

Contents

Preface	xiii
Chapter 1. Introduction	1
1.1 Basic Concepts of Semiconductor Band and Bonding Diagrams	1
1.2 The Invention of Semiconductor Lasers	4
1.3 The Field of Optoelectronics	8
1.4 Overview of the Book	15
Problems	19
References	19
Bibliography	21
PART I FUNDAMENTALS	25
Chapter 2. Basic Semiconductor Electronics	27
2.1 Maxwell's Equations and Boundary Conditions	27
2.2 Semiconductor Electronics Equations	30
2.3 Generation and Recombination in Semiconductors	40
2.4 Examples and Applications to Optoelectronic Devices	48
2.5 Semiconductor p - N and n - P Heterojunctions	53
2.6 Semiconductor n - N Heterojunctions and Metal–Semiconductor Junctions	69
Problems	73
References	74
Chapter 3. Basic Quantum Mechanics	77
3.1 Schrödinger Equation	78
3.2 The Square Well	80
3.3 The Harmonic Oscillator	90
3.4 The Hydrogen Atom and Exciton in 2D and 3D	95
3.5 Time-Independent Perturbation Theory	97
3.6 Time-Dependent Perturbation Theory	104
Appendix 3A: Löwdin's Renormalization Method	107
Problems	110
References	111

Chapter 4. Theory of Electronic Band Structures in Semiconductors	113
4.1 The Bloch Theorem and the $\mathbf{k} \cdot \mathbf{p}$ Method for Simple Bands	113
4.2 Kane's Model for Band Structure: The $\mathbf{k} \cdot \mathbf{p}$ Method with the Spin–Orbit Interaction	118
4.3 Luttinger–Kohn Model: The $\mathbf{k} \cdot \mathbf{p}$ Method for Degenerate Bands	126
4.4 The Effective Mass Theory for a Single Band and Degenerate Bands	130
4.5 Strain Effects on Band Structures	132
4.6 Electronic States in an Arbitrary One-Dimensional Potential	144
4.7 Kronig–Penney Model for a Superlattice	152
4.8 Band Structures of Semiconductor Quantum Wells	158
4.9 Band Structures of Strained Semiconductor Quantum Wells	168
Problems	172
References	174
PART II PROPAGATION OF LIGHT	179
Chapter 5. Electromagnetics and Light Propagation	181
5.1 Time–Harmonic Fields and Duality Principle	181
5.2 Poynting's Theorem and Reciprocity Relations	183
5.3 Plane Wave Solutions for Maxwell's Equations in Homogeneous Media	186
5.4 Light Propagation in Isotropic Media	186
5.5 Wave Propagation in Lossy Media: Lorentz Oscillator Model and Metal Plasma	189
5.6 Plane Wave Reflection from a Surface	197
5.7 Matrix Optics	202
5.8 Propagation Matrix Approach for Plane Wave Reflection from a Multilayered Medium	206
5.9 Wave Propagation in Periodic Media	210
Appendix 5A: Kramers–Kronig Relations	220
Problems	223
References	224
Chapter 6. Light Propagation in Anisotropic Media and Radiation	227
6.1 Light Propagation in Uniaxial Media	227
6.2 Wave Propagation in Gyrotropic Media: Magneto optic Effects	239

6.3	General Solutions to Maxwell's Equations and Gauge Transformations	246
6.4	Radiation and the Far-Field Pattern	249
	Problems	254
	References	256
Chapter 7.	Optical Waveguide Theory	257
7.1	Symmetric Dielectric Slab Waveguides	257
7.2	Asymmetric Dielectric Slab Waveguides	268
7.3	Ray Optics Approach to Waveguide Problems	271
7.4	Rectangular Dielectric Waveguides	273
7.5	The Effective Index Method	279
7.6	Wave Guidance in a Lossy or Gain Medium	281
7.7	Surface Plasmon Waveguides	285
	Problems	290
	References	293
Chapter 8.	Coupled-Mode Theory	295
8.1	Waveguide Couplers	295
8.2	Coupled Optical Waveguides	300
8.3	Applications of Optical Waveguide Couplers	307
8.4	Optical Ring Resonators and Add-Drop Filters	311
8.5	Distributed Feedback (DFB) Structures	322
	Appendix 8A: Coupling Coefficients for Parallel Waveguides	332
	Appendix 8B: Improved Coupled-Mode Theory	333
	Problems	334
	References	339
PART III	GENERATION OF LIGHT	345
Chapter 9.	Optical Processes in Semiconductors	347
9.1	Optical Transitions Using Fermi's Golden Rule	347
9.2	Spontaneous and Stimulated Emissions	353
9.3	Interband Absorption and Gain of Bulk Semiconductors	360
9.4	Interband Absorption and Gain in a Quantum Well	365
9.5	Interband Momentum Matrix Elements of Bulk and Quantum-Well Semiconductors	371
9.6	Quantum Dots and Quantum Wires	375
9.7	Intersubband Absorption	384
9.8	Gain Spectrum in a Quantum-Well Laser with Valence-Band Mixing Effects	391

