Springer Handbook of Nanomaterials

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Springer Handbook of Nanomaterials

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With 685 Figures and 64 Tables

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Foreword

Nanomaterials are based on structures with characteristic features on the scale of nanometers. This size is small if we compare with normal things around us, but it is not particularly small on the atomic scale. In fact, distances between individual atoms are typically a tenth of a nanometer (an Ångström), so a piece of a material with a side of a nanometer may contain hundreds or even a thousand atoms. Therefore a nanomaterial usually has some resemblance to a bulk material based on the same atoms, but the normal material has been modified to reach superior properties such as higher mechanical strength, different optical and magnetic performance, permeability to a fluid, or something else. Thus nanomaterials may allow us to obtain properties that were previously impossible to achieve, impractical to manufacture, or too expensive for use on a scale large enough to be significant in daily life.

Among the general public, and even the scientific community, nanomaterials are widely perceived as *new* in many different way – newly invented, newly used by human cultures, and newly studied.

In fact, nanomaterials are not new at all. Nature itself is filled with nanofeatures that have evolved in biological systems, one well known example being moths' eyes with nanostructured surfaces that provide antireflection and allow efficient use of feeble light.

Looking at history, we can also see that human beings have been using nanomaterials of various sorts for a very long time. Let us take three examples: nanocarbons, nanometals, and nanoceramics.

Nanocarbons can be created in abundance on the nanometer scale when organic matter burns. Such carbon nanoparticles were used by humans as far back as forty thousand years ago to depict and decorate. The particles were mixed with fat and used for painting in the caves of Altamira and Lascaux in Spain and France, to mention two especially striking and well known cases. This kind of carbon, in principle, is also an essential ingredient in ink and printing paste, and it was used by monastic scribes and by Gutenberg and his followers to make texts of explosive cultural significance and stunning beauty.

Nanometals have also been utilized for thousands of years. An example is the world famous Lycurgus glass cup, now in the holdings of the British Museum. This cup, which was probably created in Rome during the 4th century AD, contains embedded nanoparticles of gold and silver. Because of these particles, the cup normally seems to be a light green color, but it becomes ruby red when light is shone through it. The Lycurgus cup is a wonder of craftsmanship from Antiquity, and it is based on nanotechnology.

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Finally, let's consider *nanoceramics*. The world's most widely used artificial material is the nanoceramic cement, which was used extensively by the Romans in constructing buildings, baths and aqueducts. Furthermore, recent archaeological discoveries indicate that the Romans were not the first, that the Macedonians were using cement centuries earlier.

Even research on nanomaterials is not as new as it seems. The term apparently began appearing in the titles of scientific publications only 15 years ago. But today's *nano* was the subject of an older literature under the term *ultrafine*.

As the examples above indicate, nanomaterials are well rooted in the past. But they are also very much of the future. Let us consider a few specific examples.

Nanocarbons, used for cave painting and the printing of the Gutenberg Bible, are very much in focus today, in the forms of fullerenes, nanotubes and nanodiamonds, all of which offer a multitude of possibilities for future technology. Two-dimensional carbon in the form of graphene has unique properties directly based on quantum physics, and it may have important applications in transparent electronics and elsewhere. Graphane, its hydrogenated cousin, is exciting in its own right.

Nanometals, employed by the Romans to create the amazing Lycurgus glass cup, are the basis today for manifold applications, including thermal collectors that harness the sun's energy and innovative *plasmonic* solar cells. Indeed, *plasmonics* is becoming a household word because of its relevance for light-emitting diodes, sensors and catalysts for chemical reactions, just to mention a few technologies.

Thus many aspects of nanomaterials are indeed truly new and are the subject of intense worldwide interest in today's academic and industrial research laboratories. This *Handbook*, which is a testimony to this growing body of knowledge, presents welcome and authoritative surveys over nanocarbons, nanometals and nanoceramics in its first three parts. Other sections cover nanocomposites and nanoporous materials, as well as organic and biological nanomaterials. Applications and impacts are discussed at the end, together with important questions of toxicology, hazards and safety. These issues are of great importance. We should remember the terrible impact that asbestos – in fact, a natural nanomaterial – had on human health before it was widely banned. We certainly do not want to discover one day that, in our quest for new materials to solve technological problems, we have unleashed another dangerous nanomaterial into the world.

