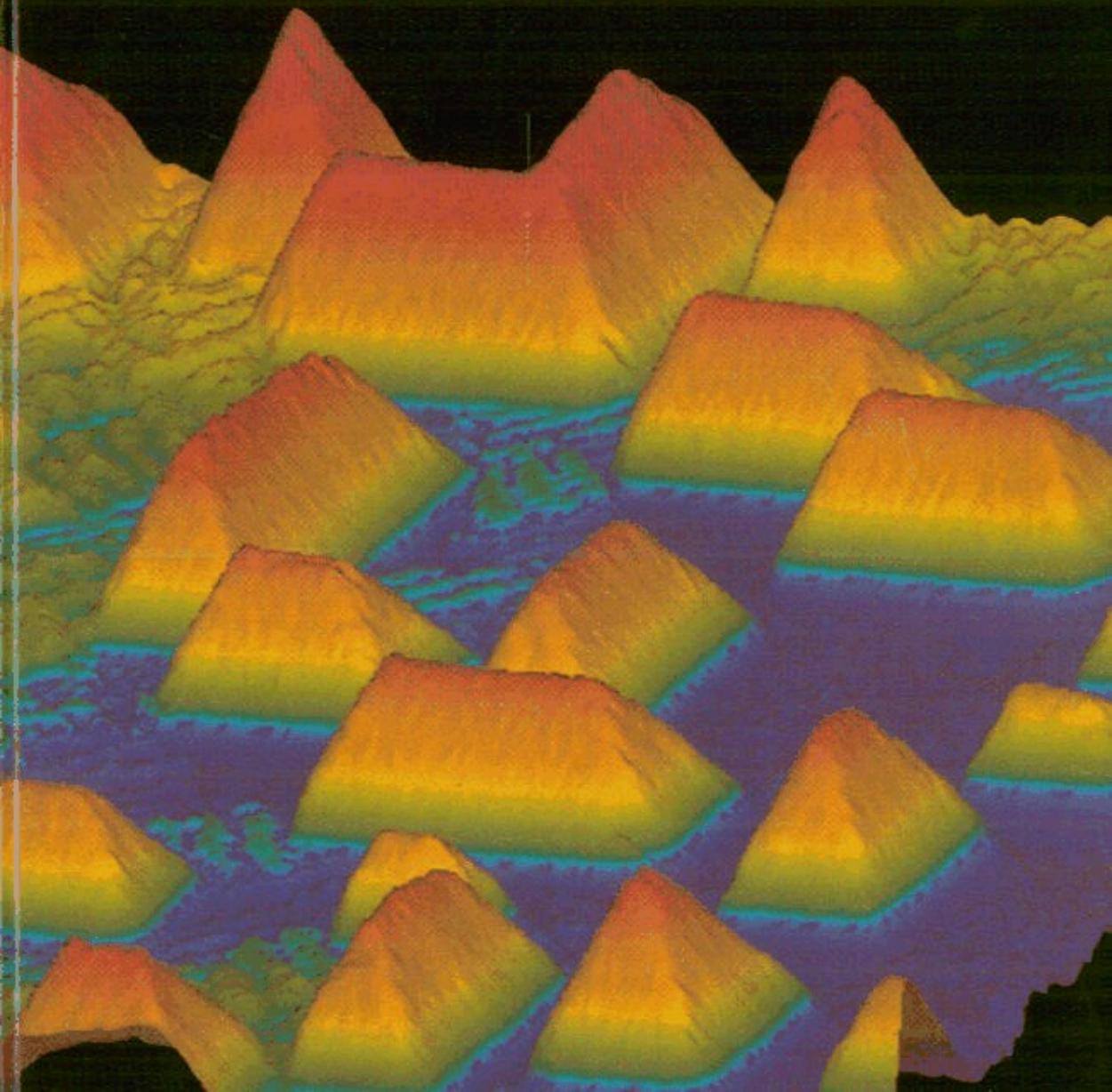


# **LOW-DIMENSIONAL semiconductor structures**

Fundamentals and device applications

Edited by **Keith Barnham and Dimitri Vvedensky**



# Contents

<i>List of contributors</i>	xii
<i>Preface</i>	xiii
<hr/>	
<b>1 Epitaxial Growth of Semiconductors</b>	1
D. D. Vvedensky	
<hr/>	
1.1 Introduction	1
1.2 Epitaxial Growth Techniques	3
1.2.1 Molecular-beam Epitaxy	3
1.2.2 Vapour-phase Epitaxy	6
1.2.3 Molecular-beam Epitaxy with Heteroatomic Precursors	7
1.3 Epitaxial Growth Modes	8
1.4 <i>In Situ</i> Observation of Growth Kinetics and Surface Morphology	10
1.4.1 Reflection High-energy Electron Diffraction	11
1.4.2 Scanning Tunnelling Microscopy	12
1.4.3 Atomic Force Microscopy	13
1.5 Atomistic Processes during Homoepitaxy	16
1.5.1 Growth Kinetics on Vicinal GaAs(001)	16
1.5.2 Anisotropic Growth and Surface Reconstructions	19
1.5.2.1 Vicinal GaAs(001)	19
1.5.2.2 Vicinal Si(001)	21
1.6 Models of Homoepitaxial Kinetics	23
1.6.1 The Theory of Burton, Cabrera and Frank	23
1.6.2 Homogeneous Rate Equations	24
1.6.3 Multilayer Growth on Singular Surfaces	27
1.7 Mechanisms of Heteroepitaxial Growth	29
1.7.1 Kinetics and Equilibrium with Misfit Strain	29
1.7.2 The Frenkel-Kontorova Model	30
1.8 Direct Growth of Quantum Heterostructures	32
1.8.1 Quantum Wells and Quantum-well Superlattices	33
1.8.2 Quantum Wire Superlattices	34
1.8.3 Self-organized Quantum Dots	37
1.8.3.1 Stranski-Krastanov Growth of InAs on GaAs(001)	38
