

Contents

Preface to the Second Edition *xxi*

Part I Background to Materials Chemistry 1

- 1 What Is Materials Chemistry? 3
 - A. Different Types of Materials 3
 - B. The Role of Chemistry in Materials Science 6
 - C. Structure–Property Correlations 7
 - D. Uses of Materials 8
 - E. Approaches to Producing New Materials with Novel Properties 10
 - F. The Interface with Technology 11
 - G. A Broader Perspective 11
 - H. Terminology 12
 - I. Example Journals Where Materials Science Publications Can Be Found 12
 - J. Study Questions (for Class Discussions or Essays) 13

- 2 Fundamental Principles that Underlie Materials Chemistry 15
 - A. Why Are Different Materials Different? 15
 - B. The Role of Different Elements 15
 - C. Different Types of Chemical Bonds 17
 1. Van der Waals Forces and the Lennard-Jones Potential 17
 2. Covalent Bonds 18
 - a. Bond Angles 19
 - b. Bond Lengths 24
 - c. Bond Torsion 25
 - d. Bond Polarity 27
 3. Coordinate Bonds 27
 - a. Main Group Elements 27
 - b. Transition Metals 28
 - c. Bonding in the Lanthanide Elements 29
 4. Hydrogen Bonding 30
 5. Ionic Assemblies 30
 6. Metallic Bonding 31
 7. Electronic Energy Bands and Band Gaps 31
 - D. Size of the Molecular Units 33
 - E. Different Shapes of the Component Molecules and the Influence on Solid-state Structure 34
 - F. Ultrastructures 37

- G. Color 37
 - 1. Emission of Colored Light 38
 - 2. Absorption of Specific Wavelengths of Visible Light 38
 - H. Further Reading 38
 - I. Study Questions (for Class Discussions or Essays) 39
- 3 Background to Basic Synthesis and Reaction Chemistry 41
- A. Overview and Underlying Principles 41
 - B. Element Isolation Processes 42
 - 1. Reaction of an Oxide at High Temperatures with Carbon or Hydrogen 43
 - 2. Reaction of an Oxide with an Element that Has a Greater Affinity for Oxygen 44
 - 3. Isolation via Chlorination or Oxidation 44
 - 4. Electrolytic Reduction 44
 - 5. Microbial Extraction of Metals 44
 - 6. Pyrolysis and Vapor Deposition 45
 - C. Techniques for Materials Synthesis 46
 - 1. Classical "Wet Chemistry" 46
 - 2. Molten-state Chemistry 46
 - 3. Vapor State and Vapor/Solid Reactions 47
 - 4. Chemical Vapor Deposition 47
 - D. Reaction Kinetics 47
 - E. Separations 48
 - 1. Importance of Separation Methods 48
 - 2. Differential Solubility 48
 - 3. Differential Volatility 48
 - 4. Ion Exchange Columns, Chromatography, and Gel Permeation Methods 48
 - F. Materials-related Reaction Chemistry 49
 - 1. Formation of Inter-element Compounds 49
 - 2. Importance of Halides in Materials Synthesis 49
 - 3. Oxides 50
 - 4. Acidic Hydroxides and Condensation Reactions to Oxides 50
 - 5. Hydrides, Sulfides, Nitrides, and Carbides 52
 - 6. Metathetical Exchange Reactions 53
 - 7. Nucleophilic Substitution 53
 - 8. Electrophilic Substitution 54
 - 9. Coordination Chemistry 55
 - 10. Organometallic Chemistry 55
 - 11. Branching and Cross-linking 57
 - 12. Polymerization–depolymerization Equilibria 58
 - 13. Small Rings, Cages, and Short Chains 59
 - G. Further Reading 59
 - H. Study Questions (for Class Discussions or Essays) 59
- 4 Chemistry of Representative Elements Utilized in Materials Science 61
- A. General Comments 61
 - B. Nonmetals 61
 - 1. Carbon Chemistry 61
 - a. The Element 64
 - b. Organic Compounds from Oil 64

