

# Semiconductor Physical Electronics

Sheng S. Li

*Department of Electrical Engineering  
University of Florida  
Gainesville, Florida*

Plenum Press • New York and London

# Contents

## CHAPTER 1. Classification of Solids and Crystal Structure

1.1. Introduction .....	1
1.2. The Bravais Lattice .....	2
1.3. The Crystal Structure .....	5
1.4. Miller Indices and the Unit Cell .....	6
1.5. The Reciprocal Lattice and Brillouin Zone .....	8
1.6. Types of Crystal Bindings .....	11
1.7. Defects in a Crystalline Solid .....	13
1.7.1. Vacancies and Interstitials .....	13
1.7.2. Line and Surface Defects .....	16
Problems .....	18
Bibliography .....	18

## CHAPTER 2. Lattice Dynamics

2.1. Introduction .....	21
2.2. The One-Dimensional Linear Chain .....	22
2.3. Dispersion Relation for a Three-Dimensional Lattice .....	27
2.4. Concept of Phonons .....	29
2.5. The Density of States and Lattice Spectrum .....	30
2.6. Lattice Specific Heat .....	32
2.7. Elastic Constants and Velocity of Sound .....	35
Problems .....	37
References .....	39
Bibliography .....	39

## CHAPTER 3. Semiconductor Statistics

3.1. Introduction .....	41
3.2. Maxwell-Boltzmann (M-B) Statistics .....	42
3.3. Fermi-Dirac (F-D) Statistics .....	45

3.4. Bose–Einstein (B–E) Statistics .....	50
3.5. Statistics in the Shallow-Impurity States .....	52
Problems .....	53
Bibliography .....	54

## CHAPTER 4. Energy Band Theory

4.1. Introduction .....	55
4.2. The Bloch–Floquet Theorem .....	56
4.3. The Kronig–Penney Model .....	57
4.4. The Nearly-Free Electron Approximation .....	62
4.5. The Tight-Binding (LCAO) Approximation .....	68
4.5.1. The Simple Cubic Lattice .....	71
4.5.2. The Body-Centered Cubic Lattice (the <i>s</i> -like states) .....	72
4.6. Energy Band Structures for Semiconductors .....	73
4.7. The Effective Mass Concept .....	78
4.8. Energy Band Structure and Density of States in a Superlattice .....	80
Problems .....	83
References .....	85
Bibliography .....	85

## CHAPTER 5. Equilibrium Properties of Semiconductors

5.1. Introduction .....	87
5.2. Densities of Electrons and Holes in a Semiconductor .....	88
5.3. Intrinsic Semiconductors .....	94
5.4. Extrinsic Semiconductors .....	96
5.5. Ionization Energy of a Shallow Impurity Level .....	102
5.6. Hall Effect, Hall Mobility, and Electrical Conductivity .....	104
5.7. Heavy Doping Effects in a Degenerate Semiconductor .....	107
Problems .....	109
Reference .....	111
Bibliography .....	111

## CHAPTER 6. Excess Carrier Phenomenon in Semiconductors

6.1. Introduction .....	113
6.2. Nonradiative Recombination: Shockley–Read–Hall Model .....	114
6.3. Band-to-Band Radiative Recombination .....	118
6.4. Band-to-Band Auger Recombination .....	121
6.5. Basic Semiconductor Equations .....	124
6.6. Charge-Neutrality Conditions .....	126
6.7. The Haynes–Shockley Experiment .....	128
6.8. Minority Carrier Lifetimes and Photoconductivity Experiment .....	130
6.9. Surface States and Surface Recombination Velocity .....	135
6.10. Deep-Level Transient Spectroscopy (DLTS) Technique .....	138

