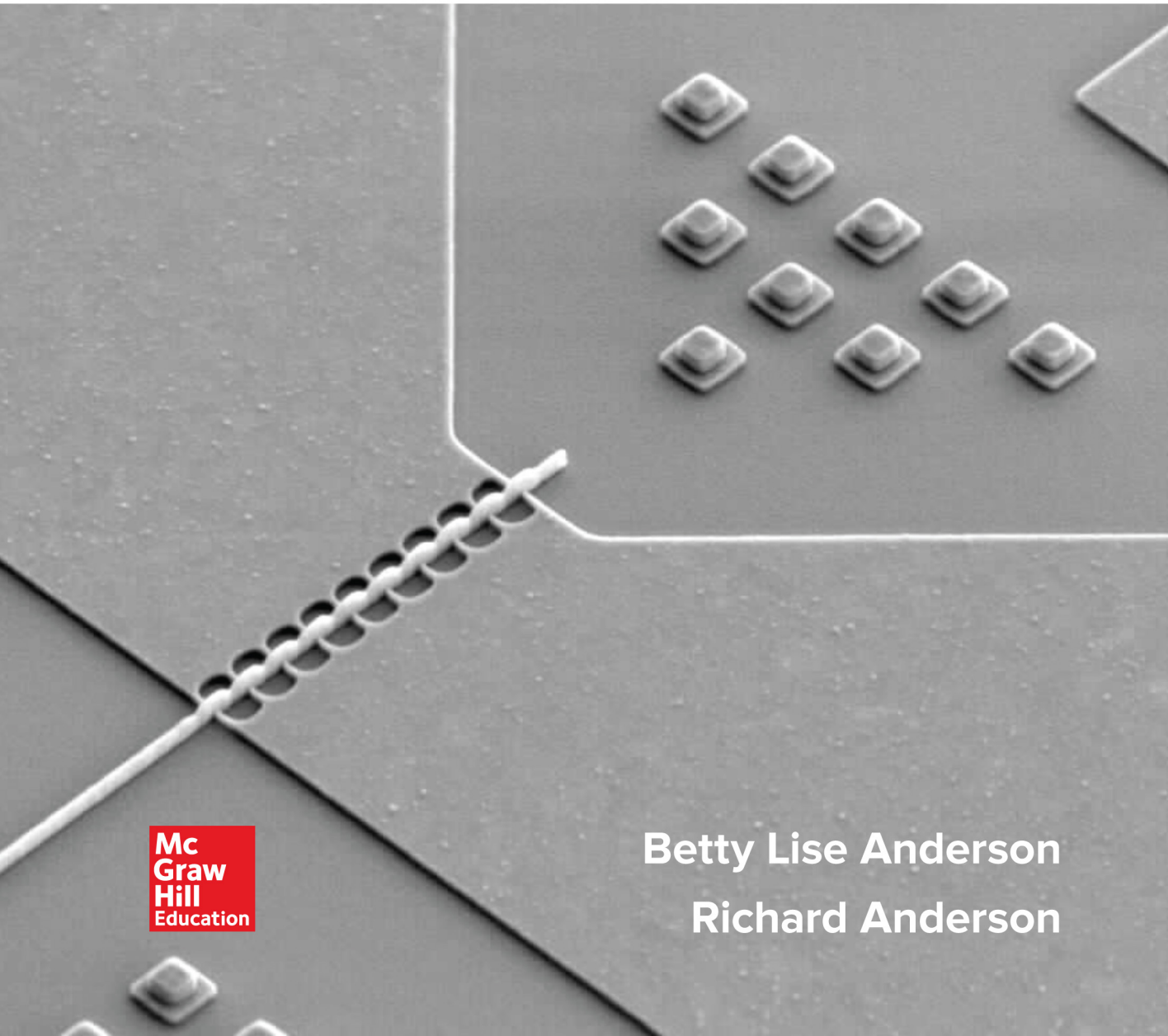


Fundamentals of **SEMICONDUCTOR DEVICES**

Second Edition



**Mc
Graw
Hill**
Education

Betty Lise Anderson
Richard Anderson

Fundamentals of Semiconductor Devices

Second Edition

Betty Lise Anderson
The Ohio State University

Richard L. Anderson





FUNDAMENTALS OF SEMICONDUCTOR DEVICES, SECOND EDITION

Published by McGraw-Hill Education, 2 Penn Plaza, New York, NY 10121. Copyright © 2018 by McGraw-Hill Education. All rights reserved. Printed in the United States of America. Previous edition © 2005. No part of this publication may be reproduced or distributed in any form or by any means, or stored in a database or retrieval system, without the prior written consent of McGraw-Hill Education, including, but not limited to, in any network or other electronic storage or transmission, or broadcast for distance learning.

Some ancillaries, including electronic and print components, may not be available to customers outside the United States.

This book is printed on acid-free paper.

1 2 3 4 5 6 7 8 9 LCR 21 20 19 18 17

ISBN 978-0-07-352956-1

MHID 0-07-352956-7

Senior Vice President, Products & Markets: *G. Scott Virkler*
Vice President, General Manager, Products & Markets: *Marty Lange*
Vice President, Content Design & Delivery: *Betsy Whalen*
Managing Director: *Thomas Timp*
Brand Manager: *Raghothaman Srinivasan/Thomas M. Scaife, Ph.D.*
Director, Product Development: *Rose Koos*
Product Developer: *Tina Bower*
Marketing Manager: *Shannon O'Donnell*
Director, Content Design & Delivery: *Linda Avenarius*
Program Manager: *Lora Neyens*
Content Project Manager: *Sherry Kane*
Buyer: *Laura Fuller*
Design: *Egzon Shaqiri*
Content Licensing Specialists: *Carrie Burger/Lorraine Buczek*
Cover Image: *Courtesy IMEC*
Compositor: *SPi Global*
Printer: *LSC Communications*

All credits appearing on page or at the end of the book are considered to be an extension of the copyright page.

Library of Congress Cataloging-in-Publication Data

Names: Anderson, Betty Lise, author. | Anderson, Richard L., author.
Title: Fundamentals of semiconductor devices / Betty Lise Anderson, The Ohio State University; Richard L. Anderson.
Description: Second edition. | Dubuque : McGraw-Hill Education, 2017.
Identifiers: LCCN 2016036979 | ISBN 9780073529561 (alk. paper)
Subjects: LCSH: Semiconductors. | Transistors.
Classification: LCC TK7871.85 A495 2017 | DDC 621.3815/2—dc23 LC record available at <https://lcn.loc.gov/2016036979>

The Internet addresses listed in the text were accurate at the time of publication. The inclusion of a website does not indicate an endorsement by the authors or McGraw-Hill Education, and McGraw-Hill Education does not guarantee the accuracy of the information presented at these sites.

