国外电子信息精品著作(影印版)

纳米电子学基础

Fundamentals of Nanoelectronics

George W. Hanson

科学出版社

国外电子信息精品著作(影印版)

Fundamentals of Nanoelectronics

纳米电子学基础

George W. Hanson

科学出版社

北京

图字:01-2012-2723

内 容 简 介

本书分三个部分,分别在纳米物理学、单电子效应和多电子效应方面进行介绍,内容丰富、论述详实。书中有很多实验结果用来支持文中描述的物理概念,这使读者能够看到概念的真实性以及在实际技术中的重要应用,还有大量的章末问题能加强读者解决问题的能力。本书是第一本真正适用于大学工程和应用科学学生的纳米电子学教科书。

图书在版编目(CIP)数据

纳米电子学基础=Fundamentals of Nanoelectronics:英文/(美)汉森(Hanson G. W.)编著. 一影印版. —北京:科学出版社,2012

(国外电子信息精品著作)

ISBN:978-7-03-034382-6

Ⅰ.纳… Ⅱ.汉… Ⅲ.纳米材料-电子器件-英文 Ⅳ.TN103

中国版本图书馆 CIP 数据核字(2012)第 103155 号

责任编辑:张宇 余丁 / 责任印制:张倩 / 封面设计:陈敬

科学出版社 出版

北京东黄城根北街 16 号

邮政编码:100717

http://www.sciencep.com

新科印刷有限公司 印刷

科学出版社发行 各地新华书店经销

*

2012 年 6 月第 一 版 开本:787×1092 1/16

2012 年 6 月第一次印刷 印张:25 1/4

字数:578 000

定价:80.00 元

(如有印装质量问题,我社负责调换)

《国外电子信息精品著作》序

20 世纪 90 年代以来，信息科学技术成为世界经济的中坚力量。随着经济全球化的进一步发展，以微电子、计算机、通信和网络技术为代表的信息技术，成为人类社会进步过程中发展最快、渗透性最强、应用面最广的关键技术。信息技术的发展带动了微电子、计算机、通信、网络、超导等产业的发展，促进了生命科学、新材料、能源、航空航天等高新技术产业的成长。信息产业的发展水平不仅是社会物质生产、文化进步的基本要素和必备条件，也是衡量一个国家的综合国力、国际竞争力和发展水平的重要标志。在中国，信息产业在国民经济发展中占有举足轻重的地位，成为国民经济重要支柱产业。然而，中国的信息科学支持技术发展的力度不够，信息技术还处于比较落后的水平，因此，快速发展信息科学技术成为我国迫在眉睫的大事。

要使我国的信息技术更好地发展起来，需要科学工作者和工程技术人员付出艰辛的努力。此外，我们要从客观上为科学工作者和工程技术人员创造更有利于发展的环境，加强对信息技术的支持与投资力度，其中也包括与信息技术相关的图书出版工作。

从出版的角度考虑，除了较好较快地出版具有自主知识产权的成果外，引进国外的优秀出版物是大有裨益的。洋为中用，将国外的优秀著作引进到国内，促进最新的科技成就迅速转化为我们自己的智力成果，无疑是值得高度重视的。科学出版社引进一批国外知名出版社的优秀著作，使我国从事信息技术的广大科学工作者和工程技术人员能以较低的价格购买，对于推动我国信息技术领域的科研与教学是十分有益的事。

此次科学出版社在广泛征求专家意见的基础上，经过反复论证、仔细遴选，共引进了接近 30 本外版书，大体上可以分为两类，第一类是基础理论著作，第二类是工程应用方面的著作。所有的著作都涉及信息领域的最新成果，大多数是 2005 年后出版的，力求“层次高、

内容新、参考性强”。在内容和形式上都体现了科学出版社一贯奉行的严谨作风。

当然，这批书只能涵盖信息科学技术的一部分，所以这项工作还应该继续下去。对于一些读者面较广、观点新颖、国内缺乏的好书还应该翻译成中文出版，这有利于知识更好更快地传播。同时，我也希望广大读者提出好的建议，以改进和完善丛书的出版工作。

总之，我对科学出版社引进外版书这一举措表示热烈的支持，并盼望这一工作取得更大的成绩。

中国科学院院士
中国工程院院士
2006 年 12 月

To Sheila

PREFACE

Nanotechnology refers to any technology that uses nanoscopic objects or devices, i.e., devices on the order of a nanometer (one nanometer is one billionth of a meter). This is roughly the size one would obtain by shrinking a grain of sand by a factor of one thousand, and then again by another factor of one thousand. Thus, it is the technology of the very small.

