

# Contents

|   |    |
|---|----|
| <b>Foreword</b> .....   | V  |
| References .....  | IX |
| <b>Preface</b> .....  | XI |
| <b>Introduction to the Important and Exciting Aspects of<br/>Carbon-Nanotube Science and Technology</b> |    |
| David Tománek, Ado Jorio, Mildred S. Dresselhaus, and Gene<br>Dresselhaus .....                         | 1  |
| 1 Introduction .....  | 1  |
| 2 Applications and Metrology .....  | 3  |
| 3 Synthesis .....   | 4  |
| 4 Defect Control .....  | 5  |
| 5 Mechanical and Thermal Properties .....   | 5  |
| 6 Electronic Structure and Atomic Arrangement .....   | 6  |
| 7 Advances in Photophysics .....  | 8  |
| 8 Transport Properties.....   | 9  |
| 9 Double-Wall Carbon Nanotubes .....  | 10 |
| 10 Chemical Reactivity .....  | 10 |
| 11 Related Structures.....  | 10 |
| 12 Graphene .....   | 11 |
| 13 Outlook .....  | 11 |
| Index .....   | 12 |
| <b>Potential Applications of Carbon Nanotubes</b>   |    |
| Morinobu Endo, Michael S. Strano, and Pulickel M. Ajayan .....  | 13 |
| 1 Introduction .....  | 13 |
| 2 Applications of Carbon Nanotubes .....  | 16 |
| 2.1 Carbon Nanotubes in Electronics .....   | 17 |
| 2.2 Carbon Nanotubes in Energy Applications .....   | 22 |
| 2.3 Carbon Nanotubes for Mechanical Applications .....  | 27 |
| 2.4 Carbon-Nanotube Sensors .....   | 31 |
| 2.5 Carbon Nanotubes in Field Emission<br>and Lighting Applications .....                               | 36 |
| 2.6 Carbon Nanotubes for Biological Applications .....  | 38 |

|     |  |    |
|-----|--|----|
| 2.7 | Carbon Nanotubes in Miscellaneous Applications . . . . .       | 42 |
| 2.8 | Environmental and Health Effects of Carbon Nanotubes . . . . . | 45 |
| 3   | Conclusions . . . . .  | 46 |
|     | References . . . . .   | 49 |
|     | Index . . . . .  | 61 |

### Carbon-Nanotube Metrology

|       |  |    |
|-------|--|----|
|       | Ado Jorio, Esko Kauppinen, and Abdou Hassanien . . . . .           | 63 |
| 1     | Introduction . . . . .   | 63 |
| 2     | Electronic Microscopy . . . . .                                    | 65 |
| 2.1   | Introduction . . . . .   | 65 |
| 2.2   | Sample Preparation . . . . .                                       | 66 |
| 2.3   | Morphology . . . . .   | 67 |
| 2.4   | Atomic Structure by HRTEM . . . . .                                | 68 |
| 2.5   | Chiral Indices Determination by Electron Diffraction . . . . .     | 70 |
| 2.5.1 | Bessel-Function Analysis . . . . .                                 | 70 |
| 2.5.2 | Intrinsic Layerline Distance Analysis . . . . .                    | 70 |
| 3     | Scanning Probe Microscopy . . . . .                                | 71 |
| 3.1   | Introduction . . . . .   | 71 |
| 3.2   | Sample Preparation . . . . .                                       | 73 |
| 3.3   | Imaging the Structure and Electronic Properties of SWNTs . . . . . | 73 |
| 3.4   | Single-Electron States of SWNTs . . . . .                          | 76 |
| 3.5   | Defects . . . . .  | 77 |
| 3.6   | Local Vibrational Spectroscopy in SWNTs . . . . .                  | 78 |
| 4     | Optics . . . . .   | 79 |
| 4.1   | Basic Principles . . . . .   | 79 |
| 4.2   | Optical Absorption . . . . .                                       | 82 |
| 4.3   | Resonance Raman Spectroscopy . . . . .                             | 83 |
| 4.3.1 | The Radial Breathing Mode (RBM) . . . . .                          | 85 |
| 4.3.2 | The Tangential Modes (G Band) . . . . .                            | 87 |
| 4.3.3 | The Disorder-Induced Feature (D Band) . . . . .                    | 89 |
| 4.3.4 | Other Raman Features . . . . .                                     | 89 |
| 4.4   | Photoluminescence . . . . .  | 90 |
| 5     | Summary and Outlook . . . . .                                      | 91 |
|       | References . . . . .   | 93 |
|       | Index . . . . .  | 99 |

