

Springer
Handbook *of*
**Nano-
technology**



Bhushan
Editor

3rd Edition

Contents

List of Abbreviations	XLI
------------------------------------	------------

1 Introduction to Nanotechnology

<i>Bharat Bhushan</i>	1
1.1 Nanotechnology – Definition and Examples	1
1.2 Background and Research Expenditures	4
1.3 Lessons from Nature (Biomimetics)	6
1.4 Applications in Different Fields	9
1.5 Various Issues	10
1.6 Research Training	11
1.7 Organization of the Handbook	11
References	12

Part A Nanostructures, Micro-/Nanofabrication and Materials

2 Nanomaterials Synthesis and Applications: Molecule-Based Devices

<i>Françisco M. Raymo</i>	17
2.1 Chemical Approaches to Nanostructured Materials	18
2.2 Molecular Switches and Logic Gates	22
2.3 Solid State Devices	30
2.4 Conclusions and Outlook	42
References	43

3 Introduction to Carbon Nanotubes

<i>Marc Monthieux, Philippe Serp, Emmanuel Flahaut, Manitra Razafinimanana, Christophe Laurent, Alain Peigney, Wolfgang Bacsá, Jean-Marc Broto</i>	47
3.1 Structure of Carbon Nanotubes	48
3.2 Synthesis of Carbon Nanotubes	53
3.3 Growth Mechanisms of Carbon Nanotubes	70
3.4 Properties of Carbon Nanotubes	74
3.5 Carbon Nanotube-Based Nano-Objects	80
3.6 Applications of Carbon Nanotubes	85
3.7 Toxicity and Environmental Impact of Carbon Nanotubes	99
3.8 Concluding Remarks	100
References	101

4	Nanowires	
	<i>Mildred S. Dresselhaus, Yu-Ming Lin, Oded Rabin, Marcie R. Black, Jing Kong, Gene Dresselhaus</i>	119
4.1	Synthesis	121
4.2	Characterization and Physical Properties of Nanowires	130
4.3	Applications	152
4.4	Concluding Remarks	159
	References	159
5	Template-Based Synthesis of Nanorod or Nanowire Arrays	
	<i>Huamei (Mary) Shang, Guozhong Cao</i>	169
5.1	Template-Based Approach	170
5.2	Electrochemical Deposition	171
5.3	Electrophoretic Deposition	175
5.4	Template Filling	180
5.5	Converting from Reactive Templates	182
5.6	Summary and Concluding Remarks	182
	References	183
6	Templated Self-Assembly of Particles	
	<i>Tobias Kraus, Heiko Wolf</i>	187
6.1	The Assembly Process	189
6.2	Classes of Directed Particle Assembly	194
6.3	Templates	202
6.4	Processes and Setups	205
6.5	Conclusions	206
	References	207
7	Three-Dimensional Nanostructure Fabrication by Focused Ion Beam Chemical Vapor Deposition	
	<i>Shinji Matsui</i>	211
7.1	Three-Dimensional Nanostructure Fabrication	212
7.2	Nanoelectromechanics	215
7.3	Nanooptics: Brilliant Blue Observation from a <i>Morpho</i> Butterfly Scale Quasistructure	223
7.4	Nanobiology	224
7.5	Summary	228
	References	228
8	Introduction to Micro-/Nanofabrication	
	<i>Babak Ziaie, Antonio Baldi, Massood Z. Atashbar</i>	231
8.1	Basic Microfabrication Techniques	232
8.2	MEMS Fabrication Techniques	244
8.3	Nanofabrication Techniques	256
8.4	Summary and Conclusions	265
	References	265

9	Nanoimprint Lithography – Patterning of Resists Using Molding	
	<i>Helmut Schiff, Anders Kristensen</i>	271
9.1	Emerging Nanopatterning Methods	273
9.2	Nanoimprint Process	277
9.3	Tools and Materials for Nanoimprinting.....	288
9.4	Nanoimprinting Applications	294
9.5	Conclusions and Outlook.....	302
	References	304
10	Stamping Techniques for Micro- and Nanofabrication	
	<i>Etienne Menard, John A. Rogers</i>	313
10.1	High-Resolution Stamps	314
10.2	Microcontact Printing	316
10.3	Nanotransfer Printing.....	318
10.4	Applications	322
10.5	Conclusions.....	329
	References	330
11	Material Aspects of Micro- and Nanoelectromechanical Systems	
	<i>Christian A. Zorman, Mehran Mehregany</i>	333
11.1	Silicon	333
11.2	Germanium-Based Materials	340
11.3	Metals	341
11.4	Harsh-Environment Semiconductors	343
11.5	GaAs, InP, and Related III–V Materials	349
11.6	Ferroelectric Materials	350
11.7	Polymer Materials	351
11.8	Future Trends	352
	References	353

