Contents

1 Introduction 1
  1.1 The Way into the Nanoworld 1
  1.1.1 From Micro- to Nanotechniques 1
  1.1.2 Definition of Nanostructures 2
  1.1.3 Insight into the Nanoworld 3
  1.1.4 Intervention into the Nanoworld 4
  1.2 Building Blocks in Nanotechnology 5
  1.3 Interactions and Topology 7
  1.4 The Microscopic Environment of the Nanoworld 9

2 Molecular Basics 13
  2.1 Particles and Bonds 13
  2.1.1 Chemical Bonds in Nanotechnology 13
  2.1.2 Van der Waals Interactions 14
  2.1.3 Dipole–Dipole Interactions 14
  2.1.4 Ionic Interactions 16
  2.1.5 Metal Bonds 16
  2.1.6 Covalent Bonds 17
  2.1.7 Coordinative Bonds 19
  2.1.8 Hydrogen Bridge Bonds 20
  2.1.9 Polyvalent Bonds 20
  2.2 Chemical Structure 23
  2.2.1 Binding Topologies 23
  2.2.2 Building Blocks of Covalent Architecture 24
  2.2.3 Units for a Coordinative Architecture 27
  2.2.4 Building Blocks for Weakly Bound Aggregates 27
  2.2.5 Assembly of Complex Structures through the Internal Hierarchy of
    Binding Strengths 28
  2.2.6 Reaction Probability and Reaction Equilibrium 29

3 Microtechnological Foundations 33
  3.1 Planar Technology 33
  3.2 Preparation of Thin Layers 37
3.2.1 Condition and Preprocessing of the Substrate Surface 37
3.2.2 Layer Deposition from the Gas Phase 39
3.2.3 Evaporation 42
3.2.4 Sputtering 43
3.2.5 Chemical Vapor Deposition 46
3.2.6 Galvanic Deposition 48
3.2.7 Deposition by Spinning (Spin Coating) 50
3.2.8 Shadow-mask Deposition Techniques 53
3.3 Preparation of Ultrathin Inorganic Layers and Surface-bound Nanoparticles 54
3.3.1 Ultrathin Layers by Vacuum Deposition Processes 54
3.3.2 Deposition of Ultrathin Films from the Liquid Phase 55
3.3.3 In Situ Generation of Ultrathin Inorganic Films by Chemical Surface Modification 56
3.3.4 In Situ Formation of Ultrathin Inorganic Layers on Heteroorganic Materials 57
3.3.5 Immobilization of Nanoparticles 58
3.3.6 In Situ Formation of Inorganic Nanoparticles 59
3.4 Structure Generation and Fabrication of Lithographic Masks 59
3.4.1 Adhesive Mask Technique 59
3.4.2 Role of Resist in Photolithography 63
3.4.3 Serial Pattern Transfer 64
3.4.4 Group Transfer Processes 67
3.4.5 Maskless Structure Generation 68
3.4.6 Soft Lithography 68
3.5 Etching Processes 70
3.5.1 Etching Rate and Selectivity 70
3.5.2 Isotropic and Anisotropic Etching Processes 71
3.5.3 Lithographic Resolution in Etching Processes 72
3.5.4 Wet Etching Processes 73
3.5.5 Dry Etching Processes 76
3.5.6 High-resolution Dry Etching Techniques 78
3.5.7 Choice of Mask for Nanolithographic Etching Processes 80
3.6 Packaging 80
3.7 Biogenic and Bioanalogue Molecules in Technical Microstructures 84

