Springer Handbooks provide a concise compilation of approved key information on methods of research, general principles, and functional relationships in physical sciences and engineering. The world’s leading experts in the fields of physics and engineering will be assigned by one or several renowned editors to write the chapters comprising each volume. The content is selected by these experts from Springer sources (books, journals, online content) and other systematic and approved recent publications of physical and technical information.

The volumes are designed to be useful as readable desk reference books to give a fast and comprehensive overview and easy retrieval of essential reliable key information, including tables, graphs, and bibliographies. References to extensive sources are provided.
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, more broadly, in the physical sciences. Later that month, he announced in his State of the Union Address an ambitious US$ 497 million federal, multiagency 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 US scientific research. With strong bipartisan support in Congress, most of this request was appropriated, and the NNI was born. Often, federal budget initiatives only last a year or so. It is most encouraging that the NNI has remained a high priority of the G.W. Bush Administration and Congress, reflecting enormous progress in the field and continued strong interest and support by industry.

Nanotechnology is the ability to manipulate individual atoms and molecules to produce nanostructured materials and submicron 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 nm, 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 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. Clinical trials are already underway for nanomaterials that offer the promise of cures for certain cancers. It is widely felt that nanotechnology will be 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/nanoelectro-mechanical 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.

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, Prof. Bhushan has harnessed his own knowledge and experience, gained in several industries and universities, and has assembled internationally recognized authors from four continents to write chapters covering a wide array of nanotechnology topics, including the latest advances. The authors come from both academia and industry. The topics include major advances in many fields where nanoscale science and engineering is being pursued and illustrate how the field of nanotechnology has continued to emerge and blossom. Given the accelerating pace of discovery and applications in nanotechnology, it is a challenge to cap-
ture it all in one volume. As in earlier editions, professor Bhushan does an admirable job.

Professor Bharat Bhushan’s comprehensive book is intended to serve both as a textbook for university courses as well as a reference for researchers. The first and second editions were timely additions to the literature on nanotechnology and stimulated further interest in this important new field, while serving as invaluable resources to members of the international scientific and industrial community. The increasing demand for up-to-date information on this fast moving field led to this third edition. It is increasingly important that scientists and engineers, whatever their specialty, have a solid grounding in the fundamentals and potential applications of nanotechnology. This third edition addresses that need by giving particular attention to the widening audience of readers. It also includes a discussion of the social, ethical and political issues that tend to surround any emerging technology.

The editor 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 1990s 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 e-mail 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 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 than 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 into 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 even perhaps likely, that in 20 years we may be speaking of the nanotech revolution.

The first edition of Springer Handbook of Nanotechnology was timely to assemble chapters in the broad field of nanotechnology. Given the fact that the second edition was in press one year after the publication of the first edition in April 2004, it is clear that the handbook has shown to be a valuable reference for experienced researchers as well as for a novice in the field. The third edition has one Part added and an expanded scope should have a wider appeal.
Preface to the 3rd Edition

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 of the 20th century classic science lectures, 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 testament to his vision. In recognition of this reality, National Science and Technology Council (NSTC) of the White House created the Interagency Working Group on Nanoscience, Engineering and Technology (IWGN) in 1998. 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 technology, more broadly. Later that month, he announced in his State of the Union Address an ambitious US$ 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. The objective of this initiative was to form a broad-based coalition in which the academe, the private sector, and local, state, and federal governments work together to push the envelop of nanoscience and nanoengineering to reap nanotechnology’s potential social and economic benefits.

The funding in the US has continued to increase. In January 2003, the US senate introduced a bill to establish a National Nanotechnology Program. On December 3, 2003, President George W. Bush signed into law the 21st Century Nanotechnology Research and Development Act. The legislation put into law programs and activities supported by the National Nanotechnology Initiative. The bill gave nanotechnology a permanent home in the federal government and authorized US$ 3.7 billion to be spent in the four year period beginning in October 2005, for nanotechnology initiatives at five federal agencies. The funds would provide grants to researchers, coordinate R&D across five federal agencies (National Science Foundation (NSF), Department of Energy (DOE), NASA, National Institute of Standards and Technology (NIST), and Environmental Protection Agency (EPA)), establish interdisciplinary research centers, and accelerate technology transfer into the private sector. In addition, Department of Defense (DOD), Homeland Security, Agriculture and Justice as well as the National Institutes of Health (NIH) also fund large R&D activities. They currently account for more than one-third of the federal budget for nanotechnology.