### Carbon Nanotube Synthesis and Organization

|     |   |     |
|-----|---|-----|
|     | Ernesto Joselevich, Hongjie Dai, Jie Liu, Kenji Hata,<br>and Alan H. Windle . . . . . | 101 |
| 1   | Introduction . . . . .  | 102 |
| 2   | Bulk Production Methods . . . . .   | 103 |
| 2.1 | Arc Discharge and Laser Vaporization . . . . .  | 103 |
| 2.2 | Chemical Vapor Deposition (CVD) . . . . .   | 103 |
| 2.3 | Mass Production . . . . .   | 105 |

|       |  |     |
|-------|--|-----|
| 2.4   | Toward Selective Synthesis . . . . .   | 106 |
| 3     | Purification . . . . .   | 107 |
| 3.1   | Dry Methods . . . . .  | 107 |
| 3.2   | Wet Methods . . . . .  | 108 |
| 4     | Sorting . . . . .  | 109 |
| 4.1   | Classification of Sorting Methods and Selective Processes . . . . .              | 109 |
| 4.2   | Nondestructive Sorting . . . . .   | 110 |
| 4.3   | Selective Elimination . . . . .  | 114 |
| 4.4   | General Principles and Perspectives of Sorting . . . . .                         | 115 |
| 5     | Organization into Fibers . . . . .   | 116 |
| 5.1   | Processing Principles . . . . .  | 117 |
| 5.2   | Liquid Suspensions of Carbon Nanotubes . . . . .                                 | 118 |
| 5.3   | Spinning Carbon Nanotube Fibers from Liquid-Crystalline Suspensions . . . . .    | 119 |
| 5.4   | Wet Spinning of CNT Composite Fibers . . . . .                                   | 120 |
| 5.5   | Dry Spinning from Carbon Nanotube Forests . . . . .                              | 122 |
| 5.6   | Direct Spinning from Carbon Nanotube Fibers from the CVD Reaction Zone . . . . . | 123 |
| 6     | Organization on Surfaces . . . . .   | 125 |
| 6.1   | Vertically Aligned Growth and Supergrowth . . . . .                              | 126 |
| 6.1.1 | Supergrowth . . . . .  | 126 |
| 6.1.2 | SWNT-Solid . . . . .   | 131 |
| 6.2   | Organized Assembly of Preformed Nanotubes . . . . .                              | 133 |
| 6.3   | Horizontally Aligned Growth . . . . .  | 137 |
| 6.3.1 | Field-Directed Growth . . . . .  | 137 |
| 6.3.2 | Flow-Directed Growth . . . . .   | 139 |
| 6.3.3 | Surface-Directed Growth: “Nanotube Epitaxy” . . . . .                            | 141 |
| 6.3.4 | Patterned Growth on Surfaces . . . . .   | 147 |
| 7     | Summary and Outlook . . . . .  | 148 |
|       | References . . . . .   | 149 |
|       | Index . . . . .  | 163 |

### **Mechanical Properties, Thermal Stability and Heat Transport in Carbon Nanotubes**

Takahiro Yamamoto, Kazuyuki Watanabe, and Eduardo R. Hernández 165

|       |  |     |
|-------|--|-----|
| 1     | Introduction . . . . .   | 165 |
| 2     | Mechanical Properties and Thermal Stability of Nanotubes . . . . . | 167 |
| 2.1   | Elasticity at the Nanoscale . . . . .                              | 167 |
| 2.2   | Mechanical Properties of Nanotubes: Elastic Regime . . . . .       | 167 |
| 2.3   | Beyond the Elastic Regime . . . . .                                | 172 |
| 2.4   | Thermal Stability of Nanotubes . . . . .                           | 175 |
| 2.5   | Summary of Mechanical Properties and Thermal Stability . . . . .   | 177 |
| 3     | Heat-Transport Properties . . . . .                                | 178 |
| 3.1   | Ballistic Heat Transport in SWNTs . . . . .                        | 178 |
| 3.1.1 | Landauer Theory for Phonon Transport . . . . .                     | 178 |

|       |  |     |
|-------|--|-----|
| 3.1.2 | Quantization of Thermal Conductance . . . . .              | 180 |
| 3.1.3 | Electron Contribution to the Thermal Conductance . . . . . | 181 |
| 3.2   | Quasiballistic Heat Transport in SWNTs . . . . .           | 182 |
| 3.2.1 | Length Effect of the Thermal Conductivity . . . . .        | 182 |
| 3.2.2 | Influence of Defects on the Thermal Conductivity . . . . . | 184 |
| 3.3   | Diffusive Heat Transport in SWNTs . . . . .                | 185 |
| 3.4   | Heat Transport in MWNTs . . . . .                          | 186 |
| 3.5   | Summary of Heat Transport . . . . .                        | 188 |
| 4     | Summary and Outlook . . . . .                              | 188 |
|       | References . . . . .                                       | 189 |
|       | Index . . . . .  | 194 |