1.8.3.2 Controlled Positioning of Quantum Dots	40
1.8.3.3 Ge ‘Hut’ Clusters on Si(001)	40

---

1.9	Growth on Patterned Substrates	42
1.9.1	Selective Area Growth	43
1.9.2	Quantum Wires on ‘V-Grooved’ Surfaces	43
1.9.3	Stranski–Krastanov Growth on Patterned Substrates	44
1.10	Future Directions	46
	<i>Exercises</i>	47
	<i>References</i>	51
<b>2</b>	<b>Electrons in Quantum Semiconductor Structures: An Introduction</b>	
	<b>E. A. Johnson</b>	<b>56</b>
2.1	Introduction	56
2.2	Ideal Low-dimensional Systems	57
2.2.1	Free Electrons in Three Dimensions: A Review	57
2.2.2	Ideal Two-dimensional Electron Gas	58
2.2.3	Ideal Zero- and One-dimensional Electron Gases	60
2.2.4	Quantum Wells, Wires, and Dots	61
2.3	Real Electron Gases: Single Particle Models	61
2.3.1	Ideal Square Well	62
2.3.2	Some Generalizations	65
2.3.2.1	Holes in Quantum Wells	65
2.3.2.2	Non-parabolicity	65
2.3.3	Finite Quantum Wells and Real Systems	66
2.3.4	Interface Effects	70
2.3.4.1	Effective Mass for Parallel Transport	70
2.3.4.2	Effective-mass Correction to Conduction-band Discontinuities	71
2.3.5	Quantum Wires	73
2.3.5.1	Quantum Point Contacts	74
2.3.6	Quantum Dots	75
	<i>Exercises</i>	76
	<i>References</i>	77
<b>3</b>	<b>Electrons in Quantum Semiconductors Structures: More Advanced Systems and Methods</b>	
	<b>E. A. Johnson</b>	<b>79</b>
3.1	Introduction	79
3.2	Many-body Effects	79
3.2.1	The Hartree Approximation	79
3.2.2	Beyond the Hartree Approximation	81

