

# Contents

## 1. Introduction

1.1	A Survey of Semiconductors .....	2
1.1.1	Elemental Semiconductors .....	2
1.1.2	Binary Compounds .....	2
1.1.3	Oxides .....	3
1.1.4	Layered Semiconductors .....	3
1.1.5	Organic Semiconductors .....	4
1.1.6	Magnetic Semiconductors .....	4
1.1.7	Other Miscellaneous Semiconductors .....	4
1.2	Growth Techniques .....	5
1.2.1	Czochralski Method .....	5
1.2.2	Bridgman Method .....	6
1.2.3	Chemical Vapor Deposition .....	6
1.2.4	Molecular Beam Epitaxy .....	7
1.2.5	Liquid Phase Epitaxy .....	10
	Summary .....	11

## 2. Electronic Band Structures

2.1	Quantum Mechanics .....	14
2.2	Translational Symmetry and Brillouin Zones .....	16
2.3	A Pedestrian's Guide to Group Theory .....	21
2.3.1	Definitions and Notations .....	21
2.3.2	Symmetry Operations of the Diamond and Zinc-Blende Structures .....	26
2.3.3	Representations and Character Tables .....	28
2.3.4	Some Applications of Character Tables .....	36
2.4	Empty Lattice or Nearly Free Electron Energy Bands .....	43
2.4.1	Nearly Free Electron Band Structure in a Zinc-Blende Crystal .....	44
2.4.2	Nearly Free Electron Energy Bands in Diamond Crystals	48
2.5	Band Structure Calculation by Pseudopotential Methods .....	54
2.5.1	Pseudopotential Form Factors in Zinc-Blende- and Diamond-Type Semiconductors .....	57
2.5.2	Empirical and Self-Consistent Pseudopotential Methods	61
2.6	The $\mathbf{k}\cdot\mathbf{p}$ Method of Band-Structure Calculations .....	63
2.6.1	Effective Mass of a Nondegenerate Band Using the $\mathbf{k}\cdot\mathbf{p}$ Method .....	64

---

2.6.2	Band Dispersion near a Degenerate Extremum: Top Valence Bands in Diamond- and Zinc-Blende-Type Semiconductors . . . . .	67
2.7	Tight-Binding or LCAO Approach to the Band Structure of Semiconductors . . . . .	78
2.7.1	Molecular Orbitals and Overlap Parameters . . . . .	78
2.7.2	Band Structure of Group-IV Elements by the Tight-Binding Method . . . . .	82
2.7.3	Overlap Parameters and Nearest-Neighbor Distances . . . . .	89
	Problems . . . . .	91
	Summary . . . . .	98
<b>3. Vibrational Properties of Semiconductors, and Electron-Phonon Interactions</b>		
3.1	Phonon Dispersion Curves of Semiconductors . . . . .	102
3.2	Models for Calculating Phonon Dispersion Curves of Semiconductors . . . . .	105
3.2.1	Force Constant Models . . . . .	105
3.2.2	Shell Model . . . . .	106
3.2.3	Bond Models . . . . .	107
3.2.4	Bond Charge Models . . . . .	109
3.3	Electron-Phonon Interactions . . . . .	113
3.3.1	Strain Tensor and Deformation Potentials . . . . .	114
3.3.2	Electron-Acoustic-Phonon Interaction at Degenerate Bands . . . . .	119
3.3.3	Piezoelectric Electron-Acoustic-Phonon Interaction . . . . .	122
3.3.4	Electron-Optical-Phonon Deformation Potential Interactions . . . . .	123
3.3.5	Fröhlich Interaction . . . . .	125
3.3.6	Interaction Between Electrons and Large-Wavevector Phonons: Intervalley Electron-Phonon Interaction . . . . .	127
	Problems . . . . .	129
	Summary . . . . .	147
<b>4. Electronic Properties of Defects</b>		
4.1	Classification of Defects . . . . .	150
4.2	Shallow or Hydrogenic Impurities . . . . .	151
4.2.1	Effective Mass Approximation . . . . .	152
4.2.2	Hydrogenic or Shallow Donors . . . . .	156
4.2.3	Donors Associated with Anisotropic Conduction Bands	161
4.2.4	Acceptor Levels in Diamond- and Zinc-Blende-Type Semiconductors . . . . .	164
4.3	Deep Centers . . . . .	170
4.3.1	Green's Function Method for Calculating Defect Energy Levels . . . . .	173

