

Semiconductor Physics and Devices

Basic Principles

Fourth Edition

Donald A. Neamen
University of New Mexico



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SEMICONDUCTOR PHYSICS & DEVICES: BASIC PRINCIPLES, FOURTH EDITION

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CONTENTS

Preface	x
Prologue—Semiconductors and the Integrated Circuit	xvii

PART I—Semiconductor Material Properties

CHAPTER 1

The Crystal Structure of Solids 1

1.0	Preview	1
1.1	Semiconductor Materials	1
1.2	Types of Solids	2
1.3	Space Lattices	3
1.3.1	Primitive and Unit Cell	3
1.3.2	Basic Crystal Structures	4
1.3.3	Crystal Planes and Miller Indices	6
1.3.4	Directions in Crystals	9
1.4	The Diamond Structure	10
1.5	Atomic Bonding	12
*1.6	Imperfections and Impurities in Solids	14
1.6.1	Imperfections in Solids	14
1.6.2	Impurities in Solids	16
*1.7	Growth of Semiconductor Materials	17
1.7.1	Growth from a Melt	17
1.7.2	Epitaxial Growth	19
1.8	Summary	20
	Problems	21

CHAPTER 2

Introduction to Quantum Mechanics 25

2.0	Preview	25
2.1	Principles of Quantum Mechanics	26
2.1.1	Energy Quanta	26
2.1.2	Wave-Particle Duality	27
2.1.3	The Uncertainty Principle	30

2.2	Schrodinger's Wave Equation	31
2.2.1	The Wave Equation	31
2.2.2	Physical Meaning of the Wave Function	32
2.2.3	Boundary Conditions	33
2.3	Applications of Schrodinger's Wave Equation	34
2.3.1	Electron in Free Space	35
2.3.2	The Infinite Potential Well	36
2.3.3	The Step Potential Function	39
2.3.4	The Potential Barrier and Tunneling	44
2.4	Extensions of the Wave Theory to Atoms	46
2.4.1	The One-Electron Atom	46
2.4.2	The Periodic Table	50
2.5	Summary	51
	Problems	52

CHAPTER 3

Introduction to the Quantum Theory of Solids 58

3.0	Preview	58
3.1	Allowed and Forbidden Energy Bands	59
3.1.1	Formation of Energy Bands	59
*3.1.2	The Kronig-Penney Model	63
3.1.3	The k-Space Diagram	67
3.2	Electrical Conduction in Solids	72
3.2.1	The Energy Band and the Bond Model	72
3.2.2	Drift Current	74
3.2.3	Electron Effective Mass	75
3.2.4	Concept of the Hole	78
3.2.5	Metals, Insulators, and Semiconductors	80
3.3	Extension to Three Dimensions	83
3.3.1	The k-Space Diagrams of Si and GaAs	83
3.3.2	Additional Effective Mass Concepts	85

- 3.4 Density of States Function 85**
 - 3.4.1 *Mathematical Derivation* 85
 - 3.4.2 *Extension to Semiconductors* 88
- 3.5 Statistical Mechanics 91**
 - 3.5.1 *Statistical Laws* 91
 - 3.5.2 *The Fermi-Dirac Probability Function* 91
 - 3.5.3 *The Distribution Function and the Fermi Energy* 93
- 3.6 Summary 98**
- Problems 100**

CHAPTER 4

The Semiconductor in Equilibrium 106

- 4.0 Preview 106**
- 4.1 Charge Carriers in Semiconductors 107**
 - 4.1.1 *Equilibrium Distribution of Electrons and Holes* 107
 - 4.1.2 *The n_0 and p_0 Equations* 109
 - 4.1.3 *The Intrinsic Carrier Concentration* 113
 - 4.1.4 *The Intrinsic Fermi-Level Position* 116
- 4.2 Dopant Atoms and Energy Levels 118**
 - 4.2.1 *Qualitative Description* 118
 - 4.2.2 *Ionization Energy* 120
 - 4.2.3 *Group III-V Semiconductors* 122
- 4.3 The Extrinsic Semiconductor 123**
 - 4.3.1 *Equilibrium Distribution of Electrons and Holes* 123
 - 4.3.2 *The $n_0 p_0$ Product* 127
 - *4.3.3 *The Fermi-Dirac Integral* 128
 - 4.3.4 *Degenerate and Nondegenerate Semiconductors* 130
- 4.4 Statistics of Donors and Acceptors 131**
 - 4.4.1 *Probability Function* 131
 - 4.4.2 *Complete Ionization and Freeze-Out* 132
- 4.5 Charge Neutrality 135**
 - 4.5.1 *Compensated Semiconductors* 135
 - 4.5.2 *Equilibrium Electron and Hole Concentrations* 136
- 4.6 Position of Fermi Energy Level 141**
 - 4.6.1 *Mathematical Derivation* 142
 - 4.6.2 *Variation of E_F with Doping Concentration and Temperature* 144
 - 4.6.3 *Relevance of the Fermi Energy* 145

- 4.7 Summary 147**
- Problems 149**

CHAPTER 5

Carrier Transport Phenomena 156

- 5.0 Preview 156**
- 5.1 Carrier Drift 157**
 - 5.1.1 *Drift Current Density* 157
 - 5.1.2 *Mobility Effects* 159
 - 5.1.3 *Conductivity* 164
 - 5.1.4 *Velocity Saturation* 169
- 5.2 Carrier Diffusion 172**
 - 5.2.1 *Diffusion Current Density* 172
 - 5.2.2 *Total Current Density* 175
- 5.3 Graded Impurity Distribution 176**
 - 5.3.1 *Induced Electric Field* 176
 - 5.3.2 *The Einstein Relation* 178
- *5.4 *The Hall Effect* 180
- 5.5 Summary 183**
- Problems 184**