- c. Free Radical Reactions 65
 - d. Oxidation Reactions 65
 - e. Addition Across Double or Triple Bonds 66
 - f. Formation of Organometallic Compounds 67
2. Silicon Chemistry 67
- a. The Element 67
 - b. Silicon Reaction Chemistry 68
 - c. Differences from Carbon Compounds 70
3. Boron Chemistry 70
- a. The Element 70
 - b. Borides 70
 - c. Borates 71
 - d. Boron Halides 72
 - e. Boron Hydrides 72
4. Phosphorus Chemistry 72
- a. The Element 73
 - b. Phosphides 74
 - c. Phosphorus Halides 74
 - d. Phosphorus Acids, Phosphates, and Phosphites 75
 - e. Organo-phosphorus Chemistry (Phosphines, Phosphine Oxides, Phosphites, and Phosphate Esters) 75
 - f. Phosphorus in Polymers 75
5. Nitrogen, Oxygen, and Sulfur Chemistry 75
- C. Main Group Metals 76
- D. Transition Metals 78
- E. Lanthanide and Actinide Elements 82
- F. Further Reading 83
- G. Study Questions (for Class Discussions or Essays) 84
- 5 Structure Determination and Special Techniques for Materials Characterization 85
- A. Purpose 85
 - B. Analysis of Bulk Materials 85
 - 1. Elemental Microanalysis 85
 - 2. Infrared–Raman Spectroscopy 85
 - 3. Solid-state Nuclear Magnetic Resonance Spectroscopy 86
 - 4. Thermal Analysis 87
 - a. Differential Scanning Calorimetry 87
 - b. Thermogravimetric Analysis (TGA) 88
 - c. Thermomechanical Analysis (TMA) 89
 - 5. Stress–strain and Impact Analysis 89
 - 6. X-ray Diffraction 92
 - a. Powder X-ray Diffraction 92
 - b. Wide Angle X-ray Diffraction (WAX) and Small Angle Diffraction (SAX) 93
 - c. Single-crystal X-ray Diffraction 94
 - 7. Refractive Index and Chromatic Dispersion 94
 - a. Refractive Index (RI) 94
 - b. Chromatic Dispersion 96
 - 8. Magnetic Susceptibility 96
 - 9. Electrical Conductivity 98

- 10. Transmission Electron Microscopy 100
- C. Surface and Thin Film Analysis Techniques 101
 - 1. Scanning Electron Microscopy (SEM) 101
 - 2. Scanning Tunneling Microscopy (STM) and Atomic Force Microscopy (AFM) 102
 - a. Scanning Tunneling Microscopy 102
 - b. Atomic Force Microscopy 103
 - 3. X-ray Photoelectron Spectroscopy (XPS) 104
 - 4. Total Internal Reflection Infrared Spectroscopy 105
 - 5. Ellipsometry 105
 - 6. Contact Angles 106
- D. Solution Analysis Techniques 107
 - 1. General Comments 107
 - 2. Solution-state NMR Spectroscopy 107
 - 3. Solution-state Light Scattering Techniques 107
 - 4. Gel Permeation Chromatography 107
- E. Further Reading 109
- F. Study Questions (for Class Discussions or Essays) 109

Part II Different Types of Materials 111

- 6 Small Molecules in Solids 113
 - A. Importance of Small-molecule Materials 113
 - B. Packing of Small Molecules in the Solid State 113
 - 1. Shape Fitting 114
 - 2. Dipolar or Charged Molecules 115
 - 3. Hydrogen Bonding 115
 - C. Self-assembly by Crystallization 115
 - D. Spherical Molecules in the Solid State 116
 - E. Disk-shaped Molecules and Other Flat Structures 116
 - 1. General Observations 116
 - 2. Liquid Crystallinity from Disk-shaped Molecules 117
 - 3. Electronic Phenomena from Disk- or Wafer-shaped Molecules in the Solid State 119
 - F. Rod-shaped Molecules 121
 - G. Charge-transfer Complexes 122
 - H. Further Reading 123
 - I. Study Questions (for Class Discussions or Essays) 124
- 7 Porous Solids 125
 - A. Significance 125
 - B. Clathrate Systems (Inclusion Compounds) 125
 - 1. General Description 125
 - 2. Clathrates of Water Ice 126
 - 3. Urea and Thiourea 128
 - 4. Perhydrotriphenylene (PHTP) 128
 - 5. Cyclophosphazenes 130
 - 6. Cyclodextrins, Cryptates, and Crown Ethers 131
 - 7. Hofmann and Werner-type Complexes 132
- C. Metal-organic Frameworks 133
 - 1. General Characteristics of MOFs 133
 - 2. Synthesis of MOFs 133
 - 3. Uses of MOFs 134
- D. Zeolites 135
- E. Inverse Opals and Related "Colloidal Crystal Templated" Structures 137
- F. Molecular Imprinting Technology 138
- G. Other Porous Materials 139
- H. Further Reading 140
- I. Study Questions (for Class Discussions or Essays) 141