BRIEF CONTENTS

Preface xii

PART 1

Materials 1

- 1 Electron Energy and States in Semiconductors 3
- 2 Homogeneous Semiconductors 48
- 3 Current Flow in Homogeneous Semiconductors 113
- 4 Nonhomogeneous Semiconductors 162
- Supplement to Part 1:** Introduction to Quantum Mechanics 180

PART 2

Diodes 223

- 5 Prototype pn Homojunctions 227
- 6 Additional Considerations for Diodes 302
- Supplement to Part 2:** Diodes 338

PART 3

Field-Effect Transistors 357

- 7 The MOSFET 367

8 Other Field-Effect Transistors 439

Supplement to Part 3: Additional Consideration for MOSFETs 493

PART 4

Bipolar Junction Transistors 539

9 Bipolar Junction Transistors: Statics 544

10 Time-Dependent Analysis of BJTs 590

Supplement to Part 4: Bipolar Devices 623

PART 5

Optoelectronic and Power Semiconductor Devices 643

11 Optoelectronic Devices 644

12 Power Semiconductor Devices 699

Appendix A Constants 750

Appendix B List of Symbols 754

Appendix C Fabrication 769

Appendix D Some Useful Integrals 792

Appendix E Useful Equations 793

Index 803

PART 1 Materials 1

Chapter 1

Electron Energy and States in Semiconductors 3

- 1.1 Introduction and Preview 3
- 1.2 A Brief History 4
- 1.3 Application to the Hydrogen Atom 5
 - 1.3.1 *The Bohr Model for The Hydrogen Atom* 5
 - 1.3.2 *Application to Molecules: Covalent Bonding* 11
 - 1.3.3 *Quantum Numbers and the Pauli Exclusion Principle* 13
 - 1.3.4 *Covalent Bonding in Crystalline Solids* 14
- 1.4 Wave-Particle Duality 21
- 1.5 The Wave Function 22
 - 1.5.1 *Probability and the Wave Function* 22
- 1.6 The Electron Wave Function 23
 - 1.6.1 *The Free Electron in One Dimension* 23
 - 1.6.2 *The De Broglie Relationship* 26
 - 1.6.3 *The Free Electron in Three Dimensions* 27
 - 1.6.4 *The Quasi-Free Electron Model* 28
 - 1.6.5 *Reflection and Tunneling* 32
- 1.7 A First Look at Optical Emission and Absorption 33
- 1.8 Crystal Structures, Planes, and Directions 39
- 1.9 Summary 41

- 1.10 References 42
- 1.11 Review Questions 42
- 1.12 Problems 43

Chapter 2

Homogeneous Semiconductors 48

- 2.1 Introduction and Preview 48
- 2.2 Pseudo-Classical Mechanics for Electrons in Crystals 49
 - 2.2.1 *One-Dimensional Crystals* 49
 - 2.2.2 *Three-Dimensional Crystals* 55
- 2.3 Conduction Band Structure 57
- 2.4 Valence Band Structure 58
- 2.5 Intrinsic Semiconductors 60
- 2.6 Extrinsic Semiconductors 62
 - 2.6.1 *Donors* 62
 - 2.6.2 *Acceptors* 66
- 2.7 The Concept of Holes 68
 - 2.7.1 *Hole Charge* 68
- 2.8 Effective Mass of Electrons and Holes 70
- 2.9 Density-of-States Functions for Electrons in Bands 72
 - 2.9.1 *Density of States and Density-of-States Effective Mass* 72
- 2.10 Fermi-Dirac Statistics 73
 - 2.10.1 *Fermi-Dirac Statistics for Electrons and Holes in Bands* 75
- 2.11 Electron and Hole Distributions with Energy 78
- 2.12 Temperature Dependence of Carrier Concentrations in Nondegenerate Semiconductors 90
 - 2.12.1 *Carrier Concentrations at High Temperatures* 91

- 2.12.2 *Carrier Concentrations at Low Temperatures (Carrier Freeze-Out)* 95
- 2.13 Degenerate Semiconductors 95
 - 2.13.1 *Impurity-Induced Band-Gap Narrowing* 96
 - 2.13.2 *Apparent Band-Gap Narrowing* 98
- 2.14 Summary 101
 - 2.14.1 *Nondegenerate Semiconductors* 102
 - 2.14.2 *Degenerate Semiconductors* 103
- 2.15 References 103
- 2.16 Review Questions 104
- 2.17 Problems 104

Chapter 3

Current Flow in Homogeneous Semiconductors 113

- 3.1 Introduction 113
- 3.2 Drift Current 113
- 3.3 Carrier Mobility 117
 - 3.3.1 *Carrier Scattering* 121
 - 3.3.2 *Scattering Mobility* 123
 - 3.3.3 *Impurity Band Mobility* 124
 - 3.3.4 *Temperature Dependence of Mobility* 126
 - 3.3.5 *High-Field Effects* 126
- 3.4 Diffusion Current 130
- 3.5 Carrier Generation and Recombination 133
 - 3.5.1 *Band-to-Band Generation and Recombination* 135
 - 3.5.2 *Two-Step Processes* 135
- 3.6 Optical Processes in Semiconductors 135
 - 3.6.1 *Absorption* 136
 - 3.6.2 *Emission* 139
- 3.7 Continuity Equations 141
- 3.8 Minority Carrier Lifetime 144
 - 3.8.1 *Rise Time* 146
 - 3.8.2 *Fall Time* 146
- 3.9 Minority Carrier Diffusion Lengths 149
- 3.10 Quasi Fermi Levels 152
- 3.11 Summary 154

- 3.12 References 156
- 3.13 Review Questions 156
- 3.14 Problems 157

Chapter 4

Nonhomogeneous Semiconductors 162

- 4.1 Constancy of The Fermi Level at Equilibrium 162
- 4.2 Graded Doping 164
- 4.3 Nonuniform Composition 170
- 4.4 Graded Doping and Graded Composition Combined 173
- 4.5 Summary 175
- 4.6 References 175
- 4.7 Review Questions 175
- 4.8 Problems 176