---

4.3.2	An Application of the Green's Function Method: Linear Combination of Atomic Orbitals .....	178
4.3.3	Another Application of the Green's Function Method: Nitrogen in GaP and GaAsP Alloys .....	182
4.3.4	Final Note on Deep Centers .....	187
Problems .....		188
Summary .....		192
<b>5. Electrical Transport</b>		
5.1	Quasi-Classical Approach .....	193
5.2	Carrier Mobility for a Nondegenerate Electron Gas .....	196
5.2.1	Relaxation Time Approximation .....	196
5.2.2	Nondegenerate Electron Gas in a Parabolic Band .....	197
5.2.3	Dependence of Scattering and Relaxation Times on Electron Energy .....	198
5.2.4	Momentum Relaxation Times .....	199
5.2.5	Temperature Dependence of Mobilities .....	210
5.3	Modulation Doping .....	213
5.4	High-Field Transport and Hot Carrier Effects .....	215
5.4.1	Velocity Saturation .....	217
5.4.2	Negative Differential Resistance .....	218
5.4.3	Gunn Effect .....	220
5.5	Magneto-Transport and the Hall Effect .....	222
5.5.1	Magneto-Conductivity Tensor .....	222
5.5.2	Hall Effect .....	224
5.5.3	Hall Coefficient for Thin Film Samples (van der Pauw Method) .....	225
5.5.4	Hall Effect for a Distribution of Electron Energies .....	226
Problems .....		227
Summary .....		231
<b>6. Optical Properties I</b>		
6.1	Macroscopic Electrodynamics .....	234
6.1.1	Digression: Units for the Frequency of Electromagnetic Waves .....	237
6.1.2	Experimental Determination of Optical Constants .....	237
6.1.3	Kramers-Kronig Relations .....	240
6.2	The Dielectric Function .....	243
6.2.1	Experimental Results .....	243
6.2.2	Microscopic Theory of the Dielectric Function .....	244
6.2.3	Joint Density of States and Van Hove Singularities .....	251
6.2.4	Van Hove Singularities in $\epsilon_i$ .....	252
6.2.5	Direct Absorption Edges .....	258
6.2.6	Indirect Absorption Edges .....	259
6.2.7	"Forbidden" Direct Absorption Edges .....	263

---

6.3	Excitons . . . . .	266
6.3.1	Exciton Effect at $M_0$ Critical Points . . . . .	269
6.3.2	Absorption Spectra of Excitons . . . . .	272
6.3.3	Exciton Effect at $M_1$ Critical Points or Hyperbolic Excitons . . . . .	278
6.3.4	Exciton Effect at $M_3$ Critical Points . . . . .	281
6.4	Phonon-Polaritons and Lattice Absorption . . . . .	282
6.4.1	Phonon-Polaritons . . . . .	285
6.4.2	Lattice Absorption and Reflection . . . . .	288
6.4.3	Multiphonon Lattice Absorption . . . . .	289
6.4.4	Dynamic Effective Ionic Charges in Heteropolar Semiconductors . . . . .	293
6.5	Absorption Associated with Extrinsic Electrons . . . . .	295
6.5.1	Free-Carrier Absorption in Doped Semiconductors . . . . .	296
6.5.2	Absorption by Carriers Bound to Shallow Donors and Acceptors . . . . .	301
6.6	Modulation Spectroscopy . . . . .	305
6.6.1	Frequency Modulated Reflectance and Thermoreflectance . . . . .	309
6.6.2	Piezoreflectance . . . . .	311
6.6.3	Electroreflectance (Franz-Keldysh Effect) . . . . .	312
6.6.4	Photoreflectance . . . . .	319
6.6.5	Reflectance Difference Spectroscopy . . . . .	322
	Problems . . . . .	323
	Summary . . . . .	331

## 7. Optical Properties II

7.1	Emission Spectroscopies . . . . .	333
7.1.1	Band-to-Band Transitions . . . . .	339
7.1.2	Free-to-Bound Transitions . . . . .	342
7.1.3	Donor–Acceptor Pair Transitions . . . . .	344
7.1.4	Excitons and Bound Excitons . . . . .	350
7.1.5	Luminescence Excitation Spectroscopy . . . . .	357
7.2	Light Scattering Spectroscopies . . . . .	362
7.2.1	Macroscopic Theory of Inelastic Light Scattering by Phonons . . . . .	362
7.2.2	Raman Tensor and Selection Rules . . . . .	365
7.2.3	Experimental Determination of Raman Spectra . . . . .	371
7.2.4	Microscopic Theory of Raman Scattering . . . . .	379
7.2.5	A Detour into the World of Feynman Diagrams . . . . .	381
7.2.6	Brillouin Scattering . . . . .	385
7.2.7	Experimental Determination of Brillouin Spectra . . . . .	387
7.2.8	Resonant Raman and Brillouin Scattering . . . . .	388
	Problems . . . . .	409
	Summary . . . . .	413