6.11. Surface Photovoltage (SPV) Technique .....	141
Problems .....	143
References .....	145
Bibliography .....	145

## CHAPTER 7. Transport Properties of Semiconductors

7.1. Introduction .....	147
7.2. Galvanomagnetic, Thermoelectric, and Thermomagnetic Effects .....	149
7.2.1. Electrical Conductivity $\sigma_n$ .....	149
7.2.2. Electronic Thermal Conductivity $K_n$ .....	151
7.2.3. Thermoelectric Coefficients .....	152
7.2.4. Galvanomagnetic and Thermomagnetic Coefficients .....	153
7.3. Boltzmann Transport Equation .....	155
7.4. Derivation of Transport Coefficients .....	156
7.4.1. Electrical Conductivity $\sigma_n$ .....	158
7.4.2. Hall Coefficient $R_H$ .....	161
7.4.3. Seebeck Coefficient $S_n$ .....	164
7.4.4. Nernst Coefficient $Q_n$ .....	164
7.4.5. Transverse Magnetoresistance .....	165
7.5. Transport Coefficients for the Mixed Conduction Case .....	169
7.5.1. Electrical Conductivity $\sigma$ .....	169
7.5.2. Hall Coefficient $R_H$ .....	169
7.5.3. Seebeck Coefficient $S$ .....	170
7.5.4. Nernst Coefficient $Q$ .....	171
7.6. Transport Coefficients for Some Semiconductors .....	171
Problems .....	179
References .....	181
Bibliography .....	181

## CHAPTER 8. Scattering Mechanisms and Carrier Mobilities in Semiconductors

8.1. Introduction .....	183
8.2. Differential Scattering Cross Section .....	186
8.3. Ionized Impurity Scattering .....	189
8.4. Neutral Impurity Scattering .....	192
8.5. Acoustic Phonon Scattering .....	193
8.5.1. Deformation Potential Scattering .....	194
8.5.2. Piezoelectric Scattering .....	196
8.6. Optical Phonon Scattering .....	198
8.7. Scattering by Dislocations .....	200
8.8. Electron and Hole Mobilities in Semiconductors .....	201
8.9. Hot Electron Effects in a Semiconductor .....	204
Problems .....	209
References .....	210
Bibliography .....	211

**CHAPTER 9. Optical Properties and Photoelectric Effects**

9.1. Optical Constants of a Solid .....	214
9.2. Free-Carrier Absorption Process .....	219
9.3. Fundamental Absorption Process .....	222
9.3.1. Direct Transition Process .....	224
9.3.2. Indirect Transition Process .....	225
9.4. The Photoconductive Effect .....	228
9.4.1. Kinetics of Photoconduction .....	235
9.4.2. Practical Applications of Photoconductivity .....	237
9.5. The Photovoltaic (Dember) Effect .....	238
9.6. The Photomagnetolectric Effect .....	240
Problems .....	244
References .....	245
Bibliography .....	245

**CHAPTER 10. Metal-Semiconductor Contacts**

10.1. Introduction .....	247
10.2. Metal Work Function and Schottky Effect .....	248
10.3. Thermionic Emission Theory .....	249
10.4. Ideal Schottky Barrier Contact .....	252
10.5. Current Flow in a Schottky Barrier Diode .....	256
10.5.1. Thermionic Emission Model .....	257
10.5.2. Image Lowering Effect .....	258
10.5.3. The Diffusion Model .....	259
10.6. I-V Characteristics of a Silicon and a GaAs Schottky Diode .....	261
10.7. Determination of Barrier Height .....	264
10.8. Enhancement of Effective Barrier Height .....	269
10.9. Applications of Schottky Diodes .....	275
10.9.1. Photodetectors and Solar Cells .....	275
10.9.2. Schottky-Clamped Transistors .....	277
10.9.3. Microwave Mixers .....	278
10.10. Ohmic Contacts .....	279
Problems .....	284
References .....	285
Bibliography .....	285

**CHAPTER 11. p-n Junction Diodes**

11.1. Introduction .....	287
11.2. Equilibrium Properties of a p-n Junction Diode .....	287
11.3. p-n Junction Under Bias Conditions .....	293
11.4. Minority Carrier Distribution and Current Flow .....	296
11.5. Diffusion Capacitance and Conductance .....	301
11.6. Minority Carrier Storage and Transient Behavior .....	304
11.7. Zener and Avalanche Breakdowns .....	307
11.8. Tunnel Diode .....	312
11.9. p-n Heterojunction Diodes .....	314

