Springer Handbook of Nanotechnology

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Springer Handbook of Nanotechnology

Bharat Bhushan (Ed.)

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Foreword by Neal Lane

In a January 2000 speech at the California Institute of Technology, former President W. J. Clinton talked about the exciting promise of "nanotechnology" and the importance of expanding research in nanoscale science and engineering and in the physical sciences, more broadly. Later that month, he announced in his State of the Union Address an ambitious $ 497 million federal, multi-agency national nanotechnology initiative (NNI) in the fiscal year 2001 budget; and he made the NNI a top science and technology priority within a budget that emphasized increased investment in U.S. scientific research. With strong bipartisan support in Congress, most of this request was appropriated, and the NNI was born.

Nanotechnology is the ability to manipulate individual atoms and molecules to produce nanostructured materials and sub-micron objects that have applications in the real world. Nanotechnology involves the production and application of physical, chemical and biological systems at scales ranging from individual atoms or molecules to about 100 nanometers, as well as the integration of the resulting nanostructures into larger systems. Nanotechnology is likely to have a profound impact on our economy and society in the early 21st century, perhaps comparable to that of information technology or advances in cellular and molecular biology. Science and engineering research in nanotechnology promises breakthroughs in areas such as materials and manufacturing, electronics, medicine and healthcare, energy and the environment, biotechnology, information technology and national security. It is widely felt that nanotechnology will lead to the next industrial revolution.

Nanometer-scale features are built up from their elemental constituents. Micro- and nanosystems components are fabricated using batch-processing techniques that are compatible with integrated circuits and range in size from micro- to nanometers. Micro- and nanosystems include Micro/NanoElectroMechanical Systems (MEMS/NEMS), micromechatronics, optoelectronics, microfluidics and systems integration. These systems can sense, control, and activate on the micro/nanoscale and can function individually or in arrays to generate effects on the macroscale. Due to the enabling nature of these systems and the significant impact they can have on both the commercial and defense applications, industry as well as the federal government have taken special interest in seeing growth nurtured in this field. Micro- and nanosystems are the next logical step in the "silicon revolution".

Prof. Neal Lane

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Served in the Clinton Administration as Assistant to the President for Science and Technology and Director of the White House Office of Science and Technology Policy (1998–2001) and, prior to that, as Director of the National Science Foundation (1993–1998). While at the White House, he was instrumental in creating NNI.

The discovery of novel materials, processes, and phenomena at the nanoscale and the development of new experimental and theoretical techniques for research provide fresh opportunities for the development of innovative nanosystems and nanostructured materials. There is an increasing need for a multidisciplinary, systems-oriented approach to manufacturing micro/nanodevices which function reliably. This can only be achieved through the cross-fertilization of ideas from different disciplines and the systematic flow of information and people among research groups.

Nanotechnology is a broad, highly interdisciplinary, and still evolving field. Covering even the most important aspects of nanotechnology in a single book that reaches readers ranging from students to active researchers in academia and industry is an enormous challenge. To prepare such a wide-ranging book on nanotechnology, Professor Bhushan has harnessed his own knowledge and experience, gained in several industries and universities, and has assembled about 90 internationally recognized authors from three continents to write 38 chapters. The authors come from both academia and industry.

Professor Bharat Bhushan's comprehensive book is intended to serve both as a textbook for university courses as well as a reference for researchers. It is a timely addition to the literature on nanotechnology, which I anticipate will stimulate further interest in this important new field and serve as an invaluable resource to members of the international scientific and industrial community.

The Editor-in-Chief and his team are to be warmly congratulated for bringing together this exclusive, timely, and useful Nanotechnology Handbook.

Foreword by James R. Heath

Nanotechnology has become an increasingly popular buzzword over the past five years or so, a trend that has been fueled by a global set of publicly funded nanotechnology initiatives. Even as researchers have been struggling to demonstrate some of the most fundamental and simple aspects of this field, the term nanotechnology has entered into the public consciousness through articles in the popular press and popular fiction. As a consequence, the expectations of the public are high for nanotechnology, even while the actual public definition of nanotechnology remains a bit fuzzy.