While there has been considerable hype in the popular media about the promises, and possible perils, of nanotechnology, the field is truly in its infancy. At this time it is impossible to know which aspects of nanotechnology currently under consideration will lead to mature, established fields and to practical applications. It is certain, however, that many as-yet unimagined areas of nanotechnology will be developed in the future. It is also certain that nanotechnology will play an increasingly important role in everyday life, as devices move from the research laboratory to the commercial market.

To develop nanotechnology, scientists and engineers need to understand the fundamental physical principles governing objects having dimensions on the order of nanometers. This is the realm of quantum mechanics, in general, as well as related areas in solid state physics, chemistry, and biology. For example, although there are many proposals to develop

nanoscale devices based on electron movement in metals and semiconductors, there is also considerable interest in developing chemical and biological computers, molecular electronics, and other information processing devices outside of the traditional electron physics disciplines.

This book was written to provide an introduction to fundamental concepts of nanoelectronics, including single electron effects and electron transport in nanoscopic systems, for electrical engineers and applied scientists. The intended audience for the book is junior and senior level undergraduate students, although it can also serve as an introduction to the subject for beginning graduate students. Of paramount importance is the idea of understanding quantum dots, quantum wires, and quantum wells, and nanoelectronic applications of these structures. In particular, attention is focused on the quantization of electrical properties, such as conductance quantization and ballistic transport in low-dimensional systems, quantum interference effects arising from the wave nature of electrons, and tunneling phenomena in nanoelectronic devices. Topics were chosen that emphasize, to a large degree, quantum counterparts of classical electronic and electrical devices familiar to junior and senior level undergraduate students, such as transistors and wires. The level of presentation assumes that the reader has some background in basic physics, including fundamental concepts in mechanics, energy, and electromagnetics, and in electrical circuits and traditional electronics. Furthermore, some basic knowledge of the physics of field-effect transistors would be helpful. In the electrical engineering curriculum at most universities, such background material has usually been covered by some point in the junior year.

Although quantum mechanics and solid state physics are treated at an introductory level, the book is not intended to replace discipline specific books or courses in these areas. However, in the ever-increasingly congested undergraduate curriculum at most institutions, a course such as the one this book is intended to accompany can serve as an introduction to the area, and spur interest for further study.

ACKNOWLEDGMENTS

I would like to thank Patricia Whaley and the folks at Quantum Dot Corporation for their helpful comments, and Peter Burke for sharing his expertise, and for his thoughtful considerations of this work. I would also like to thank Richard Sorbello and Carolyn Aita at the University of Wisconsin-Milwaukee for their help, and for their encouragement and interest in this area. Furthermore, Iam grateful to the anonymous reviewers who provided detailed comments and suggestions that significantly improved this work.

PHOTO CREDITS

Cover: Colored scanning electron micrograph of two intertwined carbon nanotubes. The image shows approximately 15 microns of tube-length. Dr. Kostas Kostarelos and David McCarthy / Science PhotoLibrary / Photo Researchers, Inc.

Chapter 1: Opener: © Infineon Technologies AG. 1.1: © 2006 Southeastern Universities Research Association. All Rights Reserved. 1.2: © 2004 by David Masse. © MMVII The Porticus Centre. All Rights Reserved. 1.3: Courtesy of the Center for Applied Microtechnology, University of Washington. 1.4: Courtesy of Data Storage Systems Center, Carnegie Mellon University

Chapter 2: Opener: Based on Tonomura, et al., *Amer. Jour. Phys.* 57, 117. 1989. Courtesy of the American Institute of Physics. © Hitachi Ltd. Advanced Research Laboratory. 2.6: Based on Tonomura, et al., *Amer. Jour. Phys.* 57, 117. 1989. Courtesy of the American Institute of Physics. © Hitachi Ltd. Advanced Research Laboratory.