8 Ceramics and Inorganic Glasses 143

- A. Overview 143
- B. Oxide Ceramics 143
- C. Oxide Ceramics and Glasses Obtained or Produced Directly from Mineralogical Materials 145
 - 1. General Observations 145
 - 2. Silica, Silicates, and Aluminosilicates – General Characteristics 145
 - 3. Aluminosilicate Clays and Related Minerals – Properties and Structure 150
 - 4. Chrysotile and Other Forms of Asbestos 156
 - 5. Ceramic Composites 157
 - 6. Glasses 157
 - a. General Features 157
 - b. Methods of Glass Formation 157
 - c. Silicate Glasses 158
 - d. Pyrex-type Glass 159
 - e. Glass Ceramics 159
 - f. "Gorilla" Glass 159
 - g. Phosphate Glasses 160
 - h. Borate Glasses 160
 - i. Fabrication of Glasses 160
- D. Oxide Ceramics and Glasses from Small-molecule Inorganic and Organometallic Precursors 160
 - 1. Optical Waveguides (Optical Fibers) 161
 - 2. The Sol-gel Process for Low-temperature Ceramics Formation 161
 - 3. Zeolites 165
 - 4. Hydrothermal Synthesis 165
 - 5. Calcium Hydroxyapatite (HAP) 165
 - 6. Other Oxide Ceramics 166
- E. Perovskites 166
- F. Color in Oxide Ceramics 167
- G. Non-oxide Ceramics and Related Materials 168
 - 1. General Aspects 168
 - 2. Silicon Carbide (SiC) 168
 - 3. Silicon Nitride (Si₃N₄) 172
 - 4. Boron Nitride (BN) and Other Boron-containing Ceramics 174

