

NANO SCIENCE AND NANO TECHNOLOGY

SUNDAR SINGH



A Pragati Edition

Contents

1. PRELIMINARIES IN NANOSCIENCE

1-26

- 1.1 Nanoscience 1
- 1.2 Nanotechnology 2
- 1.3 History of Nanotechnology 4
- 1.4 Size Dependence of Properties: Nanomaterials 5
- 1.5 Nanotechnology in Various Fields 6
- 1.6 Moore's Law 9
- 1.7 Length Scales 11
- 1.8 Crystal Structure 14
 - 1.8.1. Bravais Lattices in Two Dimensions 15
 - 1.8.2. Bravais Lattices in Three Dimensions 15
- 1.9. Close Packing of Structures 18
- 1.10 Simple Crystal Structures 19
 - 1.10.1. Single Element Crystals 19
 - 1.10.2. Compound Crystals 21
- Solved Examples** 23
- Review Questions** 25

2. BAND STRUCTURE OF SOLIDS

27-57

- 2.1 Free Electron Theory 27
 - 2.1.1 Free Electron Gas in One Dimension 28
 - 2.1.2 Fermi Energy 30
 - 2.1.3. Density of (Electronic) States 31
- 2.2 The Band Theory of Solids 32
- 2.3 Distinction between Conductors, Insulators, and Semiconductors 34
 - I. Insulators 34
 - II. Conductors 34
 - III. Semiconductors 35
- 2.4 Energy Bands and Band Gaps of Semiconductors 35
- 2.5 Effective Mass 39
- 2.6 Fermi Surfaces 42
- 2.7 Localized Particles 44
- 2.8 Deep Traps Versus Shallow Traps 47
- 2.9 Mobility 48
 - 2.9.1 Effects of Temperature and Impurity Concentration on Mobility
- 2.10 Excitons 51
- 2.11 Types of Exciton 52

I.	Mott-Wannier Exciton	52
II.	Frenkel Exciton	53
	Solved Examples	53
	Review Questions	56

3. QUANTUM NANOSTRUCTURES : QUANTUM WELLS, WIRES AND DOTS

58-96

3.1	Low Dimensional Structures and Materials	58
3.2	Classification of Low Dimensional Materials	59
3.3	Quantum Size Effects	59
3.4	Quantum Confinement	61
3.5	Preparation of Quantum Nanostructures	62
	I. Bottom-up Methods	62
	II. Top-down Methods	63
3.6	Fabrication of Quantum Dot Arrays	64
3.7	Quantum Well and Superlattice	65
	3.7.1 Application of Schroedinger Equation to Infinite Potential Well	67
3.8	Quantum Wires	69
	3.8.1 Application of Schroedinger Equation to the Problem of Particle in 2D Box	70
3.9	Quantum Dots	73
	3.9.1 Application of Schroedinger Equation to a Particle in Quantum Box (3D)	73
3.10	Particle in an Infinite Circular Box: Two Dimensions of Confinement	76
3.11	Particle in an Infinite Spherical Box: 3D Confinement	79
3.12	Application of Schroedinger Equation to the Potential Step	82
3.13	Nanodots and Quantum Dots (0D)	87
3.14	Nanowires and Nanorods (1D)	88
3.15	Thin Films (2D)	89
3.16	Three Dimensional Nanostructured Materials	89
	Solved Examples	90
	Review Questions	95

4. DENSITY OF STATES

97-107

4.1	Introduction	97
4.2	Density of States in Three Dimensions (Bulk)	97
4.3	Density of States in Two Dimensions (Quantum Well)	99
4.4	Density of States in One Dimension (Quantum Wire)	101
4.5	Density of States in Zero Dimensional System (Quantum Dot)	103
4.6	Comparison of DOS for 3D, 2D, 1D and 0D Nanostructures	104
	Solved Examples	104
	Review Questions	106

5. SYNTHESIS OF NANOMATERIALS—PHYSICAL METHODS 108–141

- 5.1 Introduction 108
- 5.2 Factors Affecting Synthesis of Nanoparticles 108
- 5.3 Top-down Approaches 110
- 5.4 Bottom-up Approaches 112
- 5.5 Ball Milling 113
- 5.6 Photolithography 116
- 5.7 Electron-beam Lithography 119
- 5.8 X-ray Lithography 122
- 5.9 Gas Phase Condensation 125
- 5.10 Vacuum Deposition 127
- 5.11 Physical Vapour Deposition (PVD) 128
 - 5.11.1 Thermal Evaporation 129
 - 5.11.2 E-beam Evaporation 131
 - 5.11.3 Sputtering Deposition 132
 - 5.11.4 Pulsed Laser Deposition (PLD) 134
 - 5.11.5 Thermal Evaporation versus Sputtering 136
- 5.12 Molecular Beam Epitaxy (MBE) 136
 - 5.12.1 MBE Growth of Quantum Dots 137
- 5.13 Cluster Beam Evaporation 139