Why shouldn't those expectations be high? The late 1990's witnessed a major information technology (IT) revolution and a minor biotechnology revolution. The IT revolution impacted virtually every aspect of life in the western world. I am sitting on an airplane at 30,000 feet at the moment, working on my laptop, as are about half of the other passengers on this plane. The plane itself is riddled with computational and communications equipment. As soon as we land, many of us will pull out cell phones, others will check email via wireless modem, some will do both. This picture would be the same if I was landing in Los Angeles, Beijing, or Capetown. I will probably never actually print this text, but will instead submit it electronically. All of this was unthinkable a dozen years ago. It is therefore no wonder that the public expects marvelous things to happen quickly. However, the science that laid the groundwork for the IT revolution dates back 60 years or more, with its origins in the fundamental solid state physics.

By contrast, the biotech revolution was relatively minor and, at least to date, not particularly effective. The major diseases that plagued mankind a quarter century ago are still here. In some third world countries, the average lifespan of individuals has actually decreased from where it was a full century ago. While the costs of electronics technologies have plummeted, health care costs have continued to rise. The biotech revolution may have a profound impact, but the task at hand is substantially more difficult to what was required for the IT revolution. In effect, the IT revolution was based on the advanced engineering of two-dimensional digital circuits constructed from relatively simple components – extended solids. The biotech revolution is really dependent upon the ability to reverse engineer three-dimensional analog systems constructed from quite complex components – proteins. Given that the basic science behind biotech is substantially younger than the science that has supported IT, it is perhaps not surprising that the biotech revolution has not really been a proper revolution yet, and it likely needs at least another decade or so to come to fruition.

Where does nanotechnology fit into this picture? In many ways, nanotechnology depends upon the ability to engineer two- and three-dimensional systems constructed from complex components such as macromolecules, biomolecules, nanostructured solids, etc. Furthermore, in terms of patents, publications, and other metrics that can be used to gauge the birth and evolution of a field, nanotech lags some 15–20 years behind biotech. Thus, now is the time that the fundamental science behind nanotechnology is being explored and developed. Nevertheless, progress with that science is moving forward at a dramatic pace. If the scientific community can keep up this pace and if the public sector will continue to support this science, then it is possible, and perhaps even likely, that in 20 years from now we may be speaking of the nanotech revolution.

The Nanotechnology Handbook is timely in assembling chapters in the broad field of nanotechnology with an emphasis on reliability. The handbook should be a valuable reference for experienced researchers as well as for a novice in the field.

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Worked in the group of Nobel Laureate Richard E. Smalley at Rice University (1984–88) and co-invented Fullerene molecules which led to a revolution in Chemistry including the realization of nanotubes. The work on Fullerene molecules was cited for the 1996 Nobel Prize in Chemistry. Later he joined the University of California at Los Angeles (1994–2002), and co-founded and served as a Scientific Director of The California Nanosystems Institute.