- 5. Aluminum Nitride (AlN) 175
 - 6. Other Ceramics Formed by Preceramic Polymer Processes 176
 - H. Fabrication of Ceramics and Glasses 176
 - 1. General Comments 176
 - 2. "Sculpting" 176
 - 3. Melting, Extrusion, and Molding 177
 - 4. Powder Sintering 177
 - 5. Sol-gel Fabrication 178
 - I. Future Challenges in Ceramics and Glass Science 178
 - J. Suggestions for Further Reading 179
 - K. Study Questions (for Class Discussions or Essays) 179
- 9 Polymers: Fundamental Aspects 181
- A. Overview 181
 - B. Synthesis of Polymers 182
 - 1. General Principles 182
 - 2. Addition Polymerization 182
 - a. Polymerization Mechanism 182
 - b. Free Radical Initiation 188
 - c. Atom Transfer Radical Polymerization (ATRP) 190
 - d. Anionic Initiation 191
 - e. Coordination Initiation 192
 - f. Cationic Initiation 194
 - 3. Condensation Polymerization 195
 - 4. Ring-opening Polymerization 196
 - 5. Electrochemical Polymerization 197
 - 6. Secondary Reactions 198
 - a. Modification of Polymer Structure 198
 - b. Cross-linking Reactions 198
 - C. Structure-property Relationships and Polymer Design 198
 - 1. Influence of Molecular Architecture 198
 - a. Linear Polymers 198
 - b. Variations within the Linear Chain Architecture 199
 - c. Random or Regular Copolymers 200
 - d. Block Copolymers 200
 - e. Branched Structures, Stars, and Dendrimers 200
 - f. Combs and Grafts 200
 - g. Combinations of Rings and Chains 201
 - 2. Molecular Weights and Distributions 201
 - 3. Chain Flexibility 201
 - 4. Influence of Different Skeletal Elements and Backbone Bonding 202
 - 5. Specific Influence of Different Side Groups 202
 - D. Examples of Classical Polymeric Materials 203
 - 1. Polymers Produced by Addition Reactions 204
 - a. Polyethylene 204
 - b. PTFE or Teflon[®] 204
 - c. Polystyrene 205
 - d. PMMA 205
 - 2. Polyurethanes (End-functionalized Addition Reactions) 205
 - 3. Polymers Produced by Condensation Reactions 205
 - a. PET, Dacron[®], or Mylar[®] 205
 - b. Poly(hexamethylene adipamide) (Nylon 66) 206
 - c. Poly(*p*-phenylene terephthalamide) (Kevlar) 206
 - d. Synthetic Polypeptides 206
 - e. Polyimides 206
 - f. Polycarbonates 207
 - g. Polysulfones 207
 - h. Polyether Ketones (PEK) and Polyether Ether Ketones (PEEK) 207
 - i. Epoxy Polymers 207
 - j. Condensation Resins 207
 - 4. Polymers Produced by Ring-opening Polymerizations 207
 - a. Poly(lactic-glycolic acid) (PLGA) 207
 - b. Polycaprolactam (Nylon-6) 208
 - c. Polytetrahydrofuran 208
 - d. PEO 208
 - E. Inorganic Elements in Polymers 208
 - 1. Rationale and Terminology 208
 - 2. Poly(dimethylsiloxane) (PDMS, Silicone Rubber) 209
 - 3. Polyphosphazenes 210
 - 4. Polysilanes (by Condensation and Ring-opening Polymerizations) 213
 - 5. Poly(ferrocenylsilanes) 213
 - 6. Organic Polymer Chains with Organometallic Side Groups 214
 - 7. Electronically Conductive Polymers 214
 - F. Further Reading 214
 - G. Study Questions (for Class Discussions or Essays) 215
- 10 Polymer Morphology and Fabrication 217
- A. Overview 217
 - B. Consequences of Cross-Linking 217
 - C. Polymers in the Solid State 217
 - 1. Chain Entanglement 217
 - 2. Microcrystallinity 218
 - 3. Liquid Crystallinity (LC) 220
 - D. Composites 221
 - 1. Different Types of Multicomponent Systems 221
 - 2. Important Mechanical Properties 222
 - 3. Polymer Composite Materials 223
 - 4. Homogeneous Versus Heterogeneous Polymeric Solids 224
 - 5. Defects in Solids 224
 - 6. Polymer Alloys - Blends 225
 - 7. Interpenetrating Polymer Networks 226
 - 8. Polymer-Ceramic "Alloys" (Ceramers) 227
 - 9. Heterophase Materials - General Observations 227
 - 10. Reasons for Polymer-Phase Segregation 228
 - 11. Phase-Separated Polymer-Polymer Composites 228
 - 12. Phase-Separated Block Copolymers 229