Review Questions 140

6. SYNTHESIS OF NANOMATERIALS—CHEMICAL METHODS 142–172

- 6.1 Introduction 142
- 6.2 Chemical Vapour Deposition (CVD) 142
 - 6.2.1 Classification of CVD Processes 144
 - 6.2.2 Characteristics of CVD Coatings 146
 - 6.2.3 CVD Apparatus 146
 - 6.2.4 Precursors 146
 - 6.2.5 Materials Produced by CVD Processes 147
- 6.3 Metal Organic Chemical Vapour Deposition (MOCVD) 147
- 6.4 Thin Film Deposition Methods 148
- 6.5 Sol-Gel Process 149
- 6.6 Electrodeposition 151
- 6.7 Spray Pyrolysis 153
- 6.8 Solvothermal Synthesis 155
- 6.9 Hydrothermal Synthesis 156
- 6.10 Colloidal Synthesis 158
- 6.11 LaMer and Dinegar Growth Model 161
- 6.12 Capping Agents and Surfactants 168

6.13 Chemical Bath Deposition (CBD)	170
<i>Review Questions</i>	171

7. SOME TECHNIQUES FOR CRYSTAL GROWTH AND DEVICE FABRICATION

173-192

7.1 Czochralski Method of Crystal Growth	173
7.1.1 Beneficial Effects of Oxygen Impurities	174
7.1.2 Negative Effects of Oxygen Impurities	175
7.2 Oxidation	175
7.2.1 Thermal Oxidation System	176
7.3 Diffusion	177
7.4 Ion Implantation	180
7.5 Etching	182
7.6 Types of Etching	183
I. Wet Etching	183
II. Dry (or Plasma) Etching	185
III. Reactive Ion Etching	186
7.7 Metallization	186
(a) Metallization Materials	188
(b) Metallization Techniques	189

Solved Examples 191

Review Questions 192

8. CHARACTERIZATION TECHNIQUES-I

193-211

8.1 Introduction	193
8.2 Atomic Structures	193
8.3 X-Ray Crystallography	194
8.4 Debye-Scherrer Method	196
8.5 Particle Size Determination	197
8.6 Surface Structures	198
I. Low Energy Electron Diffraction (LEED)	198
II. Reflection High Energy Electron Diffraction (RHEED)	199
8.7 Increase in Width of XRD Peaks of Nanoparticles	200
8.7.1 Instrumental Broadening	201
8.7.2 Broadening due to Sample Imperfection	201
8.8 Scherrer Formula	202
8.9 Disorder of Second kind and Peak Broadening	202
8.10 Shifts in Absorption Spectra Peaks of Nanoparticles	203
8.11 Shifts in Photoluminescence (PL) Peaks	204
8.12 Small Angle X-Ray Scattering (SAXS)	206

Solved Examples 208
Review Questions 211

9. CHARACTERIZATION TECHNIQUES-II (Optical and Electron Microscopy)

212-242

- 9.1 Introduction 212
 - 9.2 Optical Microscopy 213
 - 9.2.1 Compound Microscope 214
 - 9.2.2 Diffraction and Abbe's Theory of Imaging 215
 - 9.2.3 Rayleigh's Criterion of Resolution 216
 - 9.2.4 Defects in Lenses 216
 - 9.2.5 Sample Preparation 217
 - 9.2.6 Image Contrast 217
 - 9.3 Fluorescence Microscopy 217
 - 9.4 Field Ion Microscopy (FIM) 224
 - 9.5. Transmission Electron Microscope (TEM) 226
 - 9.6. Scanning Electron Microscope (SEM) 229
 - 9.7. Scanning Probe Microscopy (SPM) 233
 - 9.8 Scanning Tunneling Microscope (STM) 234
 - 9.9 Atomic Force Microscope (AFM) 238
- Review Questions** 241

10. SPECTROSCOPIC TECHNIQUES

242-271

- 10.1 Introduction 243
- 10.2 Ultraviolet-Visible (UV-Vis) Spectroscopy 243
- 10.3 Infrared (IR) Spectroscopy 247
- 10.4 Fourier Transform Infrared (FTIR) Spectroscopy 250
- 10.5 Raman Spectroscopy 254 —
- 10.6 Photoluminescence (PL) Spectroscopy 259
- 10.7 Nuclear Magnetic Resonance (NMR) 263
 - (a) Introduction 263
 - (b) Theory of NMR 263
 - (c) Analysis of NMR: Bloch Equations 265
 - (d) Chemical Shifts 268
 - (e) Structure of Fullerenes 269
 - (f) Applications of NMR 269
 - (g) Advantages 269

Solved Examples 269

Review Questions 270

11. MULTIPLE BEAM INTERFEROMETRY

- 11.1 Introduction 272
- 11.2 Characteristics of Multiple Beam Interference Pattern 273
- 11.3 Tolanski Fringes 274
- 11.4 Conditions for High Precision Measurement 275
- 11.5 Optical Arrangement for Multiple Beam Interferometry 276
- 11.6 Preparation of Samples 277
- 11.7 Applications of Multiple Beam Interferometry 278
- 11.8 Elevation Measurements by Transmitted Light 280
- 11.9 Importance of Interferometry 281
- Review Questions 281**