European Union (EU) made nanosciences and nanotechnologies a priority in Sixth Framework Program (FP6) in 2002 for a period of 2003–2006. They had dedicated small funds in FP4 and FP5 before. FP6 was tailored to help better structure European research and to cope with the strategic objectives set out in Lisbon in 2000. Japan identified nanotechnology as one of its main research priorities in 2001. The funding levels increases sharply from US$400 million in 2001 to around US$950 million in 2004. In 2003, South Korea embarked upon a ten-year program with around US$ 2 billion of public funding, and Taiwan has committed around US$ 600 million of public funding over six years. Singapore and China are also investing on a large scale. Russia is well funded as well.

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 scales, ranging from individual atoms or molecules to submicron dimensions, 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, comparable to that of semiconductor technology, information technology, or cellular and molecular biology. Science and technology research in nanotechnology promises 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 be the next industrial revolution.

There is an increasing need for a multidisciplinary, system-oriented approach to design and manufactur-
ing of 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. Reliability is a critical technology for many micro- and nanosystems and nanostructured materials. A broad based handbook was needed, and the first edition of Springer Handbook of Nanotechnology was published in April 2004. It presented an overview of nanomaterial synthesis, micro/nanofabrication, micro- and nanocomponents and systems, scanning probe microscopy, reliability issues (including nanotribology and nanomechanics) for nanotechnology, and industrial applications. When the handbook went for sale in Europe, it was sold out in ten days. Reviews on the handbook were very flattering.

Given the explosive growth in nanoscience and nanotechnology, the publisher and the editor decided to develop a second edition after merely six months of publication of the first edition. The second edition (2007) came out in December 2006. The publisher and the editor again decided to develop a third edition after six month of publication of the second edition. This edition of the handbook integrates the knowledge from nanostructures, fabrication, materials science, devices, and reliability point of view. It covers various industrial applications. It also addresses social, ethical, and political issues. Given the significant interest in biomedical applications, and biomimetics a number of additional chapters in this arena have been added. The third edition consists of 53 chapters (new 10, revised 28, and as is 15). The chapters have been written by 139 internationally recognized experts in the field, from academia, national research labs, and industry, and from all over the world.

This handbook 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 the development of third edition in June 2007, and we worked very hard to get all the chapters to the publisher in a record time of about 12 months. 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. Last but not the least, I would like to thank my secretary Caterina Runyon-Spears for various administrative duties and her tireless efforts are highly appreciated.

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

February 2010

Bharat Bhushan

Editor
On 29 December 1959 at the California Institute of Technology, Nobel Laureate Richard P. Feynman gave at talk at the Annual meeting of the American Physical Society that has become one of the 20th century classic science lectures, 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 the fabrication of nanoobjects have been a testament to his vision. In recognition of this reality, the National Science and Technology Council (NSTC) of the White House created the Interagency Working Group on Nanoscience, Engineering and Technology (IWGN) in 1998. 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, more broadly, technology. Later that month, he announced in his State of the Union Address an ambitious $497 million federal, multiagency national nanotechnology initiative (NNI) in the fiscal year 2001 budget, and made the NNI a top science and technology priority. The objective of this initiative was to form a broad-based coalition in which the academe, the private sector, and local, state, and federal governments work together to push the envelope of nanoscience and nanoengineering to reap nanotechnology’s potential social and economic benefits.

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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 the development of the second edition in October 2004, and we worked very hard to get all the chapters to the publisher in a record time of about 7 months. I wish to sincerely thank the authors for offering to write comprehensive chapters on a tight schedule. This is generally an added responsibility to 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 chapter suggestions as well as authors in the handbook. I would also like to thank my colleague, Dr. Zhenhua Tao, whose efforts during the preparation of this handbook were very useful. Last but not the least, I would like to thank my secretary Caterina Runyon-Spears for various administrative duties; her tireless efforts are highly appreciated.

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

May 2005

Bharat Bhushan
Editor
Preface to the 1st Edition

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.