- 13. Filled Thermoplastics and Thermosetting Materials 231
 - 14. Laminates 231
 - 15. Biomineralization 232
 - E. Soft Matter 232
 - 1. Overview 232
 - 2. Elastomers 232
 - 3. Organogels 233
 - 4. Hydrogels 233
 - F. Color in Synthetic Polymers 233
 - G. Fabrication of Polymers 234
 - 1. Solution Casting of Films 234
 - 2. Melt-Fabrication of Films 235
 - 3. Fabrication of Fibers 235
 - 4. Injection Molding 235
 - 5. Thermoforming 236
 - 6. Blow Molding 236
 - 7. Sintering 236
 - 8. Polymerization Combined with Fabrication 236
 - 9. Multilayer Assembly of Films 236
 - 10. Three-dimensional Printing 236
 - H. Future Challenges in Polymeric Materials Science 237
 - I. Further Study 238
 - J. Study Questions (for Class Discussions or Essays) 238
- 11 Carbon-Based Materials 241**
- A. Background 241
 - B. Diamond 241
 - C. Carbon Fiber 243
 - D. Glassy Carbon (Vitreous Carbon) 245
 - E. Amorphous Carbon 245
 - F. Fullerenes 246
 - G. Graphite 247
 - H. Graphene 248
 - 1. Background 248
 - 2. Synthesis 249
 - 3. Chemical Modification 249
 - I. Carbon Nanotubes 249
 - 1. Description 249
 - 2. Synthesis and Fabrication 250
 - 3. Useful Properties 251
 - J. sp^3 Nanofibers 251
 - K. Graphene or Nanotube Analogs: Relationship of Carbon Materials to Other Layered and Fibrous Solids 252
 - L. Further Reading 253
 - M. Study Questions (for Class Discussions or Essays) 254
- 12 Metals and Alloys 257**
- A. Important Aspects of Metal Science and Technology 257
 - 1. Background 257
 - 2. Advantages and Disadvantages of Metals as Materials 258

- 3. Major Differences Between Transition and Main Group Metals 258
- 4. Scope of this Chapter 258
- B. Isolation of Specific Metals from Their Ores 259
 - 1. Iron and Steel 259
 - 2. Nickel 262
 - 3. Chromium 262
 - 4. Aluminum 262
 - 5. Magnesium 263
 - 6. Titanium 263
 - 7. Tin 264
 - 8. Copper 264
 - 9. Silver 265
 - 10. Gold 265
 - 11. Lanthanide Elements 265
- C. The Solid-State Structure of Metals and Alloys 266
 - 1. Packing of Spheres 266
 - 2. Slip Planes, Dislocations, and Grain Boundaries in Metals 268
 - 3. Homogeneous Metallic Alloys 270
 - 4. Phase-Separated Metal Alloys 271
- D. Corrosion 272
- E. Electrical Conductivity 274
- F. Thermal Conductivity of Metals 276
- G. Magnetic Properties of Metals 277
- H. The Color of Metals 277
- I. Mechanical Properties of Metals 279
- J. Fabrication of Metals 279
- K. Future Challenges in Metal Materials Science 280
- L. Further Reading 280
- M. Study Questions (for Class Discussions or Essays) 281

- 13 Superconductors 283**
- A. Overview 283
 - B. Nomenclature 285
 - C. Synthesis of High-Temperature Superconductors 286
 - D. Solid-State Structure 287
 - E. Theories of Superconductivity 290
 - F. Other Superconducting Systems 291
 - G. Current and Proposed Uses of Superconductors 291
 - H. Challenges for the Future 292
 - I. Further Reading 292
 - J. Study Questions (for Class Discussions or Essays) 293

Part III Materials in Advanced Technology 295

- 14 Semiconductor Basics 297**
- A. Importance of Semiconductors 297
 - B. Logic and Memory Devices 297
 - C. Semiconductor Principles 298

- 1. Composition 298
 - 2. The Band Gap 298
 - 3. Electron and Hole Mobilities 300
 - 4. Direct and Indirect Band Gap Semiconductors 300
 - 5. Dopants 301
 - 6. Importance of Oxidation Behavior 302
 - D. Preparation of Semiconductor-Grade Silicon and Compound Semiconductors 302
 - 1. Single-Crystal Silicon 302
 - 2. Polycrystalline Silicon 303
 - 3. Amorphous Semiconductor Silicon 304
 - 4. Compound Semiconductors 304
 - E. Polymeric Semiconductors 305
 - 1. Rationale 305
 - 2. Polythiazyl (Polysulfur Nitride) 305
 - 3. Polyacetylene and Its Semiconduction Mechanism 307
 - 4. Poly(Phenylene Vinylene) 310
 - 5. Poly(Para-Phenylene) 311
 - 6. Polypyrrole and Polythiophene 311
 - 7. Polyaniline 311
 - 8. Graphite and Related Layered Solids 312
 - F. Further Reading 312
 - G. Study Questions (for Class Discussions or Essays) 312
- 15 Photolithography and Microlithography 315**
- A. The Process 315
 - 1. Terminology 315
 - 2. The Role of Chemistry 315
 - 3. Principles of Semiconductor Fabrication 315
 - 4. Overview of the Semiconductor Manufacturing Process 316
 - a. Microlithography Principles 316
 - b. The Overall Sequence of Steps in Microlithography 317
 - 5. Equipment 318
 - a. Microlithography Masks 318
 - b. Microlithography Equipment 319
 - c. Pellicles 320
 - d. Steppers 320
 - B. Photoresists 320
 - 1. General Features of Resists 320
 - 2. Novolac Positive Tone Resists 320
 - 3. Chemical Amplification 321
 - 4. Poly(4-Hydroxystyrene) Resists 322
 - 5. Multilayer Lithography 322
 - 6. All-Dry Resists 322
 - C. Electron Beam Lithography 323
 - D. X-Ray Lithography 323
 - E. Circuit Wiring 323
 - F. Further Reading 323
 - G. Study Questions (for Class Discussions or Essays) 324

