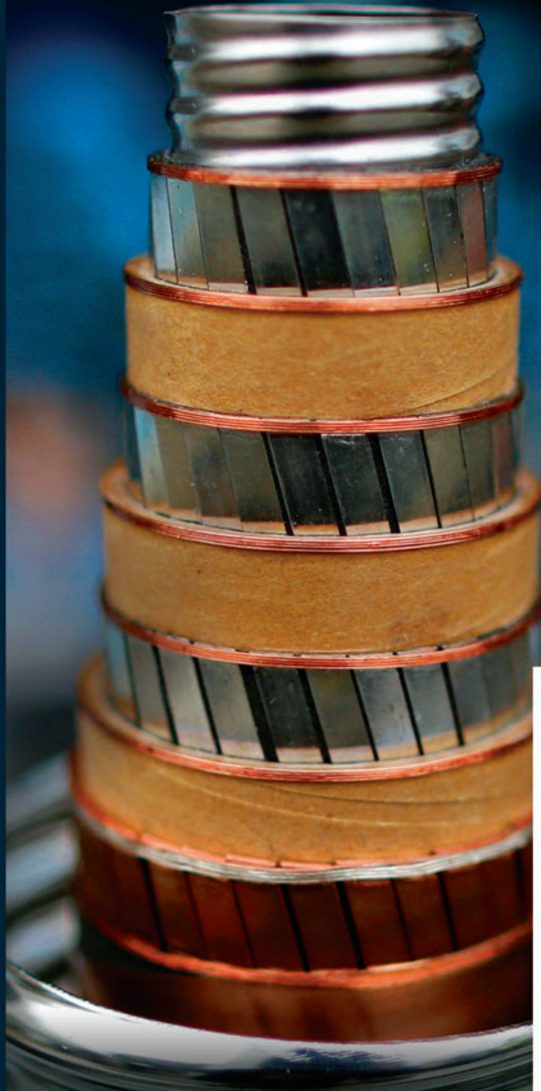
Fourth Edition

PRINCIPLES OF Electronic Materials & Devices



McGraw Hill Education

S. O. KASAP

This textbook represents a first course in electronic materials and devices for undergraduate students. With the additional topics, *Principles of Electronic Materials and Devices*, Fourth Edition can also be used in a graduate-level introductory course in electronic materials for electrical engineers and material scientists. The fourth edition is an extensively revised and extended version of the third edition based on reviewer comments and the developments in electronic and optoelectronic materials over the last ten years.

The fourth edition is one of the few books on the market that has a broad coverage of electronic materials that today's scientists and engineers need. The revisions have improved the rigor without sacrificing the original semi-quantitative approach that both the students and instructors like.

IMPORTANT FEATURES

- The principles are developed with the minimum of mathematics and with the emphasis on physical ideas. Quantum mechanics is part of the course but without its difficult mathematical formalism.
- Robust illustration package
- The end of each chapter includes a section called Additional Topics to further develop important concepts, to introduce interesting applications, or to prove a theorem.

NEW TO THE FOURTH EDITION

- Over 20 new and expanded topics (see Preface for full list)
- 20% more worked examples
- Over 30% more homework problems
- New end-of-chapter problems with practical applications

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PRINCIPLES OF ELECTRONIC MATERIALS AND DEVICES

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FOURTH EDITION

S. O. Kasap
University of Saskatchewan
Canada

Mc Graw Hill Education

PRINCIPLES OF ELECTRONIC MATERIALS AND DEVICES, FOURTH EDITION

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BRIEF CONTENTS

Paul Dirac (1902–1984) and Werner Heisenberg (1901–1976) walking outdoors in Cambridge circa 1930. They received the Nobel Prize in Physics in 1928 and 1932, respectively.

Courtesy of AIP Emilio Segre Visual Archives, Physics Today Collection

Max Planck (1858–1947), a German theoretical physicist, was one of the originators of quantum theory, and won the Nobel Prize in Physics in 1918. His Nobel citation is *“in recognition of the services he rendered to the advancement of Physics by his discovery of energy quanta”.*.