The editor and authors are to be congratulated on the successful completion of this *Handbook of Nanomaterials*. It will surely be a work of great and lasting importance for the scientific community.

Uppsala, November 2012 Prof. Claes G. Granqvist

Foreword

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It has been more than a decade since President Bill Clinton talked about the promise of nanotechnology and the importance of increasing investments in nanoscale science and engineering research in a speech at the California Institute of Technology on January 21, 2000. In his remarks, the President recalled Richard Feynman's American Physical Society talk there in 1959. The following week, in his State of the Union Address, President Clinton announced his *21st Century Research Fund*, a \$3 billion budget increase, which included the multiagency national nanotechnology initiative (NNI). The first year's budget allocation to NNI was close to half a billion US\$, nearly doubling what the agencies had been spending on nanoscale research; and with the continuous support of succeeding administrations the budget quadrupled in a decade. This strong federal support, initially based on the promise of a revolutionary new technology, was justified by steady scientific and technological advances at the nanometer scale and by the growth of commercial applications, especially in biotechnology and nanoelectronics, offering new ways to tackle disease and new industrial tools and toys. As President Clinton's former science advisor, I am confident that he is as pleased with the progress in nanotechnology as are all of us – inside and outside government – who worked with him to develop and implement the NNI.

One way to define nanotechnology, perhaps, is that it is the knowledge and engineering (design and control) of physical, chemical, and biological systems at the nanometer (10^{-9} m) scale – from the size of individual molecules to dimensions of the order 100 nm. Nanotechnology is, by its nature, a field of synthesis and synergy often requiring physics, chemistry, biology, and almost all areas of engineering in the performance of research and engineering design, for example inventing and optimizing the tools needed to synthesize and manipulate matter at the nanometer scale. As with other new fields, rapid advances in nanotechnology have led to specialization into subdisciplines, one of the most natural and important being *nanomaterials*.

Nanomaterials science and engineering includes the production, properties, and applications of materials at the nanometer scale; it is a part of nanotechnology and at the same time, evidently, a subfield of materials science. The main goal of materials science – macroscopic and nanoscale – is providing new and improved building blocks for engineers in all fields. That said, *nanomaterials* science has distinct features compared to the more mature science and engineering of macroscopic materials, the most salient being its revolutionary nature. New materials and groups of materials with surprising properties continue to be discovered – graphene and topological insulators are two examples from the recent past. As with all exploration at the frontiers of knowledge, it is impossible to predict what discoveries will be made or how those discoveries might lead to applications, commercial or otherwise. But the history of science and technology suggests that some of those advances will surpass all our expectations. Already we are seeing the benefits of nanotechnology in computers and telecommunication devices, computer chips and sensors in automobiles, electric car batteries, medicines and sun creams, tablecloths and socks, tennis rackets, boats, golf clubs – and more. Given the likelihood that ongoing research will yield many more *nanomaterials*, with surprising properties and, at the same time, the continued exponential growth in the number of applications, it seems clear that *nanomaterials* will, at some level, transform most aspects of our lives. It is not too much of a stretch to suggest that President Clinton's policy decision to set up the NNI, which has supported thousands of scientists and engineers working in the field, has indeed helped move us closer to realizing Feynman's prediction – or, perhaps we should say his vision – of a revolutionary new technology. In the world of *nanomaterials* there is still *plenty of room at the bottom* to use Richard Feynman's famous words.

A handbook, by one definition, is a compilation of knowledge about a particular field, collected into a single volume publication that is convenient to use as a ready reference. Since *nanomaterials* science can now be considered a self-sufficient discipline, a handbook is appropriate and timely. This new *Springer Handbook of Nanomaterials* targets several audiences: researchers working in industry or academia, as well as graduate students studying related fields. The organization of the book follows the usual classification scheme of macroscopic materials science, with information of a materials group – e.g., metals – collected together; other aspects can be followed easily by using the well-developed index.

Putting together a handbook in a new field is a formidable challenge. I would like to congratulate the editor and all of the authors who collaborated to plan, collect materials, and write this important groundbreaking *Springer Handbook of Nanomaterials*.