- 16 Semiconductor Devices 325**
 - A. Overview 325
 - B. Simple Devices Based on the Presence of a Single Semiconductor Unit 325
 - 1. Thermistors 325
 - 2. Photocells 325
 - C. Components of Metal Oxide Integrated Circuit (MOS) 326
 - 1. Overview 326
 - 2. Transistors and the P-N Junction 326
 - 3. Integrated Circuits 327
 - 4. Memory Chips 328
 - 5. Capacitors 329
 - 6. Rectifiers 329
 - D. Other Devices Based on a P-N Junction 330
 - 1. Influence of the Fermi Level 330
 - 2. Photovoltaic Cells: Generation of Electric Power from Light 332
 - a. The Bilayer-Doped Silicon Cell 332
 - b. Bilayer Cells Comprised of Two Different Semiconductors 334
 - c. Polymer-based Photovoltaic Cells 334
 - d. Perovskite Solar Cells 334
 - e. Dye-based Photovoltaic Cells 334
 - 3. Conversion of Electric Power to Light 335
 - a. Light-Emitting Diodes (LEDs) 335
 - b. Semiconductor Lasers and Pointers 336
 - c. Organic Oligomeric and Polymeric Light-Emitting Devices (OLEDs) 338
 - 4. Imaging Sensors 339
 - E. Light Frequency Conversion: Quantum Dots 341
 - F. Challenges in Semiconductor Materials Science 341
 - G. Further Reading 342
 - H. Study Questions (for Class Discussions or Essays) 342
- 17 Optical and Photonic Devices 345**
 - A. Overview 345
 - 1. The Production of Light 345
 - 2. Passive Versus Responsive Optical Materials 346
 - 3. Importance of Refractive Index 346
 - 4. Optical Dispersion 348
 - 5. Optical Birefringence 350
 - 6. Origins of Color in Optical Materials 351
 - B. Passive Optical Devices 351
 - 1. Materials and Devices for Passive Optical Applications 351
 - 2. General-Purpose Optical Materials 352
 - 3. Lenses and Prisms 352
 - 4. Optical Waveguides 353
 - 5. Waveguide Multiplex/Demultiplex Devices 355
 - 6. Optical Color Filters 356
 - 7. Optical Polarizing Filters 357
 - C. Responsive Optical Materials 359
 - 1. General Observations 359