Part B MEMS/NEMS and BioMEMS/NEMS

12	MEMS/NEMS Devices and Applications	
	<i>Darrin J. Young, Christian A. Zorman, Mehran Mehregany</i>	359
12.1	MEMS Devices and Applications	361
12.2	Nanoelectromechanical Systems (NEMS).....	380
12.3	Current Challenges and Future Trends	383
	References	384
13	Next-Generation DNA Hybridization and Self-Assembly Nanofabrication Devices	
	<i>Michael J. Heller, Benjamin Sullivan, Dietrich Dehlinger, Paul Swanson, Dalibor Hodko</i>	389
13.1	Electronic Microarray Technology.....	391
13.2	Electric Field-Assisted Nanofabrication Processes	397
13.3	Conclusions.....	399
	References	400

14 Single-Walled Carbon Nanotube Sensor Concepts	
<i>Cosmin Roman, Thomas Helbling, Christofer Hierold</i>	403
14.1 Design Considerations for SWNT Sensors.....	404
14.2 Fabrication of SWNT Sensors.....	412
14.3 Example State-of-the-Art Applications.....	416
14.4 Concluding Remarks.....	421
References	421
15 Nanomechanical Cantilever Array Sensors	
<i>Hans Peter Lang, Martin Hegner, Christoph Gerber</i>	427
15.1 Technique.....	427
15.2 Cantilever Array Sensors.....	429
15.3 Modes of Operation.....	430
15.4 Microfabrication.....	434
15.5 Measurement Setup.....	434
15.6 Functionalization Techniques.....	438
15.7 Applications.....	439
15.8 Conclusions and Outlook.....	445
References	446
16 Biological Molecules in Therapeutic Nanodevices	
<i>Stephen C. Lee, Bharat Bhushan</i>	453
16.1 Definitions and Scope.....	454
16.2 Assembly Approaches.....	461
16.3 Sensing Devices.....	471
16.4 Concluding Remarks: Barriers to Practice.....	478
References	480
17 G-Protein Coupled Receptors: Progress in Surface Display and Biosensor Technology	
<i>Wayne R. Leifert, Tamara H. Cooper, Kelly Bailey</i>	485
17.1 The GPCR:G-Protein Activation Cycle.....	488
17.2 Preparation of GPCRs and G-Proteins.....	489
17.3 Protein Engineering in GPCR Signaling.....	490
17.4 GPCR Biosensing.....	491
17.5 The Future of GPCRs.....	499
References	499
18 Microfluidic Devices and Their Applications to Lab-on-a-Chip	
<i>Chong H. Ahn, Jin-Woo Choi</i>	503
18.1 Materials for Microfluidic Devices and Micro/Nanofabrication Techniques.....	504
18.2 Active Microfluidic Devices.....	507
18.3 Smart Passive Microfluidic Devices.....	513
18.4 Lab-on-a-Chip for Biochemical Analysis.....	520
References	527

19 Centrifuge-Based Fluidic Platforms	
<i>Jim V. Zoval, Guangyao Jia, Horacio Kido, Jitae Kim, Nahui Kim, Marc J. Madou</i>	531
19.1 Why Centripetal Force for Fluid Propulsion?	532
19.2 Compact Disc or Microcentrifuge Fluidics	534
19.3 CD Applications	538
19.4 Conclusion	549
References	550

20 Micro-/Nanodroplets in Microfluidic Devices	
<i>Yung-Chieh Tan, Shia-Yen Teh, Abraham P. Lee</i>	553
20.1 Active or Programmable Droplet Systems	554
20.2 Passive Droplet Control Techniques	557
20.3 Applications	564
20.4 Conclusions	566
References	566