**8. Photoelectron Spectroscopy**

8.1	Photoemission . . . . .	419
8.1.1	Angle-Integrated Photoelectron Spectra of the Valence Bands . . . . .	428
8.1.2	Angle-Resolved Photoelectron Spectra of the Valence Bands . . . . .	431
8.1.3	Core Levels . . . . .	439
8.2	Inverse Photoemission . . . . .	444
8.3	Surface Effects . . . . .	445
8.3.1	Surface States and Surface Reconstruction . . . . .	445
8.3.2	Surface Energy Bands . . . . .	446
8.3.3	Fermi Level Pinning and Space Charge Layers . . . . .	448
	Problems . . . . .	453
	Summary . . . . .	455

**9. Effect of Quantum Confinement on Electrons  
and Phonons in Semiconductors**

9.1	Quantum Confinement and Density of States . . . . .	458
9.2	Quantum Confinement of Electrons and Holes . . . . .	461
9.2.1	Semiconductor Materials for Quantum Wells and Superlattices . . . . .	462
9.2.2	Classification of Multiple Quantum Wells and Superlattices . . . . .	464
9.2.3	Confinement of Energy Levels of Electrons and Holes .	465
9.2.4	Some Experimental Results . . . . .	475
9.3	Phonons in Superlattices . . . . .	480
9.3.1	Phonons in Superlattices: Folded Acoustic and Confined Optic Modes . . . . .	480
9.3.2	Folded Acoustic Modes: Macroscopic Treatment . . . .	485
9.3.3	Confined Optical Modes: Macroscopic Treatment . . . .	486
9.3.4	Electrostatic Effects in Polar Crystals: Interface Modes . . . . .	488
9.4	Raman Spectra of Phonons in Semiconductor Superlattices . . .	497
9.4.1	Raman Scattering by Folded Acoustic Phonons . . . .	497
9.4.2	Raman Scattering by Confined Optical Phonons . . . .	502
9.4.3	Raman Scattering by Interface Modes . . . . .	504
9.4.4	Macroscopic Models of Electron–LO Phonon (Fröhlich) Interaction in Multiple Quantum Wells . . . .	507
9.5	Electrical Transport: Resonant Tunneling . . . . .	511
9.5.1	Resonant Tunneling Through a Double-Barrier Quantum Well . . . . .	512
9.5.2	I–V Characteristics of Resonant Tunneling Devices . . .	515
9.6	Quantum Hall Effects in Two-Dimensional Electron Gases . .	519
9.6.1	Landau Theory of Diamagnetism in a Three-Dimensional Free Electron Gas . . . . .	520

9.6.2	Magneto-Conductivity of a Two-Dimensional Electron Gas: Filling Factor . . . . .	523
9.6.3	The Experiment of von Klitzing, Pepper and Dorda . . . . .	524
9.6.4	Explanation of the Hall Plateaus in the Integral Quantum Hall Effect . . . . .	527
9.7	Concluding Remarks . . . . .	531
	Problems . . . . .	532
	Summary . . . . .	535

**Appendix: Pioneers of Semiconductor Physics Remember...**

Ultra-Pure Germanium: From Applied to Basic Research or an Old Semiconductor Offering New Opportunities By <i>Eugene E. Haller</i> . . . . .	539
Two Pseudopotential Methods: Empirical and Ab Initio By <i>Marvin L. Cohen</i> . . . . .	542
The Early Stages of Band-Structures Physics and Its Struggles for a Place in the Sun By <i>Conyers Herring</i> . . . . .	544
Cyclotron Resonance and Structure of Conduction and Valence Band Edges in Silicon and Germanium By <i>Charles Kittel</i> . . . . .	547
Optical Properties of Amorphous Semiconductors and Solar Cells By <i>Jan Tauc</i> . . . . .	550
Optical Spectroscopy of Shallow Impurity Centers By <i>Elias Burstein</i> . . . . .	553
On the Prehistory of Angular Resolved Photoemission By <i>Neville V. Smith</i> . . . . .	558
The Discovery and Very Basics of the Quantum Hall Effect By <i>Klaus von Klitzing</i> . . . . .	560
The Birth of the Semiconductor Superlattice By <i>Leo Esaki</i> . . . . .	562

<b>References</b>	567
-------------------	-----

<b>Subject Index</b>	601
----------------------	-----

**Table of Fundamental Physical Constants** (Inside Front Cover)

**Table of Units** (Inside Back Cover)