- 2. Liquid Crystalline (LC) Devices 359
 - 3. Photochromic Materials 361
 - 4. Nonlinear Optical Materials and Devices 363
 - a. The Phenomenon 363
 - b. Origins of NLO Behavior 364
 - c. Inorganic NLO Crystals 366
 - d. Organic NLO Materials 366
 - e. Poling 366
 - f. Orientation by Self-Assembly 366
 - g. Devices 366
 - 5. Electrochromic Devices 369
 - 6. Thermochromism as an Alternative to Photochromism 371
 - D. Challenges for the Future 371
 - E. Further Reading 371
 - F. Study Questions (for Class Discussions or Essays) 372
- 18 Materials and Devices for Energy Generation and Storage 375**
- A. General Observations 375
 - B. Fuel Cells 377
 - 1. Background 377
 - 2. General Principles 377
 - 3. Polymer Electrolyte Membrane (PEM) Fuel Cells 379
 - 4. Phosphoric Acid Fuel Cells 383
 - 5. Alkaline Fuel Cells 383
 - 6. Molten Carbonate Fuel Cells 384
 - 7. Solid Oxide Fuel Cells 385
 - C. Battery Electrolyte Materials 386
 - 1. Background 386
 - 2. Lithium Ion "(Rocking Chair)" Batteries 387
 - 3. Principles Behind Lithium Ion Transport Membranes 388
 - 4. Metallic Lithium/Solid Polymer or Gel Electrolyte Batteries 390
 - 5. Example Polymers for Lithium Battery Applications 391
 - 6. Lithium-Seawater Batteries 392
 - 7. Solid-State Batteries 393
 - D. Capacitors and Supercapacitors 393
 - E. Challenges for the Future 394
 - 1. Materials for Future Fuel Cell Development 394
 - 2. Materials for Future Battery Science and Technology 395
 - 3. Materials for Improved Capacitors and Supercapacitors 396
 - F. Further Reading 396
 - G. Study Questions (for Class Discussions or Essays) 397
- 19 Membranes 399**
- A. Background 399
 - B. Porous Membranes 400
 - 1. Mechanism of Operation 400
 - 2. Fabrication of Porous Membranes 400
 - 3. Microfiltration Membranes 401

- C. Membranes that Function by a Chemical Reaction 401
 - D. Nonporous Membranes that Function Through Physical Interactions 401
 - 1. Underlying Principles 401
 - 2. Desalination Membranes 403
 - 3. Poly(dimethylsiloxane) Membranes for Oxygen and Carbon Dioxide Separations 403
 - 4. Dialysis Membranes 404
 - 5. Membranes for Controlled Drug Delivery 404
 - E. Gel Membranes 404
 - 1. General Principles 404
 - 2. Gel Membranes as On-Off Switching Systems 405
 - F. Testing of Membranes 406
 - 1. Gas Separations 406
 - 2. Liquid Separations 407
 - 3. Controlled Drug Release and Dialysis Membranes 407
 - G. Sound Transducer Membranes 408
 - 1. Principle of Operation 408
 - 2. Poly(Vinylidene Fluoride) 409
 - 3. Ceramic-Type Piezoelectric Materials 410
 - H. Challenges for the Future 410
 - I. Further Reading 411
 - J. Study Questions (for Class Discussions or Essays) 412
- 20 Surface Science of Materials 413**
- A. Perspective 413
 - B. Summary of Surface Characterization Methods 414
 - C. Surfaces of Metals 414
 - 1. Significant Aspects 414
 - 2. Etching of Metal Surfaces 414
 - 3. Heterogeneous Catalysis by Metals 415
 - 4. Metal Surfaces by Vapor Deposition, Sputtering, or Solution Reactions 415
 - 5. Corrosion of Metal Surfaces 416
 - D. Ceramic Surfaces 416
 - 1. Oxide Ceramic Surfaces 416
 - 2. Chemical Modification of Glass Surfaces 416
 - 3. Non-Oxide Ceramic Fiber Surfaces 417
 - 4. Ceramic Surface Decomposition by Pollutants 417
 - E. Polymer Surfaces 417
 - 1. General Characteristics of Polymer Surfaces 417
 - 2. Unusual Aspects of Polymer Surfaces 417
 - 3. Chemical Modification of Polymer Surfaces 418
 - 4. Polymer Surfaces in Offset Lithography Printing 419
 - 5. Plasma Modification of Polymer Surfaces 420
 - 6. Influence of Polymer Fabrication Method 420
 - 7. Surfaces of Micro- and Nanofibers 420
 - 8. Role of Block Copolymers at Surfaces 421
 - 9. Layer-by-Layer Assembly 421

