

Contents

1. Introduction	1
1.1 Approaching the End of Moore's Law: What Next?	1
1.2 Paradigm Changes in Semiconductor Physics and Technology	4
1.3 Surfing Through Books and Reviews	11
2. Growth and Characterization Techniques	15
2.1 Basics of Molecular Beam Epitaxy	17
2.1.1 MBE Apparatus	17
2.1.2 Understanding MBE Growth Processes	19
2.1.3 Phase Diagrams	22
2.1.4 Solid–Liquid–Vapor Equilibrium for Binary Compounds	26
2.1.5 Solid–Vapor Equilibrium for Ternary Alloys	28
2.1.6 Segregation Effects	30
2.2 Basics of Metalorganic Chemical Vapor Deposition	33
2.3 Main Characterization Techniques	35
2.3.1 Direct Imaging Methods	36
2.3.2 Transmission Electron Microscopy	40
2.3.3 Diffraction Methods	48
2.3.4 Optical Methods	54
3. Self-Organization Phenomena at Crystal Surfaces	57
3.1 Periodically Faceted Surfaces	61
3.1.1 Equilibrium Crystal Shape: Two Distinct Formulations of the Problem	61
3.1.2 Faceting: Analogy with Phase Separation	63
3.1.3 Intrinsic Surface Stress of a Solid	65
3.1.4 Thin Strained Epitaxial Film as a Model of a Surface .	67
3.1.5 Simple Lattice Model for Intrinsic Surface Stress	68
3.1.6 Capillarity Phenomena at Solid Surfaces	71
3.1.7 Periodically Faceted Surfaces	73
3.1.8 Faceting Phenomena on (311) Surfaces of GaAs and AlAs	76

3.1.9	Macroscopic Step Bunching and Faceting of Vicinal Surfaces	96
3.1.10	Variety of Periodically Faceted Surfaces	101
3.1.11	Faceted Surfaces: Understanding and Prospects	103
3.2	Surface Arrays of Two-Dimensional Islands	104
3.2.1	Homoepitaxial Systems at Submonolayer Coverage	108
3.2.2	Energetics of a Heteroepitaxial System at Submonolayer Coverage	110
3.2.3	Arrays of 2D Strained Islands at Low Temperatures	123
3.2.4	Arrays of 2D Strained Islands at Low Coverage	135
3.2.5	Equilibrium Distribution of Island Sizes	136
3.2.6	Crossover from Kinetically Controlled to Thermodynamically Limited Growth of 2D Strained Islands	140
3.2.7	Submonolayer Arrays of InAs/GaAs Islands	142
3.2.8	Submonolayer Islands at Work	145
3.3	Arrays of Three-Dimensional Coherently Strained Islands	156
3.3.1	The In(Ga)As/GaAs System: From Three-Dimensional Islands to Quantum Dots	156
3.3.2	Coherent vs. Dislocated Islands in Lattice-Mismatched Systems	165
3.3.3	Size-Limited Island Growth: Are Islands Stable Against Ripening?	168
3.3.4	Energetics of a Lattice-Mismatched Heteroepitaxial System	173
3.3.5	Dilute Array of 3D Strained Islands	175
3.3.6	Ordering of Islands in Terms of Shape	178
3.3.7	Size Ordering of Islands vs. Ostwald Ripening	180
3.3.8	Lateral Arrangement of Islands	183
3.3.9	Phase Diagram of Arrays of Interacting Strained Islands	188
3.3.10	Equilibrium Thickness of the Wetting Layer	190
3.3.11	Two Exact Theorems on the Shape vs. Volume Dependence of 3D Islands	194
3.3.12	Kinetic Theories of Size-Limited Island Growth	199
3.3.13	Experimental Studies of 3D Island Formation in the In(Ga)As/GaAs System	206
3.3.14	Temperature Ramping and Cooling in InAs/GaAs Systems: Evidence of Close-to-Equilibrium Behavior	214
3.3.15	Formation of InAs/GaAs Islands at Ultra-Low Temperatures	224
3.3.16	3D Islands in Other Material Systems	226

3.3.17	What Have we Learned about 3D Coherently Strained Islands?	231
4.	Engineering of Complex Nanostructures:	
	Working Together with Nature	235
4.1	Multisheet Arrays of Strained Islands	237
4.1.1	Vertical Correlation of Strained Islands	238
4.1.2	Order Enhancement in Multisheet Arrays	239
4.1.3	Electronically Coupled Multisheet Quantum Dots	243
4.1.4	Seeding of Quantum Dots	246
4.1.5	Engineering the Exciton Wave Function by Stacking Quantum Dots	249
4.1.6	Surface Evolution During Overgrowth of Strained Islands	251
4.1.7	Defect-Reduction Techniques	253
4.2	Anticorrelation in Multisheet Arrays of Strained Islands	263
4.2.1	Generalized Rayleigh Waves in Elastically Anisotropic Crystals	264
4.2.2	Formation of Multisheet Arrays in Elastically Anisotropic Crystals	265
4.2.3	Multisheet Arrays of CdSe/ZnSe Submonolayer Islands	269
4.2.4	Highly-Ordered Quantum Dot Superlattices	276
4.2.5	Anticorrelated Multisheet Nanostructures in III-V Semiconductors	280
4.3	Activated Alloy Phase Separation During Overgrowth of Quantum Dots	282
4.3.1	Basic Physics of Phase Separation in Alloys	282
4.3.2	Steady-State Composition-Modulated Structures in Growing Alloy Films	302
4.3.3	Alloy Growth on Stressors: Activated Phase Separation	308
5.	Devices Based on Epitaxial Nanostructures	315
5.1	Quantum Dot Heterostructure Lasers	316
5.1.1	Basic Advantages of Heterostructure Lasers	317
5.1.2	Development of Heterostructure Lasers	318
5.1.3	The Key Breakthrough: Self-Organized Growth	321
5.1.4	State of the Art in Quantum Dot Lasers: Taking an Upper Hand	323
5.2	Quantum Dot Nanostructures for Single-Electron Devices	333
6.	Conclusion	335

XII Contents

A. Energy of a Strained Disk with Perturbed Shape	337
A.1 Energy of the Disk Boundary	338
A.2 Elastic Relaxation Energy of the Disk	339
A.3 Evaluation of Integrals	341
A.4 Stiffness of the Disk against Shape Perturbations	346
B. Elastic Interaction of Two Strained Disks	349
C. Stiffness of a Hexagonal Array of Interacting Strained Disks	355
References	359
Index	385