CHAPTER 6

Nonequilibrium Excess Carriers in Semiconductors 192

- 6.0 Preview 192**
- 6.1 Carrier Generation and Recombination 193**
 - 6.1.1 *The Semiconductor in Equilibrium* 193
 - 6.1.2 *Excess Carrier Generation and Recombination* 194
- 6.2 Characteristics of Excess Carriers 198**
 - 6.2.1 *Continuity Equations* 198
 - 6.2.2 *Time-Dependent Diffusion Equations* 199
- 6.3 Ambipolar Transport 201**
 - 6.3.1 *Derivation of the Ambipolar Transport Equation* 201
 - 6.3.2 *Limits of Extrinsic Doping and Low Injection* 203
 - 6.3.3 *Applications of the Ambipolar Transport Equation* 206
 - 6.3.4 *Dielectric Relaxation Time Constant* 214
 - *6.3.5 *Haynes-Shockley Experiment* 216

- 6.4 Quasi-Fermi Energy Levels 219
- *6.5 Excess Carrier Lifetime 221
 - 6.5.1 Shockley-Read-Hall Theory of Recombination 221
 - 6.5.2 Limits of Extrinsic Doping and Low Injection 225
- *6.6 Surface Effects 227
 - 6.6.1 Surface States 227
 - 6.6.2 Surface Recombination Velocity 229
- 6.7 Summary 231
 - Problems 233

PART II—Fundamental Semiconductor Devices

CHAPTER 7

The pn Junction 241

- 7.0 Preview 241
- 7.1 Basic Structure of the pn Junction 242
- 7.2 Zero Applied Bias 243
 - 7.2.1 Built-in Potential Barrier 243
 - 7.2.2 Electric Field 246
 - 7.2.3 Space Charge Width 249
- 7.3 Reverse Applied Bias 251
 - 7.3.1 Space Charge Width and Electric Field 251
 - 7.3.2 Junction Capacitance 254
 - 7.3.3 One-Sided Junctions 256
- 7.4 Junction Breakdown 258
- *7.5 Nonuniformly Doped Junctions 262
 - 7.5.1 Linearly Graded Junctions 263
 - 7.5.2 Hyperabrupt Junctions 265
- 7.6 Summary 267
 - Problems 269

CHAPTER 8

The pn Junction Diode 276

- 8.0 Preview 276
- 8.1 pn Junction Current 277
 - 8.1.1 Qualitative Description of Charge Flow in a pn Junction 277
 - 8.1.2 Ideal Current-Voltage Relationship 278
 - 8.1.3 Boundary Conditions 279

- 8.1.4 Minority Carrier Distribution 283

- 8.1.5 Ideal pn Junction Current 286

- 8.1.6 Summary of Physics 290

- 8.1.7 Temperature Effects 292

- 8.1.8 The "Short" Diode 293

8.2 Generation-Recombination Currents and High-Injection Levels 295

- 8.2.1 Generation-Recombination Currents 296

- 8.2.2 High-Level Injection 302

8.3 Small-Signal Model of the pn Junction 304

- 8.3.1 Diffusion Resistance 305

- 8.3.2 Small-Signal Admittance 306

- 8.3.3 Equivalent Circuit 313

*8.4 Charge Storage and Diode Transients 314

- 8.4.1 The Turn-off Transient 315

- 8.4.2 The Turn-on Transient 317

*8.5 The Tunnel Diode 318

8.6 Summary 321

- Problems 323

CHAPTER 9

Metal-Semiconductor and Semiconductor Heterojunctions 331

9.0 Preview 331

9.1 The Schottky Barrier Diode 332

- 9.1.1 Qualitative Characteristics 332

- 9.1.2 Ideal Junction Properties 334

- 9.1.3 Nonideal Effects on the Barrier Height 338

- 9.1.4 Current-Voltage Relationship 342

- 9.1.5 Comparison of the Schottky Barrier Diode and the pn Junction Diode 345

9.2 Metal-Semiconductor Ohmic Contacts 349

- 9.2.1 Ideal Nonrectifying Barrier 349

- 9.2.2 Tunneling Barrier 351

- 9.2.3 Specific Contact Resistance 352

9.3 Heterojunctions 354

- 9.3.1 Heterojunction Materials 354

- 9.3.2 Energy-Band Diagrams 354

- 9.3.3 Two-Dimensional Electron Gas 356

- *9.3.4 Equilibrium Electrostatics 358

- *9.3.5 Current-Voltage Characteristics 363

9.4

CHA
Func
Semi

10.0

10.1

10.2

10.3

10.4

*10.5

10.6

CHA I
Metal-
Trans

11.0

11.1

9.4 Summary 363**Problems 365****CHAPTER 10****Fundamentals of the Metal–Oxide–Semiconductor Field-Effect Transistor 371****10.0 Preview 371****10.1 The Two-Terminal MOS Structure 372***10.1.1 Energy-Band Diagrams 372**10.1.2 Depletion Layer Thickness 376**10.1.3 Surface Charge Density 380**10.1.4 Work Function Differences 382**10.1.5 Flat-Band Voltage 385**10.1.6 Threshold Voltage 388***10.2 Capacitance–Voltage Characteristics 394***10.2.1 Ideal C–V Characteristics 394**10.2.2 Frequency Effects 399**10.2.3 Fixed Oxide and Interface Charge Effects 400***10.3 The Basic MOSFET Operation 403***10.3.1 MOSFET Structures 403**10.3.2 Current–Voltage Relationship—Concepts 404***10.3.3 Current–Voltage Relationship—Mathematical Derivation 410**10.3.4 Transconductance 418**10.3.5 Substrate Bias Effects 419***10.4 Frequency Limitations 422***10.4.1 Small-Signal Equivalent Circuit 422**10.4.2 Frequency Limitation Factors and Cutoff Frequency 425****10.5 The CMOS Technology 427****10.6 Summary 430****Problems 433****CHAPTER 11****Metal–Oxide–Semiconductor Field-Effect Transistor: Additional Concepts 443****11.0 Preview 443****11.1 Nonideal Effects 444***11.1.1 Subthreshold Conduction 444**11.1.2 Channel Length Modulation 446**11.1.3 Mobility Variation 450**11.1.4 Velocity Saturation 452**11.1.5 Ballistic Transport 453***11.2 MOSFET Scaling 455***11.2.1 Constant-Field Scaling 455**11.2.2 Threshold Voltage—First Approximation 456**11.2.3 Generalized Scaling 457***11.3 Threshold Voltage Modifications 457***11.3.1 Short-Channel Effects 457**11.3.2 Narrow-Channel Effects 461***11.4 Additional Electrical Characteristics 464***11.4.1 Breakdown Voltage 464***11.4.2 The Lightly Doped Drain Transistor 470**11.4.3 Threshold Adjustment by Ion Implantation 472****11.5 Radiation and Hot-Electron Effects 475***11.5.1 Radiation-Induced Oxide Charge 475**11.5.2 Radiation-Induced Interface States 478**11.5.3 Hot-Electron Charging Effects 480***11.6 Summary 481****Problems 483****CHAPTER 12****The Bipolar Transistor 491****12.0 Preview 491****12.1 The Bipolar Transistor Action 492***12.1.1 The Basic Principle of Operation 493**12.1.2 Simplified Transistor Current Relation—Qualitative Discussion 495**12.1.3 The Modes of Operation 498**12.1.4 Amplification with Bipolar Transistors 500***12.2 Minority Carrier Distribution 501***12.2.1 Forward-Active Mode 502**12.2.2 Other Modes of Operation 508***12.3 Transistor Currents and Low-Frequency****Common-Base Current Gain 509***12.3.1 Current Gain—Contributing Factors 509**12.3.2 Derivation of Transistor Current Components and Current Gain Factors 512*