**Quasiparticle and Excitonic Effects in the Optical Response of Nanotubes and Nanoribbons**

|   |  |     |
|---|--|-----|
|   | Catalin D. Spataru, Sohrab Ismail-Beigi, Rodrigo B. Capaz, and Steven G. Louie . . . . . | 195 |
| 1 | Introduction . . . . .   | 196 |
| 2 | Methodology . . . . .  | 197 |
| 3 | First-Principles Studies of the Optical Spectra of SWNTs . . . . .                       | 199 |
| 4 | Diameter and Chirality Dependence of Exciton Properties . . . . .                        | 204 |
| 5 | Symmetries and Selection Rules of Excitons . . . . .                                     | 206 |
| 6 | Radiative Lifetime . . . . .   | 210 |
| 7 | Pressure, Strain and Temperature Effects . . . . .                                       | 214 |
| 8 | Related Structures: Boron-Nitride Nanotubes and Graphene Nanoribbons . . . . .           | 216 |
| 9 | Conclusion . . . . .   | 221 |
|   | References . . . . .   | 222 |
|   | Index . . . . .  | 227 |

**Role of the Aharonov–Bohm Phase in the Optical Properties of Carbon Nanotubes**

|   |   |     |
|---|---|-----|
|   | Tsuneya Ando . . . . .                                    | 229 |
| 1 | Introduction . . . . .                                    | 229 |
| 2 | Effective-Mass Description . . . . .                      | 229 |
| 3 | Excitons . . . . .  | 233 |
| 4 | Exciton Fine Structure and Aharonov–Bohm Effect . . . . . | 236 |
| 5 | Exciton Absorption for Crosspolarized Light . . . . .     | 240 |
| 6 | Optical Phonons . . . . .                                 | 242 |
|   | References . . . . .                                      | 246 |
|   | Index . . . . .   | 249 |

**Excitonic States and Resonance Raman Spectroscopy of Single-Wall Carbon Nanotubes**

|     |  |     |
|-----|--|-----|
|     | Riichiro Saito, Cristiano Fantini, and Jie Jiang . . . . . | 251 |
| 1   | Introduction . . . . .                                     | 251 |
| 1.1 | Outline . . . . .  | 251 |

|     |   |     |
|-----|---|-----|
| 1.2 | Overview of Resonance Raman Measurements . . . . .                            | 252 |
| 1.3 | Overview of the Raman Intensity Calculation . . . . .                         | 253 |
| 2   | Measurement of Raman Spectra . . . . .  | 255 |
| 2.1 | Raman Spectra of SWNTs . . . . .  | 255 |
| 2.2 | The Radial Breathing Mode . . . . .   | 255 |
| 2.3 | G-Band . . . . .  | 257 |
| 2.4 | D-Band . . . . .  | 260 |
| 2.5 | G'-Band . . . . .   | 261 |
| 2.6 | Intermediate-Frequency Modes . . . . .  | 262 |
| 2.7 | Other Two-Phonon Modes . . . . .  | 264 |
| 3   | Resonance Raman Profile . . . . .   | 264 |
| 3.1 | Experimental Optical Transition Energies . . . . .                            | 264 |
| 4   | Electron-Phonon and Electron-Photon Matrix Elements . . . . .                 | 267 |
| 4.1 | Extended Tight-Binding Method for Electrons and Phonons . . . . .             | 267 |
| 4.2 | Dipole Approximation for the Optical Matrix Element . . . . .                 | 269 |
| 4.3 | Electron-Phonon Matrix Element Calculation . . . . .                          | 270 |
| 4.4 | Extension to the Exciton Matrix Element Calculation . . . . .                 | 272 |
| 4.5 | Raman Intensity Calculation . . . . .   | 275 |
| 4.6 | RBM and G-Band: Length, Type, Chirality,<br>and Diameter Dependence . . . . . | 276 |
| 5   | Future Directions, Summary . . . . .  | 279 |
|     | References . . . . .  | 280 |
|     | Index . . . . .   | 285 |