- F. Surfaces of Semiconductors 423
 - 1. Oxidation of Silicon Surfaces 423
 - 2. High Surface Area Semiconductors 423
 - G. Assembly of Molecules on Surfaces 423
 - 1. Langmuir-Blodgett Techniques 423
 - 2. Self-Assembly on Gold Surfaces 425
 - 3. Surface Patterning by AFM 426
 - H. Adhesion and Surface Chemistry 426
 - 1. General Characteristics of Adhesion 426
 - 2. Chemical Bonding as a Source of Adhesion 426
 - 3. Physical Bonding of Surfaces 426
 - I. Relationship of Adhesion to Other Materials Topics 427
 - 1. Soft Contact Printing 427
 - 2. Biomedical Materials Surfaces 427
 - J. Further Reading 428
 - K. Study Questions (for Class Discussions or Essays) 429
- 21 Biomedical Materials 431
- A. Special Requirements for Biomedical Materials 431
 - B. Traditional Biomedical Materials 432
 - 1. Metals 433
 - 2. Ceramics 433
 - 3. Biostable Polymers 434
 - 4. Bioerodible Polymers 437
 - a. Collagen 437
 - b. Alginates 437
 - c. Poly(lactic-glycolic acid) (PLGA) (14) 437
 - d. Polyanhydrides (15) 438
 - e. Polycaprolactone and poly(trimethylene carbonate) 438
 - f. Bioerodible polyphosphazenes (21) 438
 - C. Materials for Specific Medical Applications 438
 - 1. Cardiovascular Materials 438
 - a. General Features 438
 - b. Prosthetic Heart Valves 439
 - c. Artificial Heart Pumps 440
 - d. Replacement Blood Vessels and Arterial Reinforcement Materials 441
 - e. Stents 441
 - f. Renal Dialysis and Blood Oxygenation 441
 - g. Pacemaker Materials 442
 - 2. Surgical Sutures, Clips, and Staples 442
 - 3. Orthopedic Materials 442
 - 4. Optical Material in Medicine 443
 - 5. Controlled Drug and Vaccine Delivery 443
 - a. Membranes 443
 - b. Antibacterial Surfaces 445
 - c. Responsive Hydrogels 445
 - d. Bioerodible Drug Release Systems 445
 - e. Microspheres, Vesicles, and Micelles 445
 - 6. Tissue Engineering 447
- D. Immobilization of Enzymes and Cells 448
 - 1. Purpose 448
- E. Fabrication and Testing of Biomedical Materials 449
 - 1. Fabrication 449
 - 2. Evaluation of Biomedical Materials 449
- F. Unsolved Challenges in Biomedical Materials Research 450
- G. Further Reading 451
- H. Study Questions (for Class Discussions or Essays) 452
- 22 Miniaturization in Materials Science 453
- A. Background 453
 - B. Definitions 453
 - C. Motivation 454
 - D. Nanostructures and Novel Properties 455
 - E. Synthesis and Fabrication of Nanostructures 456
 - 1. "Top-Down" Nanostructure Preparation 456
 - 2. "Bottom-Up" Assembly Methods 457
 - F. Examples of Classical Nanostructures 458
 - 1. Nanofibers 458
 - 2. Nanowires 459
 - 3. Nanoscale Particles 459
 - a. Carbon Nanoparticles 459
 - b. Ceramic Nanospheres 459
 - c. Polymer Nanospheres 460
 - d. Metal Nanoparticles 460
 - e. Semiconductor Nanoparticles 460
 - f. Plasmonics 460
 - g. Micelles 462
 - 4. Nanochannels and Nanotunnels 462
 - a. Clathrate and Zeolite Nanotunnels 462
 - G. Molecular Machines 462
 - 1. Overview 462
 - 2. Building Blocks for Molecular Machines 463
 - H. Special Challenges in Nano-Electronics, Photonics, and Molecular Machines 464
 - I. Molecular-Size Constructs 465
 - 1. Perspective 465
 - 2. Fullerenes 465
 - 3. Polyhedral Boranes and Carboranes 465
 - 4. Organic Spintronics 466
 - J. Major Challenges and Opportunities in Miniaturization Science and Technology 466
 - K. Further Reading 467
 - L. Study Questions (for Class Discussions or Essays) 468
- Appendix Terminology 469
- Index 475