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Elementary Quantum Physics 213

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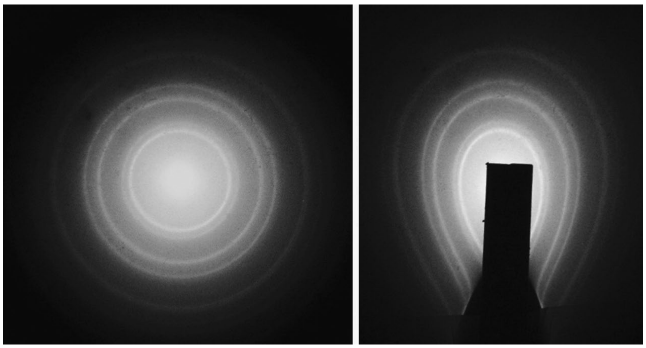
Modern Theory of Solids 313



Left: Circular bright rings make up the diffraction pattern obtained when an electron beam is passed through a thin polycrystalline aluminum sheet. The pattern results from the wave behavior of the electrons; the waves are diffracted by the Al crystals. Right: A magnet brought to the screen bends the electron paths and distorts the diffraction pattern. The magnet would have no effect if the pattern was due to X-rays, which are electromagnetic waves. Courtesy of Farley Chicilo

PREFACE

FOURTH EDITION

The textbook represents a first course in electronic materials and devices for undergraduate students. With the additional topics, the text can also be used in a graduate-level introductory course in electronic materials for electrical engineers and material scientists. The fourth edition is an extensively revised and extended version of the third edition based on reviewer comments and the developments in electronic and optoelectronic materials over the last ten years. The fourth edition has many new and expanded topics, new worked examples, new illustrations, and new homework problems. The majority of the illustrations have been greatly improved to make them clearer. A very large number of new homework problems have been added, and many more solved problems have been provided that put the concepts into applications. More than 50% of the illustrations have gone through some kind of revision to improve the clarity. Furthermore, more terms have been added under *Defining Terms,* which the students have found very useful. Bragg's diffraction law that is mentioned in several chapters is kept as Appendix A for those readers who are unfamiliar with it.

The fourth edition is one of the few books on the market that have a broad coverage of electronic materials that today's scientists and engineers need. I believe that the revisions have improved the rigor without sacrificing the original semiquantitative approach that both the students and instructors liked. The major revisions in scientific content can be summarized as follows:

Chapter 1	Thermal expansion; kinetic molecular theory; atomic diffusion; molecular collisions and vacuum deposition; particle flux density; line defects; planar defects; crystal surfaces; Grüneisen's rule.
Chapter 2	Temperature dependence of resistivity, strain gauges, Hall effect; ionic conduction; Einstein relation for drift mobility and diffusion; ac conductivity; resistivity of thin films; interconnects in microelectronics; electromigration.
Chapter 3	Electron as a wave; infinite potential well; confined electron in a finite potential energy well; stimulated emission and photon amplification; He–Ne laser, optical fiber amplification.
Chapter 4	Work function; electron photoemission; secondary emission; electron affinity and photomultiplication; Fermi–Dirac statistics; conduction in metals; thermoelectricity and Seebeck coefficient; thermocouples; phonon concentration changes with temperature.
Chapter 5	Degenerate semiconductors; direct and indirect recombination; *E* vs. *k* diagrams for direct and indirect bandgap semiconductors; Schottky junction and depletion layer; Seebeck effect in semiconductors and voltage drift.
Chapter 6	The *pn* junction; direct bandgap *pn* junction; depletion layer capacitance; linearly graded junction; hyperabrupt junctions; light emitting diodes (LEDs); quantum well high intensity LEDs; LED materials and structures; LED characteristics; LED spectrum; brightness

	and efficiency of LEDs; multi-junction solar cells.
Chapter 7	Atomic polarizability; interfacial polarization; impact ionization in gases and breakdown; supercapacitors.
Chapter 8	anisotropic and giant magnetoresistance; magnetic recording materials; longitudinal and vertical magnetic recording; materials for magnetic storage; superconductivity.
Chapter 9	Refractive and group index of Si; dielectric mirrors; free carrier absorption; liquid crystal displays.

ORGANIZATION AND FEATURES

In preparing the fourth edition, as in previous edition, I tried to keep the general treatment and various proofs at a semiquantitative level without going into detailed physics. Many of the problems have been set to satisfy engineering accreditation requirements. Some chapters in the text have additional topics to allow a more detailed treatment, usually including quantum mechanics or more mathematics. Cross referencing has been avoided as much as possible without too much repetition and to allow various sections and chapters to be skipped as desired by the reader. The text has been written so as to be easily usable in one-semester courses by allowing such flexibility.