12.3.3	Summary	517		
12.3.4	Example Calculations of the Gain Factors	517		
12.4	Nonideal Effects	522		
12.4.1	Base Width Modulation	522		
12.4.2	High Injection	524		
12.4.3	Emitter Bandgap Narrowing	526		
12.4.4	Current Crowding	528		
*12.4.5	Nonuniform Base Doping	530		
12.4.6	Breakdown Voltage	531		
12.5	Equivalent Circuit Models	536		
*12.5.1	Ebers-Moll Model	537		
12.5.2	Gummel-Poon Model	540		
12.5.3	Hybrid-Pi Model	541		
12.6	Frequency Limitations	545		
12.6.1	Time-Delay Factors	545		
12.6.2	Transistor Cutoff Frequency	546		
12.7	Large-Signal Switching	549		
12.7.1	Switching Characteristics	549		
12.7.2	The Schottky-Clamped Transistor	551		
*12.8	Other Bipolar Transistor Structures	552		
12.8.1	Polysilicon Emitter BJT	552		
12.8.2	Silicon-Germanium Base Transistor	554		
12.8.3	Heterojunction Bipolar Transistors	556		
12.9	Summary	558		
	Problems	560		
CHAPTER 13				
The Junction Field-Effect Transistor 571				
13.0	Preview	571		
13.1	JFET Concepts	572		
13.1.1	Basic pn JFET Operation	572		
13.1.2	Basic MESFET Operation	576		
13.2	The Device Characteristics	578		
13.2.1	Internal Pinchoff Voltage, Pinchoff Voltage, and Drain-to-Source Saturation Voltage	578		
13.2.2	Ideal DC Current-Voltage Relationship—Depletion Mode JFET	582		
13.2.3	Transconductance	587		
13.2.4	The MESFET	588		
*13.3	Nonideal Effects	593		
13.3.1	Channel Length Modulation	594		
13.3.2	Velocity Saturation Effects	596		
13.3.3	Subthreshold and Gate Current Effects	596		
*13.4	Equivalent Circuit and Frequency Limitations	598		
13.4.1	Small-Signal Equivalent Circuit	598		
13.4.2	Frequency Limitation Factors and Cutoff Frequency	600		
*13.5	High Electron Mobility Transistor	602		
13.5.1	Quantum Well Structures	603		
13.5.2	Transistor Performance	604		
13.6	Summary	609		
	Problems	611		
PART III—Specialized Semiconductor Devices				
CHAPTER 14				
Optical Devices 618				
14.0	Preview	618		
14.1	Optical Absorption	619		
14.1.1	Photon Absorption Coefficient	619		
14.1.2	Electron-Hole Pair Generation Rate	622		
14.2	Solar Cells	624		
14.2.1	The pn Junction Solar Cell	624		
14.2.2	Conversion Efficiency and Solar Concentration	627		
14.2.3	Nonuniform Absorption Effects	628		
14.2.4	The Heterojunction Solar Cell	629		
14.2.5	Amorphous Silicon Solar Cells	630		
14.3	Photodetectors	633		
14.3.1	Photoconductor	633		
14.3.2	Photodiode	635		
14.3.3	PIN Photodiode	640		
14.3.4	Avalanche Photodiode	641		
14.3.5	Phototransistor	642		
14.4	Photoluminescence and Electroluminescence	643		
14.4.1	Basic Transitions	644		
14.4.2	Luminescence Efficiency	645		
14.4.3	Materials	646		
14.5	Light-Emitting Diodes	647		
14.5.1	Basic Principles	647		
14.5.2	Device Structures and Characteristics	648		
14.5.3	Efficiency and Power	650		
14.5.4	Applications	651		
14.6	Laser Diodes	652		
14.6.1	Basic Principles	652		
14.6.2	Device Structures and Characteristics	653		
14.6.3	Efficiency and Power	655		
14.6.4	Applications	656		
14.7	Solar Photovoltaic Cells	657		
14.7.1	Basic Principles	657		
14.7.2	Device Structures and Characteristics	658		
14.7.3	Efficiency and Power	660		
14.7.4	Applications	661		
CHAPTER 15				
Semiconductor Devices 662				
15.0	Preview	662		
15.1	Tunnel Diodes	663		
15.1.1	Basic Principles	663		
15.1.2	Device Structures and Characteristics	664		
15.2	Gunn Diodes	665		
15.2.1	Basic Principles	665		
15.2.2	Device Structures and Characteristics	666		
15.3	Impurity Semiconductors	667		
15.3.1	Basic Principles	667		
15.3.2	Device Structures and Characteristics	668		
15.4	Polar Semiconductors	669		
15.4.1	Basic Principles	669		
15.4.2	Device Structures and Characteristics	670		
15.5	Polymer Semiconductors	671		
15.5.1	Basic Principles	671		
15.5.2	Device Structures and Characteristics	672		
15.6	The Organic Light-Emitting Diode	673		
15.6.1	Basic Principles	673		
15.6.2	Device Structures and Characteristics	674		