Chapter 3: Opener: Courtesy Almaden Research Center/Research Division/NASA/Media Services. 3.1: Courtesy IBM Research, Almaden Research Center. 3.2: Courtesy IBM Research, Almaden Research Center. Unauthorized use not permitted.

Chapter 4: Opener: From J.M. Zuo, M. Kim, M. O'Keeffe, and J.C.H. Spence, *Nature* 401, 49–52 (1999). Used by permission. 4.12: Courtesy Wikipedia, The Free Encyclopedia. 4.14: Courtesy Carol and Mike Werner/Phototake NYC. 4.19: Reprinted with permission from Roukes, M. L. et al., "Quenching of the Hall Effect in a One-Dimensional Wire," *Phys. Rev. Lett.* 59 (1987): 3011. © 1987, American Physical Society.

Chapter 5: Opener: Image reproduced by permission of IBM Research, Almaden Research Center. Unauthorized use not permitted. 5.12: Based on a figure from S. M. Sze, *Physics of Semiconductor Devices*, John Wiley & Sons, 1969. Used by permission. Page 147 footnote: Reprinted with permission from L. Peterson, P. Laitenberger, E. Laegsgaard, and F. Besenbacher, *Phys. Rev. B*, 58, 7361 1998. Copyright 1998 by the American Physical Society. 5.33: Based on Figure 6.8 (page 55) from *Band Theory and Electronic Properties of Solids* by John Singleton, Oxford University Press, 2001. Reprinted with permission from John Singleton and Oxford University Press. Data from M.D. Sturge, *Phys. Rev.* 127, 768 (1962). 5.35: Based on a figure from Saito, R., G. Dresselhaus, and M. S. Dresselhaus, *Physical Properties of Carbon Nanotubes*, Singapore: World Scientific, 1998. Used by permission. 5.36: Based on a figure in *Physical Properties of Carbon Nanotubes* by R. Saito, G. Dresselhaus, and M.S. Dresselhaus. Singapore: World Scientific Publishing Co. Pte. Ltd., 1998. Used by permission. 5.37: Based on a figure in *Physical Properties of Carbon Nanotubes* by R. Saito, G. Dresselhaus, and M.S. Dresselhaus. Singapore: World Scientific Publishing Co. Pte. Ltd., 1998. Used by permission. 5.38: Based on a figure in *Physical Properties of Carbon Nanotubes* by R. Saito, G. Dresselhaus, and M.S. Dresselhaus. Singapore: World Scientific Publishing Co. Pte. Ltd., 1998. Used by permission. 5.39: Courtesy Shenzhen Nano-Technologies Port Co., Ltd.

Chapter 6: Opener: From Park, J.-Y., et al., "Electrical Cutting and Nicking of Carbon Nanotubes Using an Atomic Force Microscope." *Appl. Phys. Lett.*, 80 (2002): 4446. © 2002, American Institute of Physics. 6.12: From Bonard, J. M. et al., "Field Emission of Individual Carbon Nanotubes in the Scanning Electron Microscope," *Phys. Rev. Lett.* 89 (2002): 197602. © 2002, American Physical Society. 6.17: From Quan, W.-Y., D. M. Kim, and M. K. Cho, "Unified Compact Theory of Tunneling Gate Current in Metal–Oxide-Semiconductor Structures: Quantum and Image Force Barrier Lowering," *J. Appl. Phys.* 92 (2002): 3724. © 2002, American Institute of Physics. 6.20: Courtesy Institut für Allgemeine Physik at the Vienna University of Technology. 6.21: Image reproduced by permission of IBM Research, Almaden Research Center. Unauthorized use not permitted.