Appendix 9A: Coordinate Transformation of the Basis Functions and the Momentum Matrix Elements	398
Problems	401
References	405
Chapter 10. Fundamentals of Semiconductor Lasers	411
10.1 Double-Heterojunction Semiconductor Lasers	412
10.2 Gain-Guided and Index-Guided Semiconductor Lasers	428
10.3 Quantum-Well Lasers	432
10.4 Strained Quantum-Well Lasers	446
10.5 Strained Quantum-Dot Lasers	457
Problems	472
References	474
Chapter 11. Advanced Semiconductor Lasers	487
11.1 Distributed Feedback Lasers	487
11.2 Vertical Cavity Surface-Emitting Lasers	502
11.3 Microcavity and Photonic Crystal Lasers	515
11.4 Quantum-Cascade Lasers	530
11.5 GaN-Based Blue–Green Lasers and LEDs	548
11.6 Coupled Laser Arrays	571
Appendix 11A: Hamiltonian for Strained Wurtzite Crystals	578
Appendix 11B: Band-Edge Optical Transition Matrix Elements	581
Problems	583
References	584
PART IV MODULATION OF LIGHT	603
Chapter 12. Direct Modulation of Semiconductor Lasers	605
12.1 Rate Equations and Linear Gain Analysis	605
12.2 High-Speed Modulation Response with Nonlinear Gain Saturation	611
12.3 Transport Effects on Quantum-Well Lasers: Electrical versus Optical Modulation	614
12.4 Semiconductor Laser Spectral Linewidth and the Linewidth Enhancement Factor	622
12.5 Relative Intensity Noise Spectrum	629
Problems	632
References	632
Chapter 13. Electrooptic and Acousto-optic Modulators	639
13.1 Electrooptic Effects and Amplitude Modulators	639
13.2 Phase Modulators	648

13.3	Electrooptic Effects in Waveguide Devices	652
13.4	Scattering of Light by Sound: Raman–Nath and Bragg Diffractions	658
13.5	Coupled-Mode Analysis for Bragg Acousto-optic Wave Couplers	661
	Problems	664
	References	666
Chapter 14. Electroabsorption Modulators		669
14.1	General Formulation for Optical Absorption Due to an Electron–Hole Pair	670
14.2	Franz–Keldysh Effect: Photon-Assisted Tunneling	673
14.3	Exciton Effect	677
14.4	Quantum Confined Stark Effect (QCSE)	683
14.5	Electroabsorption Modulator	691
14.6	Integrated Electroabsorption Modulator-Laser (EML)	693
14.7	Self-Electrooptic Effect Devices (SEEDs)	702
	Appendix 14A: Two-Particle Wave Function and the Effective Mass Equation	705
	Appendix 14B: Solution of the Electron–Hole Effective-Mass Equation with Excitonic Effects	709
	Problems	714
	References	714
PART V DETECTION OF LIGHT AND SOLAR CELLS		721
Chapter 15. Photodetectors and Solar Cells		723
15.1	Photoconductors	723
15.2	<i>p-n</i> Junction Photodiodes	734
15.3	<i>p-i-n</i> Photodiodes	740
15.4	Avalanche Photodiodes	744
15.5	Intersubband Quantum-Well Photodetectors	756
15.6	Solar Cells	761
	Problems	776
	References	778
Appendix A. Semiconductor Heterojunction Band Lineups in the Model–Solid Theory		787
Appendix B. Optical Constants of GaAs and InP		797

Appendix C. Electronic Properties of Si, Ge, and a Few Binary, Ternary, and Quaternary Compounds	801
Appendix D. Parameters for InN, GaN, AlN, and Their Ternary Compounds	807
Index	811