- 14.5** Light Emitting Diodes 648
 14.5.1 *Generation of Light* 648
 14.5.2 *Internal Quantum Efficiency* 649
 14.5.3 *External Quantum Efficiency* 650
 14.5.4 *LED Devices* 652
14.6 Laser Diodes 654
 14.6.1 *Stimulated Emission and Population Inversion* 655
 14.6.2 *Optical Cavity* 657
 14.6.3 *Threshold Current* 658
 14.6.4 *Device Structures and Characteristics* 660
14.7 Summary 661
 Problems 664

CHAPTER 15

Semiconductor Microwave and Power Devices 670

- 15.0** Preview 670
15.1 Tunnel Diode 671
15.2 Gunn Diode 672
15.3 Impatt Diode 675
15.4 Power Bipolar Transistors 677
 15.4.1 *Vertical Power Transistor Structure* 677
 15.4.2 *Power Transistor Characteristics* 678
 15.4.3 *Darlington Pair Configuration* 682
15.5 Power MOSFETs 684
 15.5.1 *Power Transistor Structures* 684
 15.5.2 *Power MOSFET Characteristics* 685
 15.5.3 *Parasitic BJT* 689
15.6 The Thyristor 691
 15.6.1 *The Basic Characteristics* 691
 15.6.2 *Triggering the SCR* 694

- 15.6.3 *SCR Turn-Off* 697
 15.6.4 *Device Structures* 697

- 15.7** Summary 701
 Problems 703

APPENDIX A

- Selected List of Symbols** 707

APPENDIX B

- System of Units, Conversion Factors, and General Constants** 715

APPENDIX C

- The Periodic Table** 719

APPENDIX D

- Unit of Energy—The Electron Volt** 720

APPENDIX E

- “Derivation” of Schrodinger’s Wave Equation** 722

APPENDIX F

- Effective Mass Concepts** 724

APPENDIX G

- The Error Function** 729

APPENDIX H

- Answers to Selected Problems** 730

- Index** 738

Chapters 2 and 3 introduce quantum mechanics and the quantum theory of solids, which together provide the necessary basic physics. Chapters 4 through 6 cover the semiconductor material physics. Chapter 4 considers the physics of the semiconductor in thermal equilibrium, Chapter 5 treats the transport phenomena of the charge carriers in a semiconductor, and the nonequilibrium excess carrier characteristics are developed in Chapter 6. Understanding the behavior of excess carriers in a semiconductor is vital to the goal of understanding the device physics.

Part II consists of Chapters 7 through 13. Chapter 7 treats the electrostatics of the basic pn junction and Chapter 8 covers the current–voltage, including the dc and small-signal, characteristics of the pn junction diode. Metal–semiconductor junctions, both rectifying and ohmic, and semiconductor heterojunctions are considered in Chapter 9. The basic physics of the metal–oxide–semiconductor field-effect transistor (MOSFET) is developed in Chapters 10 with additional concepts presented in Chapter 11. Chapter 12 develops the theory of the bipolar transistor and Chapter 13 covers the junction field-effect transistor (JFET). Once the physics of the pn junction is developed, the chapters dealing with the three basic transistors may be covered in any order—these chapters are written so as not to depend on one another.

Part III consists of Chapters 14 and 15. Chapter 14 considers optical devices, such as the solar cell and light emitting diode. Finally, semiconductor microwave devices and semiconductor power devices are presented in Chapter 15.

Eight appendices are included at the end of the book. Appendix A contains a selected list of symbols. Notation may sometimes become confusing, so this appendix may aid in keeping track of all the symbols. Appendix B contains the system of units, conversion factors, and general constants used throughout the text. Appendix H lists answers to selected problems. Most students will find this appendix helpful.

USE OF THE BOOK

The text is intended for a one-semester course at the junior or senior level. As with most textbooks, there is more material than can be conveniently covered in one semester; this allows each instructor some flexibility in designing the course to his or her own specific needs. Two possible orders of presentation are discussed later in a separate section in this preface. However, the text is not an encyclopedia. Sections in each chapter that can be skipped without loss of continuity are identified by an asterisk in both the table of contents and in the chapter itself. These sections, although important to the development of semiconductor device physics, can be postponed to a later time.

The material in the text has been used extensively in a course that is required for junior-level electrical engineering students at the University of New Mexico. Slightly less than half of the semester is devoted to the first six chapters; the remainder of the semester is devoted to the pn junction, the metal–oxide–semiconductor field-effect transistor, and the bipolar transistor. A few other special topics may be briefly considered near the end of the semester.

As mentioned, although the MOS transistor is discussed prior to the bipolar transistor or junction field-effect transistor, each chapter dealing with the basic types of transistors is written to stand alone. Any one of the transistor types may be covered first.

NOTES TO THE READER

This book introduces the physics of semiconductor materials and devices. Although many electrical engineering students are more comfortable building electronic circuits or writing computer programs than studying the underlying principles of semiconductor devices, the material presented here is vital to an understanding of the limitations of electronic devices, such as the microprocessor.

Mathematics is used extensively throughout the book. This may at times seem tedious, but the end result is an understanding that will not otherwise occur. Although some of the mathematical models used to describe physical processes may seem abstract, they have withstood the test of time in their ability to describe and predict these physical processes.

The reader is encouraged to continually refer to the preview sections at the beginning of each chapter so that the objective of the chapter and the purpose of each topic can be kept in mind. This constant review is especially important in the first six chapters, dealing with the basic physics.

The reader must keep in mind that, although some sections may be skipped without loss of continuity, many instructors will choose to cover these topics. The fact that sections are marked with an asterisk does not minimize the importance of these subjects.

