Quantum Mechanics for Tomorrow's Engineers

Discover the foundations of quantum mechanics, and explore how these principles are powering a new generation of advances in quantum engineering, in this ground-breaking undergraduate textbook. It explains physical and mathematical principles using cutting-edge electronic, optoelectronic and photonic devices, linking underlying theory with real-world applications; focuses on current technologies and avoids historic approaches, getting students quickly up-to-speed to tackle contemporary engineering challenges; provides an introduction to the foundations of quantum information, and a wealth of real-world quantum examples, including quantum well infrared photodetectors, solar cells, quantum teleportation, quantum computing, band gap engineering, quantum cascade lasers, low-dimensional materials, and van der Waals heterostructures; and includes pedagogical features such as objectives and end-of-chapter homework problems to consolidate student understanding, and solutions for instructors. Designed to inspire the development of future quantum devices and systems, this is the perfect introduction to quantum mechanics for undergraduate electrical engineers and materials scientists.

JUNICHIRO KONO is Karl F. Hasselmann Chair in Engineering, Professor of Electrical & Computer Engineering, Professor of Physics & Astronomy, Professor of Materials Science & NanoEngineering, and Chair of Applied Physics at Rice University, which he joined in 2000. His research focuses on optical studies of condensed matter systems and photonic applications of nanosystems, including semiconductor nanostructures and carbon-based nanomaterials. He has made a number of pioneering contributions to the diverse fields of semiconductor optics, terahertz spectroscopy and devices, ultrafast and quantum optics, and condensed matter physics. He is a Fellow of APS, OSA, and SPIE. He is a leader in optical studies of condensed matter systems and photonic applications of nanosystems.

"Kono's ten years of teaching a course to engineering undergraduates leads to an introductory book on quantum and information science with refreshing directness, which may also serve as a reference. It includes clear concepts of quantum entanglement and measurement, information theory of circuits and algorithms, and solid accounts of the quantum advantage and quantum materials"

L. J. Sham, University of California, San Diego

"This book provides the essential shortcuts for beginners to learn quantum physics that can be directly applied to the frontline research in modern quantum engineering applications. The author makes an excellent effort to balance rigor and intuition by selecting suitable pedagogical topics, while preserving the core of quantum mechanics for engineering science."

Philip Kim, Harvard University

JUNICHIRO KONO
Rice University, Houston

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Contents

To Alissa, Renée, and Yuko

Preface

This book is for engineers and material scientists interested in learning quantum mechanics. Though many readers will read this book out of intrinsic interest in the subject, others will do so out of necessity: they will find their colleagues interpreting data, diagnosing problems with instruments, or designing better devices using quantum mechanics. Perhaps there was a time when engineers and materials scientists were better off investing their time in other areas of study, but that time is over. There seems to be no technical field that quantum mechanics has not invaded.

Quantum mechanics was born and developed near the beginning of the twentieth century, and it has become one of today's most fundamental physical theories. Its principles provide the most powerful and precise ways of describing the universe – from the smallest subatomic particles to the large-scale structure of the cosmos. The methods and implications of quantum mechanics have not only profoundly influenced how scientists and philosophers think and look at nature but also have significantly contributed to the development of today's technology in computation and communications.

It is evident that the impact of quantum mechanics will continue to increase in electronics, optoelectronics, and photonics, and will further expand into many other technological fields, including energy, artificial intelligence, thermoelectrics, medicine, biotechnology, and neuroengineering. Most importantly, the degree of miniaturization of modern electronic devices has reached the point where quantum mechanical effects have to be explicitly considered and precisely controlled. In the not-so-distant future, Moore's law will cease to apply, and entirely new, genuinely quantum technologies will need to be developed to go beyond today's silicon-based classical solid-state device technologies.

Every undergraduate student, not only in science but also in engineering, must thus study quantum mechanics. Although there are many excellent volumes of undergraduate-level quantum mechanics textbooks, only a few are geared toward engineering students.

Book Outline

Specifically, the goal of this book is to provide engineering undergraduate students with the physical understanding and mathematical prowess necessary for designing quantum devices and systems, including quantum computers. The main players throughout this book are thus electrons in solids (as opposed to electrons in atomic gases, plasmas, or biological cells).

By studying this textbook, it is hoped that students will learn: (1) when, or under what conditions, quantum effects become non-negligible in devices, (2) how to calculate the quantum states (wavefunctions) and energies of electrons moving in artificial potential structures, and (3) what determines the electrical and optical properties of quantum solid-state devices.