---

3.2.3	The 2DEG at a Heterojunction Interface	82
3.2.4	The Ideal Heterojunction	85
3.3	Some Calculational Methods	86
3.3.1	The WKB Approximation	87
3.3.2	The 2DEG in Doping Wells	90
3.3.2.1	The Delta Well (Spike Doping)	93
3.3.3	The Thomas–Fermi Approximation for Two-dimensional Systems	95
3.3.3.1	The Thomas–Fermi Approximation for Heterojunctions and Delta Wells	96
3.4	Quantum Wires and Quantum Dots	97
3.4.1	Quantum Point Contacts and Quantized Conductance Steps	97
3.4.2	A Closer Look at Quantum Dots	101
3.4.3.	The Coulomb Blockade and Single-electron Transistors	104
3.5	Superlattices	106
3.5.1	Superlattices and Multi-quantum-wells	107
3.5.2	Miniband Properties: The WKB Approximation	109
3.5.3	Doping Superlattices	112
3.5.3.1	Delta-Doped $n$ - $i$ - $p$ - $i$ s	114
3.5.3.2	Compositional and Doping Superlattices	115
3.5.4	Other Types of Superlattices	116
	<i>Exercises</i>	118
	<i>References</i>	122
<b>4</b>	<b>Phonons in Low-dimensional Semiconductor Structures</b>	
	<b>M. P. Blencowe</b>	123
4.1	Introduction	123
4.2	Phonons in Heterostructures	124
4.2.1	Superlattices	125
4.2.2	Mesoscopic Phonon Phenomena	131
4.3	Electron–Phonon Interactions in Heterostructures	135
4.4	Conclusion	144
	<i>Exercises</i>	145
	<i>References</i>	147
<b>5</b>	<b>Localization and Quantum Transport</b>	
	<b>A. MacKinnon</b>	149
5.1	Introduction	149
5.2	Localization	151
5.2.1	Percolation	151
5.2.2	The Anderson Transition and the Mobility Edge	151

5.3	5.2.3 Variable Range Hopping	154
	5.2.4 Minimum Metallic Conductivity	154
5.3	Scaling Theory and Quantum Interference	155
	5.3.1 The Gang of Four	155
	5.3.2 Experiments on Weak Localization	157
	5.3.3 Quantum Interference	158
	5.3.4 Negative Magnetoresistance	159
	5.3.5 Single Rings and Non-local Transport	160
	5.3.6 Spin-orbit Coupling, Magnetic Impurities, etc.	163
	5.3.7 Universal Conductance Fluctuations	163
	5.3.8 Ballistic Transport	163
5.4	Interaction Effects	164
	5.4.1 The $\ln T$ Correction	164
	5.4.2 Wigner Crystallization	164
5.5	The Quantum Hall Effect	165
	5.5.1 General	165
	5.5.2 The Quantum Hall Effect Measurements	168
	5.5.3 The Semiclassical Theory	170
	5.5.4 The Fractional Quantum Hall Effect	172
	<i>Exercises</i>	175
	<i>References</i>	178

---

**6 Electronic States and Optical Properties of Quantum Wells**

	J. Nelson	180
6.1	Introduction	180
6.2	The Envelope Function Scheme	183
6.3	The Parabolic Band Model	187
6.4	Effects of Band Mixing	192
	6.4.1 Light Particle Band Non-parabolicity	192
	6.4.2 Valence Band Non-parabolicity	193
6.5	Multiple Well Effects	194
6.6	Effects of the Coulomb Interaction	197
	6.6.1 Excitons in Bulk Semiconductors	197
	6.6.2 Excitons in Quantum Wells	198
6.7	Effects of Applied Bias	201
6.8	Optical Absorption in a Quantum Well	205
6.9	Optical Characterization	209
	6.9.1 Measurement of Absorption	209
	6.9.2 Features of Optical Spectra	211
	6.9.2.1 Band Non-parabolicity	211
	6.9.2.2 Valence Band Mixing	212