Part C Scanning-Probe Microscopy

21 Scanning Probe Microscopy – Principle of Operation, Instrumentation, and Probes	
<i>Bharat Bhushan, Othmar Marti</i>	573
21.1 Scanning Tunneling Microscope	575
21.2 Atomic Force Microscope	579
21.3 AFM Instrumentation and Analyses	595
References	612

22 General and Special Probes in Scanning Microscopies	
<i>Jason Hafner, Edin (I-Chen) Chen, Ratnesh Lal, Sungho Jin</i>	619
22.1 Atomic Force Microscopy	620
22.2 Scanning Tunneling Microscopy	630
References	631

23 Noncontact Atomic Force Microscopy and Related Topics	
<i>Franz J. Giessibl, Yasuhiro Sugawara, Seizo Morita, Hirotaka Hosoi, Kazuhisa Sueoka, Koichi Mukasa, Akira Sasahara, Hiroshi Onishi</i>	635
23.1 Atomic Force Microscopy (AFM)	636
23.2 Applications to Semiconductors	641
23.3 Applications to Insulators	647
23.4 Applications to Molecules	654
References	658

24 Low-Temperature Scanning Probe Microscopy	
<i>Markus Morgenstern, Alexander Schwarz, Udo D. Schwarz</i>	663
24.1 Microscope Operation at Low Temperatures	664
24.2 Instrumentation	666

24.3	Scanning Tunneling Microscopy and Spectroscopy	669
24.4	Scanning Force Microscopy and Spectroscopy	688
	References	700
25	Higher Harmonics and Time-Varying Forces in Dynamic Force Microscopy	
	<i>Ozgur Sahin, Calvin F. Quate, Olav Solgaard, Franz J. Giessibl</i>	711
25.1	Modeling of Tip-Sample Interaction Forces in Tapping-Mode AFM ...	712
25.2	Enhancing the Cantilever Response to Time-Varying Forces	714
25.3	Application Examples	720
25.4	Higher-Harmonic Force Microscopy with Small Amplitudes	724
	References	728
26	Dynamic Modes of Atomic Force Microscopy	
	<i>André Schirmeisen, Boris Anczykowski, Hendrik Hölscher, Harald Fuchs</i>	731
26.1	Motivation – Measurement of a Single Atomic Bond	732
26.2	Harmonic Oscillator: a Model System for Dynamic AFM	736
26.3	Dynamic AFM Operational Modes	737
26.4	Q-Control	750
26.5	Dissipation Processes Measured with Dynamic AFM	754
26.6	Conclusions	758
	References	758
27	Molecular Recognition Force Microscopy: From Molecular Bonds to Complex Energy Landscapes	
	<i>Peter Hinterdorfer, Andreas Ebner, Hermann Gruber, Ruti Kapon, Ziv Reich</i>	763
27.1	Ligand Tip Chemistry	764
27.2	Immobilization of Receptors onto Probe Surfaces	766
27.3	Single-Molecule Recognition Force Detection	767
27.4	Principles of Molecular Recognition Force Spectroscopy	769
27.5	Recognition Force Spectroscopy: From Isolated Molecules to Biological Membranes	771
27.6	Recognition Imaging	779
27.7	Concluding Remarks	781
	References	781

Part D Bio-/Nanotribology and Bio-/Nanomechanics

28	Nanotribology, Nanomechanics, and Materials Characterization	
	<i>Bharat Bhushan</i>	789
28.1	Description of AFM/FFM and Various Measurement Techniques	791
28.2	Surface Imaging, Friction, and Adhesion	802
28.3	Wear, Scratching, Local Deformation, and Fabrication/Machining	828
28.4	Indentation	836