Houston, January 2013 Neal Lane

Preface

Those who control materials, control technology, stated Eiji Kobayashi, Senior Advisor of Panasonic Corporation, explaining the importance of materials science and engineering. I would translate this quote to *those who control* nano*materials control* nano*technology*; and, considering the effect of the development of nanomaterials and nanotechnology on our global infrastructure, it is not too bold to state that those control technology at large, too. Nanomaterials have a determinant role in many of advanced products around us. Stamp-sized sound recording devices, modern passenger and fighter jets, spaceships and space stations, extreme tall buildings and long bridges, none of these could be created without these marvelous materials. As one could not foresee 50 years ago, the fast development that provided the opportunity for these objects to be realized, now we cannot imagine our life without them.

The editor considers materials science as the knowledge of structure; properties of materials predicted or explained with the help of this knowledge; experimental and theoretical tools designed and established for preparing, characterizing and modifying processes, and last but not least showing application possibilities of the resulted materials. After defining nanomaterials we can simply transpose this description for nanomaterials science. Materials are considered *nanomaterials* when their structure, processing, characterization or application differ from the macroscopic materials and this difference relates to the – normally sub-100 nm – feature size. The *description* of the nanomaterials in this Springer Handbook follows the thorough but concise explanation of the synergy of structure, properties, processing, and applications. Specifically, our aim was to point out the distinction between the properties of bulk and nanomaterials and the reasons for these differences.

To fulfill these goals, we provide a balanced report of the literature of each materials group. The format follows the well-established structure of the Springer Handbooks with chapters as the basic units that are organized into several groups. In each chapter, authors cover materials of their expertise, however, they focus not only on their own work, but report the interesting and important efforts in the community, establishing a balance between references and scientific results reported in tables and figures. We describe nanomaterials in textbook style for newcomers, encyclopedia-like elements and – to follow the fast-space of new results – review or research papers for the experienced reader. Beyond scientific and moral correctness we also look for clarity by concise and easy-to-follow text, well-designed and clear figures which were all professionally drawn by graphics designers.

The book is divided in Parts A to G and covers carbon-based nanomaterials: fullerenes, nanotubes, nanofibers and nanodiamond, noble and common metals and alloys, ceramic materials, crystalline and glassy oxides and other compounds; composites, hybrid structures and solutions as well as porous metals, ceramics and silicon; organic and bio-nanomaterials, bones and fibers and select applications, respectively. This higher level structure conforms to the macroscopic classification of materials and it is composed of chapters. Each chapter is self-consistent and builds up of similar parts, history, definitions, production of the given materials, properties, and applications. All of these parts are richly illustrated and consist of a balanced ratio of important basics and recent results.

My pleasant obligation is to thank all of the help I received in planning and implementing the handbook. First of all, I need to acknowledge the diligent work of the authors in developing the chapters which involves more effort than a review paper, and the reward is not so immediate and evident. Their expertise, energy and time are greatly appreciated. I also would like to thank the advices and help of my colleagues at Rice University and at Rensselaer Polytechnic Institute; as well as Professors Thomas F. George, Bob Curl, Phaedon Avouris, Li Song and Jinquan Wei for keeping contact with many authors. The great workmanship of the Springer publishing team and the continuous support of the managing editors Mayra Castro and Werner Skolaut are also appreciated. I also need to thank my colleagues and friends, Laszlo B. Kish, Claes-Goran Granqvist, Pulickel M. Ajayan and Richard W. Siegel that the collaboration with them oriented me to nanomaterials science. Last, but not least, I thank for the help and pa-

tience of my wife, Agnes, without her I would have not been able to finish this job.

I wish the reader a pleasant and beneficial time when using the Springer Handbook of Nanomaterials, and I hope that it serves as a frequently opened reference work.

Houston, November 2012 Robert Vajtai

About the Editor

Robert Vajtai is a Faculty Fellow at Rice University, Houston, Texas, in the Department of Mechanical Engineering and Materials Science. His expertise covers synthesis, processing, characterization of physical and chemical properties of new, advanced material forms and structures. More specifically Dr. Vajtai's interests are in nanostructured materials, nanocomposites and nanomaterials; as well as their applications in thermal management, energy storage, microelectromechanical systems, sensors and electronic devices.