Some important features are:

- The principles are developed with the minimum of mathematics and with the emphasis on physical ideas. Quantum mechanics is part of the course but without its difficult mathematical formalism.
- There are numerous worked examples or solved problems, most of which have a practical significance. Students learn by way of examples, however simple, and to that end a large number (227 in total) of solved problems have been provided.
- Even simple concepts have examples to aid learning.
- Most students would like to have clear diagrams to help them visualize the explanations and understand concepts. The text includes 565 illustrations that have been professionally prepared to reflect the concepts and aid the explanations in the text. There are also numerous photographs of practical devices and scientists and engineers to enhance the learning experience.
- The end-of-chapter questions and problems (346 in total) are graded so that they start with easy concepts and eventually lead to more sophisticated concepts. Difficult problems are identified with an asterisk (*). Many practical applications with diagrams have been included.
- There is a glossary, *Defining Terms,* at the end of each chapter that defines some of the concepts and terms used, not only within the text but also in the problems.
- The end of each chapter includes a section *Additional Topics* to further develop important concepts, to introduce interesting applications, or to prove a theorem. These topics are intended for the keen student and can be used as part of the text for a two-semester course.
- The text is supported by McGraw-Hill's textbook website that contains resources, such as solved problems, for both students and instructors.
- The fourth edition is supported by an extensive PowerPoint presentation for instructors who have adopted the book for their course. The PowerPoint has all the illustrations in color, and includes additional color photos. The basic concepts and equations are also highlighted in additional slides.
- There is a regularly updated online extended *Solutions Manual* for all instructors; simply locate the McGraw-Hill website for this textbook. The Solutions Manual provides not only detailed explanations to the solutions, but also has color diagrams as well as

references and helpful notes for instructors. (It also has the answers to those “why?” questions in the text.)

ACKNOWLEDGMENTS

My gratitude goes to my past and present graduate students and postdoctoral research fellows, who have kept me on my toes and read various sections of this book. I have been fortunate to have a colleague and friend like Charbel Tannous (Brest University) who, as usual, made many sharply critical but helpful comments, especially on Chapter 8. My best friend and colleague of many years Robert Johanson (University of Saskatchewan), with whom I share teaching this course, also provided a number of critical comments towards the fourth edition. A number of reviewers, at various times, read various portions of the manuscript and provided extensive comments. A number of instructors also wrote to me with their own comments. I incorporated the majority of the suggestions, which I believe made this a better book. No textbook is perfect, and I'm sure that there will be more suggestions (and corrections) for the next edition. I'd like to personally thank them all for their invaluable critiques.

I'd like to thank Tina Bower, my present Product Developer, and Raghu Srinivasan, my former Global Brand Manager, at McGraw-Hill Education for their continued help throughout the writing and production of this edition. They were always enthusiastic, encouraging, forgiving (every time I missed a deadline) and always finding solutions. It has been a truly great experience working with MHE since 1993. I'm grateful to Julie De Adder (Photo Affairs) who most diligently obtained the permissions for the third-party photos in the fourth edition without missing any. The copyright fees (exuberant in many cases) have been duly paid and photos from this book or its PowerPoint should not be copied into other publications without contacting the original copyright holder. If you are an instructor and like the book, and would like to see a fifth edition, perhaps a color version, the best way to make your comments and suggestions heard is not to write to me but to write directly to the Electrical Engineering Editor, McGraw-Hill Education, 501 Bell St., Dubuque, IA 52001, USA. Both instructors and students are welcome to email me with their comments. While I cannot reply to each email, I do read all my emails and take note; it was those comments that led to a major content revision in this edition.

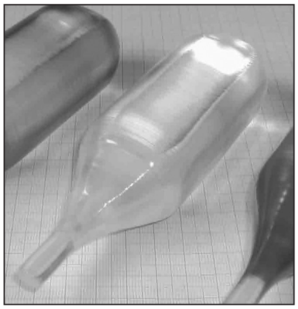
Safa Kasap
Saskatoon, March, 2017

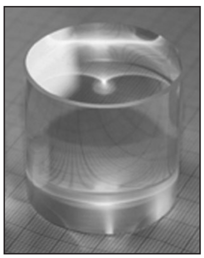
> “The important thing in science is not so much to obtain new facts as to discover new ways of thinking about them.”
>
> *Sir William Lawrence Bragg*

To Nicolette

Left: GaAs ingots and wafers. GaAs is a III–V compound semiconductor because Ga and As are from Groups III and V, respectively.
Right: An $In_xGa_{1-x}As$ (a III–V compound semiconductor)-based photodetector.

Left: Courtesy of Sumitomo Electric Industries. Right: Courtesy of Thorlabs.





Left: A detector structure that will be used to detect dark matter particles. Each individual cylindrical detector has a $CaWO_4$ single crystal, similar to that shown on the bottom right. These crystals are called scintillators, and convert high-energy radiation to light. The Czochralski technique is used to grow the crystal shown on top right, which is a $CaWO_4$ ingot. The detector crystal is cut from this ingot.

Left: Courtesy of Max Planck Institute for Physics. Right: Reproduced from Andreas Erb and Jean-Come Lanfranchi, *CrystEngCom,* 15, 2301, 2015, by permission of the Royal Society of Chemistry. All rights reserved.