Preface

On December 29, 1959 at the California Institute of Technology, Nobel Laureate Richard P. Feynman gave a talk at the Annual meeting of the American Physical Society that has become one classic science lecture of the 20th century, titled "There's Plenty of Room at the Bottom." He presented a technological vision of extreme miniaturization in 1959, several years before the word "chip" became part of the lexicon. He talked about the problem of manipulating and controlling things on a small scale. Extrapolating from known physical laws, Feynman envisioned a technology using the ultimate toolbox of nature, building nanoobjects atom by atom or molecule by molecule. Since the 1980s, many inventions and discoveries in fabrication of nanoobjects have been a testament to his vision. In recognition of this reality, in a January 2000 speech at the same institute, former President W. J. Clinton talked about the exciting promise of "nanotechnology" and the importance of expanding research in nanoscale science and engineering. Later that month, he announced in his State of the Union Address an ambitious $ 497 million federal, multi-agency national nanotechnology initiative (NNI) in the fiscal year 2001 budget, and made the NNI a top science and technology priority. Nanotechnology literally means any technology done on a nanoscale that has applications in the real world. Nanotechnology encompasses production and application of physical, chemical and biological systems at size scales, ranging from individual atoms or molecules to submicron dimensions as well as the integration of the resulting nanostructures into larger systems. Nanofabrication methods include the manipulation or self-assembly of individual atoms, molecules, or molecular structures to produce nanostructured materials and sub-micron devices. Micro- and nanosystems components are fabricated using top-down lithographic and nonlithographic fabrication techniques. Nanotechnology will have a profound impact on our economy and society in the early 21st century, comparable to that of semiconductor technology, information technology, or advances in cellular and molecular biology. The research and development in nanotechnology will lead to potential breakthroughs in areas such as materials and manufacturing, nanoelectronics, medicine and healthcare, energy, biotechnology, information technology and national security. It is widely felt that nanotechnology will lead to the next industrial revolution.

Reliability is a critical technology for many micro- and nanosystems and nanostructured materials. No book exists on this emerging field. A broad based handbook is needed. The purpose of this handbook is to present an overview of nanomaterial synthesis, micro/nanofabrication, micro- and nanocomponents and systems, reliability issues (including nanotribology and nanomechanics) for nanotechnology, and industrial applications. The chapters have been written by internationally recognized experts in the field, from academia, national research labs and industry from all over the world.

The handbook integrates knowledge from the fabrication, mechanics, materials science and reliability points of view. This book is intended for three types of readers: graduate students of nanotechnology, researchers in academia and industry who are active or intend to become active in this field, and practicing engineers and scientists who have encountered a problem and hope to solve it as expeditiously as possible. The handbook should serve as an excellent text for one or two semester graduate courses in nanotechnology in mechanical engineering, materials science, applied physics, or applied chemistry.

We embarked on this project in February 2002, and we worked very hard to get all the chapters to the publisher in a record time of about 1 year. I wish to sincerely thank the authors for offering to write comprehensive chapters on a tight schedule. This is generally an added responsibility in the hectic work schedules of researchers today. I depended on a large number of reviewers who provided critical reviews. I would like to thank Dr. Phillip J. Bond, Chief of Staff and Under Secretary for Technology, US Department of Commerce, Washington, D.C. for suggestions for chapters as well as authors in the handbook. I would also like to thank my colleague, Dr. Huiwen Liu, whose efforts during the preparation of this handbook were very useful.

I hope that this handbook will stimulate further interest in this important new field, and the readers of this handbook will find it useful.

September 2003

Bharat Bhushan
Editor

Editors Vita

Dr. Bharat Bhushan received an M.S. in mechanical engineering from the Massachusetts Institute of Technology in 1971, an M.S. in mechanics and a Ph.D. in mechanical engineering from the University of Colorado at Boulder in 1973 and 1976, respectively, an MBA from Rensselaer Polytechnic Institute at Troy, NY in 1980, Doctor Technicae from the University of Trondheim at Trondheim, Norway in 1990, a Doctor of Technical Sciences from the Warsaw University of Technology at Warsaw, Poland in 1996, and Doctor Honouris Causa from the Metal-Polymer Research Institute of National Academy of Sciences at Gomel, Belarus in 2000. He is a registered professional engineer (mechanical). He is presently an Ohio Eminent Scholar and The Howard D. Winbigler Professor in the Department of Mechanical Engineering, Graduate Research Faculty Advisor in the Department of Materials Science and Engineering, and the Director of the Nanotribology Laboratory for Information Storage & MEMS/NEMS (NLIM) at the Ohio State University, Columbus, Ohio. He is an internationally recognized expert of tribology on the macro- to nanoscales, and is one of the most prolific authors in the field. He is considered by some a pioneer of the tribology and mechanics of magnetic storage devices and a leading researcher in the fields of nanotribology and nanomechanics using scanning probe microscopy and applications to micro/nanotechnology. He has authored 5 technical books, 45 handbook chapters, more than 450 technical papers in referred journals, and more than 60 technical reports, edited more than 25 books, and holds 14 U.S. patents. He is founding editor-in-chief of World Scientific Advances in Information Storage Systems Series, CRC Press Mechanics and Materials Science Series, and Microsystem Technologies – Micro- & Nanosystems and Information Storage & Processing Systems (formerly called Journal of Information Storage and Processing Systems). He has given more than 250 invited presentations on five continents and more than 60 keynote/plenary addresses at major international conferences.

