

# Contents

**Preface to Second Edition** *ix*

**Acknowledgments** *x*

**Introduction to Second Edition** *1*

## **1 Size Matters** *13*

- 1.1 The Fundamental Importance of Size *13*
- 1.2 The Magnetic Behavior of Nanoparticles *16*
- 1.3 The Mechanical Properties of Nanostructured Materials *26*
- 1.4 The Chemical Properties of Nanoparticles *27*
- 1.5 Nanoparticles Interacting with Bacteria and Viruses *29*
- Problems *31*
- References *32*

## **2 Nanoparticles and the Environment** *35*

- 2.1 Nanoparticles in the Atmosphere *35*
- 2.2 Atmospheric Nanoparticles and Health *39*
  - 2.2.1 Entry Via the Lungs *39*
  - 2.2.2 Entry Via the Intestines *42*
  - 2.2.3 Nanoparticles and the Skin *43*
  - 2.2.4 Air Quality Specifications *44*
- 2.3 Nanoparticles and Clouds *44*
- 2.4 Marine Aerosol *48*
- 2.5 Effect of Cosmic Rays on Atmospheric Aerosol *50*
- 2.6 Nanoparticles in Space *51*
- 2.7 Environmental Applications of Nanoparticles *52*
  - 2.7.1 Water Remediation Using Magnetic Nanoparticles *52*
  - 2.7.2 Conversion of Waste Plastics to High-Grade Materials (Upcycling) *55*
- Problems *57*
- References *59*

## **3 Carbon Nanostructures: Bucky Balls and Nanotubes** *61*

- 3.1 Why Carbon? *61*
- 3.2 Discovery of the First Fullerene – C<sub>60</sub> *62*
- 3.3 Structural Symmetry of the Closed Fullerenes *64*
- 3.4 Smaller Fullerenes and “Shrink-Wrapping” Atoms *68*
- 3.5 Larger Fullerenes *70*
- 3.6 Electronic Properties of Individual Fullerenes *72*

- 3.7 Materials Produced by Assembling Fullerenes (Fullerites and Fullerides) 76
- 3.8 Discovery of Carbon Nanotubes 81
- 3.9 Structure of Single-Wall Carbon Nanotubes (SWNTs) 82
- 3.10 Electronic Properties of SWNTs 84
- 3.11 Electronic Transport in Carbon Nanotubes 86
- 3.12 Field Emission from Carbon Nanotubes 87
- 3.13 Mechanical Properties of Nanotubes 88
- 3.14 Thermal Conductivity of Nanotubes 92
- 3.15 Carbon Nanohorns 93
- 3.16 Carbon Nanobuds and Pea Pods 94
- Problems 95
- References 96

## 4 Graphene 99

- 4.1 Background 99
  - 4.1.1 Low-Dimensional Materials 99
  - 4.1.2 Discovery of Graphene 101
- 4.2 Electrical Properties of Graphene 101
  - 4.2.1 Electrical Conduction in Normal Metals 101
  - 4.2.2 Electrical Conduction in Semiconductors 104
  - 4.2.3 Electrical Conduction in Graphene 107
- 4.3 Graphene as a Testbed for Relativistic Quantum Effects 112
- 4.4 Thermal Conductivity of Graphene 112
- 4.5 Mechanical Strength of Graphene 116
- 4.6 Superconductivity in Graphene Bilayers 117
- 4.7 Current Technological Applications of Graphene 120
  - 4.7.1 Graphene Batteries 120
  - 4.7.2 Graphene Nanoelectromechanical Systems (NEMS) Accelerometers 124
  - 4.7.3 Graphene Membranes for Water Desalination 125
- 4.8 Summary 126
  - Problems 126
  - References 128

## 5 The Nanotechnology Toolkit 131

- 5.1 Making Nanostructures Using Bottom-Up Methods 131
  - 5.1.1 Making Nanoparticles Using Supersaturated Vapor 131
  - 5.1.2 Sources Producing Nanoparticle Beams in Vacuum 133
  - 5.1.3 Synthesis of Alloy, Core-Shell, and Janus Nanoparticles 137
  - 5.1.4 Mass Selection of Charged Nanoparticle Beams in Vacuum 141
  - 5.1.5 Aerodynamic Lensing and Mass Selection of Neutral Nanoparticles 147
  - 5.1.6 Plasma, Spark and Flame Metal Aerosol Sources 147
  - 5.1.7 Size Selection of Nanoparticles in Aerosols 150
  - 5.1.8 Chemical Synthesis of Nanoparticles in Liquid Suspensions 153
  - 5.1.9 Biological Synthesis of Magnetic Nanoparticles 156
  - 5.1.10 Gas-Phase Synthesis of Hydrosols 157
  - 5.1.11 Size Determination of Nanoparticles in Liquids 157
  - 5.1.12 Synthesis of Graphene 160
  - 5.1.13 Synthesis of Fullerenes 162
  - 5.1.14 Synthesis of Carbon Nanotubes 163
  - 5.1.15 Controlling the Growth of SWNTs 165