## Photoluminescence: Science and Applications

|     |  |     |
|-----|--|-----|
|     | Jacques Lefebvre, Shigeo Maruyama, and Paul Finnie . . . . .         | 287 |
| 1   | Introduction . . . . .   | 287 |
| 2   | Basic Photoluminescence Spectroscopy of Isolated Nanotubes . . . . . | 288 |
| 2.1 | Model . . . . .  | 288 |
| 2.2 | Absorption . . . . .   | 290 |
| 2.3 | Photoluminescence from Isolated SWNTs . . . . .                      | 291 |
| 2.4 | Photoluminescence Excitation Map . . . . .                           | 293 |
| 2.5 | Exciton Picture . . . . .  | 296 |
| 3   | Spectroscopic Properties of Nanotube Photoluminescence . . . . .     | 298 |
| 3.1 | Lineshape . . . . .  | 298 |
| 3.2 | Polarization . . . . .   | 299 |
| 3.3 | Quantum Efficiency . . . . .   | 300 |
| 3.4 | Photoluminescence Imaging . . . . .                                  | 303 |
| 3.5 | Time Dependence . . . . .  | 304 |
| 3.6 | Phonons . . . . .  | 305 |
| 4   | Physical and Chemical Effects . . . . .                              | 306 |
| 4.1 | External Environment . . . . .                                       | 306 |
| 4.2 | External Physical Parameters . . . . .                               | 308 |
| 5   | Applications . . . . .   | 310 |
| 5.1 | Nanotube Research . . . . .  | 310 |

|                              |     |
|------------------------------|-----|
| 5.2 Wider Applications ..... | 312 |
| 6 Conclusion .....           | 313 |
| References .....             | 314 |
| Index .....                  | 318 |

### Ultrafast Spectroscopy of Carbon Nanotubes

Ying-Zhong Ma, Tobias Hertel, Zeev Valy Vardeny,

Graham R. Fleming, and Leonas Valkunas .....

|   |     |
|---|-----|
| 1 Introduction .....  | 321 |
| 2 Background .....  | 322 |
| 2.1 Instrumentation for Ultrafast Spectroscopy .....                                | 322 |
| 2.2 Basics of Nonlinear Optics .....  | 324 |
| 3 Metallic Tubes .....  | 327 |
| 4 Semiconducting Tubes .....  | 328 |
| 4.1 Exciton Dynamics .....  | 329 |
| 4.2 Low Excitation Densities .....  | 330 |
| 4.2.1 Intersubband Relaxation .....   | 331 |
| 4.2.2 Radiative Lifetime .....  | 331 |
| 4.2.3 Correlation of the PL Decay Timescales<br>with the Tube Diameter .....        | 332 |
| 4.2.4 Environmental and Temperature Effects<br>on Exciton Population Dynamics ..... | 333 |
| 4.2.5 Transient Absorption of a Chirality-<br>Enriched SWNT Preparation .....       | 336 |
| 4.3 High Excitation Densities .....   | 338 |
| 4.3.1 Spectroscopic and Dynamic Signatures of High-<br>Intensity Excitation .....   | 338 |
| 4.3.2 Theoretical Advances .....  | 342 |
| 4.3.3 Exciton Dissociation .....  | 343 |
| 5 Comparison of S-SWNTs with $\pi$ -Conjugated Polymers .....                       | 344 |
| 6 Summary .....   | 346 |
| References .....  | 347 |
| Index .....   | 352 |

### Rayleigh Scattering Spectroscopy

Tony F. Heinz .....

|  |     |
|--|-----|
| 1 Introduction .....   | 353 |
| 2 Elastic Light Scattering .....   | 354 |
| 3 Experimental Technique .....   | 356 |
| 4 Application of the Technique .....   | 360 |
| 4.1 Electronic Transitions of Nanotubes<br>of Independently Determined Structure ..... | 360 |
| 4.2 Polarization Dependence of Nanotube Electronic Transitions ..                      | 361 |
| 4.3 Structural Stability Along the Nanotube Axis .....                                 | 362 |
| 4.4 Nanotube–Nanotube Interactions .....   | 363 |

|                      |     |
|----------------------|-----|
| 5 Outlook . . . . .  | 364 |
| References . . . . . | 366 |
| Index . . . . .      | 368 |

### **New Techniques for Carbon-Nanotube Study and Characterization**

|  |     |
|--|-----|
| Achim Hartschuh . . . . .  | 371 |
| 1 Introduction . . . . .   | 371 |
| 2 Near-Field Optical Microscopy . . . . .                          | 371 |
| 2.1 Experimental . . . . .   | 372 |
| 2.2 Results . . . . .  | 373 |
| 2.2.1 Nanoscale Optical Imaging . . . . .                          | 373 |
| 2.2.2 Nanoscale Optical Spectroscopy . . . . .                     | 375 |
| 2.3 Outlook . . . . .  | 377 |
| 3 Phonon Spectroscopy Using Inelastic Electron Tunneling . . . . . | 378 |
| 3.1 Experimental . . . . .   | 378 |
| 3.2 Results . . . . .  | 379 |
| 3.3 Outlook . . . . .  | 382 |
| 4 Coherent Phonon Generation and Detection . . . . .               | 383 |
| 4.1 Results . . . . .  | 384 |
| 4.2 Outlook . . . . .  | 389 |
| References . . . . .   | 389 |
| Index . . . . .  | 392 |