4 Preparation of Nanostructures 87
4.1 Principles of Fabrication 87
4.1.1 Subtractive and Additive Creation of Nanostructures 87
4.1.2 Nanostructure Generation by Lift-off Processes 89
4.1.3 Principles of Nanotechnical Shape-definition and Construction 91
4.2 Nanomechanical Structure Generation 96
4.2.1 Scaling Down of Mechanical Processing Techniques 96
4.2.2 Local Mechanical Cutting Processes 97
4.2.3 Surface Transport Methods 97
4.2.4 Reshaping Processes 98
4.2.5 Soft Lithography for Nanopatterning and Nanoimprinting 101
4.3 Nanolithography 105
4.3.1 Structure Transfer by Electromagnetic Radiation 105
4.3.2 DUV- and Vacuum-UV Lithography 108
4.3.3 EUV and X-ray Lithography 110
4.3.4 Multilayer Resist Techniques with Optical Pattern Transfer 113
4.3.5 Near-field Optical Micropatterning Techniques 114
4.3.6 Energetic Particles in Nanolithographic Structure Transfer 116
4.3.7 Electron Beam Lithography 117
4.3.8 Ion Beam Lithography 124
4.3.9 Atomic Beam Lithography 126
4.3.10 Molecular and Nanoparticle Beam Lithography 126
4.3.11 Direct Writing of Structures by a Particle Beam 127
4.3.12 Nanostructure Generation by Accelerated Single Particles 130
4.3.13 Patterning by Local Chemical Conversion 132
4.3.14 Nanofabrication by Self-structuring Masks 132
4.4 Nanofabrication by Scanning Probe Techniques 133
4.4.1 Mechanical Surface Modifications based on Scanning Force Microscopy (SFM) 134
4.4.2 Manipulation by a Scanning Tunneling Microscopy (STM) 135
4.4.3 Thermo-mechanical Writing of Nanostructures 137
4.4.4 Electrically Induced Structure Generation by Scanning Probe Techniques 138
4.4.5 Chemical Induced Scanning Probe Structure Generation 143
4.4.6 Nanostructure Generation by Optical Near-field Probes 145
4.4.7 Scanning Probe Methods for Nanoscale Transfer 146
4.5 Reduction of Feature Sizes by Post-Lithographic Processing 146
4.5.1 Narrowing of Nanogaps by Material Deposition 146
4.5.2 Size Reduction by Thermally Induced Reshaping 147
4.5.3 Size Reduction by Sidewall Transfer 148
4.5.4 Formation of Nanodots by Dewetting 148

5 Nanotechnical Structures 149
5.1 Nanostructures and Nanomaterials 149
5.2 Inorganic Solids 150
5.2.1 Influence of Material Morphology on Nanoscale Pattern Processes 150
5.2.2 Inorganic Dielectrics 150
5.2.3 Metals 152
5.2.4 Semiconductors 154
5.3 Carbon Nanostructures 156
5.4 Organic Solids and Layer Structures 158
5.4.1 Solids Composed of Smaller Molecules 158
5.4.2 Organic Monolayer and Multilayer Stacks 158
5.4.3 Synthetic Organic Polymers 160
5.4.4 Biopolymers 161
5.5 Molecular Monolayer and Layer Architectures 162
5.5.1 Langmuir–Blodgett Films 162
5.5.2 Self-assembled Surface Films 164
5.5.3 Binding of Molecules on Solid Substrate Surfaces 165
5.5.4 Secondary Coupling of Molecular Monolayers 167
5.5.5 Categories of Molecular Layers 168
5.5.6 Molecular Coupling Components (Linkers) and Distance Components (Spacers) 171
5.5.7 Definition of Binding Spots on Solid Substrates 172
5.6 Molecular Architectures 174
5.6.1 Single Molecules as Nanostructures 174
5.6.2 Strategies of Molecular Construction 178
5.6.3 Biogenic and Bio-analogous Nanoarchitectures 182
5.6.4 DNA Nanoarchitectures 185
5.6.5 Synthetic Supramolecules 192
5.6.6 Nanoparticles and Nanocompartments 200
5.7 Combination of Molecular Architectures and Nanoparticles With Planar Technical Structures 202

6 Characterization of Nanostructures 211
6.1 Geometrical Characterization 211
6.1.1 Layer Thickness and Vertical Structure Dimensions 211
6.1.2 Lateral Dimensions 215
6.1.3 Structures that Assist Measurement 216
6.2 Characterization of Composition of Layers and Surfaces 217
6.2.1 Atomic Composition 217
6.2.2 Characterization of the Chemical Surface State 220
6.3 Functional Characterization of Nanostructures 223

7 Nanotransducers 225
7.1 Design of Nanotransducers 225
7.2 Nanomechanical Elements 227
7.2.1 Nanomechanical Sensors 227
7.2.2 Nanometer-precision Position Measurements with Conventional Techniques 228
7.2.3 Electrically Controlled Nanoactuators 228
7.2.4 Chemically Driven Nanoactuators 230
7.2.5 Rigidity of Nanoactuators 234
7.3 Nanoelectronic Devices 235
7.3.1 Electrical Contacts and Nanowires 235
7.3.2 Nanostructured Tunneling Barriers 240
7.3.3 Quantum Dots and Localization of Elementary Particles 242
7.3.4 Nanodiodes 243
7.3.5 Electron Islands and Nanotransistors 244