Chapter 7: Opener: Reprinted with permission from Hideo Namatsu, Ph.D., *Journal of Vacuum Science & Techology B: Microelectronics and Nanometer Structures*, January 2003, Volume 21, Issue 1, pages 1–5. © 2007, American Institute of Physics. 7.5: From Pépin, A., et al., "Temperature Evolution of Multiple Tunnel Junction Devices Mode with Disordered Two-Dimensional Arrays of Metallic Islands," *Appl. Phys. Lett.* 74 (1999): 3047. © 1999, American Institute of Physics. 7.6: From Pépin, A., et al., "Temperature Evolution of Multiple Tunnel Junction Devices Mode with Disordered Two-Dimensional Arrays of Metallic Islands," *Appl. Phys. Lett.* 74 (1999): 3047. © 1999, American Institute of Physics. 7.7: From Clarke, L., et al., "Room-Temperature Coulomb-Blockade Dominated Transport in Gold Nanocluster Structures," *Semicond. Sci. Technol.* 13 (1998): A111–A114. Courtesy Martin Wybourne. 7.19: Based on a figure in Wilkins, R., E. Ben-Jacob, and R. C. Jaklevic, "Scanning-Tunneling-Microscope Observations of Coulomb Blockade and Oxide Polarization in Small Metal Droplets," *Phys. Rev. Lett.* 63 (1989): 801. © 1989, American Physical Society. 7.27: From Hadley, P., et al., "Single-Electron Effects in Metals and Nanotubes for Nanoscale Circuits," in *Proceedings of the MIOP—The German Wireless Week, 11th Conference on Microwaves, Radio Communication and Electromagnetic Compatibility*, Stuttgart, Germany, 2001. 408–412. Courtesy of Leo Kouwenhoven, Kavli Institute of Nanoscience, Delft University of Technology. 7.28: Based on a figure from Kastner, M. A. "The Single-Electron Transistor," *Rev. Mod. Phys.* 64 (1992): 849. © 1992, American Physical Society. 7.29: Based on a figure from Shirakashi, J.-I., et al., "Single-Electron Changing Effects in Nb/Nb Oxide-Based Single-Electron Transistors at Room Temperature, "*Appl. Phys. Lett.* 72 (1998): 1893. © 1998, American Institute of Physics. 7.32: Based on a figure from Ono, Y., et al., "Si Complementary Single-Electron Inverter with Voltage Gain," *Appl. Phys. Lett.* 76 (2000): 3121. © 2000, American Institute of Physics. 7.33: Based on a figure from Ono, Y., et al., "Si Complementary Single-Electron Inverter with Voltage Gain," *Appl. Phys. Lett.* 76 (2000): 3121. © 2000, American Institute of Physics. 7.34: Based on a figure from Avouris, P., et al., "Carbon Nanotube Electronics," *Proceedings of the IEEE*, 91 (2003): 1772–1784. 7.35: From Avouris, P., et al., "Carbon Nanotube Electronics," *Proceedings of the IEEE*, 91 (2003): 1772–1784. 7.36: Based on a figure from R. Martel, et al., "Single- and Multi-Wall Carbon Nanotube Field-Effect Transistors." *Applied Physics Letters*, 73, 2447 (1998). © 1998, American Institute of Physics. 7.37: Based on a figure from H.R. Shea, R. Martel, T. Hertel, T. Schmidt and PH. Avouris, "Manipulation of Carbon Nanotubes and Properties of Nanotubes Field-Effect Transistors and Rings," *Microelectronic Engineering*, 46, 101–104 (1999). Used by permission from Elsevier. 7.38: Based on a figure from Huang, Y., et al., "Gallium Nitride Nanowire Nanodevices," *Nanoletters*, 2 (2002): 101. 7.39: From De Franceschi, S. and J. A. van Dam, "Single-Electron Tunneling in InP Nanowires," *Appl. Phys. Lett.*, 83 (2003): 344. © 2003, American Institute of Physics. 7.40: From De Franceschi, S. and J. A. van Dam, "Single-Electron Tunneling in InP Nanowires," *Appl. Phys. Lett.*, 83 (2003): 344. © 2003, American Institute of Physics. 7.43: Based on a figure from from Di Ventra, M., S. T. Pantelides, and N. D. Lang, "The Benzene Molecule as a Molecular Resonant-Tunneling Transistor," *Appl. Phys. Lett.*, 76 (2000): 3448. © 2000, American Institute of Physics. 7.44: From Park, J. et al., "Coulomb Blockade and the Kondo Effect in Single-Atom Transistors," *Nature*, 417 (2002): 722–725. © 2002, Macmillan Publishers, Ltd.

