Contents

Part I Tools for Nanoscience

1 Lithography and Etching Processes
D. Mailly, C. Vieu 3
1.1 Definitions and General Considerations 3
1.2 Photoresists 3
1.2.1 Example of Processing with a Polymer Resist 4
1.2.2 Sensitivity and Contrast 5
1.2.3 Example of a Positive Resist 7
1.2.4 Transfer Stage 8
1.3 Subtractive Pattern Transfer 9
1.3.1 Wet Etching 9
1.3.2 Dry Etching 11
1.3.3 Reactive Ion Etching 13
1.4 Additive Pattern Transfer 15
1.4.1 Lift-Off 15
1.4.2 Electrolytic Growth 16
1.5 Lithography 19
1.5.1 Overview of Lithographic Methods 19
1.5.2 Proximity and Contact Photolithography 20
1.5.3 Projection Photolithography 23
1.5.4 X-Ray Photolithography 26
1.5.5 Extreme UV Lithography 28
1.5.6 Electron Projection Lithography 28
1.5.7 Ion Projection Lithography 29
1.5.8 Electron Beam Lithography 30
1.5.9 Focussed Ion Beam (FIB) Lithography 35
1.5.10 Conclusion 39
References 40

2 Growth of Organised Nano-Objects on Prepatterned Surfaces
M. Hanbücken, J. Eymery, S. Rousset 41
2.1 Physical Phenomena in Substrate Prepatterning and Periodic Growth of Adsorbates 42
2.1.1 Surface Crystallography: Surface Energy and Surface Stress 42
2.1.2 Self-Organised Surfaces: Discontinuities in the Surface Stress 47
2.1.3 3D Growth: Energy Criterion and Competition Between Bulk Elastic Energy and Surface Energy 48
2.1.4 Role of the Chemical Potential as Driving Force Behind Adsorbate Growth. Curvature Effect and Elastic Stresses 52
2.2 Physical and Chemical Methods for Producing Nano-Objects 53
2.3 Growth of Nano-Objects on a Naturally Prepatterned Surface Using Its Intrinsic Properties 56
2.3.1 Growth of Self-Organised Surfaces 56
2.3.2 Uses for Growth on Vicinal Surfaces 57
2.4 Growth of Quantum Dots on a Prepatterned Surface by Imposing a Controlled Artificial Pattern 58
2.5 Growth of Nano-Objects on a Prepatterned Vicinal Surface by Combining Natural and Artificial Patterning 61
2.5.1 Prepatterning the Si(111) Vicinal Surface 61
2.5.2 Growth of Gold Nano-Objects on Prepatterned Si(111) 63
2.6 Conclusion 64
References 65

3 Scanning Tunneling Microscopy
D. Stiévenard 69
3.1 Introduction 69
3.1.1 General Principles 69
3.1.2 General Setup 70
3.1.3 Tip Preparation 71
3.2 Tunnel Current 72
3.2.1 Tunnel Effect Between Tip and Sample 72
3.2.2 Tunnel Current: Tersoff–Hamann Theory 73
3.2.3 Extending the Tersoff–Hamann Theory 73
3.2.4 Resolution 74
3.2.5 Contrast 75
3.2.6 Measuring the Barrier Height 76
3.2.7 Examples 77
3.3 STM Spectroscopy 80
3.3.1 Elastic Current 80
3.3.2 Measuring the Band Gaps of III–V Semiconductors 82
3.3.3 Spectroscopy of Individual Quantum Dots 82
3.3.4 Inelastic Tunnel Current 84

3.4 Tip–Sample Interaction 85
3.4.1 Manipulation Modes 85
3.4.2 Local Chemistry 87
3.5 Conclusion 88
References 89

4 Atomic Force Microscopy
C. Frétigny 91
4.1 The Device 91
4.2 The Various Imaging Modes 92
4.3 Image Resolution 95
4.4 Contact Mode: Topography, Elasticity and Adhesion Imaging 98
4.4.1 Friction Mode 100
4.5 Resonant Modes 101
4.5.1 General Principles 101
4.5.2 Linear Resonant Mode 102
4.5.3 Nonlinear Resonant (Tapping) Mode 103
4.6 Force Measurements 107
4.6.1 Non-Contact Measurements 108
4.6.2 Elasticity and Adhesion Measurements on a Single Molecule 108
4.7 Magnetic and Electrical Measurements 109
4.7.1 Magnetic Measurements 109
4.7.2 Electrical Measurements 109
4.8 Measuring Mechanical Properties 112
4.8.1 Nanoindentation 112
4.8.2 Measuring Contact Stiffness 112
4.8.3 Contact Resonance Frequency 113
4.8.4 Friction Forces 114
4.9 Applications in Nanotechnology 115
4.10 Conclusion 118
References 118