It is also important that the reader keep in mind that there may be questions still unanswered at the end of a course. Although the author dislikes the phrase, "it can be shown that . . ." there are some concepts used here that rely on derivations beyond the scope of the text. This book is intended as an introduction to the subject. Those questions remaining unanswered at the end of the course, the reader is encouraged to keep "in a desk drawer." Then, during the next course in this area of concentration, the reader can take out these questions and search for the answers.

ORDER OF PRESENTATION

Each instructor has a personal preference for the order in which the course material is presented. Listed below are two possible scenarios. The first case, called the MOSFET approach, covers the MOS transistor before the bipolar transistor. It may be noted that the MOSFET in Chapters 10 and 11 may be covered before the pn junction diode.

The second method of presentation listed, called the bipolar approach, is the classical approach. Covering the bipolar transistor immediately after discussing the pn junction diode is the traditional order of presentation. However, because the MOSFET is left until the end of the semester, time constraints may shortchange the amount of class time devoted to this important topic.

Unfortunately, because of time constraints, every topic in each chapter cannot be covered in a one-semester course. The remaining topics must be left for a second-semester course or for further study by the reader.

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MOSFET approach	
Chapter 1	Crystal structure
Chapters 2, 3	Selected topics from quantum mechanics and theory of solids
Chapter 4	Semiconductor physics
Chapter 5	Transport phenomena
Chapter 6	Selected topics from nonequilibrium characteristics
Chapter 7	The pn junction
Chapters 10, 11	The MOS transistor
Chapter 8	The pn junction diode
Chapter 9	A brief discussion of the Schottky diode
Chapter 12	The bipolar transistor
	Other selected topics
Bipolar approach	
Chapter 1	Crystal structure
Chapters 2, 3	Selected topics from quantum mechanics and theory of solids
Chapter 4	Semiconductor physics
Chapter 5	Transport phenomena
Chapter 6	Selected topics from nonequilibrium characteristics
Chapters 7, 8	The pn junction and pn junction diode
Chapter 9	A brief discussion of the Schottky diode
Chapter 12	The bipolar transistor
Chapters 10, 11	The MOS transistor
	Other selected topics

NEW TO THE FOURTH EDITION

Order of Presentation: The two chapters dealing with MOSFETs were moved ahead of the chapter on bipolar transistors. This change emphasizes the importance of the MOS transistor.

Semiconductor Microwave Devices: A short section was added in Chapter 15 covering three specialized semiconductor microwave devices.

New Appendix: A new Appendix F has been added dealing with effective mass concepts. Two effective masses are used in various calculations in the text. This appendix develops the theory behind each effective mass and discusses when to use each effective mass in a particular calculation.

Preview Sections: Each chapter begins with a brief introduction, which then leads to a preview section given in bullet form. Each preview item presents a particular objective for the chapter.

Exercise Problems: Over 100 new Exercise Problems have been added. An Exercise Problem now follows each example. The exercise is very similar to the worked example so that readers can immediately test their understanding of the material just covered. Answers are given to each exercise problem.

Test Your Understanding: Approximately 40 percent new Test Your Understanding problems are included at the end of many of the major sections of the chapter. These exercise problems are, in general, more comprehensive than those presented at the end of each example. These problems will also reinforce readers' grasp of the material before they move on to the next section.

End-of-Chapter Problems: There are 330 new end-of-chapter problems, which means that approximately 48 percent of the problems are new to this edition.

RETAINED FEATURES OF THE TEXT

- **Mathematical Rigor:** The mathematical rigor necessary to more clearly understand the basic semiconductor material and device physics has been maintained.
- **Examples:** An extensive number of worked examples are used throughout the text to reinforce the theoretical concepts being developed. These examples contain all the details of the analysis or design, so the reader does not have to fill in missing steps.
- **Summary section:** A summary section, in bullet form, follows the text of each chapter. This section summarizes the overall results derived in the chapter and reviews the basic concepts developed.
- **Glossary of important terms:** A glossary of important terms follows the Summary section of each chapter. This section defines and summarizes the most important terms discussed in the chapter.
- **Checkpoint:** A checkpoint section follows the Glossary section. This section states the goals that should have been met and the abilities the reader should have gained. The Checkpoints will help assess progress before moving on to the next chapter.
- **Review questions:** A list of review questions is included at the end of each chapter. These questions serve as a self-test to help the reader determine how well the concepts developed in the chapter have been mastered.
- **End-of-chapter problems:** A large number of problems are given at the end of each chapter, organized according to the subject of each section in the chapter.
- **Summary and Review Problems:** A few problems, in a Summary and Review section, are open-ended design problems and are given at the end of most chapters.
- **Reading list:** A reading list finishes up each chapter. The references, which are at an advanced level compared with that of this text, are indicated by an asterisk.
- **Answers to selected problems:** Answers to selected problems are given in the last appendix. Knowing the answer to a problem is an aid and a reinforcement in problem solving.

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ONLINE RESOURCES

A website to accompany this text is available at www.mhhe.com/ncamen. The site includes the solutions manual as well as an image library for instructors. Instructors can also obtain access to C.O.S.M.O.S. for the fourth edition. C.O.S.M.O.S. is a Complete Online Solutions Manual Organization System instructors can use to create exams and assignments, create custom content, and edit supplied problems and solutions.

ACKNOWLEDGMENTS

I am indebted to the many students I have had over the years who have helped in the evolution of this fourth edition as well as to the previous editions of this text. I am grateful for their enthusiasm and constructive criticism.