28.5	Boundary Lubrication	840
28.6	Conclusion	849
	References	851
29	Surface Forces and Nanorheology of Molecularly Thin Films	
	<i>Marina Ruths, Jacob N. Israelachvili</i>	857
29.1	Introduction: Types of Surface Forces	858
29.2	Methods Used to Study Surface Forces	860
29.3	Normal Forces Between Dry (Unlubricated) Surfaces	864
29.4	Normal Forces Between Surfaces in Liquids	868
29.5	Adhesion and Capillary Forces	878
29.6	Introduction: Different Modes of Friction and the Limits of Continuum Models	884
29.7	Relationship Between Adhesion and Friction Between Dry (Unlubricated and Solid Boundary Lubricated) Surfaces	885
29.8	Liquid Lubricated Surfaces	896
29.9	Effects of Nanoscale Texture on Friction	908
	References	911
30	Friction and Wear on the Atomic Scale	
	<i>Enrico Gnecco, Roland Bennewitz, Oliver Pfeiffer, Anisoara Socoliuc, Ernst Meyer</i>	923
30.1	Friction Force Microscopy in Ultrahigh Vacuum	924
30.2	The Tomlinson Model	928
30.3	Friction Experiments on the Atomic Scale	930
30.4	Thermal Effects on Atomic Friction	935
30.5	Geometry Effects in Nanocontacts	938
30.6	Wear on the Atomic Scale	942
30.7	Molecular Dynamics Simulations of Atomic Friction and Wear	944
30.8	Energy Dissipation in Noncontact Atomic Force Microscopy	947
30.9	Conclusion	949
	References	949
31	Computer Simulations of Nanometer-Scale Indentation and Friction	
	<i>Susan B. Sinnott, Seong-Jun Heo, Donald W. Brenner, Judith A. Harrison, Douglas L. Irving</i>	955
31.1	Computational Details	956
31.2	Indentation	961
31.3	Friction and Lubrication	976
31.4	Conclusions	1002
	References	1002
32	Force Measurements with Optical Tweezers	
	<i>Othmar Marti, Katrin Hübner</i>	1013
32.1	Optical Tweezers	1013
32.2	Influence of Surfaces and Viscosity	1017

32.3	Thermal Noise Imaging	1018
32.4	Applications in Cell Biology	1018
	References	1021
33	Scale Effect in Mechanical Properties and Tribology	
	<i>Bharat Bhushan, Michael Nosonovsky</i>	1023
33.1	Nomenclature	1024
33.2	Introduction	1025
33.3	Scale Effect in Mechanical Properties	1027
33.4	Scale Effect in Surface Roughness and Contact Parameters	1031
33.5	Scale Effect in Friction	1034
33.6	Scale Effect in Wear	1046
33.7	Scale Effect in Interface Temperature	1046
33.8	Closure	1047
33.A	Statistics of Particle Size Distribution	1049
	References	1052
34	Structural, Nanomechanical, and Nanotribological Characterization of Human Hair Using Atomic Force Microscopy and Nanoindentation	
	<i>Bharat Bhushan, Carmen LaTorre</i>	1055
34.1	Human Hair, and Skin and Hair Care Products	1058
34.2	Experimental	1068
34.3	Structural Characterization Using an AFM	1080
34.4	Nanomechanical Characterization Using Nanoindentation, Nanoscratch, and AFM	1087
34.5	Multiscale Tribological Characterization	1112
34.6	Conditioner Thickness Distribution and Binding Interactions on Hair Surface	1145
34.7	Surface Potential Studies of Human Hair Using Kelvin Probe Microscopy	1153
34.8	Conclusions	1164
34.A	Shampoo and Conditioner Treatment Procedure	1166
34.B	Conditioner Thickness Approximation	1166
	References	1167
35	Cellular Nanomechanics	
	<i>Roger Kamm, Jan Lammerding, Mohammad Mofrad</i>	1171
35.1	Overview	1171
35.2	Structural Components of a Cell	1173
35.3	Experimental Methods	1179
35.4	Theoretical and Computational Descriptions	1185
35.5	Mechanics of Subcellular Structures	1188
35.6	Current Understanding and Future Needs	1196
	References	1196

36 Optical Cell Manipulation

<i>Carsten Stüber, Tobias Kießling, Anatol Fritsch, Franziska Wetzel, Christian Schulze, Dan Strehle, Josef Käs</i>	1201
36.1 Interaction of Laser Light with Cells.....	1202
36.2 Optical Tweezers.....	1206
36.3 Holographic Optical Tweezers.....	1209
36.4 Optical Rotation.....	1211
36.5 Microdissection or Laser Scalpels.....	1213
36.6 Cell Sorting.....	1215
36.7 The Optical Stretcher.....	1218
36.8 Conclusion and Outlook.....	1222
References	1222