Supplement to Part 1

Introduction to Quantum Mechanics 180

- S1.1 Introduction 180
- S1.2 The Wave Function 180
- S1.3 Probability and the Wave Function 182
 - S1.3.1 *Particle in a One-Dimensional Potential Well* 182
- S1.4 Schrödinger's Equation 184
- S1.5 Applying Schrödinger's Equation to Electrons 185
- S1.6 Some Results From Quantum Mechanics 186
 - S1.6.1 *The Free Electron* 187
 - S1.6.2 *The Quasi-Free Electron* 188
 - S1.6.3 *The Potential Energy Well* 189
 - S1.6.4 *The Infinite Potential Well in One Dimension* 190
 - S1.6.5 *Reflection and Transmission at a Finite Potential Barrier* 193
 - S1.6.6 *Tunneling* 195
 - S1.6.7 *The Finite Potential Well* 203
 - S1.6.8 *The Hydrogen Atom Revisited* 205
 - S1.6.9 *The Uncertainty Principle* 205

- S1.7** Phonons 207
 - S1.7.1 Carrier Scattering by Phonons* 211
 - S1.7.2 Indirect Electron Transitions* 213
- S1.8** Summary 217
- S1.9** References 217
- S1.10** Review Questions 217
- S1.11** Problems 218

PART 2

Diodes 223

Chapter 5

Prototype pn Homojunctions 227

- 5.1** Introduction 227
- 5.2** Prototype pn Junctions (Qualitative) 229
 - 5.2.1 Energy Band Diagrams of Prototype pn Junctions* 229
 - 5.2.2 Description of Current Flow in a pn Prototype Homojunction* 236
 - 5.2.3 Tunnel Diodes* 241
- 5.3** Prototype pn Homojunctions (Quantitative) 245
 - 5.3.1 Energy Band Diagram at Equilibrium (Step Junction)* 245
 - 5.3.2 Energy Band Diagram with Applied Voltage* 248
 - 5.3.3 Current-Voltage Characteristics of pn Homojunctions* 254
 - 5.3.4 Reverse-Bias Breakdown* 275
- 5.4** Small-Signal Impedance of Prototype Homojunctions 277
 - 5.4.1 Junction (Differential) Resistance* 278
 - 5.4.2 Junction (Differential) Capacitance* 279
 - 5.4.3 Stored-Charge Capacitance* 281
- 5.5** Transient Effects 285
 - 5.5.1 Turn-Off Transient* 285
 - 5.5.2 Turn-On Transient* 287
- 5.6** Effects of Temperature 291

- 5.7** Summary 292
- 5.8** Review Questions 296
- 5.9** Problems 296

Chapter 6

Additional Considerations for Diodes 302

- 6.1** Introduction 302
- 6.2** Nonstep Homojunctions 302
 - 6.2.1 Linearly Graded Junctions* 306
 - 6.2.2 Hyperabrupt Junctions* 309
- 6.3** Semiconductor Heterojunctions 310
 - 6.3.1 The Energy Band Diagrams of Semiconductor–Semiconductor Heterojunctions* 310
 - 6.3.2 Tunneling-Induced Dipoles* 314
 - 6.3.3 Effects of Interface States* 318
 - 6.3.4 Effects of Lattice Mismatch on Heterojunctions* 322
- 6.4** Metal-Semiconductor Junctions 323
 - 6.4.1 Ideal Metal-Semiconductor Junctions (Electron Affinity Model)* 323
 - 6.4.2 Influence of Interface-Induced Dipoles* 325
 - 6.4.3 The Current-Voltage Characteristics of Metal-Semiconductor Junctions* 326
 - 6.4.4 Ohmic (Low-Resistance) Contacts* 330
 - 6.4.5 I - V_a Characteristics of Heterojunction Diodes* 331
- 6.5** Capacitance in Nonideal Junctions and Heterojunctions 332
- 6.6** Summary 332
- 6.7** References 333
- 6.8** Review Questions 333
- 6.9** Problems 334

Supplement to Part 2

Diodes 338

- S2.1** Introduction 338
- S2.2** Dielectric Relaxation Time 338

- S2.2.1 *Case 1: Dielectric Relaxation Time for Majority Carriers* 338
- S2.2.2 *Case 2: Dielectric Relaxation Time for Minority Carriers* 341
- S2.3 Junction Capacitance** 342
 - S2.3.1 *Junction Capacitance in a Prototype (Step) Junction* 342
 - S2.3.2 *Junction Capacitance in a Nonuniformly Doped Junction* 344
 - S2.3.3 *Varactors* 345
 - S2.3.4 *Stored-Charge Capacitance of Short-Base Diodes* 346
- S2.4 Second-Order Effects in Schottky Diodes** 348
 - S2.4.1 *Tunneling Through Schottky Barriers* 349
 - S2.4.2 *Barrier Lowering in Schottky Diodes Due to The Image Effect* 351
- S2.5 Summary** 353
- S2.6 Review Questions** 354
- S2.7 References** 354
- S2.8 Problems** 354

PART 3

Field-Effect Transistors 357

- The Generic FET 358
- Transistors in Circuits 362
- The Basis for Deriving the I_D - V_{DS} Characteristics of a FET 362

Chapter 7

The MOSFET 367

- 7.1 Introduction** 367
- 7.2 MOSFETs (Qualitative)** 367
 - 7.2.1 *Introduction to MOS Capacitors* 367
 - 7.2.2 *MOS Capacitor Hybrid Diagrams* 373
 - 7.2.3 *MOSFETs at Equilibrium (Qualitative)* 376
 - 7.2.4 *MOSFETs Not at Equilibrium (Qualitative)* 378

- 7.3 Drift Model for MOSFETs (Quantitative)** 389
 - 7.3.1 *Long-Channel Drift MOSFET Model with Constant Channel Mobility* 390
 - 7.3.2 *More Realistic Long-Channel Models: Effect of Fields on the Mobility* 404
 - 7.3.3 *Series Resistance* 420
- 7.4 Comparison of Models with Experiment** 421
- 7.5 Ballistic Model for MOSFETs** 423
- 7.6 Some Short-Channel Effects** 426
 - 7.6.1 *Dependence of Effective Channel Length on V_{DS}* 426
 - 7.6.2 *Dependence of Threshold Voltage on the Drain Voltage* 428
- 7.7 Subthreshold Leakage Current** 429
- 7.8 Summary** 432
- 7.9 References** 435
- 7.10 Review Questions** 435
- 7.11 Problems** 436