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REVIEWERS FOR THE FOURTH EDITION

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 Michael Stroschio, *University of Illinois-Chicago*
 Andrei Sazonov, *University of Waterloo*

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Semiconductors and the Integrated Circuit

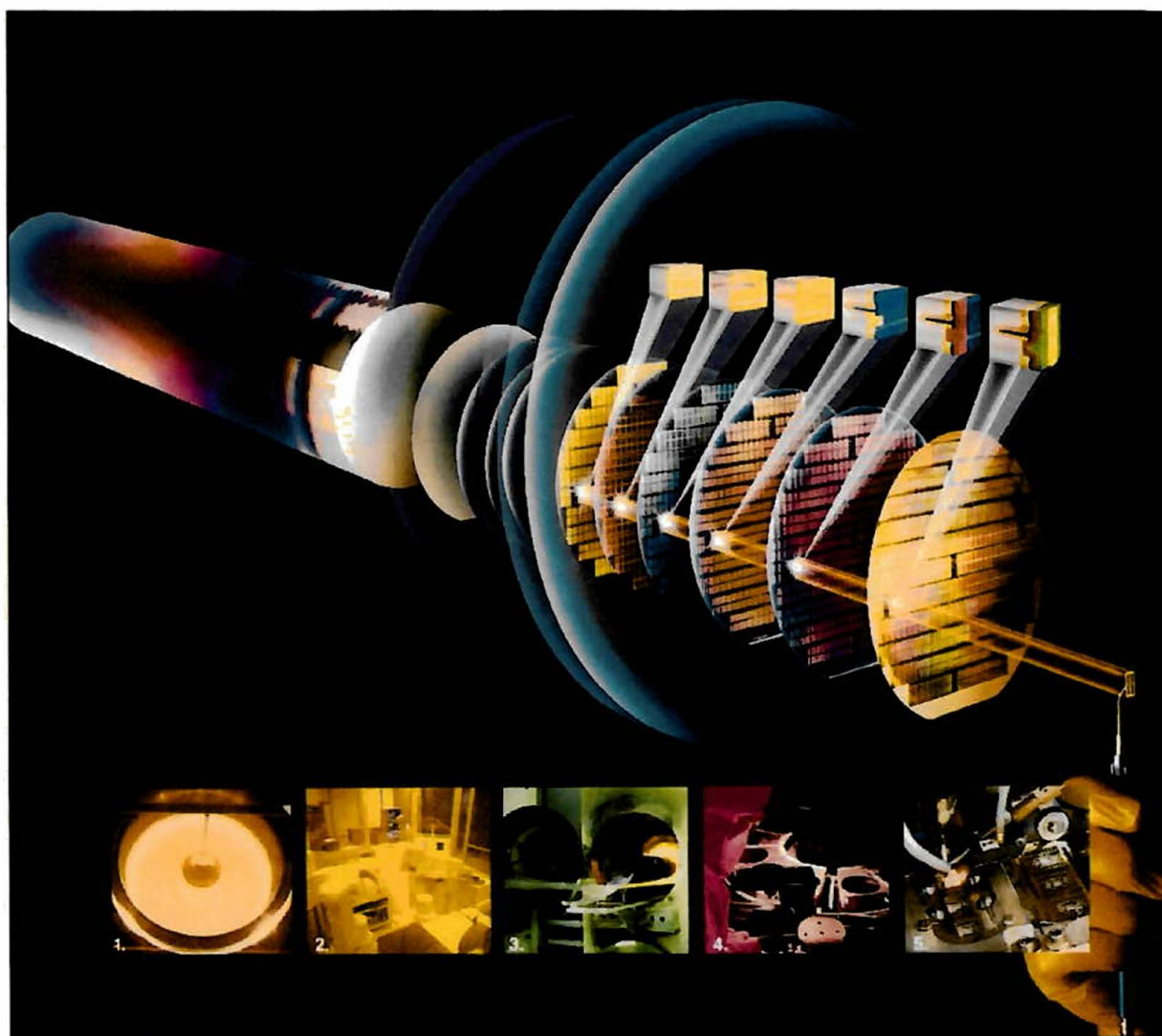
PREVIEW

We often hear that we are living in the information age. Large amounts of information can be obtained via the Internet, for example, and can be obtained very quickly over long distances via satellite communications systems. The information technologies are based upon digital and analog electronic systems, with the transistor and integrated circuit (IC) being the foundation of these remarkable capabilities. Wireless communication systems, including printers, faxes, laptop computers, ipods, and of course the cell phones are big users of today's IC products. The cell phone is not just a telephone any longer, but includes e-mail services and video cameras, for example. Today, a relatively small laptop computer has more computing capability than the equipment used to send a man to the moon a few decades ago. The semiconductor electronics field continues to be a fast-changing one, with thousands of technical papers published and many new electronic devices developed each year. ■

HISTORY

The semiconductor device has a fairly long history, although the greatest explosion of IC technology has occurred during the last two or three decades.¹ The metal-semiconductor contact dates back to the early work of Braun in 1874, who discovered the asymmetric nature of electrical conduction between metal contacts and semiconductors, such as copper, iron, and lead sulfide. These devices were used as detectors in early experiments on radio. In 1906, Pickard took out a patent for a point contact

¹This brief introduction is intended to give a flavor of the history of the semiconductor device and integrated circuit. Thousands of engineers and scientists have made significant contributions to the development of semiconductor electronics—the few events and names mentioned here are not meant to imply that these are the only significant events or people involved in the semiconductor history.



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detector using silicon and, in 1907, Pierce published rectification characteristics of diodes made by sputtering metals onto a variety of semiconductors.

By 1935, selenium rectifiers and silicon point contact diodes were available for use as radio detectors. A significant advance in our understanding of the metal-semiconductor contact was aided by developments in semiconductor physics. In 1942, Bethe developed the thermionic-emission theory, according to which the current is determined by the process of emission of electrons into the metal rather than by drift or diffusion. With the development of radar, the need for better and more reliable detector diodes and mixers increased. Methods of achieving high-purity silicon and germanium were developed during this time and germanium diodes became a key component in radar systems during the Second World War.

Another big breakthrough came in December 1947 when the first transistor was constructed and tested at Bell Telephone Laboratories by William Shockley, John Bardeen, and Walter Brattain. This first transistor was a point contact device and used polycrystalline germanium. The transistor effect was soon demonstrated in silicon as well. A significant improvement occurred at the end of 1949 when single-crystal material was used rather than the polycrystalline material. The single crystal yields uniform and improved properties throughout the whole semiconductor material.