Dr. Bhushan is an accomplished organizer. He organized the first symposium on Tribology and Mechanics of Magnetic Storage Systems in 1984 and the first international symposium on Advances in Information Storage Systems in 1990, both of which are now held annually. He is the founder of an ASME Information Storage and Processing Systems Division founded in 1993 and served as the founding chair during 1993–1998. His biography has been listed in over two dozen Who's Who books including Who's Who in the World and has received more than a dozen awards for his contributions to science and technology from professional societies, industry, and U.S. government agencies. He is also the recipient of various international fellowships including the Alexander von Humboldt Research Prize for Senior Scientists, Max Planck Foundation Research Award for Outstanding Foreign Scientists, and the Fulbright Senior Scholar Award. He is a foreign member of the International Academy of Engineering (Russia), Belorussian Academy of Engineering and Technology and the Academy of Triboengineering of Ukraine, an honorary member of the Society of Tribologists of Belarus, a fellow of ASME, IEEE, and the New York Academy of Sciences, and a member of STLE, ASEE, Sigma Xi and Tau Beta Pi.

Dr. Bhushan has previously worked for the R & D Division of Mechanical Technology Inc., Latham, NY; the Technology Services Division of SKF Industries Inc., King of Prussia, PA; the General Products Division Laboratory of IBM Corporation, Tucson, AZ; and the Almaden Research Center of IBM Corporation, San Jose, CA.

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Part D Molecularly Thick Films for Lubrication

Part E Industrial Applications and Microdevice Reliability

List of Abbreviations

μCP	microcontact printing
μTAS	micro-total analysis systems
2-DEG	two-dimensional electron gas

A

A	adenine
ABS	air-bearing surface
ADEPTS	antibody directed enzyme-prodrug therapy
AFAM	atomic force acoustic microscopy
AFM	atomic force microscope/microscopy
AIDCN	2-amino-4,5-imidazoledicarbonitrile
AM	amplitude modulation
APCVD	atmospheric pressure chemical vapor deposition
ASA	anti-stiction agent
ATP	adenosine triphosphat

B

BE	boundary element
BioMEMS	biological or biomedical microelectromechanical systems
BP	bit pitch
BPI	bits per inch
bpsi	bits per square inch
BSA	bovine serum albumin

C

C	cytosine
CA	constant amplitude
CBA	cantilever beam array
CCVD	catalytic chemical vapor deposition
CDS	correlated double sampling
CDW	charge density wave
CE	capillary electrophoresis
CE	constant excitation mode
CFM	chemical force microscopy
CG	controlled geometry
CNT	carbon nanotube
COC	cyclic olefin copolymers
COF	chip-on-flex
COGs	cost of goods
CSM	continuous stiffness measurement
CTE	coefficient of thermal expansion
CTLs	cytoxic T-lymphocytes
CVD	chemical vapor deposition