### **High Magnetic Field Phenomena in Carbon Nanotubes**

|  |     |
|--|-----|
| Junichiro Kono, Robin J. Nicholas, and Stephan Roche . . . . .     | 393 |
| 1 Introduction . . . . .   | 393 |
| 2 Band Structure in Magnetic Fields . . . . .                      | 394 |
| 2.1 Parallel Field: Role of the Aharonov–Bohm Phase . . . . .      | 394 |
| 2.2 Perpendicular Field: Onset of Landau Levels . . . . .          | 395 |
| 3 Magnetization . . . . .  | 397 |
| 3.1 Theory of the Magnetic Susceptibility . . . . .                | 397 |
| 3.2 Magnetic-Susceptibility Measurements . . . . .                 | 399 |
| 4 Magneto-transport . . . . .                                      | 400 |
| 4.1 Disorder and Quantum Interference . . . . .                    | 401 |
| 4.2 Weak Localization and Magnetoresistance Oscillations . . . . . | 401 |
| 4.3 Most Recent Experiments . . . . .                              | 404 |
| 5 Magneto-Optics . . . . .   | 405 |
| 5.1 Bandgap Shrinkage and Aharonov–Bohm Splitting . . . . .        | 406 |
| 5.2 Magnetic Brightening of “Dark” Excitons: Theory . . . . .      | 407 |
| 5.3 Magnetic Brightening of “Dark” Excitons: Experiment . . . . .  | 410 |
| 5.4 Perpendicular Field Effects . . . . .                          | 414 |
| 6 Summary and Remaining Problems . . . . .                         | 415 |
| References . . . . .   | 416 |

|   |     |
|---|-----|
| Index . . . . .   | 421 |
| <b>Carbon-Nanotube Optoelectronics</b>  |     |
| Phaedon Avouris, Marcus Freitag, and Vasili Perebeinos . . . . .                        | 423 |
| 1 The Nature of the Optically Excited State . . . . .                                   | 423 |
| 2 Exciton Properties . . . . .  | 425 |
| 2.1 Low-Energy Exciton Bandstructure –<br>Dark and Bright Excitons . . . . .            | 425 |
| 2.2 Exciton Radiative and Nonradiative Lifetimes . . . . .                              | 427 |
| 2.3 Exciton–Optical Phonon Sidebands in Absorption Spectra . . . . .                    | 428 |
| 2.4 Impact Excitation, Auger Recombination<br>and Exciton Annihilation . . . . .        | 430 |
| 2.5 Franz–Keldysh, Stark Effects and Exciton Ionization<br>by Electric Fields . . . . . | 433 |
| 3 Overview of CNT Electronics – Unipolar and Ambipolar FETs . . . . .                   | 435 |
| 4 Photoconductivity and Light Detection . . . . .                                       | 436 |
| 4.1 Types of Nanotube Photodetectors . . . . .  | 436 |
| 4.2 CNT Photoconductor . . . . .  | 437 |
| 4.3 Photocurrent Spectroscopy and Quantum Efficiency . . . . .                          | 437 |
| 4.4 Photovoltage in Asymmetric CNTFETs –<br>Schottky-Barrier Diodes . . . . .           | 439 |
| 4.5 Photovoltage in a CNT p–n Junction . . . . .  | 440 |
| 4.6 Photovoltage Imaging . . . . .  | 441 |
| 5 Electroluminescence . . . . .   | 442 |
| 5.1 Ambipolar Mechanism . . . . .   | 442 |
| 5.2 Mechanism of the Spot Movement in Ambipolar Transistors . . . . .                   | 443 |
| 5.3 Electroluminescence Spectrum and Efficiency<br>of the Radiative Decay . . . . .     | 444 |
| 6 Unipolar Mechanism for Infrared Emission . . . . .                                    | 444 |
| 7 Conclusions – Future . . . . .  | 446 |
| References . . . . .  | 448 |
| Index . . . . .   | 453 |