Chapter 8: Opener: Courtesy of Prof. Dr. Roland Wiesendanger, Executive Director of the Institute of Applied Physics (IAP) and Interdisciplinary Nanoscience Center Hamburg (INCH).

Chapter 9: Opener: From Harper, J., et al., "Microstructure of GaSb-on-InAs Heterojunction Examined with Cross-Sectional Scanning Tunneling Microscopy," *Appl. Phys. Lett.* 73 (1998): 2805. 9.5: Based on a figure from N. Mayhew, D. Phil. thesis, Oxford University, 1993. (Published in A.M. Fox, "Optoelectronics in Quantum Well Structures," *Contemporary Physics* 37, 11 (1996)). Reprinted with permission from A.M. Fox. 9.8: Based on a figure from Chui, H. C., et al., "Short Wavelength Intersubband Transitions in In GaAs/AlGaAs Quantum Wells Grown on GaAs," *Appl. Phy. Lett.* 64 (1994): 736. © 1994, American Institute of Physics. 9.12: Based on a figure from Saito, R., et al., "Electronic Structure of Chiral Graphene Tubules," *Appl. Phys. Lett.* 60 (1992): 2204. © 1992, American Institute of Physics. 9.14: Reprinted with permission from Quantum Dot Corporation. 9.15: Reprinted with permission from Quantum Dot Corporation. 9.16: From Seydel C., "Quantum Dots Get Wet," *Science* 4 April 2003, 300: 80 [DOI: 10.1126/Science.300.5616.80]. Courtesy Xiaohu Gao and Shuming Nie, Emory University School of Medicine. 9.17: Based on a figure from Link, S. and M. A. El-Sayed, "Spectral Properties and Relaxation Dynamics of Surface Plasmon Electronic Oscillations in Gold and Silver Nanodots and Nanorods," *J. Phys Chem B* 103 (1999): 8410–8426. 9.18: From Sun, Y., B. T. Mayers, and Y. Xia, "Template-Engaged Replacement Reaction: A One-Step Approach to the Large-Scale Synthesis of Metal Nanostructures with Hollow Interiors," *Nano Lett.* 2 (2002): 481. © 2002, American Chemical Society. 9.19: Based on a figure from Li, M., L. Chen, and S. Y. Chou, "Direct Three-Dimensional Patterning Using Nanoimprint Lithography," *Appl. Phys. Lett.* 78 (2001): 3322. © 2001, American Institute of Physics. 9.20: Reused with permission from Li, M., L. Chen, and S. Y. Chou, "Direct Three-Dimensional Patterning Using Nanoimprint Lithography," *Appl. Phys. Lett.* 78 (2001): 3322. © 2001, American Institute of Physics. 9.23: Courtesy of Jonathan Bird and Yuki Takagaki. 9.24: Reprinted with permission from Gilberto Medeiros-Ribeiro at HPL Palo Alto.