6.9.2.3	Interwell Coupling	214
6.9.2.4	Electric Field	214
6.10	Quantum-well Solar Cells	215
6.10.1	Photoconversion	215
6.10.2	Basic Principles	217
6.10.2.1	Photocurrent	217
6.10.2.2	Recombination Current	221
6.10.2.3	Carrier Escape	221
6.11	Concluding Remarks	222
	<i>Exercises</i>	222
	<i>References</i>	225
<b>7</b>	<b>Non-Linear Optics in Low-dimensional Semiconductors</b>	
	<b>C. C. Phillips</b>	227
7.1	Introduction	227
7.2	Non-dissipative NLO Processes	229
7.3	Dissipative NLO Effects	231
7.4	Potential Applications of NLO	232
7.4.1	Serial Channel Applications	232
7.4.2	Multi-channel Applications: Optical Computing	233
7.5	Excitonic Optical Saturation in MQWs	234
7.5.1	Excitonic Absorption at Low Intensities	234
7.5.2	Saturation of Excitonic Peaks at High Intensities	237
7.6	The Quantum Confined Stark Effect	239
7.7	Doping Superlattices ('n-i-p-i' Crystals)	242
7.8	Hetero-n-i-p-i Structures	246
7.8.1	Band Filling Effects in Hetero-n-i-p-is	247
7.8.2	The QCSE in Hetero-n-i-p-is	249
7.9	Concluding Remarks	254
	<i>Exercises</i>	255
	<i>References</i>	257
<b>8</b>	<b>Semiconductor Lasers</b>	
	<b>A. Khan, P. N. Stavrinou and G. Parry</b>	260
8.1	Introduction	260
8.2	Basic Laser Theory	262
8.2.1	Laser Threshold	265
8.2.2	Threshold Current Density	267
8.2.3	Power Output	270

8.3	Fundamental Gain Calculations	272
8.3.1	Electronic Band Structure and Densities of States	272
8.3.2	Carrier Density and Inversion	274
8.3.3	Gain Expression	276
8.3.4	Optical Gain in 2D and 3D Active Regions	277
8.4	Strained Layers	280
8.4.1	Optical Interband Matrix Element	284
8.5	Some other Laser Geometries	286
	<i>Exercises</i>	292
	<i>References</i>	294

**9 Mesoscopic Devices**


---

T. J. Thornton	296
----------------	-----

9.1	Introduction	296
9.2	Quantum Interference Transistors	297
9.2.1	Quantum Interference and Negative Magnetoresistance	297
9.2.2	The Aharonov-Bohm Effect	303
9.2.3	Universal Conductance Fluctuations	306
9.2.4	Quantum Interference Transistors	309
9.2.4.1	The Gated Ring Interferometer	310
9.2.4.2	The Stub Tuner	311
9.2.4.3	Problems with Quantum Interference Transistors	311
9.3	Ballistic Electron Devices	314
9.3.1	Electron Transmission and the Landauer-Büttiker Formula	315
9.3.2	Quantized Conductance in Ballistic Point Contacts	316
9.3.3	Multi-terminal Devices	318
9.3.3.1	The Negative Bend Resistance	318
9.3.3.2	Quenching of the Hall Effect	319
9.3.4	Possible Applications of Ballistic Electron Devices	320
9.3.5	Boundary Scattering in Ballistic Structures	323
9.4	Quantum Dot Resonant Tunnelling Devices	325
9.4.1	Resonant Tunnelling through Quantum Wells	326
9.4.2	Resonant Tunnelling through Quantum Dots	328
9.4.3	Gated Resonant Tunnelling through Quantum Dots	329
9.5	Coulomb Blockade and Single-electron Transistors	331
9.5.1	Coulomb Blockade in the Current-biased Single Junction	332
9.5.2	Coulomb Blockade in Double Junctions	334
9.5.3	Necessary Conditions for Efficient Coulomb Blockade	335
9.5.4	Single-electron Transistors	335
9.5.5	Co-tunnelling and Multiple Tunnel Junctions	339
9.5.6	Possible Applications of Single-electron Transistors	340

9.6	The Future of Mesoscopic Devices	342
	<i>Exercises</i>	343
	<i>References</i>	345
<b>10</b>	<b>High-speed Heterostructure Devices</b>	
	<b>J. J. Harris</b>	<hr/>
10.1	Introduction	348
10.2	Field-effect Transistors	349
	10.2.1 The Si MOSFET	349
	10.2.2 GaAs/AlGaAs High-electron-mobility Transistor	355
	10.2.3 InGaAs HEMTs	358
	10.2.4 Delta-doped FETs	361
10.3	Vertical Transport Devices	363
	10.3.1 Unipolar Diodes	364
	10.3.2 Hot-electron Devices	365
	10.3.3 Resonant Tunnelling Structures	367
	10.3.4 Superlattice Devices	370
	10.3.5 Heterojunction Bipolar Transistors	372
10.4	Conclusions	375
	<i>Exercises</i>	375
	<i>References</i>	377
	<i>Solutions to Selected Exercises</i>	379
	<i>Index</i>	387