Chapter 8

Other Field-Effect Transistors 439

- 8.1 Introduction** 439
- 8.2 Measurement of Threshold Voltage and Low-Field Mobility** 440
- 8.3 Complementary MOSFETs (CMOS)** 444
 - 8.3.1 *Operation of The CMOS Inverter* 444
 - 8.3.2 *Matching of CMOS Devices* 447
- 8.4 Switching in CMOS Inverter Circuits** 449
 - 8.4.1 *Effect of Load Capacitance* 449
 - 8.4.2 *Propagation (Gate) Delay in CMOS Switching Circuits* 451
 - 8.4.3 *Pass-Through Current in CMOS Switching* 454
- 8.5 Other MOSFETs** 454
 - 8.5.1 *Silicon on Insulator (SOI) MOSFETs* 454
 - 8.5.2 *FinFETs* 463
 - 8.5.3 *Nonvolatile MOSFETs* 465
- 8.6 Other FETS** 468
 - 8.6.1 *Heterojunction Field-Effect Transistors (HFETs)* 468

- 8.6.2 *Metal-Semiconductor Field-Effect Transistors (MESFETs)* 475
- 8.6.3 *Junction Field-Effect Transistors (JFETs)* 479
- 8.6.4 *Tunnel Field-Effect Transistors (TFETs)* 480
- 8.7 Bulk Channel FETs: Quantitative 484
- 8.8 Summary 487
- 8.9 References 488
- 8.10 Review Questions 489
- 8.11 Problems 489

Supplement to Part 3

Additional Consideration for MOSFETs 493

- S3.1 Introduction 493
- S3.2 Dependence of the Channel Charge Q_{ch} on the Longitudinal Field \mathcal{E}_L 493
- S3.3 Threshold Voltage for MOSFETs 495
 - S3.3.1 *Fixed Charge* 496
 - S3.3.2 *Interface Trapped Charge* 497
 - S3.3.3 *Bulk Charge* 497
 - S3.3.4 *Effect of Charges on the Threshold Voltage* 498
 - S3.3.5 *Flat Band Voltage* 499
 - S3.3.6 *Threshold Voltage Control* 502
 - S3.3.7 *Channel Quantum Effects* 504
- S3.4 MOSFET Analog Equivalent Circuit 506
 - S3.4.1 *Small-Signal Equivalent Circuit* 507
 - S3.4.2 *CMOS Amplifiers* 511
- S3.5 Unity Current Gain Cutoff Frequency f_T 511
- S3.6 MOS Capacitors 514
 - S3.6.1 *Ideal MOS Capacitance* 514
 - S3.6.2 *The C - V_G Characteristics of Real MOS Capacitors* 519
 - S3.6.3 *MOSFET Parameter Analyses from C - V_G Measurements* 520
- S3.7 Dynamic Random-Access Memories (DRAMs) 521
- S3.8 MOSFET Scaling [6] 523

- S3.9 Device and Interconnect Degradation 526
 - S3.9.1 *MOSFET Integrated Circuit Reliability* 531
- S3.10 Summary 532
- S3.11 References 533
- S3.12 Review Questions 534
- S3.13 Problems 534

PART 4

Bipolar Junction Transistors 539

Chapter 9

Bipolar Junction Transistors: Statics 544

- 9.1 Introduction 544
- 9.2 Output Characteristics (Qualitative) 548
- 9.3 Current Gain 550
- 9.4 Model of a Prototype BJT 551
 - 9.4.1 *Collection Efficiency M* 554
 - 9.4.2 *Injection Efficiency γ* 555
 - 9.4.3 *Base Transport Efficiency α_T* 557
- 9.5 Doping Gradients in BJTs 563
 - 9.5.1 *The Graded-Base Transistor* 565
 - 9.5.2 *Effect of Base Field on β* 570
- 9.6 Heterojunction Bipolar Transistors (HBTs) 570
 - 9.6.1 *Uniformly Doped HBT* 571
 - 9.6.2 *Graded-Composition HBT: (Si: SiGe-Base: Si HBTs)* 575
 - 9.6.3 *Double Heterojunction Bipolar Transistor, (DHBT)* 577
- 9.7 Comparison of Si-Base, SiGe-Base, and GaAs-Base HBTs 579
- 9.8 The Basic Ebers-Moll dc Model 579
- 9.9 Summary 583
- 9.10 References 584
- 9.11 Review Questions 585
- 9.12 Problems 586

Chapter 10**Time-Dependent Analysis of BJTs** 590

- 10.1 Introduction 590
- 10.2 Ebers-Moll ac Model 590
- 10.3 Small-Signal Equivalent Circuits 592
 - 10.3.1 Hybrid-Pi Models 594
- 10.4 Stored-Charge Capacitance in BJTs 598
- 10.5 Frequency Response 603
 - 10.5.1 Unity Current Gain Frequency f_T 604
 - 10.5.2 Base Transit Time t_T 606
 - 10.5.3 Base-Collector Transit Time t_{BC} 607
 - 10.5.4 Maximum Oscillation Frequency f_{max} 608
- 10.6 High-Frequency Transistors 608
 - 10.6.1 Double Poly Si Self-Aligned Transistor 608
- 10.7 BJT Switching Transistor 611
 - 10.7.1 Output Low-To-High Transition Time 612
 - 10.7.2 Schottky-Clamped Transistor 614
 - 10.7.3 Double Heterojunction Bipolar Transistor (DHBT) 615
- 10.8 BJTs, MOSFETs, and BiMOS 616
 - 10.8.1 Comparison of BJTs and MOSFETs 616
 - 10.8.2 BiMOS 618
- 10.9 Summary 620
- 10.10 References 620
- 10.11 Review Questions 621
- 10.12 Problems 621

Supplement to Part 4**Bipolar Devices** 623

- S4.1 Introduction 623
- S4.2 Current Crowding and Base Resistance in BJTs 623
- S4.3 Base Width Modulation (Early Effect) 627
- S4.4 Avalanche Breakdown 632
- S4.5 High Injection 632
- S4.6 Base Push-Out (Kirk) Effect 633

- S4.7 Recombination in the Emitter-Base Junction 635
- S4.8 Offset Voltage in BJTs 636
- S4.9 Lateral Bipolar Transistors 637
- S4.10 Summary 638
- S4.11 References 638
- S4.12 Review Questions 639
- S4.13 Problems 639

PART 5**Optoelectronic and Power Semiconductor Devices** 643Chapter 11**Optoelectronic Devices** 644