Chapter 10: Opener: Ann Bentley & Professor Art Ellis, Materials Science and Engineering Department, University of Wisconsin-Madison. Image courtesy the Nickel Insititute. 10.4: From Toimil Molares, M. E., et al., "Electrical Characterization of Electrochemically Grown Single Copper Nanowires," *Appl. Phys. Lett.* 82 (2003): 2139. © 2003, American Institute of Physics. 10.5: Based on a figure from Toimil Molares, M. E., et al., "Electrical Characterization of Electrochemically Grown Single Copper Nanowires," *Appl. Phys. Lett.* 82 (2003): 2139. © 2003, American Institute of Physics. 10.9: Based on a figure from Thomas, K. J., et al., "Interaction Effects in a One-Dimensional Constriction," *Phys. Rev. B* 58 (1998): 4846. © 1998, American Physical Society. 10.10: Based on Fig. 6 from van Wees, B. J., L.P. Kouwenhoven, E.M.M. Willems, C.J.P.M. Harmans, J.E. Mooij, H. van Houten, C.W.J. Beenakker, J.G. Williamson, and C.T. Foxon, "Quantum Ballistic and Adiabatic Electron Transport Studied with Quantum Point Contacts," *Phys. Rev. B* 43 (1991): 12431. © 1991, American Physical Society. 10.11: Based on a figure from Dreher, M. F., Pauly, J. Heurich, J.C. Cuevas, E. Scheer, and P. Nielaba, "Structure and Conductance Histogram of Atomic-Sized Au Contacts," *Phys. Rev. B* 72 (2005): 075435. © 2005, American Physical Society. 10.12: Based on a figure from Dreher, M. F., Pauly, J. Heurich, J.C. Cuevas, E. Scheer, and P. Nielaba, "Structure and Conductance Histogram of Atomic-Sized Au Contacts," *Phys. Rev. B* 72 (2005): 075435. © 2005, American Physical Society. 10.13: From Tsukagoshi, K., B. W. Alphenaar, and H. Ago, "Coherent Transport of Electron Spin in a Ferro Magnetically Contacted Carbon Nanotube," *Nature* 401 (1999): 572. Courtesy Macmillan Publishers Ltd. and Bruce Alphenaar. 10.14: Based on a figure from S. Li, Z.Y.C. Rutherglen, and P.J. Burke, "Electrical Properties of 0.4 cm Llong Single-Walled Carbon Nanotubes," *Nano Lett.*, 4: 2003–2007, 2004. © 2004 American Chemical Society. 10.15: Based on a figure from Hanson, G.W. "Current on an Infinitely-Long Carbon Nanotube Antenna Excited by a Gap Generator," *IEEE Trans. Antennas Propagat.* 54 (2006): 76–81. © 2006, IEEE. 10.20: Courtesy of WTEC Inc. and Dr. James M. Daughton/NVE Corporation. Based on a graph by Professor Eshel Ben-Jacob.

CONTENTS

PREFACE ix

PHOTO CREDITS xi

PART I FUNDAMENTALS OF NANOSCOPIC PHYSICS 1

1 INTRODUCTION TO NANOELECTRONICS 3

1.1 The "Top-Down" Approach 5
1.1.1 Lithography, 6

1.2 The "Bottom-Up" Approach 11

1.3 Why Nanoelectronics? 11

1.4 Nanotechnology Potential 13

1.5 Main Points 14

1.6 Problems 15

2 CLASSICAL PARTICLES, CLASSICAL WAVES, AND QUANTUM PARTICLES 16

2.1 Comparison of Classical and Quantum Systems 17

2.2 Origins of Quantum Mechanics 19

2.3 Light as a Wave, Light as a Particle 20
2.3.1 Light as a Particle, or Perhaps a Wave—The Early Years, 20
2.3.2 A Little Later—Light as a Wave, 20
2.3.3 Finally, Light as a Quantum Particle, 24

2.4 Electrons as Particles, Electrons as Waves 27
2.4.1 Electrons as Particles—The Early Years, 27
2.4.2 A Little Later—Electrons (and Everything Else) as Quantum Particles, 28
2.4.3 Further Development of Quantum Mechanics, 31

2.5 Wavepackets and Uncertainty 32

2.6 Main Points 40

2.7 Problems 41

3 QUANTUM MECHANICS OF ELECTRONS 43

3.1 General Postulates of Quantum Mechanics 45
3.1.1 Operators, 47
3.1.2 Eigenvalues and Eigenfunctions, 48
3.1.3 Hermitian Operators, 49
3.1.4 Operators for Quantum Mechanics, 52
3.1.5 Measurement Probability, 56