### Electrical Transport in Single-Wall Carbon Nanotubes

|  |     |
|--|-----|
| Michael J. Biercuk, Shahal Ilani, Charles M. Marcus,<br>and Paul L. McEuen . . . . . | 455 |
| 1 Introduction and Basic Properties . . . . .  | 455 |
| 1.1 Band Structure . . . . .   | 456 |
| 1.2 1D Transport in Nanotubes . . . . .  | 458 |
| 2 Classical (Incoherent) Transport in Nanotubes . . . . .                            | 460 |
| 2.1 Contacts to Nanotubes: Schottky Barriers . . . . .                               | 460 |
| 2.2 The Effect of Disorder . . . . .   | 463 |
| 2.3 Electron–Phonon Scattering in Nanotubes . . . . .                                | 464 |
| 3 Nanotube Devices and Advanced Geometries . . . . .                                 | 466 |
| 3.1 High-Performance Transistors . . . . .   | 467 |



|       |   |     |
|-------|---|-----|
| 3.2   | Radio-Frequency and Microwave Devices . . . . .         | 469 |
| 3.3   | P–N Junction Devices . . . . .                          | 470 |
| 4     | Quantum Transport . . . . .                             | 474 |
| 4.1   | Quantum Transport in One Dimension . . . . .            | 474 |
| 4.1.1 | Luttinger Liquid . . . . .                              | 474 |
| 4.1.2 | Ballistic Transport . . . . .                           | 476 |
| 4.2   | Superconducting Proximity Effect . . . . .              | 476 |
| 4.3   | Quantum Transport with Ferromagnetic Contacts . . . . . | 478 |
| 5     | Nanotube Quantum Dots . . . . .                         | 479 |
| 5.1   | Single Dots . . . . .                                   | 480 |
| 5.2   | Band and Spin Effects in Single Quantum Dots . . . . .  | 480 |
| 5.2.1 | Shell Filling in Nanotube Dots . . . . .                | 480 |
| 5.2.2 | Nanotube Dots with Ferromagnetic Contacts . . . . .     | 481 |
| 5.3   | Kondo Effects in Nanotube Dots . . . . .                | 481 |
| 5.3.1 | Nonequilibrium Singlet–Triplet Kondo Effect . . . . .   | 482 |
| 5.3.2 | Orbital and SU(4) Kondo . . . . .                       | 482 |
| 5.4   | Multiple Quantum Dots . . . . .                         | 483 |
| 6     | Future Directions . . . . .                             | 484 |
|       | References . . . . .                                    | 485 |
|       | Index . . . . .   | 492 |

### Double-Wall Carbon Nanotubes

|       |   |     |
|-------|---|-----|
|       | Rudolf Pfeiffer, Thomas Pichler, Yoong Ahm Kim, and Hans Kuzmany      | 495 |
| 1     | Introduction . . . . .  | 495 |
| 1.1   | Fingerprints of Double-Wall Carbon Nanotubes . . . . .                | 496 |
| 2     | Preparation of Double-Wall Carbon Nanotubes . . . . .                 | 496 |
| 2.1   | DWNT Growth from Chemical Vapor Deposition . . . . .                  | 497 |
| 2.2   | DWNT Growth from Precursor Material . . . . .                         | 501 |
| 2.2.1 | DWNT Growth from Fullerene Peapods . . . . .                          | 501 |
| 2.2.2 | DWNT Growth from Ferrocene . . . . .                                  | 503 |
| 2.2.3 | DWNT Growth from Other Carbon Precursors . . . . .                    | 506 |
| 2.2.4 | Theoretical Models for the Fullerene Coalescence . . . . .            | 507 |
| 3     | Properties and Applications of DWNTs . . . . .                        | 508 |
| 3.1   | Electronic and Optical Properties, Transport . . . . .                | 508 |
| 3.1.1 | Model Calculations . . . . .  | 509 |
| 3.1.2 | Experimental Results for Electronics and Structure . . . . .          | 511 |
| 3.1.3 | Transport . . . . .   | 511 |
| 3.2   | Raman Scattering . . . . .  | 512 |
| 3.2.1 | The Nature of the Radial Breathing Mode Response . . . . .            | 513 |
| 3.2.2 | Tangential Modes and Overtones . . . . .                              | 513 |
| 3.2.3 | Temperature, Pressure, and Doping Effects . . . . .                   | 514 |
| 3.3   | $^{13}\text{C}$ Substitution and Nuclear Magnetic Resonance . . . . . | 516 |
| 3.4   | Thermal and Chemical Stability, Mechanical Properties . . . . .       | 517 |
| 3.4.1 | Thermal Stability . . . . .   | 518 |

|  |     |
|--|-----|
| 3.4.2 Pore Structure and Oxidative Stability<br>of the Bundled DWNTs ..... | 518 |
| 3.4.3 Mechanical Properties .....  | 520 |
| 4 Summary and Outlook .....  | 521 |
| 4.1 Outlook .....  | 522 |
| References .....   | 523 |
| Index .....  | 530 |