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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 National Academy of Sciences at Gomel, Belarus in 2000. He is a registered professional engineer. He is presently an Ohio Eminent Scholar and The Howard D. Winbigler Professor in the College of Engineering, and the Director of the Nanoprobe Laboratory for Bio- and Nanotechnology and Biomimetics (NLB²) at the Ohio State University, Columbus, Ohio. His research interests include fundamental studies with a focus on scanning probe techniques in the interdisciplinary areas of bio/nanotribology, bio/nanomechanics and bio/nanomaterials characterization, and applications to bio/nanotechnology and biomimetics. He is an internationally recognized expert of bio/nanotribology and bio/nanomechanics using scanning probe microscopy, and is one of the most prolific authors. He is considered by some a pioneer of the tribology and mechanics of magnetic storage devices. He has authored 6 scientific books, more than 90 handbook chapters, more than 700 scientific papers (h factor – 45+; ISI Highly Cited in Materials Science, since 2007), and more than 60 technical reports, edited more than 45 books, and holds 17 US and foreign patents. He is co-editor of Springer NanoScience and Technology Series and co-editor of Microsystem Technologies. He has given more than 400 invited presentations on six continents and more than 140 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 two dozen awards for his contributions to science and technology from professional societies, industry, and US 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), Byelorussian Academy of Engineering and Technology and the Academy of Triboenineering of Ukraine, an honorary member of the Society of Tribologists of Belarus, a fellow of ASME, IEEE, STLE, and the New York Academy of Sciences, and a member of 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. He has held visiting professor appointments at University of California at Berkeley, University of Cambridge, UK, Technical University Vienna, Austria, University of Paris, Orsay, ETH Zurich and EPFL Lausanne.
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<td>μCP</td>
<td>microcontact printing</td>
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<tr>
<td>1-D</td>
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<td>18-methyl eicosanoic acid</td>
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</tr>
<tr>
<td>MOSFET</td>
<td>metal–oxide–semiconductor field-effect transistor</td>
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<tr>
<td>MP</td>
<td>metal particle</td>
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<tr>
<td>MPTMS</td>
<td>mercaptopropyltrimethoxysilane</td>
</tr>
<tr>
<td>MRFM</td>
<td>magnetic resonance force microscopy</td>
</tr>
<tr>
<td>MRFM</td>
<td>molecular recognition force microscopy</td>
</tr>
<tr>
<td>MRI</td>
<td>magnetic resonance imaging</td>
</tr>
<tr>
<td>MRP</td>
<td>molecular recognition phase</td>
</tr>
<tr>
<td>MsCl</td>
<td>mechanosensitive channel of large conductance</td>
</tr>
<tr>
<td>MST</td>
<td>microsystem technology</td>
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<tr>
<td>MT</td>
<td>microtubule</td>
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<tr>
<td>mTAS</td>
<td>micro total analysis system</td>
</tr>
<tr>
<td>MTTF</td>
<td>mean time to failure</td>
</tr>
<tr>
<td>MUMP</td>
<td>multiuser MEMS process</td>
</tr>
<tr>
<td>MVD</td>
<td>molecular vapor deposition</td>
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<tr>
<td>MWCNT</td>
<td>multiwall carbon nanotube</td>
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<tr>
<td>MWNT</td>
<td>multiwall nanotube</td>
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<tr>
<td>MYD/BHW</td>
<td>Muller–Yushchenko–Derjaguin/Burgess–Hughes–White</td>
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<tr>
<td>NA</td>
<td>numerical aperture</td>
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<tr>
<td>NADIS</td>
<td>nanoscale dispensing</td>
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<tr>
<td>NASA</td>
<td>National Aeronautics and Space Administration</td>
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<tr>
<td>NEM</td>
<td>nanoelectromechanical system</td>
</tr>
<tr>
<td>NGL</td>
<td>next-generation lithography</td>
</tr>
<tr>
<td>NHS</td>
<td>$N$-hydroxysuccinimidyl</td>
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<td>NIH</td>
<td>National Institute of Health</td>
</tr>
<tr>
<td>NIL</td>
<td>nanoimprint lithography</td>
</tr>
<tr>
<td>NIST</td>
<td>National Institute of Standards and Technology</td>
</tr>
<tr>
<td>NMP</td>
<td>no-moving-part</td>
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<tr>
<td>NMR</td>
<td>nuclear magnetic resonance</td>
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<tr>
<td>NMR</td>
<td>nuclear mass resonance</td>
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<tr>
<td>NNI</td>
<td>National Nanotechnology Initiative</td>
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</tbody>
</table>
List of Abbreviations