- 11.1 Introduction and Preview 644
- 11.2 Photodetectors 644
 - 11.2.1 Generic Photodetector 644
 - 11.2.2 Solar Cells 652
 - 11.2.3 The pin (PIN) Photodetector 658
 - 11.2.4 Avalanche Photodiodes 660
- 11.3 Light-Emitting Diodes 661
 - 11.3.1 Spontaneous Emission in a Forward-Biased Junction 661
 - 11.3.2 Blue, Ultraviolet, and White LEDs 664
 - 11.3.3 Infrared LEDs 664
 - 11.3.4 White LEDs and Solid-State Lighting 671
- 11.4 Laser Diodes 674
 - 11.4.1 Optical Gain 675
 - 11.4.2 Feedback 677
 - 11.4.3 Gain + Feedback = Laser 680
 - 11.4.4 Laser Structures 682
 - 11.4.5 Other Semiconductor Laser Materials 686
- 11.5 Image Sensors (Imagers) 686
 - 11.5.1 Charge-Coupled Devices (CCDs) 686
 - 11.5.2 Linear Image Sensors 688
 - 11.5.3 Area Image Sensors 691
- 11.6 Summary 692

- 11.7 References 693
- 11.8 Review Questions 694
- 11.9 Problems 694

Chapter 12

Power Semiconductor Devices 699

- 12.1 Introduction and Preview 699
- 12.2 Rectifying Diodes 700
 - 12.2.1 Junction Breakdown 700
 - 12.2.2 Specific On-Resistance 710
 - 12.2.3 Transient Losses 718
 - 12.2.4 Merged Pin-Schottky (MPS) Diodes 723
- 12.3 Thyristors (npnp Switching Devices) 725
 - 12.3.1 The Four-Layer Diode Switch 725
 - 12.3.2 Two-Transistor Model of an npnp Switch 729
 - 12.3.3 Silicon-Controlled Rectifiers (SCRs) 730
 - 12.3.4 TRIAC 733
 - 12.3.5 Gate Turn-Off Thyristors (GTOs) 735
- 12.4 The Power MOSFET 736
- 12.5 The Insulated-Gate Bipolar Transistor 740
- 12.6 Power MOSFET versus IGBT 745
- 12.7 Summary 746
- 12.8 References 747
- 12.9 Review Questions 748
- 12.10 Problems 748

Appendices

Appendix A Constants 750

Appendix B List of Symbols 754

Appendix C Fabrication 769

- C.1 Introduction 769
- C.2 Substrate Preparation 769
 - C.2.1 The Raw Material 770
 - C.2.2 Crystal Growth 770
 - C.2.3 Defects 773
 - C.2.4 Epitaxy 774
- C.3 Doping 777
 - C.3.1 Diffusion 777
 - C.3.2 Ion Implantation 778
- C.4 Lithography 780
- C.5 Conductors and Insulators 782
 - C.5.1 Metallization 782
 - C.5.2 Poly Si 783
 - C.5.3 Oxidation 783
 - C.5.4 Silicon Nitride 784
- C.6 Silicon Oxynitride (SiO_xN_y or SiON) 785
- C.7 Clean Rooms 787
- C.8 Packaging 787
 - C.8.1 Wire Bonding 788
 - C.8.2 Lead Frame 789
 - C.8.3 Surface-Mount Packages 790
- C.9 Summary 791

Appendix D Some Useful Integrals 792

Appendix E Useful Equations 793

- General Physics 793
- Semiconductor Materials 793
- Junctions 794
- Field-Effect Transistors 796
- Bipolar Junction Transistors 798
- Optoelectronic Devices 801
- Power Semiconductor Devices 802

Index 803

PREFACE

This is a textbook on the operating principles of semiconductor devices. It is appropriate for undergraduate (junior or senior) or beginning graduate students in electrical engineering, as well as students of computer engineering, physics, and materials science. It is also useful as a reference for practicing engineers and scientists who are involved with modern semiconductor devices.

Prerequisites are courses in chemistry and physics and in basic electric circuits, which are normally taken in the freshman and sophomore years.

The text is appropriate for a two- or three-semester course on semiconductor devices. However, it can be used for a one-semester course by eliminating some of the more advanced material and assigning some of the sections as read-only. The authors have attempted to organize the material so that some of the detail derivation sections can be skipped without affecting the comprehension of other sections.

This book is divided into five parts:

1. Materials
2. Diodes
3. Field-effect transistors
4. Bipolar transistors
5. Optoelectronic and power semiconductor devices

The first four parts are followed by “Supplements” that, while not required for an understanding of the basic principle of device operation, contain related material that may be assigned at the discretion of the instructor.

Part 1, “Materials,” contains four chapters and a Supplement. The first two chapters contain considerable review material from the prerequisite courses. This material is included because it is used extensively in later chapters to explain the principles of device operation. Depending on the detailed content on the prerequisite courses, much of the material in these chapters can be relegated to reading assignments.

The level of quantum mechanics to be covered in a course like this varies widely. In this book some basic concepts are included in the main chapters of Part 1. Those wishing to cover quantum mechanics in more detail will find more extensive material in the Supplement to Part 1.

The basic operating principles of large and small devices of a particular type (e.g., diodes, field-effect transistors, bipolar junction transistors, and

photodetectors) are the same. However the relative importance of many of the parameters involved in device operation depends on the device dimensions. In this book the general behavior of devices of large dimensions is treated first. In each case, we treat “prototype” devices (such as step junctions and long channel field-effect transistors) from which the fundamental physics can be learned, and then we develop more realistic models considering second-order effects. These second-order effects can have significant influence on the electrical characteristics of modern small-geometry devices. The instructor can go into as much depth as desired or as time permits.

Topics treated that are typically omitted in undergraduate texts are:

- The differences between the electron and hole effective masses as used in density-of-states calculations and conductivity calculations.
- The differences in electron and hole mobilities (and thus diffusion coefficients) depending on whether they are majority carriers or minority carriers.
- The effects of doping gradients in the base of bipolar junction transistors (and/or the composition and heterojunction BJTs) on the current gain in switching speed.
- Band gap reduction in degenerate semiconductors. While this has little effect on the electrical characteristics of diodes or field-effect transistors, its effect in the emitter of bipolar junction transistors can reduce the current gain by orders of magnitude.
- The use of wide band-gap semiconductors (e.g., GaN and 4H-SiC) for use in high-power semiconductor devices.

While the major emphasis is on silicon and silicon-based devices, the operation of compound semiconductor devices, alloy devices (e.g., Si:Ge, AlGaAs) and heterojunction devices (junctions between semiconductors of different composition) are also considered because of the increased performance that is possible with *band-gap engineering*.

Fabrication, while an important part of semiconductor engineering, is often skipped in the interest of time. This material is introduced in Appendix C and can be assigned as read-only material if desired.