5 Near-Field Optics: From Experiment to Theory
C. Boccara, R. Carminati 121
5.1 Basic Ideas and the Nature of the Problem 121
5.1.1 Resolution, Near Field and Far Field 121
5.1.2 Brief History of Near-Field Methods 122
5.1.3 Near-Field Optical Microscopy: For What Purpose? 123
5.2 Photon Scanning Tunneling Microscope (PSTM) 123
5.2.1 Frustration of Evanescent Fields 124
5.2.2 PSTM Probe in an Evanescent Field: Scattering Model 124
5.2.3 Applications of PSTM 126
5.3 Apertureless Near-Field Microscope 126
5.3.1 Nano-Antenna Radiating to the Far Field 127
5.3.2 Source of Contrast: Scattering Sphere Model 127

5.3.3 Sharp-Point Effect. Tip Resolution and Efficiency 129
5.3.4 Field Enhancement Near a Metal Tip 129
5.3.5 Apertureless SNOM: Typical SNOM Setup 131
5.4 Aperture SNOM 133
5.4.1 Metal-Coated Fibre 133
5.4.2 Energy Transmission in a Tapered Metal-Coated Fibre 134
5.4.3 Applications of Aperture SNOM 136
5.5 Plane Wave Expansion. Diffraction Limit 137
5.5.1 Propagation of a Beam in Vacuum 138
5.5.2 Uncertainty Relations and Diffraction 140
5.5.3 Diffraction Limit 140
5.6 Beyond the Diffraction Limit:
Near Field and Evanescent Waves 142
5.6.1 Evanescent Waves. Length Scales 142
5.6.2 Uncertainty Relations Revisited 143
5.7 Electromagnetic Radiation. Near Field and Far Field 143
5.7.1 Radiation from an Elementary Source (Electric Dipole) 143
5.7.2 Far-Field Radiation. Diffraction Limit Revisited 144
5.7.3 Near-Field Radiation. Quasi-Static Limit 145
5.7.4 Towards a Model 146
5.8 Dipole Emission Near a Nanostructure 146
5.8.1 Radiative Damping of Dipole Emission 147
5.8.2 Free-Space Dipole Emission 148
5.8.3 Dipole Emission Near an Object 149
5.8.4 Link with the Quantum Approach 150
5.8.5 A Simple Example: Dipole Emission Near a Plane Mirror 151
5.8.6 Dipole Emission Near a Nanoparticle.
Radiative and Non-Radiative Coupling 152
References 155

6 Emerging Nanolithographic Methods
Y. Chen, A. Pépin 157
6.1 Introduction 157
6.2 Nanoimprint Lithography 158
6.3 Applications of Nanoimprint Lithography 162
6.3.1 Microelectronics 162
6.3.2 Nanomagnetism 163
6.3.3 Nano-Optics 164
6.3.4 Chemistry and Biology 165
6.4 UV Nanoimprint Lithography (UV-NIL) 166
6.5 Nanoembossing 167
6.6 Soft Lithography 169
6.7 Near-Field Lithography 172
6.8 Conclusion 174
References 174

Part II Nanoscale Objects

7 Clusters and Colloids
A. Perez, P. Mélinon, J. Lermé, P.-F. Brevet 179
7.1 Equilibrium Shape 180
7.1.1 Liquid-Drop Model 180
7.1.2 Wulff Polyhedron 182
7.1.3 Beyond the Wulff Polyhedron 183
7.1.4 Van der Waals Binding 189
7.1.5 Covalent Binding 190
7.1.6 Ionic Binding 192
7.2 Characteristic Quantity: Radius 193
7.2.1 Thermodynamic Quantities: Melting Temperature 193
7.2.2 Electronic Quantities 196
7.3 Characteristic Quantity: Fluctuations 200
7.3.1 Melting Temperature 200
7.3.2 Kubo Model 202
7.4 Specific Quantum Effects in Nanoscale Systems and Collective Excitations 206
7.4.1 Electronic Shell Structure 207
7.4.2 Electronic Supershells 217
7.4.3 Optical Properties. Collective Excitations 225
7.5 Preparation Methods 241
7.5.1 Gas Phase Physical Methods 241
7.5.2 Liquid Phase Chemical Methods 246
7.6 Cluster or Colloid Assemblies 252
7.6.1 Assemblies of Metallic Clusters 253
7.6.2 Deposition Techniques for Clusters and Colloids 254
7.6.3 Characteristic Mechanisms for the Formation of Nanostructures by Cluster Assembly . 256
7.6.4 Examples of New Nanostructured Systems Prepared by Cluster Deposition 260
7.7 Conclusion and Prospects 266
References 277

