Contents

About the Editor xi
Dedication xii
List of Contributors xiii
Foreword xv
Acknowledgements xvii
List of Abbreviations xix

Introduction to the Meta-Nanotube Book 1
Marc Monthioux

1 Time for a Third-Generation of Carbon Nanotubes 1
2 Introducing Meta-Nanotubes 2
   2.1 Doped Nanotubes (X:CNTs) 3
   2.2 Functionalized Nanotubes (X-CNTs) 3
   2.3 Decorated (Coated) Nanotubes (X/CNTs) 3
   2.4 Filled Nanotubes (X@CNTs) 3
   2.5 Heterogeneous Nanotubes (X*CNTs) 4
3 Introducing the Meta-Nanotube Book 4
References 5

1 Introduction to Carbon Nanotubes 7
Marc Monthioux

1.1 Introduction 7
1.2 One Word about Synthesizing Carbon Nanotubes 7
1.3 SWCNTs: The Perfect Structure 11
1.4 MWCNTs: The Amazing (Nano)Textural Variety 18
1.5 Electronic Structure 29
1.6 Some Properties of Carbon Nanotubes 31
1.7 Conclusion 36
References 36

2 Doped Carbon Nanotubes: (X:CNTs) 41
Alain Pénicaud, Pierre Petit and John E. Fischer

2.1 Introduction 41
   2.1.1 Scope of this Chapter 41
   2.1.2 A Few Definitions 42
   2.1.3 Doped/Intercalated Carbon Allotropes – a Brief History 43
   2.1.4 What Happens upon Doping SWCNTs? 48
2.2 n-Doping of Nanotubes

2.2.1 Synthetic Routes for Preparing Doped SWCNTs 52
2.2.2 Crystalline Structure and Chemical Composition of n-Doped Nanotubes 54
2.2.3 Modification of the Electronic Structure of SWCNTs upon Doping 59
2.2.4 Electrical Transport in Doped SWCNTs 61
2.2.5 Spectroscopic Evidence for n-Doping 65
2.2.6 Solutions of Reduced Nanotubes 72

2.3 p-Doping of Carbon Nanotubes 73

2.3.1 p-Doping of SWCNTs with Halogens 74
2.3.2 p-Doping with Acceptor Molecules 80
2.3.3 p-Doping of SWCNTs with FeCl₃ 84
2.3.4 p-Doping of SWCNTs with SOCl₂ 87
2.3.5 p-Doping of SWCNTs with Acids 87
2.3.6 p-Doping of SWCNTs with Superacids 91
2.3.7 p-Doping with other Oxidizing Agents 95
2.3.8 Diameter Selective Doping 96

2.4 Practical Applications of Doped Nanotubes 99

2.5 Conclusions, Perspectives 100

References 101

3 Functionalized Carbon Nanotubes: (X-CNTs) 113

Stéphane Campidelli, Stanislaus S. Wong and Maurizio Prato

3.1 Introduction 113

3.2 Functionalization Routes 113

3.2.1 Noncovalent Sidewall Functionalization of SWCNTs 114
3.2.2 Covalent Functionalization of SWCNTs 114

3.3 Properties and Applications 125

3.3.1 Electron Transfer Properties and Photovoltaic Applications 125
3.3.2 Chemical Sensors (FET-Based) 137
3.3.3 Opto-Electronic Devices (FET-Based) 139
3.3.4 Biosensors 145

3.4 Conclusion 149

References 150

4 Decorated (Coated) Carbon Nanotubes: (X/CNTs) 163

Revathi R. Bacsa and Philippe Serp

4.1 Introduction 163

4.2 Metal-Nanotube Interactions – Theoretical Aspects 166

4.2.1 Curvature-Induced Effects 168
4.2.2 Effect of Defects and Vacancies on the Metal-Graphite Interactions 169
5b Fullerenes inside Carbon Nanotubes: The Peapods 273

Ferenc Simon and Marc Monthioux

5b.1 Introduction 273
5b.2 The Discovery of Fullerene Peapods 274
5b.3 Classification of Peapods 277
5b.4 Synthesis and Behavior of Fullerene Peapods 279
5b.4.1 Synthesis of Peapods 279
5b.4.2 Behavior of Peapods under Various Treatments 289
5b.5 Properties of Peapods 295
5b.5.1 Structural Properties 295
5b.5.2 Peapod Band Structure from Theory and Experiment 298
5b.5.3 Transport Properties 301
5b.5.4 Optical Properties 302
5b.5.5 Vibrational Properties 303
5b.5.6 Magnetic Properties 305
5b.6 Applications of Peapods 308
5b.6.1 Demonstrated Applications 308
5b.6.2 Expected Applications 310
Acknowledgements 314
References 314

6 Heterogeneous Nanotubes: (X*CNTs, X*BNNTs) 323

Dmitri Golberg, Mauricio Terrones

6.1 Overall Introduction 323
6.2 Pure BN Nanotubes 324
6.2.1 Introduction 324
6.2.2 Synthesis of BN Nanotubes 325
6.2.3 Morphology and Structure of BN Nanotubes 331
6.2.4 Properties of BN Nanotubes 337
6.2.5 Stability of BN Nanotubes to High-Energy Irradiation 346
6.2.6 Boron Nitride Meta-Nanotubes 346
6.2.7 Other BN Nanomaterials 353
6.2.8 Challenging Applications 355
6.3 B$_x$C$_y$N$_z$ Nanotubes and Nanofibers 359
6.3.1 Tuning the Electronic Structure with C-Substituted BN Nanotubes 359
6.3.2 Production and Characterization of B$_x$C$_y$N$_z$ Nanotubes and Nanofibers 362
6.4 B-Substituted or N-Substituted Carbon Nanotubes 368
6.4.1 Substituting Carbon Nanotubes with B or N 368
6.4.2 Synthesis Strategies for Producing B- or N-Substituted CNTs 370
6.4.3 Morphology and Structure of Substituted CNTs 374
Introducing Meta-Nanotubes. Carbon nanotubes can be modified in many ways, generally involving chemical treatments that make use of the polyaromatic nature of their skeleton. Chapter 1 of this book is dedicated to an introduction to pristine carbon nanotubes. Because it is doubtful that any reader of this book would ignore what carbon nanotubes are in the first place, it was wondered whether such a chapter was necessary. We finally decided it was, because the world of carbon nanotubes, and nanocarbons generally speaking, is related to the complex and labyrinthine world of carbon materials, which has kept scientists and engineers busy for more than a century. 

1. An introduction to carbon nanotubes. Description of lesson and intended student body. My goal of writing the educational transfer plan (ETP) on carbon nanotubes was to briefly introduce to the high school chemistry student this growing novel area of organic chemistry in order to enrich their high school chemistry curriculum. Although knowledge of the fullerenes and carbon nanotubes are not currently a California State Standard, I feel it is important to create an awareness of the nanosciences and their potential applications in the future of nanotechnology. As a high school t