D

DAS	dimer adatom stacking
DBR	distributed Bragg reflector
DCs	dendritic cells
DFB	distributed feedback
DFM	dynamic force microscopy
DFT	density functional theory
DLC	diamond-like carbon
DLP	digital light processing
DLVO	Derjaguin–Landau–Verwey–Overbeek
DMD	digital micromirror device
DMT	Derjaguin–Muller–Toporov
DOS	density of states
DPN	dip-pen nanolithography
DRIE	deep reactive ion etching
DSC	differential scanning calorimetry
DSP	digital signal processor
DT	diphteria toxin
DWNTs	double-wall nanotubes

E

EAM	embedded atom method
EBD	electron beam deposition
ECR-CVD	electron cyclotron resonance chemical vapor deposition
EDC	1-ethyl-3-(3-diamethylaminoprophyl) carbodiimide
EDP	ethylene diamine pyrocatechol
EDS	energy dispersive X-ray spectrometer
EELS	electron energy loss spectrometer/spectroscopy
EFC	electrostatic force constant
EFM	electric field gradient microscopy
EHD	electrohydrodynamic
EL	electro-luminiscence
EO	electro-osmosis
EOF	electro-osmotic flow
EPR	enhanced permeability and retention effect
ESD	electrostatic discharge

F

FAD	flavin adenine dinucleotide
FC	flip chip technique
FCA	filtered cathodic arc
FCP	force calibration plot
FD	finite difference
FE	finite element
FEM	finite element method/modeling

FET	field-effect transistor
FFM	friction force microscope/microscopy
FIB	focused ion beam
FID	free induction decay
FIM	field-ion microscope/microscopy
FKT	Frenkel-Kontorova-Tomlinson
FM	frequency modulation
FM-AFM	frequency modulation AFM
FMEA	failure mode effect analysis
FMM	force modulation mode
FM-SFM	frequency-modulation SFM
FS	force spectroscopy

G

G	guanine
GIO	grazing impact oscillator
GMR	giant magnetoresistance
GOD	glucose oxidase
Gox	flavoenzyme glucose oxidase

H

HARMEMS	high-aspect-ratio MEMS
HDD	hard disk drive
HF	hydrofluoric acid
HOP	highly oriented pyrolytic
HOPG	highly oriented pyrolytic graphite
HPMA	hydroxyl polymethacrylamide
HtBDC	hexa-tert-butyl-decacyclene
HTCS	high temperature superconductivity

I

IBD	ion beam deposition
IC	integrated circuit
ICAM-1	intercellular adhesion molecule-1
IFM	interfacial force microscope
ISE	indentation size effect
ITO	indium tin oxide

J

JKR	Johnson–Kendall–Roberts

K

KPFM	Kelvin probe force microscopy

L

LB	Langmuir–Blodgett
LCC	leadless chip carrier
LDOS	local density of states
LEDs	light-emitting diodes
LFA-1	leukocyte function-associated antigen-1
LFM	lateral force microscope
LFT	linear fractional transformation
LN	liquid nitrogen
LPCVD	low pressure chemical vapor deposition
LQG	linear quadratic Gaussian
LTR	loop-transfer recovery
LTSPM	low-temperature SPM
LTSTS	low-temperature scanning tunneling spectroscopy
LVDT	linear variable differential transformers

M

MAP	manifold absolute pressure
MD	molecular dynamics
MDS	molecular dynamics simulation
ME	metal evaporated
MEMS	microelectromechanical systems
MFM	magnetic field microscope/microscopy
MHA	16-mercaptohexadecanoic acid thiol
MHC	major histocompatibility complex
MHD	magnetohydrodynamic
MIM	metal/insulator/metal
MLE	maximum likelihood estimator
MOCVD	metalorganic CVD
MP	metal particle
MPTMS	mercaptopropyltrimethoxysilane
MRAM	magnetoresistive RAM
MRFM	magnetic resonance force microscopy
MRFM	molecular recognition force microscopy
MRI	magnetic resonance imaging
MTTF	mean time to failure
MWCNT	multiwall carbon nanotube

