Contents

1 Introduction 1
1.1 Introduction 1
1.2 Optical Phenomena in Semiconductors 2
1.3 Band Structure and Fundamental Bandgap 5
1.4 Quasi Particles in Solids 7
1.4.1 Electrons and Holes 7
1.4.2 Excitons 9
1.4.3 Phonons 10
1.4.4 Plasmons 12
1.5 Extrinsic Factors Affecting the Bandgap: Temperature and Stress 12
1.5.1 Temperature 12
1.5.2 Stress 13
1.6 Low Dimension Structures 14
1.6.1 Quantum Confinement 14
1.6.2 The Density of States in Quantum Confined Structures 17
1.7 Extrinsic Semiconductors. Energy Levels Inside the Forbidden Bandgap 18
1.7.1 Point Defects 18
1.7.2 Extended Defects 20
1.8 Doped Semiconductors: Effects on the Band Gap 21
1.9 Interaction of the Semiconductor with Electromagnetic Waves 24
1.9.1 Macroscopic Approach. Optical Constants 24
1.10 The Oscillator Model for the Optical Constants 26
1.10.1 Dielectric Function 26
1.10.2 Kramers Kronig Relations 27
1.11 Optical Reflection 28

1.12 Optical Transitions. Light Absorption and Emission 28
1.12.1 Einstein Coefficients 29
1.12.2 Microscopic Description of the Optical Absorption in Semiconductors 31
1.12.3 Microscopic Description of the Stimulated Emission in Semiconductors 34
1.12.4 Microscopic Description of the Spontaneous Emission in Semiconductors 35
1.12.5 Indirect Optical Transitions 36
1.12.6 The Influence of Disorder and Doping in the Absorption Coefficient. Urbach Tail 37
1.12.7 Defect and Impurity Absorption 38
1.12.8 Excitonic Absorption 38
1.13 Carrier Recombination. Luminescence 40
1.13.1 Non-radiative Recombination 41
1.13.2 Luminescence 41
1.13.3 Diffusion Length 44
1.13.4 Surface Recombination 45
1.13.5 Exciton Recombination 45
References 46

2 Basics of Optical Spectroscopy: Transmission and Reflection Measurements, Their Analysis, and Related Techniques 49
2.1 Introduction 49
2.2 Samples and Spectroscopic Equipment 52
2.2.1 Samples 52
2.2.2 Spectrophotometer 54
2.2.3 Fourier-Transform Spectrometer 57
2.3 Extraction of the Optical Constants from Standard Measurements 59
2.4 The Link Between the Optical Constants and Material Properties 61
2.4.1 Absorption Spectra and Bandstructure 61
2.4.2 Absorption Spectra and Extrinsic Absorption 63
2.4.3 Absorption Spectra Obtained by Using Polarized Light 64
2.4.4 Reflection Spectra 65
2.4.5 Modulation Spectroscopy and Photoreflection 67
2.5 Related Techniques 69
2.5.1 Photoacoustic Spectroscopy 69
2.5.2 Ellipsometry 70
2.5.3 Mapping 71
References 75

3 Raman Spectroscopy 77
3.1 Introduction 77
3.2 The Light Scattering by Phonons 80
3.2.1 Wavevector and Energy Selection Rules 80
3.2.2 Symmetry Selection Rules 81
3.3 What Semiconductor Properties Can Be Investigated with Raman Spectroscopy? 84
3.4 Experimental Description 85
3.4.1 Raman Spectrometer 85
3.4.2 The Detectors 88
3.4.3 Laser Sources 89
3.4.4 Raman Imaging 91
3.4.5 The Lateral Resolution 95
3.4.6 Probe Depth 99
3.4.7 The Microscope Objectives 103
3.5 Case Applications 106
3.5.1 Stress in Si Microelectronic Devices 106
3.5.2 Doping 114
3.5.3 Temperature Measurements Using μ-R Spectroscopy . . . 125
3.5.4 Size Effects. Phonon Confinement 132
References 136