The next significant step in the development of the transistor was the use of the diffusion process to form the necessary junctions. This process allowed better control of the transistor characteristics and yielded higher-frequency devices. The diffused mesa transistor was commercially available in germanium in 1957 and in silicon in 1958. The diffusion process also allowed many transistors to be fabricated on a single silicon slice, so the cost of these devices decreased.

THE INTEGRATED CIRCUIT (IC)

The transistor led to a revolution in electronics since it is smaller and more reliable than vacuum tubes used previously. The circuits at that time were discrete in that each element had to be individually connected by wires to form the circuit. The integrated circuit has led to a new revolution in electronics that was not possible with discrete devices. Integration means that complex circuits, consisting of millions of devices, can be fabricated on a single chip of semiconductor material.

The first IC was fabricated in February of 1959 by Jack Kilby of Texas Instruments. In July 1959, a planar version of the IC was independently developed by Robert Noyce of Fairchild. The first integrated circuits incorporated bipolar transistors. Practical MOS transistors were then developed in the mid-1960s and 1970s. The MOS technologies, especially CMOS, have become a major focus for IC design and development. Silicon is the main semiconductor material, while gallium arsenide and other compound semiconductor materials are used for optical devices and for special applications requiring very high frequency devices.

Since the first IC, very sophisticated and complex circuits have been designed and fabricated. A single silicon chip may be on the order of 1 square centimeter and some ICs may have more than a hundred terminals. An IC can contain the arithmetic, logic, and memory functions on a single chip—the primary example of this type of IC



is the microprocessor. Integration means that circuits can be miniaturized for use in satellites and laptop computers where size, weight, and power are critical parameters.

An important advantage of ICs is the result of devices being fabricated very close to each other. The time delay of signals between devices is short so that high-frequency and high-speed circuits are now possible with ICs that were not practical with discrete circuits. In high-speed computers, for example, the logic and memory circuits can be placed very close to each other to minimize time delays. In addition, parasitic capacitance and inductance between devices are reduced which also provides improvement in the speed of the system.

Intense research on silicon processing and increased automation in design and manufacturing have led to lower costs, higher fabrication yields, and greater reliability of integrated circuits.

FABRICATION

The integrated circuit is a direct result of the development of various processing techniques needed to fabricate the transistor and interconnect lines on the single chip. The total collection of these processes for making an IC is called a *technology*. The following few paragraphs provide an introduction to a few of these processes. This introduction is intended to provide the reader with some of the basic terminology used in processing.

Thermal Oxidation A major reason for the success of silicon ICs is the fact that an excellent native oxide, SiO_2 , can be formed on the surface of silicon. This oxide is used as a gate insulator in the MOSFET and is also used as an insulator, known as the field oxide, between devices. Metal interconnect lines that connect various devices can be placed on top of the field oxide. Most other semiconductors do not form native oxides that are of sufficient quality to be used in device fabrication.

Silicon will oxidize at room temperature in air forming a thin native oxide of approximately 25 Å thick. However, most oxidations are done at elevated temperatures since the basic process requires that oxygen diffuse through the existing oxide to the silicon surface where a reaction can occur. A schematic of the oxidation process is shown in Figure 0.1. Oxygen diffuses across a stagnant gas layer directly adjacent

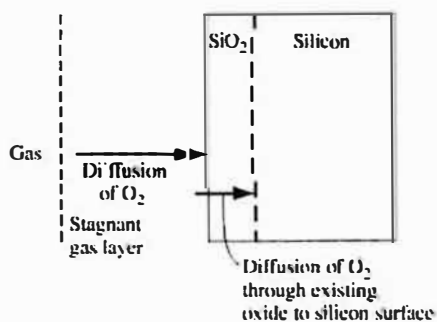


Figure 0.1 | Schematic of the oxidation process.

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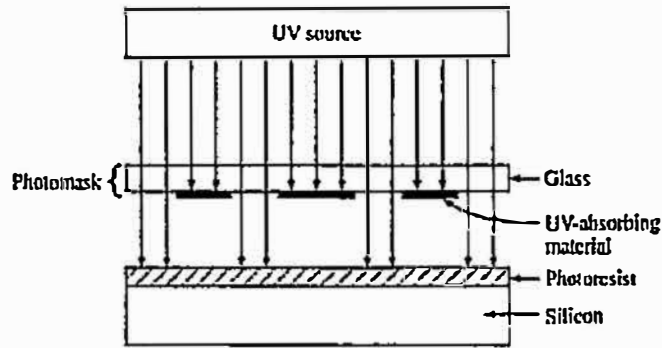


Figure 0.2 | Schematic showing the use of a photomask.

to the oxide surface and then diffuses through the existing oxide layer to the silicon surface where the reaction between O_2 and Si forms SiO_2 . Because of this reaction, silicon is actually consumed from the surface of the silicon. The amount of silicon consumed is approximately 44 percent of the thickness of the final oxide.

Photomasks and Photolithography The actual circuitry on each chip is created through the use of photomasks and photolithography. The photomask is a physical representation of a device or a portion of a device. Opaque regions on the mask are made of an ultraviolet-light-absorbing material. A photosensitive layer, called photoresist, is first spread over the surface of the semiconductor. The photoresist is an organic polymer that undergoes chemical change when exposed to ultraviolet light. The photoresist is exposed to ultraviolet light through the photomask as indicated in Figure 0.2. The photoresist is then developed in a chemical solution. The developer is used to remove the unwanted portions of the photoresist and generate the appropriate patterns on the silicon. The photomasks and photolithography process is critical in that it determines how small the devices can be made. Instead of using ultraviolet light, electrons and x-rays can also be used to expose the photoresist.

Etching After the photoresist pattern is formed, the remaining photoresist can be used as a mask, so that the material not covered by the photoresist can be etched. Plasma etching is now the standard process used in IC fabrication. Typically, an etch gas such as chlorofluorocarbons is injected into a low-pressure chamber. A plasma is created by applying a radio-frequency voltage between cathode and anode terminals. The silicon wafer is placed on the cathode. Positively charged ions in the plasma are accelerated toward the cathode and bombard the wafer normal to the surface. The actual chemical and physical reaction at the surface is complex, but the net result is that silicon can be etched anisotropically in very selected regions of the wafer. If photoresist is applied on the surface of silicon dioxide, then the silicon dioxide can also be etched in a similar way.