NOEMS nanooptoelectromechanical system
NP nanoparticle
NP nanoprobe
NSF National Science Foundation
NSOM near-field scanning optical microscopy
NSTC National Science and Technology Council
NTA nitritolriacetate
nTP nanotransfer printing

O
ODA octadecylamine
ODDMS n-octadecyldimethyl(dimethylamino)silane
ODMS n-octadecyldimethyl(dimethylamino)silane
ODP octadecylphosphonate
ODTS octadecytrichlorosilane
OLED organic light-emitting device
OM optical microscope
OMVPE organometallic vapor-phase epitaxy
OS optical stretcher
OT optical tweezers
OTRS optical tweezers Raman spectroscopy
OTS octadecytrichlorosilane
oxLDL oxidized low-density lipoprotein

P
P–V peak-to-valley
PAA poly(acrylic acid)
PAANF poly(allylamine hydrochloride)
PAPP p-aminophenyl phosphate
Pax paxillin
PBC periodic boundary condition
PBS phosphate-buffered saline
PC polycarbonate
PCB printed circuit board
PCL polycaprolactone
PCR polymerase chain reaction
PDA personal digital assistant
PDMS polydimethylsiloxane
PDP 2-pyridyldithiopropionyl
PDP pyridyldithiopropionate
PE polyethylene
PECVD plasma-enhanced chemical vapor deposition
PEEK polyethetherketone
PEG polyethylene glycol
PEI polyethyleneimine
PEN polyethylene naphthalate
PES photoemission spectroscopy
PES position error signal
PET poly(ethylencnertephthalate)
PETN pentaerythritol tetranitratre
PFDA perfluorodecanoic acid
PFDP perfluorodecylphosphonate
PFDTES perfluorodecyltriethoxysilane
PFM photonic force microscope
PFOS perfluoroocatanesulfonate
PFPE perfluoropolyether
FFT5S perfluorodecyltrichlorosilane
PhC photonic crystal
PI3K phosphatidylinositol-3-kinase
P1 polyisoprene
PID proportional–integral–differential
PKA protein kinase
PKC protein kinase C
PKI protein kinase inhibitor
PL photolithography
PLC phospholipase C
PLD pulsed laser deposition
PMAA poly(methacrylic acid)
PML promyelocytic leukemia
PMMA poly(methyl methacrylate)
POCT point-of-care testing
POM polyoxy-methylene
PP polypropylene
PPD p-phenylenediamine
PPMA poly(propyl methacrylate)
Pp polypyrrole
PS-PDMS poly(styrene-b-dimethylsiloxane)
PS/clay polystyrene/nanoclay composite
PS polystyrene
PSA prostate-specific antigen
PSD position-sensitive detector
PSD position-sensitive diode
PSD power-spectral density
PSG phosphosilicate glass
PSGL-1 P-selectin glycoprotein ligand-1
PTFE polytetrafluoroethylene
PVA polyurethane acrylate
PUR polyurethane
PVA polyvinyl alcohol
PVD physical vapor deposition
PVDC polyvinylidene chloride
PVDF polyvinylidene fluoride
PVS polyvinylsiloxane
PWR plasmon-waveguide resonance
PZT lead zirconate titanate