8 Fullerenes and Carbon Nanotubes
J.-P. Bourgoin, A. Loiseau, J.-F. Nierengarten 279
8.1 Introduction 279
8.2 Nanotubes and the Crystalline Forms of Carbon 280
8.2.1 Diamond and Graphite 280
8.2.2 Discovery of Fullerenes 281
8.2.3 Discovery of Carbon Nanotubes 281
8.3 Fullerenes 282
8.3.1 Structure of Fullerenes 282

8.3.2 Production of Fullerenes 284
8.3.3 Physicochemical Properties of Buckminsterfullerene 285
8.4 Carbon Nanotubes 289
8.4.1 Crystal Structure of Nanotubes 289
8.4.2 Electronic Structure of Carbon Nanotubes 292
8.4.3 Self-Organisation of Nanotubes 300
8.4.4 Chemical Varieties of Nanotubes 301
8.4.5 Synthesis of Nanotubes 302
8.4.6 Growth Mechanism for Carbon Nanotubes 305
8.4.7 Observation of Nanotubes 308
8.4.8 Properties of Nanotubes 311
8.4.9 From Science to Applications 313
8.5 Conclusion 318
References 321

9 Nanowires
J.-C. Labrune, F. Palmino 325
9.1 Fabrication of Nanowires 326
9.2 The Top-Down Approach 327
9.2.1 Soft Lithography 327
9.2.2 Near-Field Lithography 328
9.3 The Bottom-Up Approach 332
9.3.1 Self-Assembly on a Surface 332
9.3.2 VLS Synthesis 334
9.3.3 Use of Porous Matrices 335
9.4 Electrical Conduction in Nanowires 335
9.4.1 Electrical Contacts 336
9.4.2 Incoherent Transport 342
9.4.3 Atomic Chains and Molecules 342
9.5 Conclusion 344
References 344

10 Nano-Objects
J.-F. Nierengarten, J.-L. Gallani, N. Solladié 349
10.1 Dendrimers 349
10.1.1 Divergent Synthesis 350
10.1.2 Convergent Synthesis 352
10.2 Supramolecules 353
10.2.1 Self-Assembly by 3D Template Effect Induced by a Metal Cation 354
10.2.2 Self-Assembly by Hydrogen Bonding 359
10.2.3 Self-Assembly by Hydrophobic Interactions, π-Interactions and Charge Transfer Interactions 363
10.2.4 Molecular Machines 366

10.3 Polymolecular Assemblies 368
10.3.1 Self-Assembly in the Bulk 369
10.3.2 Self-Assembly on Surfaces 372
References 378

Part III Properties and Applications

11 Ultimate Electronics
S. Galdin-Retailleau, A. Bournel, P. Dollfus 383
11.1 CMOS Technology 386
11.2 MOSFET Scaling 392
11.2.1 Basic Principles 392
11.2.2 Short Channel Effects 392
11.2.3 Scaling Rules 393
11.2.4 State of the Art: ITRS Roadmap 395
11.2.5 Interconnects 398
11.3 NanoMOS Devices 400
11.3.1 Specific Problems 400
11.3.2 Alternatives to Conventional MOSFET Devices 408
11.4 Conclusion 412
References 413

12 Alternative Electronics
J.-N. Patillon, D. Mailly 417
12.1 Characteristic Length Scales for Nanoscopic Components 418
12.2 Single-Electron Devices (SED) 419
12.2.1 Basic Ideas 419
12.2.2 Transport by Coulomb Blockade 420
12.2.3 Double Tunnel Junction 425
12.2.4 Single-Electron Transistor 427
12.3 Quantum Interference in Nanostructures 428
12.3.1 Introduction 428
12.3.2 Conductance and Transmission. The Landauer Formula 430
12.3.3 Calculating the Correction 433
12.3.4 Effect of Magnetic Fields 434
12.3.5 Universal Conductance Fluctuations 435
12.3.6 Cutoffs 437
12.4 An Example of Interference: Aharonov–Bohm Effect 437
12.5 Superconducting Nanoelectronics: RSFQ Logic 440
12.5.1 Introduction 440
12.5.2 Superconducting Logic Components 440
12.5.3 Structure and Performance of RSFQ Components 442
References 446

13 Molecular Electronics
J.P. Bourgoin, D. Vuillaume, M. Goffman, A. Filoramo 447
13.1 Basic Building Blocks: Choice, Wealth, Complexity 448
13.2 A Little History 449
13.3 Molecular Components 450
13.3.1 Electrodes and Contacts 450
13.3.2 Relationship Between Molecular Structure and Properties . 456
13.3.3 Functions 469
13.4 Components Based on Nanotubes 479
13.4.1 Field-Effect Transistors 479
13.4.2 Single-Electron Transistors (SET) 486
13.5 From Components to Circuits 490
13.5.1 Fabrication Techniques 490
13.5.2 Circuit Architecture 497
13.6 Conclusion 498
References 499