Diffusion A thermal process that is used extensively in IC fabrication is diffusion. Diffusion is the process by which specific types of "impurity" atoms can be introduced into the silicon material. This doping process changes the conductivity type of the silicon so that pn junctions can be formed. (The pn junction is a basic building block of semiconductor devices.) Silicon wafers are oxidized to form a layer of

silicon dioxide, and windows are opened in the oxide in selected areas using photolithography and etching as just described.

The wafers are then placed in a high-temperature furnace (about 1100°C) and dopant atoms such as boron or phosphorus are introduced. The dopant atoms gradually diffuse or move into the silicon due to a density gradient. Since the diffusion process requires a gradient in the concentration of atoms, the final concentration of diffused atoms is nonlinear, as shown in Figure 0.3. When the wafer is removed from the furnace and the wafer temperature returns to room temperature, the diffusion coefficient of the dopant atoms is essentially zero so that the dopant atoms are then fixed in the silicon material.

Ion Implantation A fabrication process that is an alternative to high-temperature diffusion is ion implantation. A beam of dopant ions is accelerated to a high energy and is directed at the surface of a semiconductor. As the ions enter the silicon, they collide with silicon atoms and lose energy and finally come to rest at some depth within the crystal. Since the collision process is statistical in nature, there is a distribution in the depth of penetration of the dopant ions. Figure 0.4 shows such an example of the implantation of boron into silicon at a particular energy.

Two advantages of the ion implantation process compared to diffusion are (1) the ion implantation process is a low-temperature process and (2) very well

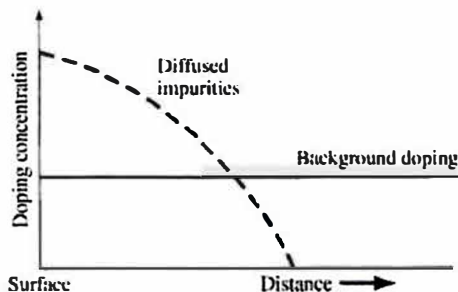


Figure 0.3 | Final concentration of diffused impurities into the surface of a semiconductor.

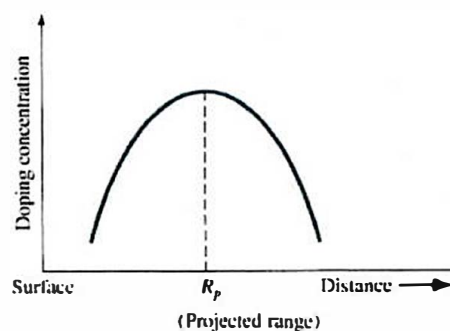


Figure 0.4 | Final concentration of ion-implanted boron into silicon.

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defined doping layers can be achieved. Photoresist layers or layers of oxide can be used to block the penetration of dopant atoms so that ion implantation can occur in very selected regions of the silicon.

One disadvantage of ion implantation is that the silicon crystal is damaged by the penetrating dopant atoms because of collisions between the incident dopant atoms and the host silicon atoms. However, most of the damage can be removed by thermal annealing the silicon at an elevated temperature. The thermal annealing temperature, however, is normally much less than the diffusion process temperature.

Metallization, Bonding, and Packaging After the semiconductor devices have been fabricated by the processing steps discussed, they need to be connected to each other to form the circuit. Metal films are generally deposited by a vapor deposition technique, and the actual interconnect lines are formed using photolithography and etching. In general, a protective layer of silicon nitride is finally deposited over the entire chip.

The individual integrated circuit chips are separated by scribing and breaking the wafer. The integrated circuit chip is then mounted in a package. Lead bonders are finally used to attach gold or aluminum wires between the chip and package terminals.

Summary: Simplified Fabrication of a pn Junction Figure 0.5 shows the basic steps in forming a pn junction. These steps involve some of the processing described in the previous paragraphs.

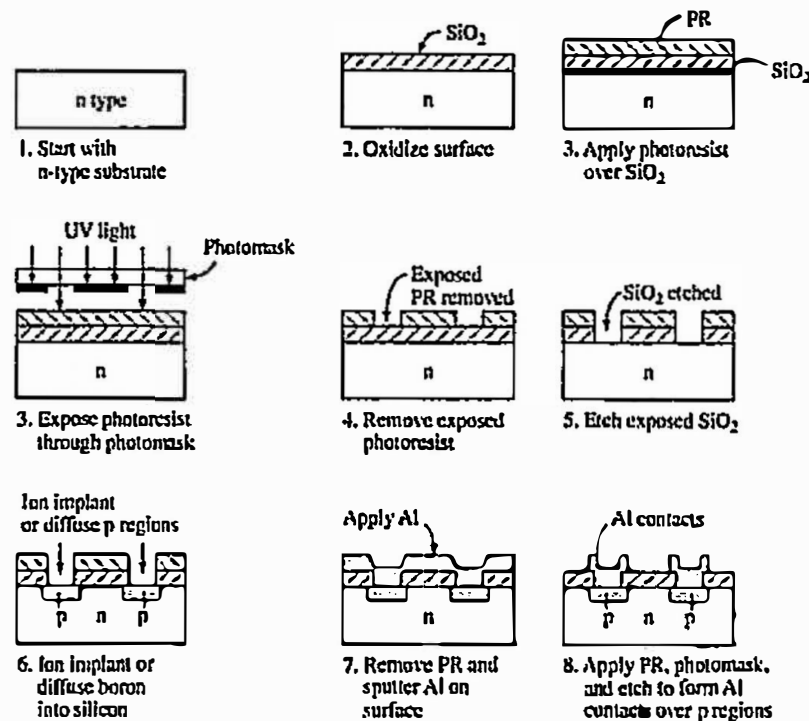


Figure 0.5 | The basic steps in forming a pn junction.

READING LIST

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