Q
QB quantum box
QCM quartz crystal microbalance
QFN quad flat no-lead
QPD quadrant photodiode
QWR quantum wire
<table>
<thead>
<tr>
<th>Abbreviation</th>
<th>Description</th>
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<tbody>
<tr>
<td>RBC</td>
<td>red blood cell</td>
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<tr>
<td>RCA</td>
<td>Radio Corporation of America</td>
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<tr>
<td>RF</td>
<td>radiofrequency</td>
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<td>RFID</td>
<td>radiofrequency identification</td>
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<td>RGD</td>
<td>arginine–glycine–aspartic</td>
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<td>RH</td>
<td>relative humidity</td>
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<tr>
<td>RHEED</td>
<td>reflection high-energy electron diffraction</td>
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<tr>
<td>RICM</td>
<td>reflection interference contrast microscopy</td>
</tr>
<tr>
<td>RIE</td>
<td>reactive-ion etching</td>
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<tr>
<td>RKKY</td>
<td>Ruderman–Kittel–Kasuya–Yoshida</td>
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<tr>
<td>RMS</td>
<td>root mean square</td>
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<tr>
<td>RNA</td>
<td>ribonucleic acid</td>
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<tr>
<td>ROS</td>
<td>reactive oxygen species</td>
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<tr>
<td>RPC</td>
<td>reverse phase column</td>
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<tr>
<td>RPM</td>
<td>revolutions per minute</td>
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<td>RSA</td>
<td>random sequential adsorption</td>
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<tr>
<td>RT</td>
<td>room temperature</td>
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<td>RTP</td>
<td>rapid thermal processing</td>
</tr>
<tr>
<td>SAE</td>
<td>specific adhesion energy</td>
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<td>SAM</td>
<td>scanning acoustic microscopy</td>
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<tr>
<td>SAM</td>
<td>self-assembled monolayer</td>
</tr>
<tr>
<td>SARS-CoV</td>
<td>syndrome associated coronavirus</td>
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<tr>
<td>SATI</td>
<td>self-assembly, transfer, and integration</td>
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<tr>
<td>SATP</td>
<td>(S-acetylthio)propionate</td>
</tr>
<tr>
<td>SAW</td>
<td>surface acoustic wave</td>
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<tr>
<td>SB</td>
<td>Schottky barrier</td>
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<td>SCFv</td>
<td>single-chain fragment variable</td>
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<td>SCM</td>
<td>scanning capacitance microscopy</td>
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<tr>
<td>SCPM</td>
<td>scanning chemical potential microscopy</td>
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<tr>
<td>Scream</td>
<td>single-crystal reactive etching and metallization</td>
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<tr>
<td>SDA</td>
<td>scratch drive actuator</td>
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<tr>
<td>SECM</td>
<td>scanning electrochemical microscopy</td>
</tr>
<tr>
<td>SEFM</td>
<td>scanning electrostatic force microscopy</td>
</tr>
<tr>
<td>SEM</td>
<td>scanning electron microscope</td>
</tr>
<tr>
<td>SFM</td>
<td>scanning force microscope</td>
</tr>
<tr>
<td>SGS</td>
<td>small-gap semiconducting</td>
</tr>
<tr>
<td>SIM</td>
<td>scanning ion conductance microscopy</td>
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<td>SIP</td>
<td>single inline package</td>
</tr>
<tr>
<td>SKPM</td>
<td>scanning Kelvin probe microscopy</td>
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<tr>
<td>SL</td>
<td>soft lithography</td>
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<tr>
<td>SLIGA</td>
<td>sacrificial LIGA</td>
</tr>
<tr>
<td>SLL</td>
<td>sacrificial layer lithography</td>
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<tr>
<td>SLM</td>
<td>spatial light modulator</td>
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<tr>
<td>SMA</td>
<td>shape memory alloy</td>
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<tr>
<td>SMM</td>
<td>scanning magnetic microscopy</td>
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<tr>
<td>SNOM</td>
<td>scanning near field optical microscopy</td>
</tr>
<tr>
<td>SNP</td>
<td>single nucleotide polymorphisms</td>
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<tr>
<td>SNR</td>
<td>signal-to-noise ratio</td>
</tr>
<tr>
<td>SOG</td>
<td>spin-on-glass</td>
</tr>
<tr>
<td>SOI</td>
<td>silicon-on-insulator</td>
</tr>
<tr>
<td>SOIC</td>
<td>small outline integrated circuit</td>
</tr>
<tr>
<td>SoS</td>
<td>silicon-on-sapphire</td>
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<tr>
<td>SP-STM</td>
<td>spin-polarized STM</td>
</tr>
<tr>
<td>SPM</td>
<td>scanning probe microscope</td>