Supplemental topics are presented in a series of *Online Modules*. These modules, whose content is beyond that normally taught in a first course on semiconductor devices, contain material which supplements that of the book proper. For example, Online Module 7 describes some basic representative circuits utilizing CMOS devices. These Online Modules are available on the web for downloading.

ACKNOWLEDGMENTS

We would like to thank, first and foremost, our spouses Bill and Claire for their love, support, patience, and help. We are also grateful to the anonymous manuscript reviewers for their comments and suggestions, as well as staff at McGraw-Hill for all their help. We thank our students and their professors for valuable feedback on the first edition of the text. In particular, we thank Professor Gary Bernstein of Notre Dame University for his extensive comments and suggestions. We also wish to thank Cor Claeys and Rita Rooyackers of IMEC for scanning electron microscopy photographs of devices.

Materials

INTRODUCTION

Semiconductors form the basis of most modern electronic systems (e.g., computers, communication networks, control systems). While there are applications for other materials in electronics (e.g., magnetic materials in hard drives), this book concentrates on electronic devices that are based on semiconductors.

Understanding the operation and design of semiconductor devices begins with an understanding of the materials involved. In Part 1 of this book, we investigate the behavior of electrons in materials, starting with the atoms themselves. Then we progress to electrons in crystalline semiconductors.

We will see that classical mechanics does not provide a complete picture of electron activity in solids. In principle, one should instead use quantum mechanics to predict the electrons' behavior, but the application of quantum mechanics is not as simple as the more familiar classical or Newtonian mechanics. We will therefore introduce pseudo-classical mechanics, which modifies familiar classical equations to account for some quantum mechanical effects.

Some basic quantum mechanical concepts important for the understanding of device operation are covered in Chapter 1. (A more detailed discussion is contained in Supplement to Part 1, found after Chapter 4.) In Chapter 2, we cover pseudo-classical mechanics, which allows us to predict the reaction of electrons to complicated fields, while using simple and intuitive pseudo-classical equations.

The use of pseudo-classical mechanics will also allow us to draw and use energy band diagrams. These diagrams are indispensable for understanding and predicting the motion of the electrons and holes, and thus the current in semiconductors.

In Chapter 3, we will see that conductivity of semiconductors is controlled by the number of charge carriers available to carry current. The charge carriers in semiconductors are electrons and holes. Their numbers are controlled by the

concentrations of impurity elements that are intentionally added to the material. The carrier concentrations also depend on temperature and on whether light is shining on the sample.

It will emerge that there are two major forms of current in semiconductors, drift current and diffusion current. Drift current is caused by the presence of an electric field, whereas diffusion current arises when the carrier concentrations vary with position.

Chapter 4 covers nonhomogeneous semiconductor materials, in which the doping or the material composition itself may vary with position. These variations can lead to internal electric fields that can enhance device performance. Most modern semiconductor devices have regions of such nonhomogeneous materials.

The Supplement to Part 1 contains additional topics relevant to semiconductor materials, including a more detailed discussion of quantum mechanics and phonons.

We will start with electrons in atoms. ■

Electron Energy and States in Semiconductors

1.1 INTRODUCTION AND PREVIEW

We begin our study of semiconductors with some fundamental physics of how electrons behave in matter. The ability to control the movement of electrons in solids is the basis of semiconductor device engineering. To understand the electronic properties of these devices, it is necessary to understand the electronic properties of the materials from which they are made and how those properties are affected by impurities (intentional and unintentional), temperature, applied voltages, device structures, and optical radiation.

Since solids are composed of atoms, we start by examining the electronic properties of atoms, and then extending those results to simple molecules and solids. In particular, the results for silicon (Si) and gallium arsenide (GaAs) are emphasized, two commonly used semiconductors in integrated circuits and semiconductor devices. Several other semiconductors and semiconductor alloys important in modern devices are also discussed.

As we investigate the atom, we'll be using quantum mechanics, a branch of science that is needed to accurately describe the behavior of very small objects such as atoms and electrons. We will see as we go along that quantum mechanics is based on the idea that energy can exist only in discrete packets, or quanta. The size of a quantum is so small that it doesn't affect one's results when one is computing the momentum or velocity of large objects such as automobiles or dust particles, but the quantum description is extremely important for electrons and atoms.

An understanding of quantum mechanics is not simple to obtain, and its use to calculate properties of more than a few systems in closed form is difficult. Fortunately, however, in semiconductors the behavior of electrons of interest can be determined by *pseudo-classical mechanics*, in which classical formulas such as Newton's laws and the Lorentz equation can be used, with the true electron mass replaced by an *effective mass*. As a result, in this section, a minimal discussion

of quantum mechanics is presented. A somewhat greater discussion of quantum mechanics appropriate to some of the electronic processes in semiconductor devices is presented in the Supplement to Part 1, after Chapter 4.

The key to understanding semiconductors is to appreciate the physical interpretation of the mathematical results. Physical understanding is emphasized in this book.

1.2 A BRIEF HISTORY

In the early twentieth century, scientists were trying to develop models that would explain the results observed from such experiments as the scattering of X-rays, the photoelectric effect, and the emission and absorption spectra of atoms. In 1910, J. J. Thomson proposed a model of the atom in which a sphere of continuous positive charge is embedded with electrons, as shown in Figure 1.1a. Ernest Rutherford, in 1911, offered an improvement to the Thomson model: In the Rutherford model of the atomic structure, all of the positive charge and virtually all of the atom's mass were assumed to be concentrated in a small region in the center of the atom. This nucleus is often treated as a sphere with a radius on the order of 10^{-14} meters. The negatively charged electrons were assumed to orbit about the positively charged nucleus, much as planets orbit the sun or satellites orbit the earth.

In 1913, Neils Bohr assumed that the electrons in the Rutherford model of the atom orbited the nucleus in circles, as shown in Figure 1.1b. From this, he predicted that for the atom to be stable, the electrons could have only certain energies, or that the energies would be *quantized*. Energy and many other observables (properties that can be directly measured) are expressed in terms of Planck's constant. Planck's constant, h , has the value 6.63×10^{-34} joule-seconds.

