

Contents

Foreword	V
References	IX
Preface	XI
Introduction to the Important and Exciting Aspects of Carbon-Nanotube Science and Technology	
David Tománek, Ado Jorio, Mildred S. Dresselhaus, and Gene Dresselhaus	
1	1
2	3
3	4
4	5
5	5
6	6
7	8
8	9
9	10
10	10
11	10
12	11
13	11
Index	12
Potential Applications of Carbon Nanotubes	
Morinobu Endo, Michael S. Strano, and Pulickel M. Ajayan	
1	13
2	16
2.1	17
2.2	22
2.3	27
2.4	31
2.5	36
2.6	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, 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, 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 321

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 with the Tube Diameter	332
4.2.4 Environmental and Temperature Effects on Exciton Population Dynamics	333
4.2.5 Transient Absorption of a Chirality- Enriched SWNT Preparation	336
4.3 High Excitation Densities	338
4.3.1 Spectroscopic and Dynamic Signatures of High- Intensity Excitation	338
4.3.2 Theoretical Advances	342
4.3.3 Exciton Dissociation	343
5 Comparison of S-SWNTs with π -Conjugated Polymers	344
6 Summary	346
References	347
Index	352

Rayleigh Scattering Spectroscopy

Tony F. Heinz 353

1 Introduction	353
2 Elastic Light Scattering	354
3 Experimental Technique	356
4 Application of the Technique	360
4.1 Electronic Transitions of Nanotubes 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
-------------	-----

Carbon-Nanotube Optoelectronics

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 – 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 and Exciton Annihilation	430
2.5 Franz–Keldysh, Stark Effects and Exciton Ionization 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 – 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 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, 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}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 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 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 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 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 and Kohn Anomalies	686
3.2	Electron-Phonon Coupling from Phonon Dispersions and Raman Linewidths	689
3.3	The Raman Spectrum of Graphene and n -Graphene Layer Systems	690
3.4	Doped Graphene: Breakdown of the Adiabatic Born- 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
	Index	711

Carbon Nanotubes

Advanced Topics in the Synthesis, Structure, Properties and
Applications

(Eds.) A. Jorio; G. Dresselhaus; M.S. Dresselhaus

2008, XXIV, 720 p. 250 illus., 11 in color., Hardcover

ISBN: 978-3-540-72864-1