This book foregoes the standard introductory quantum mechanics textbook approach of introducing quantum mechanics through a historical series of crises in late nineteenth century physics. Instead, quantum mechanics is introduced as a theory that is in use today in a wide variety of electronic, optoelectronic, and photonic devices. The essential mathematical foundations of quantum mechanics are introduced as early as possible and then immediately followed by an introduction to quantum information science, which is one of the most significant emerging applications of quantum mechanics.

Among topics that this book does *not* cover are: the hydrogen atom; quantum statistics; scattering; angular momentum; symmetry and transformations; and variational approaches. These topics were not included since they are fairly advanced and of limited use for an engineering student.

Overall, the book aims to strike a balance between rigorous mathematical derivations and example problem solving. The example problems are highly practical, including such modern topics as quantum well infrared photodetectors, solar cells, quantum teleportation, band gap engineering for LEDs, quantum cascade lasers, and band diagrams of van der Waals heterostructures.

How This Book Can Be Used for Teaching

The book is primarily aimed at undergraduate students in electrical engineering and materials science, and possibly in computer science, mechanical engineering, and chemical engineering, who are interested in learning quantum mechanics. In addition, the book can be useful for professional engineers working in areas of quantum devices, quantum computation, and quantum communications.

This text can be used for a one-semester course. It is based on the lecture notes that the author developed for his course ELEC 361: "Quantum Mechanics for Engineers," which he taught for a total period of eleven years. This was a core course in the photonics, electronics, and nanoelectronics specialization of the electrical and computer engineering curriculum at Rice University, intended as an introduction to the subject for electrical and computer engineering majors, typically in their junior or senior year.

The reader is expected to have a prior knowledge of differential equations and linear algebra. Online Resources for Instructors include: a Solutions Manual, PowerPoint lecture slides, and PowerPoint slides and JPEGs of all the figures and tables from the book.

Bibliographical References and Sources

There are a number of well-regarded undergraduate-level quantum mechanics textbooks for physics students, including

- R. P. Feynman, R. B. Leighton, and M. Sands, *The Feynman Lectures on Physics, Vol. 3: Quantum Mechanics* (Addison Wesley, 1964).
- R. Eisberg and R. Resnick, *Quantum Physics of Atoms, Molecules, Solids, Nuclei, and Particles, Second Edition* (John Wiley & Sons, 1985).
- S. Gasiorowicz, *Quantum Physics, Third Edition* (John Wiley & Sons, 2003).
- J. S. Townsend, *A Modern Approach to Quantum Mechanics, Second Edition* (University Science Book, 2013).
- D. J. Griffiths and D. F. Schroeter, *Introduction to Quantum Mechanics, Third Edition* (Cambridge University Press, 2018).

The following excellent textbooks, on the other hand, are geared toward undergraduate students studying engineering and applied physics, and are written in a similar spirit to the current textbook:

- A. Yariv, *An Introduction to Theory and Applications of Quantum Mechanics* (John Wiley & Sons, 1982).
- H. Kroemer, *Quantum Mechanics for Engineering: Materials Science and Applied Physics* (Pearson, 1994).
- J. Singh, *Quantum Mechanics: Fundamentals and Applications to Technology* (John Wiley & Sons, 1996).

- D. K. Ferry, *Quantum Mechanics: An Introduction for Device Physicists and Electrical Engineers, Second Edition* (Taylor & Francis, 2001).
- D. A. B. Miller, *Quantum Mechanics for Scientists and Engineers* (Cambridge University Press, 2008).
- A. F. J. Levi, *Applied Quantum Mechanics, Second Edition* (Cambridge University Press, 2012).

Furthermore, because of the focus of the present textbook on electrons in solid state devices, the following introductory textbooks on solid state physics, semiconductor physics, and materials science should be useful:

- J. H. Davies, *The Physics of Low-Dimensional Semiconductors: An Introduction* (Cambridge University Press, 1997).
- J. D. Livingston, *Electronic Properties of Engineering Materials* (John Wiley & Sons, 1999).
- D. A. Neamen, *Semiconductor Physics and Devices, Fourth Edition* (McGraw-Hill, 2012).
- S. H. Simon, *The Oxford Solid State Basics* (Oxford University Press, 2013).
- S. O. Kasap, *Principles of Electronic Materials and Devices* (McGraw-Hill, 2018).

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More Information