### **Doped Carbon Nanotubes: Synthesis, Characterization and Applications**

|  |     |
|--|-----|
| Mauricio Terrones, Antonio G. Souza Filho, and Apparao M. Rao .... | 531 |
| 1 Introduction .....   | 531 |
| 2 Exohedral Doping or Intercalation .....                          | 532 |
| 3 Endohedral Doping or Encapsulation .....                         | 533 |
| 4 Inplane or Substitutional Doping .....                           | 534 |
| 4.1 Substitutional Doping in Graphite .....                        | 534 |
| 4.2 Substitutional Doping in Nanotubes .....                       | 534 |
| 4.3 Synthesis Methods for Substitutional Doped Nanotubes ....      | 537 |
| 4.3.1 Arc-Discharge Method .....                                   | 537 |
| 4.3.2 Laser-Ablation Method .....                                  | 537 |
| 4.3.3 Chemical Vapor Deposition .....                              | 538 |
| 4.3.4 B and N Substitution Reactions .....                         | 538 |
| 4.3.5 Plasma-Assisted CVD .....                                    | 540 |
| 5 Characterization Techniques for Studying Doped Nanotubes ....    | 540 |
| 5.1 Morphological and Structural Characterization .....            | 540 |
| 5.1.1 Atomic Structure of N-Doped MWNTs .....                      | 541 |
| 5.1.2 Atomic Structure of B-Doped MWNTs .....                      | 542 |
| 5.1.3 Atomic Structure of Doped SWNTs .....                        | 542 |
| 5.2 Electronic and Transport Characterization .....                | 543 |
| 5.3 Raman Characterization .....                                   | 546 |
| 5.3.1 Nonsubstitutional n-Type Doped Nanotubes .....               | 546 |
| 5.3.2 Nonsubstitutional p-Type Doped Nanotubes .....               | 550 |
| 5.3.3 Raman Spectroscopy for Inplane Doped Nanotubes ....          | 551 |
| 6 Applications of Doped Nanotubes .....                            | 553 |
| 7 Perspectives and Challenges .....                                | 555 |
| References .....   | 558 |
| Index .....  | 566 |

### **Electrochemistry of Carbon Nanotubes**

|   |     |
|---|-----|
| Ladislav Kavan and Lothar Dunsch .....  | 567 |
| 1 Electrochemistry of Nanotubes: Fundamentals .....                                     | 567 |
| 1.1 Introduction .....  | 567 |
| 1.2 Potential-Dependent Reactions .....   | 568 |
| 1.3 Faradaic and Non-Faradaic Processes<br>in Nanocarbons (Nanotubes, Fullerenes) ..... | 569 |

|       |  |     |
|-------|--|-----|
| 1.4   | Doping of Nanocarbons . . . . .                                  | 571 |
| 2     | Experimental Techniques . . . . .                                | 575 |
| 2.1   | Materials in Electrochemical Studies of Nanotubes . . . . .      | 575 |
| 2.2   | Voltammetry . . . . .  | 575 |
| 2.3   | Methods of Spectroelectrochemistry . . . . .                     | 578 |
| 3     | Practical Applications of Charge Transfer at Nanotubes . . . . . | 579 |
| 3.1   | Electrochemical Synthesis and Behavior of Nanotubes . . . . .    | 579 |
| 3.2   | Practical Devices . . . . .                                      | 580 |
| 4     | Spectroelectrochemistry of Nanotubes . . . . .                   | 582 |
| 4.1   | Vis-NIR Spectroelectrochemistry . . . . .                        | 582 |
| 4.2   | Raman Spectroelectrochemistry . . . . .                          | 585 |
| 4.2.1 | SWNTs . . . . .  | 586 |
| 4.2.2 | Fullerene Peapods . . . . .                                      | 589 |
| 4.2.3 | Double-Walled Carbon Nanotubes . . . . .                         | 589 |
| 4.3   | Combined Chemical/Electrochemical Doping . . . . .               | 592 |
| 4.4   | Single-Nanotube Studies . . . . .                                | 593 |
| 5     | Summary and Outlook . . . . .                                    | 594 |
|       | References . . . . .   | 595 |
|       | Index . . . . .  | 602 |