12. NANOTECHNOLOGY IN CARBON MATERIALS

- 12.1 Introduction to Carbon 282
- 12.2 Carbon Clusters 283
- 12.3 Fullerenes 284
- 12.4 Properties of C_{60} and its Derivatives 285
- 12.5 Types of Fullerenes 286
- 12.6 Synthesis of Fullerenes 286
- 12.7 Endohedral Fullerenes 287
- 12.8 Applications of Fullerenes 287
- 12.9 Carbon Nanotubes (CNTs) 287
- 12.10 Types of Carbon Nanotubes 288
- 12.11 Synthesis of Carbon Nanotubes 288
 - I. Electric Arc Discharge Method 289
 - II. Laser Ablation Method 289
 - III. Chemical Vapour Deposition (CVD) Method 290
- 12.12 Separation of Metallic and Semiconducting Nanotubes 291
- 12.13 Structure of Carbon Nanotubes 291
- 12.14 Properties of Carbon Nanotubes 294
- 12.15 Electrical Properties of CNTs 294
- 12.16 Mechanical Properties of CNTs 297
- 12.17 Thermal Properties of CNTs 298
- 12.18 Applications of Carbon Nanotubes 298
 - I. Field Emission Applications 299
 - II. CNTs in Conductive Plastics and Shielding 299
 - III. Energy Storage in Fuel Cells 299
 - IV. CNTs in Computers 300
 - V. CNTs in Catalysis 301
 - VI. CNTs in Chemical Sensors 302

VII. Mechanical Reinforcement	302
VIII. Biomedical Applications	302
IX. Other Applications	303
12.19 Nanotubes of Other (Inorganic) Materials	303
12.19.1 Advantaes of Inorganic Nanotubes	304
12.19.2 Potential Applications of Inorganic Nanotubes	304
Review Questions	305

13. PHYSICAL PROPERTIES OF NANOMATERIALS 307–318

13.1 Introduction	307
13.2 Surface Energy	307
13.3 Melting Point Depression	307
13.3.1 Lattice Constant of Nanoparticles	311
13.4 Mechanical Properties of Nanomaterials	312
13.5 Optical Properties of Nanomaterials	313
13.6 Electrical Properties of Nanomaterials	314
13.7 Superparamagnetism	316
Review Questions	318

14. NANOMATERIAL DEVICES AND APPLICATIONS OF NANOMATERIALS 319–352

14.1 Applications of Quantum Dots	319
14.1.1 Quantum Dots in Solar Cells	320
14.1.2 Quantum Dots in LEDs	321
14.1.3 Quantum Dots in Display Technologies	322
14.1.4 Medical Applications of Quantum Dots	322
14.2 Applications of Nanowires	323
14.2.1 Nanowires in Solar Cells	323
14.2.2 Nanowires in Light Emitting Diodes (LEDs)	325
14.3 Single Electron Devices	325
14.3.1 Single Electron Transistor (SET)	325
14.3.2 Applications of SEDs	328
14.4 CNT Based Transistors	329
14.4.1 Single Wall Carbon Nanotube Field Effect Transistor (SWNT FET)	330
14.4.2 Comparison of CNTFET with Conventional FET	331
14.4.3 Applications of CNT Based Transistors	331
14.5 Heterostructures	332
14.5.1 Quantum Dot Heterostructures (QDHS) Laser	332
14.6 Optical Switching	334
14.6.1 Optical Storage	335

- 14.6.2 Optical Storage Devices 336
- 14.6.3 Advantages of Optical Storage Devices 337
- 14.6.4 Drawbacks of Optical Storage Devices 337
- 14.7 Magnetic Storage 337
 - 14.7.1 Read/Write Heads 338
 - 14.7.2 Types of Magnetic Recording 338
 - 14.7.3 Access Methods 339
 - 14.7.4 Uses of Magnetic Storage 339
 - 14.7.5 Types of Magnetic Storage Devices 339
 - 14.7.6 Traditional versus New Magnetic Storage Technologies 340
- 14.8 Giant Magnetoresistance (GMR) 341
- 14.9 Magnetic Random Access Memory (MRAM) 341
- 14.10 Microelectromechanical Systems (MEMS) 342
 - 14.10.1 Microelectromechanical Devices 344
- 14.11 Nanoelectromechanical Systems (NEMS) 345
 - 14.11.1 Resonant Frequency 346
 - 14.11.2 Materials for Active Parts of NEMS 346
 - 14.11.3 Active Mass 347
 - 14.11.4 Quality Factor 347
 - 14.11.5 Characteristics of NEMS 347
 - 14.11.6 Advantages of NEMS 348
 - 14.11.7 Negative Impacts of NEMS 348
 - 14.11.8 Challenges in the Development of NEMS 349
 - 14.11.9 Fabrication of NEMS : Nanoimprint Lithography 349
 - 14.11.10 Applications of NEMS 350
- Review Questions 351**