N

NA	nucleic acid
NBMN	3-nitrobenzal malonitrile
NC-AFM	noncontact atomic force microscopy
NCS	neocarzinostatin
NEMS	nanoelectromechanical systems
NMP	no moving part
NNI	National Nanotechnology Initiative
NSOM	near-field scanning optical microscope/microscopy
NTA	nitrilotriacetate
nTP	nanotransfer printing
NVRAM	nonvolatile random access memories

O

ODD	optical disk drives
OMVPE	organometallic vapor phase epitaxy
OT	optical tweezers
OTE	octadecyltrimethoxysilane
OTS	octadecyltrichlorosilane

OUM	Ovonyx unified memory

P

P/W	power to weight
PA	plasminogen activator
PAMAM	poly(amido) amine
PAPP	p-aminophenyl phosphate
PC	ploycarbonate
PC-RAM	phase change RAM
pDA	1,4-phenylenediamine
PDMS	polydimethylsiloxane
PDP	2-pyridyldithiopropionyl
PE	polyethylene
PECVD	plasma enhanced CVD
PEG	poly(ethylene glycol)
PES	photoemission spectroscopy
PES	position error signal
PET	poly(ethylene terephthalate)
PFDA	perfluorodecanoic acid
PFPE	perfluoropolyether
PL	photoluminescence
PMMA	poly(methylmethacrylate)
PS	polystyrene
PSG	phosphorus-doped glass
PSGL-1	P-selection glycoprotein ligand-1
PTFE	polytetrafluoroethylene
PZT	lead zirconate titanate

Q

QCM	quartz-crystal microbalance

R

RES	reticuloendothelial system
RF	radiofrequency
RH	relative humidity
RICM	reflection interface contrast microscopy
RIE	reactive ion etching
RLS	recursive least square algorithm
RPES	relative position error signal
RTP	rapid thermal processing

S

SACA	static advancing contact angle
SAED	selected area electron diffraction
SAM	self-assembling monolayer
SAM	scanning acoustic microscopy
SCM	scanning capitance microscopy
SCPM	scanning chemical potential
SEcM	scanning electrochemical microscopy
SEFM	scanning electrostatic force microscopy
SEM	scanning electron microscope/microscopy
SFA	surface forces apparatus
SFAM	scanning force acoustic microscopy
SFD	shear flow detachment
SFM	scanning force microscopy
SFS	scanning force spectroscopy
SICM	scanning ion conductance microscopy
SIMO	single-input–multi-output
SISO	single-input–single-output
SKPM	scanning Kelvin probe microscopy
SLAM	scanning local-acceleration microscopy
SMA	shape memory alloy
SMANCS	S-Methacryl-neocarzinostatin
SMM	scanning magnetic microscopy
SN	scanning nanoindentation
SNOM	scanning near-field optical microscopy
SPM	scanning probe microscopy
sPROMS	structurally programmable microfluidic system
SPS	spark plasma sintering
SRAM	static random access memory
ssDNA	single stranded DNA
SSNA	single-stranded nucleic acid molecule
SThM	scanning thermal microscopy
STM	scanning tunneling microscope/microscopy
SWCNT	single-wall carbon nanotubes
SWNT	single-wall nanotubes

T

T	thymine
TAAs	tumor associated antigens
TEM	transmission electron microscopy
TESP	tapping-mode etched silicon probe
TGA	thermo-gravimetric analysis
TIRM	total internal reflection microscopy
TMAH	tetramethyl ammonium hydroxide
TMAH	tetramethyl-aluminium hydroxide
TP	track pitch
TPI	tracks per inch
TRM/TMR	track mis-registration
T-SLAM	variable-temperature SLAM
TTF	tetrathiofulvane

U

UHV	ultrahigh vacuum

V

VCM	voice coil motor
VCO	voltage-controlled oscillator
VLS	vapor-liquid-solid
VLSI	very large-scale integration

X

XRD	X-ray diffraction