### Single-Wall Carbon Nanohorns and Nanocones

|   |  |     |
|---|--|-----|
|   | Masako Yudasaka, Sumio Iijima, and Vincent H. Crespi . . . . .                           | 605 |
| 1 | Introduction . . . . .   | 605 |
| 2 | Geometrical Definition of the Cone . . . . .   | 606 |
| 3 | Structure, Production, and Growth Mechanism<br>of Single-Wall Carbon Nanohorns . . . . . | 607 |
| 4 | Properties of Single-Wall Nanohorns . . . . .  | 611 |
| 5 | Applications of Single-Wall Nanohorns . . . . .  | 612 |
| 6 | Comparison of Single-Wall Nanohorns<br>to Single-Wall Nanotubes . . . . .                | 616 |
| 7 | Mechanical Response of Carbon Nanocones . . . . .  | 617 |
| 8 | Electronic Properties of Carbon Cones . . . . .  | 619 |
| 9 | Conclusion . . . . .   | 622 |
|   | References . . . . .   | 622 |
|   | Index . . . . .  | 628 |

### Inorganic Nanotubes and Fullerene-Like Structures (IF)

|     |   |     |
|-----|---|-----|
|     | R. Tenne, M. Remškar, A. Enyashin, and G. Seifert . . . . . | 631 |
| 1   | Introduction . . . . .                                      | 631 |
| 2   | Synthesis of INT and IF Materials . . . . .                 | 634 |
| 2.1 | Physical Techniques . . . . .                               | 634 |
| 2.2 | Soft Chemistry “Chemie Douce” . . . . .                     | 637 |
| 2.3 | High-Temperature Reactions . . . . .                        | 639 |
| 3   | Structural Characterization and Stability . . . . .         | 641 |
| 3.1 | General Considerations . . . . .                            | 641 |

|     |  |     |
|-----|--|-----|
| 3.2 | Strain-Relaxation Mechanisms in the Nanotubes . . . . .              | 643 |
| 3.3 | Studies of Some Specific Systems . . . . .                           | 645 |
| 4   | Physical Properties . . . . .  | 649 |
| 4.1 | Mechanical Properties . . . . .                                      | 649 |
| 4.2 | Electronic and Optical Properties . . . . .                          | 651 |
| 5   | Applications . . . . .   | 655 |
| 5.1 | Tribological Applications . . . . .                                  | 655 |
| 5.2 | Towards High-Strength Nanocomposites . . . . .                       | 656 |
| 5.3 | Li Intercalation and Hydrogen Sorption in $MS_2$ Nanotubes . . . . . | 656 |
| 5.4 | Solar Cells, Photocatalysis and Sensors . . . . .                    | 657 |
| 5.5 | Biotechnology . . . . .  | 658 |
| 5.6 | Catalysis . . . . .  | 658 |
| 6   | Conclusions . . . . .  | 659 |
|     | References . . . . .   | 660 |
|     | Index . . . . .  | 669 |

### **Electron and Phonon Properties of Graphene: Their Relationship with Carbon Nanotubes**

|       |   |            |
|-------|---|------------|
|       | J.-C. Charlier, P. C. Eklund J. Zhu, A. C. Ferrari . . . . .                            | 673        |
| 1     | Introduction . . . . .  | 673        |
| 2     | Electronic Properties and Transport Measurements . . . . .                              | 675        |
| 2.1   | Graphene . . . . .  | 675        |
| 2.1.1 | Electronic Band Structure . . . . .   | 675        |
| 2.1.2 | Transport Measurements in Single-Layer Graphene . . . . .                               | 678        |
| 2.2   | Graphene Nanoribbons . . . . .  | 681        |
| 2.3   | Graphite and $n$ -Graphene Layer Systems . . . . .                                      | 684        |
| 3     | Optical Phonons and Raman Spectroscopy . . . . .  | 686        |
| 3.1   | Raman D and G Bands, Double Resonance<br>and Kohn Anomalies . . . . .                   | 686        |
| 3.2   | Electron–Phonon Coupling from Phonon Dispersions<br>and Raman Linewidths . . . . .      | 689        |
| 3.3   | The Raman Spectrum of Graphene<br>and $n$ -Graphene Layer Systems . . . . .             | 690        |
| 3.4   | Doped Graphene: Breakdown of the Adiabatic Born–<br>Oppenheimer Approximation . . . . . | 694        |
| 4     | Implications for Phonons and Raman Scattering in Nanotubes . . . . .                    | 697        |
| 4.1   | Adiabatic Kohn Anomalies . . . . .  | 697        |
| 4.2   | Nonadiabatic Kohn Anomalies . . . . .   | 698        |
| 4.3   | The Raman G Peak of Nanotubes . . . . .   | 698        |
| 5     | Outlook . . . . .   | 701        |
|       | References . . . . .  | 701        |
|       | Index . . . . .   | 708        |
|       | <b>Index . . . . .</b>  | <b>711</b> |