4 Photoluminescence (PL) Techniques 143
4.1 Introduction 143
4.2 Probed Sample Region 145
4.2.1 Vertical Spatial Resolution—The 'Information Depth' 145
4.2.2 Lateral Spatial Resolution 149
4.2.3 The Impact of Actual Spatial Carrier Distributions to the PL-Line Shape 150
4.3 PL Setups and Methodology 150
4.3.1 Standard cw PL Setup 150
4.3.2 Resonantly Excited PL 156
4.3.3 PL Excitation Spectroscopy 157
4.4 Mechanisms Contributing to the PL Spectrum 159
4.4.1 Introduction 159
4.4.2 Band-to-Band Transitions 161
4.4.3 Free Excitons 161
4.4.4 Band-to-Band Transitions Versus Excitonic Transitions 163
4.4.5 Bound Excitons 164
4.4.6 Defect Related Transitions 165
4.4.7 PL Contributions at Energies Larger Than E_g 167
4.4.8 The Impact of the Parameter Excitation Density 169

4.5 Applications of Steady-State Photoluminescence 171
4.5.1 Analysis of E_g Shifts 171
4.5.2 Surface Recombination Velocity 175
4.5.3 Rare Earth or Transition Metal Atoms in Semiconductors 176
4.5.4 Infrared Fourier-Transform Photoluminescence 179
4.5.5 Photoluminescence from Indirect Materials 180
4.6 Time-Resolved Photoluminescence (TR PL) 182
4.6.1 Introduction 182
4.6.2 TR PL: Experimental 184
4.6.3 TR PL: Practical Examples 187
4.6.4 Ultrafast TR PL 190
4.7 Photoluminescence Mapping 192
4.7.1 PL Mapping: Experimental 192
4.7.2 PL Mapping: Practical Examples 194
4.7.3 Ring-Shaped PL Pattern in Biased Quantum Wells 198
4.7.4 Near-Field Scanning Optical Microscope Based PL 200
4.8 Photoluminescence at Devices 202
4.8.1 Introduction 202
4.8.2 Strain Analysis in Devices by Means of PL Scanning 203
4.8.3 Temperature Measurements at Operating Devices 204
4.8.4 TR PL at Devices 204
4.8.5 PL Mapping at Opened Devices 206
References 208

5 Cathodoluminescence 213
5.1 Introduction 213
5.2 e-Beam Excitation. The Generation Function 216
5.2.1 Excitation with an e-Beam 216
5.2.2 The Generation Function 217
5.3 Monte Carlo Simulation 223
5.4 Charge Effects. The Dead Layer 226
5.5 The CL Signal 229
5.6 Experimental Set-Up 235
5.7 Electrostatic Charge 240
5.8 Case Applications 241
5.8.1 Carrier Diffusion Length 241
5.8.2 In-Depth Analysis: Multilayer Structures. Laser Diodes and AlGaN/GaN HEMTS 244
5.8.3 Low Electron Energy Cathodoluminescence 249
5.8.4 Spectral Images: Orientation Patterned GaAs Crystals 252
5.8.5 Dislocations in Si-Doped GaAs 255
5.8.6 Nanostructures 257

5.9 PL and CL: A Comparative 259
References 259

6 Photoelectrical Spectroscopy 265
6.1 Introduction 265
6.2 Generation of Photocurrents 268
6.2.1 Conductivity and Photoconductivity 268
6.2.2 Intrinsic Photocurrent Spectra $I_{PC}(\hbar\omega)$ 270
6.2.3 Intrinsic PC Spectra in Presence of Surface Recombination 273
6.2.4 Photoconductivity from QWs, Quantum Dots, and Excitonic Photoconductivity 275
6.2.5 Extrinsic Photoconductivity 277
6.2.6 Other Photoelectrical Effects 281
6.3 Experimental 283
6.3.1 Photocurrent Setups 283
6.3.2 Sample Geometry 286
6.3.3 Direct and Time-Dependent PCs 288
6.3.4 Transient Photocurrent Spectroscopy 291
6.4 Selected Applications of Photocurrent Spectroscopy for Analytical Purposes 292
6.4.1 Intrinsic Interband PC 292
6.4.2 Defect-Related (Extrinsic) Photoconductivity 294
6.4.3 Laser Beam Induced Current (LBIC) 295
References 299

Index 301