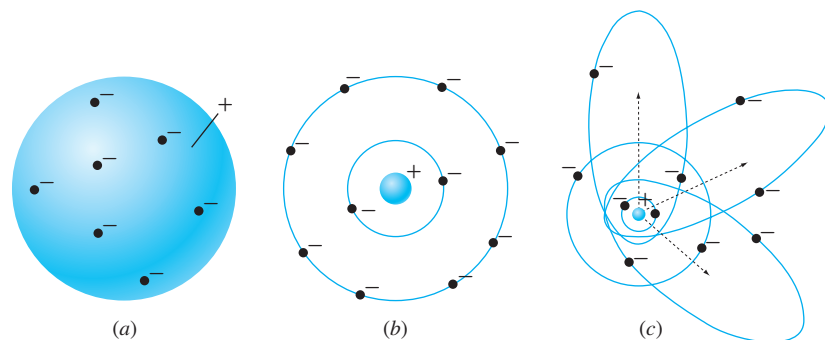


Figure 1.1 (a) The Thomson model of an atom, in which the positive charge is uniformly distributed in a sphere and the electrons are considered to be negative point charges embedded in it; (b) the Bohr model, in which the positive charge is concentrated in a small nucleus and the electrons orbit in circles; (c) the Wilson-Sommerfeld model, which is similar to the Bohr model except that it allows for elliptical orbits.

The energies Bohr predicted for electrons in atoms were in excellent agreement with the experimental results obtained from spectroscopic data.

In 1916, Wilson and Sommerfeld generalized the Bohr model to apply it to any physical system in which a particle's motion is periodic with time. This modification allows for the possibility of elliptical orbits, as shown in Figure 1.1c.

1.3 APPLICATION TO THE HYDROGEN ATOM

In this section, we briefly review the Bohr model of the hydrogen atom. The hydrogen atom is emphasized because *hydrogen-like impurities* are important in semiconductor devices, and these impurities can be treated in a manner analogous to the Bohr model. In the Supplement to Part 1, we will compare these results to those obtained using quantum mechanics as represented by Schrödinger's equation.

1.3.1 THE BOHR MODEL FOR THE HYDROGEN ATOM

We start with the Bohr model, in which the electrons revolve around the nucleus in circular paths. Because the mass of the nucleus is 1.67×10^{-27} kg, 1830 times that of the electron, the nucleus is considered to be fixed in space.

We consider as an example the neutral hydrogen atom, which has one orbiting electron, and we treat the electron and nucleus both as point charges. The coulomb force between two particles with charges Q_1 and Q_2 is

$$F = \frac{Q_1 Q_2}{4\pi\epsilon_0 r^2} = \frac{-q^2}{4\pi\epsilon_0 r^2} \quad (1.1)$$

where r is the distance between the two charges and $\epsilon_0 = 8.85 \times 10^{-12}$ farads/meter is the permittivity of free space (because there is only free space between the nucleus and the electron). The expression at the far right-hand side of Equation (1.1) is obtained by recognizing that the hydrogen nucleus has only one proton, so Q_1 is equal to $+q = 1.602 \times 10^{-19}$ Coulombs, the elemental charge, and the charge of the electron Q_2 is equal to $-q$. The resulting negative sign in Equation (1.1) indicates that the force is attractive.

We now have an expression for the attractive (centripetal) force between the two particles, and we recall from classical mechanics that the force F on a particle is equal to minus the gradient of the potential energy, or

$$F = -\nabla E_p = -\frac{dE_p}{dr} \quad (1.2)$$

In the last expression, the gradient is taken in the r direction, and E_p is the potential energy of the electron at position r . Equation (1.2) with the aid of (1.1) can be rewritten as

$$dE_p = dE_p(r) = -Fdr = \frac{q^2 dr}{4\pi\epsilon_0 r^2} \quad (1.3)$$

One can integrate both sides to obtain E_P , but there will be a constant of integration. The actual value of the potential energy is arbitrary (as is the choice of the constant), since the value of the potential energy depends entirely on one's choice of reference. We can choose a convenient reference by noting that the coulomb force at infinite distance is zero. It makes sense for this case, then, to choose $r = \infty$ as a reference point, so we define the potential energy at $r = \infty$ as the *vacuum level*, E_{vac} :

$$E_P(r = \infty) = E_{\text{vac}} \quad (1.4)$$

This is the energy required to free the electron from the influence of the nucleus, essentially by moving the electron infinitely far away from it. If the electron is infinitely far from the nucleus, it cannot really be considered part of the atom—it is now a free electron in vacuum.

Now we can solve Equation (1.3) for a given value of r :

$$\int_{E_P}^{E_{\text{vac}}} dE_P = \int_r^{\infty} \frac{q^2 dr}{4\pi\epsilon_0 r^2} \quad (1.5)$$

where E_P is the electron potential energy at some distance r from the nucleus. Integrating both sides and rearranging, we obtain

$$E_P = E_{\text{vac}} - \frac{q^2}{4\pi\epsilon_0 r} \quad (1.6)$$

Figure 1.2 shows a plot of the r dependence of E_P . From Equation (1.1), and since the force is equal to minus the gradient (slope) of the potential energy, we see that the force on the electron is directed toward the nucleus, or the coulomb force is centripetal. Since the nucleus is considered to be a point charge, E_P approaches negative infinity as r approaches zero. Since the radius of the nucleus is on the order of 10^{-14} m, however, and the radius of the smallest electron orbit is on the order of 10^{-10} m, the potential energy reaches a minimum near $r = 0$.

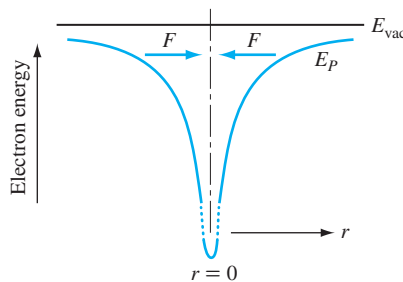


Figure 1.2 Potential energy diagram for an electron in the vicinity of a single positive point charge. The electron is considered to be a point charge.

Since the electron is revolving in a circle of radius r around the nucleus, we know from Newtonian mechanics that its centrifugal force is equal to

$$F = \frac{mv^2}{r} \quad (1.7)$$

For the atom to be stable, the net force on the electron must be zero. Equating our previous expression for the centripetal force due to the coulomb attraction [Equation (1.1)] to the centrifugal force [Equation (1.7)], we can write

$$\frac{mv^2}{r} - \frac{q^2}{4\pi\epsilon_0 r^2} = 0 \quad (1.8)$$

Bohr also postulated that the integral of the angular momentum around one complete orbit is an integer multiple of Planck's constant h :

$$\oint P_\theta d\theta = \int_0^{2\pi} mvr d\theta = nh \quad (1.9)$$

where n is an integer. Since the orbit is assumed circular in the Bohr model, r is a constant, and so are the potential energy E_P and the speed v . Therefore, the integral becomes

$$2\pi mrv = nh \quad (1.10)$$

There is a solution for each integer value of n , so we write

$$mv_n r_n = n \frac{h}{2\pi} = n\hbar \quad (1.11)$$

Here we have introduced a new symbol; it turns out that engineers and physicists (and now you) use the quantity $h/2\pi$ so much that there is a special character for it, \hbar , pronounced "h-bar." The subscripts n in Equation (1.11) indicate the particular orbital radius or speed associated with a specific quantum number n .