11.10. Junction Field-Effect Transistors .....	318
Problems .....	324
References .....	325
Bibliography .....	326

## CHAPTER 12. Photonic Devices

12.1. Introduction .....	327
12.2. Photovoltaic Devices .....	328
12.2.1. p-n Junction Solar Cells .....	329
12.2.2. Schottky Barrier and MIS Solar Cells .....	338
12.2.3. Heterojunction Solar Cells .....	341
12.2.4. Thin Film Solar Cells .....	343
12.3. Photodetectors .....	344
12.3.1. p-n Junction Photodiodes .....	348
12.3.2. p-i-n Photodiodes .....	349
12.3.3. Avalanche Photodiodes .....	353
12.3.4. Schottky Barrier Photodiodes .....	357
12.3.5. Point-Contact Photodiodes .....	358
12.3.6. Heterojunction Photodiodes .....	358
12.3.7. Photomultipliers .....	359
12.3.8. Long-Wavelength Infrared Detectors .....	360
12.4. Light-Emitting Diodes (LEDs) .....	363
12.4.1. Injection Mechanisms .....	364
12.4.2. Electronic Transitions .....	365
12.4.3. Luminescent Efficiency and Injection Efficiency .....	365
12.4.4. Application of LEDs .....	370
12.5. Semiconductor Laser Diodes .....	375
12.5.1. Population Inversion .....	375
12.5.2. Oscillation Conditions .....	377
12.5.3. Threshold Current Density .....	378
12.5.4. GaAs Laser Diodes .....	380
12.5.5. Semiconductor Laser Materials .....	384
12.5.6. Applications of Lasers .....	386
Problems .....	387
References .....	388
Bibliography .....	389

## CHAPTER 13. Bipolar Junction Transistor

13.1. Introduction .....	391
13.2. Basic Structures and Modes of Operation .....	392
13.3. Current-Voltage Characteristics .....	393
13.4. Current Gain, Base Transport Factor, and Emitter Injection Efficiency .....	401
13.5. Modeling of a Bipolar Junction Transistor .....	404
13.6. Switching Transistor .....	409
13.7. Advanced Bipolar Transistor .....	414

13.8. Thyristors .....	415
Problems .....	420
References .....	421
Bibliography .....	422

## CHAPTER 14. Metal–Oxide–Semiconductor Field-Effect Transistors

14.1. Introduction .....	423
14.2. An Ideal Metal–Oxide–Semiconductor System .....	423
14.2.1. Surface Space-Charge Region .....	426
14.2.2. Capacitance–Voltage Characteristics .....	427
14.3. Oxide Charges and Interface Traps .....	430
14.3.1. Interface Trap Charges .....	431
14.3.2. Oxide Charges .....	433
14.4. The MOS Field-Effect Transistors .....	435
14.4.1. General Characteristics of a MOSFET .....	436
14.4.2. Channel Conductance .....	437
14.4.3. Current–Voltage Characteristics .....	439
14.4.4. Small-Signal Equivalent Circuit .....	442
14.4.5. Scaled-Down MOSFETs .....	444
14.5. Charge-Coupled Devices .....	446
14.5.1. Charge Storage and Transfer .....	447
14.5.2. Charge Injection and Detection .....	450
14.5.3. Buried-Channel CCDs .....	451
Problems .....	452
References .....	453
Bibliography .....	453

## CHAPTER 15. High-Speed III–V Semiconductor Devices

15.1. Introduction .....	455
15.2. Metal–Semiconductor Field-Effect Transistors .....	456
15.2.1. Basic Device Structure and Characteristics .....	456
15.2.2. Current–Voltage Characteristics .....	460
15.2.3. Small-Signal Device Parameters .....	463
15.2.4. Second-Order Effects in a GaAs MESFET .....	467
15.3. Modulation-Doped Field-Effect Transistors (MODFETs) .....	468
15.3.1. Equilibrium Properties of the 2-DEG in GaAs .....	470
15.3.2. 2-DEG Charge Control Regime .....	474
15.3.3. Current–Voltage Characteristics .....	475
15.4. Heterojunction Bipolar Transistor .....	481
15.4.1. Device Structure and Fabrication Technology .....	481
15.4.2. Current Gain and Device Parameters .....	483
15.4.3. Current–Voltage Characteristics .....	485
15.4.4. High-Frequency Performance .....	486
15.5. Hot Electron Transistors .....	490
15.6. Resonant Tunneling Devices .....	493

CONTENTS

xiii

15.7. Transferred-Electron Devices .....	495
Problems .....	499
References .....	501
Bibliography .....	501
<b>Index</b> .....	<b>503</b>