37 Mechanical Properties of Nanostructures

<i>Bharat Bhushan</i>	1227
37.1 Experimental Techniques for Measurement of Mechanical Properties of Nanostructures.....	1229
37.2 Experimental Results and Discussion.....	1235
37.3 Finite-Element Analysis of Nanostructures with Roughness and Scratches.....	1253
37.4 Summary.....	1259
37.A Fabrication Procedure for the Double-Anchored and Cantilever Beams.....	1260
References	1262

Part E Molecularly Thick Films for Lubrication

38 Nanotribology of Ultrathin and Hard Amorphous Carbon Films

<i>Bharat Bhushan</i>	1269
38.1 Description of Common Deposition Techniques.....	1273
38.2 Chemical and Physical Coating Characterization.....	1277
38.3 Micromechanical and Tribological Coating Characterization.....	1283
38.4 Closure.....	1304
References	1305

39 Self-Assembled Monolayers for Nanotribology and Surface Protection

<i>Bharat Bhushan</i>	1309
39.1 Background.....	1309
39.2 A Primer to Organic Chemistry.....	1313
39.3 Self-Assembled Monolayers: Substrates, Spacer Chains, and End Groups in the Molecular Chains.....	1316
39.4 Contact Angle and Nanotribological Properties of SAMs.....	1319
39.5 Summary.....	1340
References	1342

40 Nanoscale Boundary Lubrication Studies	
<i>Bharat Bhushan</i>	1347
40.1 Boundary Films	1347
40.2 Nanodeformation, Molecular Conformation, Spreading, and Nanotribological Studies	1348
40.3 Nanotribological, Electrical, and Chemical Degradations Studies and Environmental Effects in Novel PFPE Lubricant Films.....	1366
40.4 Nanotribological and Electrical Studies of Ionic Liquid Films	1375
40.5 Conclusions	1392
References	1393

Part F Biomimetics

41 Multifunctional Plant Surfaces and Smart Materials	
<i>Kerstin Koch, Bharat Bhushan, Wilhelm Barthlott</i>	1399
41.1 The Architecture of Plant Surfaces	1402
41.2 Multifunctional Plant Surfaces	1417
41.3 Technical Uses of Superhydrophobicity	1426
41.4 Conclusions	1430
References	1431
42 Lotus Effect: Surfaces with Roughness-Induced Superhydrophobicity, Self-Cleaning, and Low Adhesion	
<i>Bharat Bhushan, Yong Chae Jung, Michael Nosonovsky</i>	1437
42.1 Background	1438
42.2 Modeling of Contact Angle for a Liquid in Contact with a Rough Surface	1442
42.3 Lotus Effect Surfaces in Nature	1453
42.4 How to Make a Superhydrophobic Surface	1462
42.5 Fabrication and Characterization of Micro-, Nano-, and Hierarchical Patterned Surfaces	1468
42.6 Modeling, Fabrication, and Characterization of Oleophobic/Oleophilic Surfaces.....	1509
42.7 Conclusions	1517
References	1518
43 Biological and Biologically Inspired Attachment Systems	
<i>Stanislav N. Gorb</i>	1525
43.1 Foreword	1525
43.2 Attachment Systems	1526
43.3 Biological Functions of Attachment	1527
43.4 Time Scale of Attachment.....	1529
43.5 Principles of Biological Attachment	1530
43.6 Locomotory Attachment Pads: Hairy Versus Smooth.....	1533
43.7 Dry and Wet Systems	1535
43.8 Scaling Effects	1536

43.9	Evolutionary Aspects	1537
43.10	Attachment Devices and Environment	1537
43.11	Design Principles	1539
43.12	Biomimetics: Where We Are Now	1540
43.13	Conclusions	1544
	References	1545
44	Gecko Feet: Natural Hairy Attachment Systems for Smart Adhesion	
	<i>Bharat Bhushan</i>	1553
44.1	Overview	1554
44.2	Hairy Attachment Systems	1554
44.3	Tokay Gecko	1556
44.4	Attachment Mechanisms	1561
44.5	Experimental Adhesion Test Techniques and Data	1563
44.6	Adhesion Modeling	1566
44.7	Modeling of Biomimetic Fibrillar Structures	1577
44.8	Fabrication of Biomimetic Gecko Skin	1585
44.9	Conclusion	1591
44.A	Typical Rough Surfaces	1593
	References	1594