14 Nanomagnetism and Spin Electronics
C. Chappert, A. Barthélémy 503
14.1 Nanomagnetism 504
14.1.1 Vacuum Magnetostatics 504
14.1.2 Magnetism in Matter: Fundamental Relations 505
14.1.3 Magnetism in Matter: Continuum Approximation 511
14.1.4 Novel Magnetic Effects on the Nanoscale 525
14.1.5 Magnetisation Dynamics in Magnetic Nanostructures 540
14.2 Spin Electronics 552
14.2.1 Description 552
14.2.2 Origins and Mechanisms of Spin Electronics 559
14.2.3 Magnetoresistance of Tunnel Junctions 568
References 578

15 Information Storage
D. Fraboulet, Y. Samson 583
15.1 Mass Memories 583
15.1.1 Mass Memories: The Hard Disk 585
15.1.2 Beyond the Hard Disk. Local Probe Techniques 593
15.2 Matrix Memories 595
15.2.1 General Principles of Matrix Storage 595
15.2.2 Difficulties in Reducing Memory Cells to Nanoscale Sizes .. 599
15.2.3 Matrix Memory Technology in Current Use 600
15.2.4 Memory Concepts Under Development 606
15.3 Conclusion 614
References 618

16 Optronics
J.-L. Pautrat, J.-M. Gérard, É. Bustarret, D. Cassagne, E. Hadji, C. Seassal 619
16.1 Surface Plasmons and Nanoscale Optics 619
16.1.1 Introduction 619
16.1.2 What Is a Plasmon? 620
16.1.3 Dispersion Relations, Coupling with Light, and Applications 622
16.1.4 Optical Transmission Through Subwavelength Apertures 627
16.1.5 Metal Nanoparticles 629
16.1.6 How Far Can Plasmons Take Us? 633
16.2 Semiconductor Quantum Dots 634
16.2.1 Semiconductor Lasers: From Quantum Wells to Quantum Dots 634
16.2.2 Single Quantum Dots 640
16.3 Photonic Crystals and Microcavities 646
16.3.1 Introduction 646
16.3.2 Periodic Structures 646
16.3.3 Structures Without Defects. Exploiting the Allowed Bands in Photonic Crystals 653
16.3.4 Structures with Defects 656
16.3.5 Conclusion and Prospects 661
References 662

17 Nanophotonics for Biology
J. Zyss, S. Brasselet 665
17.1 Emission and Absorption of Light by Molecular Systems 676
17.2 Molecules, Supramolecular Assemblies, and Nanoparticles 686
17.2.1 Coupling Between Nanoparticles and Biomolecules 686
17.2.2 Luminescent Nanostructures Based on Semiconductors and Metals 695
17.2.3 Molecular Engineering for Biophotonics 698
17.3 Nanophotonic Instrumentation for Biology 707
17.3.1 Optical Detection of Single Molecules by Fluorescence 707
17.3.2 Multiphoton and Nonlinear Microscopy 731
17.3.3 Mechanical Properties of Single Biomolecules 737
17.4 Conclusion 743
References 746

18 Numerical Simulation
X. Blase, C. Delerue 749
18.1 Structural Properties 750
18.1.1 Interatomic Potentials and Forces 750

18.1.2 Potential Energy Surface 752
18.1.3 Classical Molecular Dynamics 753
18.1.4 Monte Carlo Methods 755
18.2 Electron Properties 757
18.2.1 Basic Results from Quantum Mechanics 757
18.2.2 Semi-Empirical Approaches to Electron Structure 759
18.2.3 Ab Initio Methods 766
18.2.4 Ab Initio Calculation of Interatomic Forces 771
18.2.5 Using Electron Wave Functions and Eigenvalues 773
18.3 Conclusion 773
References 774

19 Computer Architectures for Nanotechnology: Towards Nanocomputing
C. Gamrat 777
19.1 Introduction 777
19.2 Computer Architecture and Basic Functions 779
19.2.1 Typical Architecture of a Computer 779
19.2.2 Memory 780
19.2.3 Interconnects 782
19.2.4 Operators 782
19.2.5 Technological Considerations 783
19.2.6 Nanomemories, Nano-operators, Nanoconnections 785
19.3 Some Ideas for a New Architecture 786
19.3.1 Calculating with Memory Alone 786
19.3.2 Reconfigurable Computer Architectures 788
19.3.3 Cellular Automata 789
19.3.4 Neural Networks 791
19.4 Computer Environment 794
19.4.1 Information Coding 794
19.4.2 Defect Tolerance 794
19.5 Prospects 798
References 799

Index 801