3.2 Time-Independent Schrödinger's Equation 62
3.2.1 Boundary Conditions on the Wavefunction, 65

3.3 Analogies Between Quantum Mechanics and Classical Electromagnetics 69

3.4 Probabilistic Current Density 71

3.5 Multiple Particle Systems 75

3.6 Spin and Angular Momentum 78

3.7 Main Points 80

3.8 Problems 81

4 FREE AND CONFINED ELECTRONS 85

4.1 Free Electrons 86
4.1.1 One-Dimensional Space, 87
4.1.2 Three-Dimensional Space, 89

4.2 The Free Electron Gas Theory of Metals 90

4.3 Electrons Confined to a Bounded Region of Space and Quantum Numbers 91
4.3.1 One-Dimensional Space, 91
4.3.2 Three-Dimensional Space, 97
4.3.3 Periodic Boundary Conditions, 98

4.4 Fermi Level and Chemical Potential 99

4.5 Partially Confined Electrons—Finite Potential Wells 101
4.5.1 Finite Rectangular Well, 102
4.5.2 Parabolic Well—Harmonic Oscillator, 109
4.5.3 Triangular Well, 110

4.6 Electrons Confined to Atoms—The Hydrogen Atom and the Periodic Table 111
4.6.1 The Hydrogen Atom and Quantum Numbers, 112
4.6.2 Beyond Hydrogen—Multiple Electron Atoms and the Periodic Table, 116

4.7 Quantum Dots, Wires, and Wells 118
4.7.1 Quantum Wells, 122
4.7.2 Quantum Wires, 124
4.7.3 Quantum Dots, 125

4.8 Main Points 127

4.9 Problems 127

5 ELECTRONS SUBJECT TO A PERIODIC POTENTIAL—BAND THEORY OF SOLIDS 131

5.1 Crystalline Materials 132

5.2 Electrons in a Periodic Potential 136

5.3 Kronig–Penney Model of Band Structure 137
5.3.1 Effective Mass, 141

5.4 Band Theory of Solids 150
5.4.1 Doping in Semiconductors, 154
5.4.2 Interacting Systems Model, 157
5.4.3 The Effect of an Electric Field on Energy Bands, 160
5.4.4 Bandstructures of Some Semiconductors, 160
5.4.5 Electronic Band Transitions—Interaction of Electromagnetic Energy and Materials, 162

5.5 Graphene and Carbon Nanotubes 170
5.5.1 Graphene, 170
5.5.2 Carbon Nanotubes, 172

5.6 Main Points 176

5.7 Problems 177

PART II SINGLE-ELECTRON AND FEW-ELECTRON PHENOMENA AND DEVICES 181

6 TUNNEL JUNCTIONS AND APPLICATIONS OF TUNNELING 183

6.1 Tunneling Through a Potential Barrier 184

6.2 Potential Energy Profiles for Material Interfaces 190
6.2.1 Metal–Insulator, Metal–Semiconductor, and Metal–Insulator–Metal Junctions, 190

6.3 Applications of Tunneling 195
6.3.1 Field Emission, 195
6.3.2 Gate–Oxide Tunneling and Hot Electron Effects in MOSFETs, 198
6.3.3 Scanning Tunneling Microscope, 202
6.3.4 Double Barrier Tunneling and the Resonant Tunneling Diode, 206

6.4 Main Points 210

6.5 Problems 210

7 COULOMB BLOCKADE AND THE SINGLE-ELECTRON TRANSISTOR 212

7.1 Coulomb Blockade 212
7.1.1 Coulomb Blockade in a Nanocapacitor, 214
7.1.2 Tunnel Junctions, 219
7.1.3 Tunnel Junction Excited by a Current Source, 222
7.1.4 Coulomb Blockade in a Quantum Dot Circuit, 226