Part G Industrial Applications

45	The Millipede –	
	A Nanotechnology-Based AFM Data-Storage System	
	<i>Gerd K. Binnig, Giovanni Cherubini, Michel Despont, Urs T. Dürig,</i> <i>Evangelos Eleftheriou, Haralampos Pozidis, Peter Vettiger</i>	1601
45.1	The Millipede Concept	1603
45.2	Thermomechanical AFM Data Storage	1604
45.3	Array Design, Technology, and Fabrication	1606
45.4	Array Characterization	1607
45.5	Three-Terminal Cantilever Design	1609
45.6	x,y,z Medium Microscanner	1610
45.7	First Write/Read Results with the 32×32 Array Chip	1613
45.8	Polymer Medium	1614
45.9	Read Channel Model	1621
45.10	System Aspects	1624
45.11	Conclusions	1629
	References	1630
46	Nanorobotics	
	<i>Bradley J. Nelson, Lixin Dong</i>	1633
46.1	Overview of Nanorobotics	1634
46.2	Actuation at Nanoscales	1635
46.3	Nanorobotic Manipulation Systems	1637

46.4	Nanorobotic Assembly	1642
46.5	Applications	1651
	References	1654

Part H Micro-/Nanodevice Reliability

47	MEMS/NEMS and BioMEMS/BioNEMS: Materials, Devices, and Biomimetics	
	<i>Bharat Bhushan</i>	1663
47.1	MEMS/NEMS Basics	1664
47.2	Nanotribology and Nanomechanics Studies of Silicon and Related Materials	1683
47.3	Lubrication Studies for MEMS/NEMS	1691
47.4	Nanotribological Studies of Biological Molecules on Silicon-Based and Polymer Surfaces and Submicron Particles for Therapeutics and Diagnostics	1698
47.5	Surfaces with Roughness-Induced Superhydrophobicity, Self-Cleaning, and Low Adhesion	1708
47.6	Component-Level Studies	1717
47.7	Conclusions	1728
47.A	Micro-Nanofabrication Techniques	1729
	References	1733
48	Friction and Wear in Micro- and Nanomachines	
	<i>Maarten P. de Boer, Alex D. Corwin, Frank W. DelRio, W. Robert Ashurst</i>	1741
48.1	From Single- to Multiple-Asperity Friction	1743
48.2	Nanotractor Device Description	1747
48.3	Concluding Remarks	1755
	References	1756
49	Failure Mechanisms in MEMS/NEMS Devices	
	<i>W. Merlijn van Spengen, Robert Modliński, Robert Puers, Anne Jourdain</i>	1761
49.1	Failure Modes and Failure Mechanisms	1762
49.2	Stiction and Charge-Related Failure Mechanisms	1763
49.3	Creep, Fatigue, Wear, and Packaging-Related Failures	1769
49.4	Conclusions	1779
	References	1779
50	Mechanical Properties of Micromachined Structures	
	<i>Harold Kahn</i>	1783
50.1	Measuring Mechanical Properties of Films on Substrates	1783
50.2	Micromachined Structures for Measuring Mechanical Properties	1785
50.3	Measurements of Mechanical Properties	1795
	References	1799

51 High-Volume Manufacturing and Field Stability of MEMS Products	
<i>Jack Martin</i>	1803
51.1 Background	1804
51.2 Manufacturing Strategy	1806
51.3 Robust Manufacturing	1808
51.4 Stable Field Performance	1825
References	1828
52 Packaging and Reliability Issues in Micro-/Nanosystems	
<i>Yu-Chuan Su, Jongbaeg Kim, Yu-Ting Cheng, Mu Chiao, Liwei Lin</i>	1835
52.1 Introduction MEMS Packaging	1835
52.2 Hermetic and Vacuum Packaging and Applications	1841
52.3 Thermal Issues and Packaging Reliability	1851
52.4 Future Trends and Summary	1858
References	1859

Part I Technological Convergence and Governing Nanotechnology

53 Governing Nanotechnology: Social, Ethical and Human Issues	
<i>William Sims Bainbridge</i>	1867
53.1 Social Science Background	1867
53.2 Human Impacts of Nanotechnology	1871
53.3 Regulating Nanotechnology	1874
53.4 The Cultural Context for Nanotechnology	1876
53.5 Conclusions	1879
References	1880
Acknowledgements	1885
About the Authors	1887
Subject Index	1919