5.2	Making Nanostructures Using Top-Down Methods	167
5.2.1	Electron-Beam Lithography	168
5.2.2	Manufacturing Nanostructures Using Focused Ion Beams	171
5.3	Combining Bottom-up and Top-Down Nanostructures	176
5.4	Imaging, Probing, and Manipulating Nanostructures	180
5.4.1	Scanning Tunneling Microscope	180
5.4.2	Manipulating Atoms and Molecules with STM	185
5.4.3	Scanning Tunneling Spectroscopy (STS)	189
5.4.4	Atomic Force Microscopy	192
5.4.5	AFM Imaging of Biological Samples in Liquids	195
5.4.6	Dip-Pen Nanolithography	198
5.4.7	Electron Microscopy	200
	Problems	204
	References	206
<b>6</b>	<b>Single-Nanoparticles Devices</b>	<b>211</b>
6.1	Data Storage on Magnetic Nanoparticles	211
6.2	Quantum Dots	218
6.3	Quantum Dot Solar Cells	222
6.4	Nanoparticles as Transistors	226
6.5	Carbon Nano-Electronics	232
6.5.1	Fullerene SET	232
6.5.2	Porphyrin Molecule SET	234
6.5.3	Carbon Nanotube SET	236
6.5.4	Limitations of SETs in Applications and Moving to Multiple Transistor Devices	236
6.6	Carbon Nanotube Light Emitters and Detectors	239
	Problems	240
	References	240
<b>7</b>	<b>Hydrosols, Nanobubbles, and Nanoscale Interfaces</b>	<b>243</b>
7.1	Reynolds Number	243
7.2	Brownian Motion	245
7.3	Stability of Hydrosols	250
7.4	Nanobubbles	257
7.4.1	Fundamental Considerations	257
7.4.2	Synthesis of Bulk Nanobubbles	260
7.4.3	Properties of Bulk Nanobubbles	262
7.4.4	Surface Nanobubbles	265
7.4.5	Applications of Nanobubbles	267
7.5	Nanofluidics	271
	Problems	277
	References	278
<b>8</b>	<b>Magic Beacons and Magic Bullets: The Medical Applications of Functional Nanoparticles</b>	<b>281</b>
8.1	Nanoparticles Interacting with Living Organisms	282
8.1.1	Targeted Nanovectors for Therapy and Diagnosis	282
8.1.2	Uptake of Nanomaterials by the Body	284
8.1.3	Types of Core Nanoparticle in Nanovectors	286
8.1.4	Targeting to Tumors by Enhanced Permeability and Retention (EPR)	288
8.1.5	Some Elementary Cell Biology	289

8.1.5.1	The Outer Cell Membrane (Plasma Membrane)	290
8.1.5.2	Membrane Proteins	291
8.1.5.3	Internal Cell Structure	292
8.1.5.4	Cytoskeleton	292
8.1.6	“Trojan horse” Targeting Using Stem Cells and Macrophages	294
8.1.7	Molecular Targeting	296
8.1.8	Magnetic Targeting	302
8.2	Treatment of Tumors by Hyperthermia	304
8.2.1	Biological Response to Heating	304
8.2.2	Magnetic Nanoparticle Hyperthermia (MNH)	307
8.2.2.1	Current State of the art in Clinical Trials	307
8.2.2.2	Limitations on the Applied RF Magnetic Field	309
8.2.2.3	Heating Mechanisms of Magnetic Nanoparticles in an AMF	311
8.2.2.4	New Nanoparticles for MNH	316
8.2.3	Optical Hyperthermia Using Near-Infrared Radiation	318
8.2.4	Hyperthermia with Carbon Nanotubes	326
8.3	Medical Diagnosis and “Theranostics” using Nanomaterials	327
8.3.1	Magnetic Resonance Imaging (MRI) and Contrast Enhancement Using Magnetic Nanoparticles	328
8.3.2	Magnetic Particle Imaging (MPI)	331
8.3.3	Imaging Using Au Nanoparticles	337
8.3.4	Imaging Using QDs	339
8.4	Antibacterial and Antiviral Applications of Nanoparticles	343
8.4.1	Nanoparticle Delivery Systems for Covid 19 Vaccines	343
8.4.2	Antibacterial Action of Ag Nanoparticles	343
8.4.3	Antiviral Action of Nanoparticles	346
	Problems	347
	References	348
<b>9</b>	<b>Radical Nanotechnology</b>	<b>355</b>
9.1	Locomotion for Nanobots and Nanofactories	356
9.1.1	Movement Within the Nanofactory using Kinesin	356
9.1.2	Moving Small Cargo in the Nanofactory: DNA Walkers	364
9.1.3	Propulsion for Swimmers	369
9.2	Onboard Processing for Nanomachines	374
9.3	Medical Micro/Nanobots	374
9.4	Molecular Assembly	376
	Problems	379
	References	379
<b>10</b>	<b>Prodding the Cosmic Fabric</b>	<b>381</b>
10.1	Zero-Point Energy of Space	381
10.2	The Casimir Force	385
10.3	The Casimir Force in Micro- and Nanomachines	389
10.4	Controlling the Casimir Force Using Phase-Change Materials	394
10.5	Repulsive Casimir Forces	395
	Problems	397
	References	398
	<b>Glossary</b>	<b>401</b>
	<b>Index</b>	<b>403</b>