If we simultaneously solve Equations (1.8) and (1.11), we can derive an expression for the *Bohr radius of the n th state*, where by "state" we mean the properties associated with a particular value of n :

$$r_n = \frac{4\pi\epsilon_0 n^2 \hbar^2}{mq^2} \quad (1.12)$$

and the speed of the electron in that particular state is

$$v_n = \frac{q^2}{4\pi\epsilon_0 n\hbar} \quad (1.13)$$

Our primary goal, however, is to find the energies associated with these states. We know that the total energy of a system is equal to the kinetic energy plus the potential energy. The kinetic energy of the n th energy level is

$$E_{K_n} = \frac{1}{2} m v_n^2 = \frac{mq^4}{2(4\pi\epsilon_0)^2 n^2 \hbar^2} \quad (1.14)$$

For the n th energy level, we can find r_n from Equation (1.12) and use that in Equation (1.6) to write for the potential energy

$$E_{Pn} = E_{\text{vac}} - \frac{mq^4}{(4\pi\epsilon_0)^2 n^2 \hbar^2} \quad (1.15)$$

Thus, the total energy E_n is

$$E_n = E_{Kn} + E_{Pn} = E_{\text{vac}} - \frac{mq^4}{2(4\pi\epsilon_0)^2 n^2 \hbar^2} \quad (1.16)$$

We say that the energy is *quantized*. It can have only discrete values associated with the quantum number n . We note that $n = 1$ refers to the smallest radius and energy of the electron in the Bohr model, $n = 2$, the next larger values, etc.

EXAMPLE 1.1

Find the energies and radii for the first four orbits in the hydrogen atom.

■ Solution

$$\begin{aligned} E_n &= E_{\text{vac}} - \frac{mq^4}{2(4\pi\epsilon_0)^2 n^2 \hbar^2} \\ &= E_{\text{vac}} - \frac{(9.11 \times 10^{-31} \text{ kg})(1.60 \times 10^{-19} \text{ C})^4}{(2)(4)^2 (3.1416)^2 (8.85 \times 10^{-12} \text{ F/m})^2 (1.05 \times 10^{-34} \text{ J} \cdot \text{s})^2} \left(\frac{1}{n}\right)^2 \\ E_n &= E_{\text{vac}} - \left(\frac{1}{n}\right)^2 (2.18 \times 10^{-18} \text{ J}) \\ &= E_{\text{vac}} - \left(\frac{1}{n}\right)^2 (13.6 \text{ eV}) \end{aligned} \quad (1.17)$$

Here a new unit of energy is introduced, the *electron volt* (eV). The electron volt is defined as the amount of energy acquired by an electron when it is accelerated through 1 volt of electric potential. To convert between SI (International System) units (joules) and electron volts, use

$$1 \text{ eV} = 1.60 \times 10^{-19} \text{ joules}$$

Electron volts are *not* SI units, and therefore they must be used with care in calculations.

The Bohr radii can be calculated from Equation (1.12):

$$\begin{aligned} r_n &= \frac{4\pi\epsilon_0 n^2 \hbar^2}{mq^2} = \frac{(4)(3.1416)(8.85 \times 10^{-12} \text{ F/m})(1.05 \times 10^{-34} \text{ J} \cdot \text{s})^2}{(9.11 \times 10^{-31} \text{ kg})(1.60 \times 10^{-19} \text{ C})^2} \times n^2 \\ r_n &= 0.0526 n^2 \text{ nm} \end{aligned} \quad (1.18)$$

The energies and Bohr radii of the first four energy levels are given in Table 1.1. These energies and radii are plotted in Figures 1.3 and 1.4, respectively.

Table 1.1 The first four Bohr energies and orbital radii for the hydrogen atom

E_n	r_n
$E_1 = E_{\text{vac}} - 13.6 \text{ eV}$	$r_1 = 0.0526 \text{ nm}$
$E_2 = E_{\text{vac}} - 3.40 \text{ eV}$	$r_2 = 0.212 \text{ nm}$
$E_3 = E_{\text{vac}} - 1.51 \text{ eV}$	$r_3 = 0.477 \text{ nm}$
$E_4 = E_{\text{vac}} - 0.850 \text{ eV}$	$r_4 = 0.848 \text{ nm}$

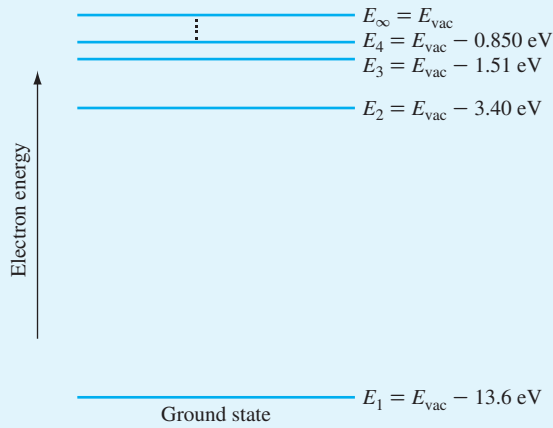


Figure 1.3 Allowed energies in the hydrogen atom. Higher energies occur increasingly close to each other, approaching the vacuum level.

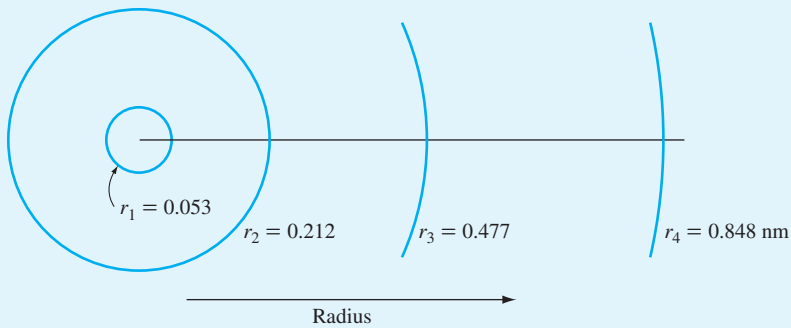


Figure 1.4 Radii of the first four electronic orbits of the hydrogen atom, according to the Bohr model.