</tr>
<tr>
<td>SPR</td>
<td>surface plasmon resonance</td>
</tr>
<tr>
<td>SPR</td>
<td>structured programmable microfluidic system</td>
</tr>
<tr>
<td>SPS</td>
<td>spark plasma sintering</td>
</tr>
<tr>
<td>SRAM</td>
<td>static random access memory</td>
</tr>
<tr>
<td>SRC</td>
<td>sampling rate converter</td>
</tr>
<tr>
<td>SSIL</td>
<td>step-and-stamp imprint lithography</td>
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<tr>
<td>SSRM</td>
<td>scanning spreading resistance microscopy</td>
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<tr>
<td>STED</td>
<td>stimulated emission depletion</td>
</tr>
<tr>
<td>STH</td>
<td>scanning thermal microscope</td>
</tr>
<tr>
<td>STM</td>
<td>scanning tunneling microscope</td>
</tr>
<tr>
<td>STORM</td>
<td>statistical optical reconstruction microscopy</td>
</tr>
<tr>
<td>STP</td>
<td>standard temperature and pressure</td>
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<tr>
<td>STS</td>
<td>scanning tunneling spectroscopy</td>
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<tr>
<td>SUN</td>
<td>Sad1p/UNC-84</td>
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<tr>
<td>SWCNT</td>
<td>single-wall carbon nanotube</td>
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<tr>
<td>SWNT</td>
<td>single-wall nanotube</td>
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<tr>
<td>T</td>
<td>tilt angle</td>
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<tr>
<td>TASA</td>
<td>template-assisted self-assembly</td>
</tr>
<tr>
<td>TCM</td>
<td>tetracyysteine motif</td>
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<tr>
<td>TCNQ</td>
<td>tetracyanoquinodimethane</td>
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<td>TCP</td>
<td>tricresyl phosphate</td>
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<td>TEM</td>
<td>transmission electron microscope</td>
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<tr>
<td>Ti</td>
<td>Texas Instruments</td>
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<tr>
<td>TIRF</td>
<td>total internal reflection fluorescence</td>
</tr>
<tr>
<td>TIRM</td>
<td>total internal reflection microscopy</td>
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<tr>
<td>TLP</td>
<td>transmission-line pulse</td>
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<tr>
<td>TM</td>
<td>tapping mode</td>
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<tr>
<td>TMAH</td>
<td>tetramethyl ammonium hydroxide</td>
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<tr>
<td>TMR</td>
<td>tetramethylrhodamine</td>
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<tr>
<td>TMS</td>
<td>tetramethylsilane</td>
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<tr>
<td>Abbreviation</td>
<td>Description</td>
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<tr>
<td>TMS</td>
<td>trimethylsilyl</td>
</tr>
<tr>
<td>TNT</td>
<td>trinitrotoluene</td>
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<tr>
<td>TP</td>
<td>track pitch</td>
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<tr>
<td>TPE-FCCS</td>
<td>two-photon excitation fluorescence cross-correlation spectroscopy</td>
</tr>
<tr>
<td>TPI</td>
<td>threads per inch</td>
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<tr>
<td>TPMS</td>
<td>tire pressure monitoring system</td>
</tr>
<tr>
<td>TR</td>
<td>torsional resonance</td>
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<tr>
<td>TREC</td>
<td>topography and recognition</td>
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<tr>
<td>TRIM</td>
<td>transport of ions in matter</td>
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<tr>
<td>TSDC</td>
<td>thermally stimulated depolarization current</td>
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<tr>
<td>TTF</td>
<td>tetrathiafulvalene</td>
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<tr>
<td>TV</td>
<td>television</td>
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<tr>
<td>VBS</td>
<td>vinculin binding site</td>
</tr>
<tr>
<td>VCO</td>
<td>voltage-controlled oscillator</td>
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<tr>
<td>VCSEL</td>
<td>vertical-cavity surface-emitting laser</td>
</tr>
<tr>
<td>vdW</td>
<td>van der Waals</td>
</tr>
<tr>
<td>VHH</td>
<td>variable heavy-heavy</td>
</tr>
<tr>
<td>VLSI</td>
<td>very large-scale integration</td>
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<tr>
<td>VOC</td>
<td>volatile organic compound</td>
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<tr>
<td>VPE</td>
<td>vapor-phase epitaxy</td>
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<td>VSC</td>
<td>vehicle stability control</td>
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<td>XPS</td>
<td>x-ray photon spectroscopy</td>
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<td>XRD</td>
<td>x-ray powder diffraction</td>
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<td>YFP</td>
<td>yellow fluorescent protein</td>
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<tr>
<td>Z-DOL</td>
<td>perfluoropolyether</td>
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