students. Well-established books on semiconductor physics are often found to be too theoretical by experimentalists and engineers. As a result, an extensive list of reading materials initially replaced the textbook. Moreover, semiconductor physics being a mature field, most of the existing treatises concentrate on the large amount of well-established topics and thus do not cover many of the exciting new developments. Soon the students took action to duplicate the lecture notes, which developed into a "course reader" sold by the Physics Department at cost. This volume is approximately "version 4.0" (in software jargon) of these lecture notes.

The emphasis of this course at Berkeley has always been on simple physical arguments, sometimes at the expense of rigor and elegance in mathematics. Unfortunately, to keep the promise of using only undergraduate physics and mathematics course materials requires compromise in handling special graduate-level topics such as group theory, second quantization, Green's functions and Feynman diagrams, etc. In particular, the use of group theory notations, so pervasive in semiconductor physics literature, is almost unavoidable. The solution adopted during the course was to give the students a "five-minute crash course" on these topics when needed. This approach has been carried over to this book. We are fully aware of its shortcomings. This is not too serious a problem in a class since the instructor can adjust the depth of the supplementary materials to satisfy the need of the students. A book lacks such flexibility. The readers are, therefore, urged to skip these "crash courses", especially if they are already familiar with them, and consult the references for further details according to their background.

The choice of topics in this book is influenced by several other factors. Most of the heavier emphasis on optical properties reflects the expertise of the authors. Since there are already excellent books emphasizing transport properties, such as the one by K. H. Seeger, our book will hopefully help to fill a void. One feature that sets this book apart from others on the market is that the materials science aspects of semiconductors are given a more important role. The growth techniques and defect properties of semiconductors are represented early on in the book rather than mentioned in an appendix. This approach recognizes the significance of new growth techniques in the development of semiconductor physics. Most of the physics students who took the course at Berkeley had little or no training in materials science and hence a brief introduction was found desirable. There were some feelings among those physics students that this course was an easier way to learn about materials science! Although the course offered at Berkeley lasted only one semester, the syllabus has since been expanded in the process of our writing this book. As a result it is highly unlikely that the volume can now be covered in one semester. However, some more specialized topics can be omitted without loss of continuity, such as high field transport and hot electron effects, dynamic effective ionic charge, donor–acceptor pair transitions, resonant Raman and Brillouin scattering, and a few more.

Homework assignment for the course at Berkeley posed a "problem" (excuse our pun). No teaching assistant was allocated by the department to help with grading of the problem sets. Since the enrollment was typically over thirty students, this represented a considerable burden on the instructor. As a "solution" we provide the students with the answers to most of the questions. Furthermore, many of the questions "lead the student by the hand" through the calculation. Others have hints or references where further details can be found. In this way the students can grade their own solutions. Some of the material not covered in the main text is given in the form of "problems" to be worked out by the student.

In the process of writing this book, and also in teaching the course, we have received generous assistance from our friends and colleagues. We are especially indebted to: Elias Burstein; Marvin Cohen; Leo Esaki; Eugene Haller; Conyers Herring; Charles Kittel; Neville Smith; Jan Tauc; and Klaus von Klitzing for sharing their memories of some of the most important developments in the history of semiconductor physics. Their notes have enriched this book by telling us their "side of the story". Hopefully, future students will be inspired by their examples to expand further the frontiers of this rich and productive field. We are also grateful to Dung-Hai Lee for his enlightening explanation of the Quantum Hall Effect.

We have also been fortunate in receiving help from the over one hundred students who have taken the course at Berkeley. Their frank (and anonymous) comments on the questionnaires they filled out at the end of the course have made this book more "user-friendly". Their suggestions have also influenced the choice of topics. Many postdoctoral fellows and visitors, too numerous to name, have greatly improved the quality of this book by pointing out errors and other weaknesses. Their interest in this book has convinced us to continue in spite of many other demands on our time. The unusually high quality of the printing and the color graphics in this book should be credited to the following people: H. Lotsch, P. Treiber, and C.-D. Bachem of Springer-Verlag, Pauline Yu and Chia-Hua Yu of Berkeley, Sabine Birtel and Tobias Ruf of Stuttgart. Last but not the least, we appreciate the support of our families. Their understanding and encouragement have sustained us through many difficult and challenging moments. PYY acknowledges support from the John S. Guggenheim Memorial Foundation in the form of a fellowship.

Stuttgart and Berkeley,
October 1995

Peter Y. Yu
Manuel Cardona

Contents

1. Introduction

CONTENTS

In textbooks on solid-state physics, a **semiconductor** is usually defined rather loosely as a material with electrical resistivity lying in the range of 10^{-2} – 10^{9} Ω cm.[1] Alternatively, it can be defined as a material whose **energy gap** (to be defined more precisely in Chap. 2) for electronic excitations lies between zero and about 4 electron volts (eV). Materials with zero bandgap are metals or semimetals, while those with an energy gap larger than 3 eV are more frequently known as insulators. There are exceptions to these definitions. For example, terms such as semiconducting diamond (whose energy gap is about 6 eV) and semi-insulating GaAs (with a 1.5 eV energy gap) are frequently used. GaN, which is receiving a lot of attention as optoelectronic material in the blue region, has a gap of 3.5 eV.

The best-known semiconductor is undoubtedly **silicon** (Si). However, there are many semiconductors besides silicon. In fact, many minerals found in nature, such as zinc-blende (ZnS) cuprite (Cu_2O) and galena (PbS), to name just a few, are semiconductors. Including the semiconductors synthesized in laboratories, the family of semiconductors forms one of the most versatile class of materials known to man.

Semiconductors occur in many different chemical compositions with a large variety of crystal structures. They can be elemental semiconductors, such as Si, carbon in the form of C_{60} or nanotubes and selenium (Se) or binary compounds such as gallium arsenide (GaAs). Many organic compounds, e. g. polyacetylene $(CH)_n$, are semiconductors. Some semiconductors exhibit magnetic ($Cd_{1-x}Mn_xTe$) or ferroelectric (SbSI) behavior. Others become superconductors when doped with sufficient carriers (GeTe and $SrTiO_3$). Many of the recently discovered high-T_c superconductors have nonmetallic phases which are semiconductors. For example, La_2CuO_4 is a semiconductor (gap $\simeq 2$ eV) but becomes a superconductor when alloyed with Sr to form $(La_{1-x}Sr_x)_2CuO_4$.

[1] Ω cm is a "hybrid" SI and cgs resistivity unit commonly used in science and engineering. The SI unit for resistivity should be Ω m