7.2 The Single-Electron Transistor 235
7.2.1 Single-Electron Transistor Logic, 243

7.3 Other SET and FET Structures 244
7.3.1 Carbon Nanotube Transistors (FETs and SETs), 244
7.3.2 Semiconductor Nanowire FETs and SETs, 249
7.3.3 Molecular SETs and Molecular Electronics, 251

7.4 Main Points 255

7.5 Problems 256

PART III MANY ELECTRON PHENOMENA 259

8 PARTICLE STATISTICS AND DENSITY OF STATES 261

8.1 Density of States 262
8.1.1 Density of States in Lower Dimensions, 264
8.1.2 Density of States in a Semiconductor, 267

8.2 Classical and Quantum Statistics 267
8.2.1 Carrier Concentration in Materials, 270
8.2.2 The Importance of the Fermi Electrons, 274
8.2.3 Equilibrium Carrier Concentration and the Fermi Level in Semiconductors, 274

8.3 Main Points 277

8.4 Problems 277

9 MODELS OF SEMICONDUCTOR QUANTUM WELLS, QUANTUM WIRES, AND QUANTUM DOTS 280

9.1 Semiconductor Heterostructures and Quantum Wells 282
9.1.1 Confinement Models and Two-Dimensional Electron Gas, 285
9.1.2 Energy Band Transitions in Quantum Wells, 288

9.2 Quantum Wires and Nanowires 294

9.3 Quantum Dots and Nanoparticles 298
9.3.1 Applications of Semiconducting Quantum Dots, 299
9.3.2 Plasmon Resonance and Metallic Nanoparticles, 304
9.3.3 Functionalized Metallic Nanoparticles, 306

9.4 Fabrication Techniques for Nanostructures 307
9.4.1 Lithography, 307
9.4.2 Nanoimprint Lithography, 309
9.4.3 Split-Gate Technology, 310
9.4.4 Self-Assembly, 312

9.5 Main Points 313

9.6 Problems 314

10 NANOWIRES, BALLISTIC TRANSPORT, AND SPIN TRANSPORT 317

10.1 Classical and Semiclassical Transport 318
10.1.1 Classical Theory of Conduction—Free Electron Gas Model, 318
10.1.2 Semiclassical Theory of Electrical Conduction—Fermi Gas Model , 321
10.1.3 Classical Resistance and Conductance, 324
10.1.4 Conductivity of Metallic Nanowires—The Influence of Wire Radius, 326

10.2 Ballistic Transport 328
10.2.1 Electron Collisions and Length Scales, 329
10.2.2 Ballistic Transport Model, 331
10.2.3 Quantum Resistance and Conductance, 332
10.2.4 Origin of the Quantum Resistance, 340

10.3 Carbon Nanotubes and Nanowires 341
10.3.1 The Effect of Nanoscale Wire Radius on Wave Velocity and Loss, 344

10.4 Transport of Spin, and Spintronics 346
10.4.1 The Transport of Spin, 347
10.4.2 Spintronic Devices and Applications, 351

10.5 Main Points 352

10.6 Problems 353

APPENDIX A SYMBOLS AND ACRONYMS **356**

APPENDIX B PHYSICAL PROPERTIES OF MATERIALS **358**

APPENDIX C CONVENTIONAL MOSFETS **362**

APPENDIX D ANSWERS TO PROBLEMS **366**

Problems Chapter 2: Classical Particles, Classical Waves, and Quantum Particles, 366
Problems Chapter 3: Quantum Mechanics of Electrons, 367
Problems Chapter 4: Free and Confined Electrons, 367
Problems Chapter 5: Electrons Subject to a Periodic Potential—Band Theory of Solids, 369
Problems Chapter 6: Tunnel Junctions and Applications of Tunneling, 369
Problems Chapter 7: Coulomb Blockade and the Single-Electron Transistor, 370
Problems Chapter 8: Particle Statistics and Density of States, 370
Problems Chapter 9: Models of Semiconductor Quantum Wells, Quantum Wires, and Quantum Dots, 370
Problems Chapter 10: Nanowires, Ballistic Transport, and Spin Transport, 371

REFERENCES **372**

INDEX **381**