Dr. Vajtai received his scientific education in physics and his Ph.D. degree in solid-state physics from the University of Szeged (then named Jozsef Attila University), Hungary. From 1987 to 2002 he was a faculty member of the Department of Experimental Physics at the University of Szeged, Hungary. He was rewarded by the Bolyai Fellowship of the Hungarian Academy of Sciences for 1999-2000. He spent sabbaticals as a Fellow of the Swedish Institute in The glosseintragAAngstrom Laboratory in Uppsala, Sweden, in the years 1998 and 1999; as an Eötvös Fellow at the EPFL in Lausanne, Switzerland in 1995/1996 and visited the Max Planck Institute in Göttingen, Germany, in 1993 via a Max Planck Fellowship. Before moving to Rice University in 2008, Dr. Vajtai spent eight years at the Rensselaer Polytechnic Institute, Troy, New York, where he was a Laboratory Manager at the Rensselaer Nanotechnology Center managing the carbon nanotechnology laboratories.

Dr. Vajtai started his research as a physicist studying laser-metal interaction, melting and oxidation of refractive metals and the nonlinear behavior of the far-from equilibrium processes and systems. Later he developed methods for pulse-probe spectroscopy of biomaterials as well as OH radicals used for the study of organic contamination of the atmosphere by airborne LIDAR systems. His research in materials science started with the synthesis of nanometals and nanosized oxides for the development of sensors. This lead to a new method for the preparation of germanium nanoparticles for building inverse opals used in infrared optical sensing. His most significant contribution is related to the synthesis of different forms of nanocarbons such as carbon nanotubes, graphene and macroscopic systems designed and built from these carbon allotropes, e.g., electromechanical parts and nanotube wires. Recently, his interest extended to various atomically thin layers, hexagonal boron nitride, transition-metal dichalcogenides and oxides.

He has more than 145 journal publications in peer reviewed scientific journals and he delivered numerous invited, keynote and plenary lectures on the topic.

Dr. Vajtai is a passionate teacher, he lectured physics, thermodynamics and electrodynamics courses with hundreds of experimental demonstrations; introductory and advanced courses of materials science. He received several mentoring awards, among those the Siemens-Westinghouse Mentoring Award.

Robert Vajtai is a Faculty Fellow in the Department of Mechanical Engineering & Materials Science at Rice University. He received his undergraduate and Ph.D. degrees from the University of Szeged, then named Jozsef Attila University, Hungary.

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Contents

Part B NanoMetals

Part C NanoCeramics

List of Abbreviations

α-SMA	α-smooth muscle actin
p-NP	*p*-nitrophenol
0-D	zero-dimensional
1-D	one-dimensional
2-D	two-dimensional
2-PAM	2-pyridine-aldoxime methiodide
2Q	double-quantum
3-D	three-dimensional
3Q	triple-quantum
4Hop	4-hexadecyloxyphenyl

A

AA	ascorbic acid
AAM	anodized aluminum membrane
AAO	anodic aluminum oxide
AAO	anodized aluminum oxide
AAS	atomic absorption spectroscopy
Ab	antibody
AC	alternating current
Acac	acetylacetone
ACNT	aligned carbon nanotube
ACQ	aggregation-caused quenching
AChE	acetylcholine esterase
ACP	amorphous calcium phosphate
AD	arc discharge
AEE	aggregation-enhanced emission
AES	Auger electron spectroscopy
AES	3-(2-aminoethylaminopropyl)trimethoxysilane
AFC	alkaline fuel cell
AFC	antiferromagnetically coupled
AFM	atomic force microscopy
AIE	aggregation-induced emission
AIEE	aggregation-induced enhanced emission
ALD	atomic layer deposition
AlPO	aluminophosphate
AM	alveolar macrophage
anti-EGFR	anti-epidermal growth factor receptor
AOC	aromatic organic compounds
APC	antigen-presenting cell
APES	aminopropyltrimethoxysilane
APPES	ambient pressure photoelectron spectroscopy
APS	3-aminopropyltrimethoxysilane
APT	atom probe tomography
APTES	(aminopropyl) triethoxysilane
APTS	3-aminopropyltriethoxysilane
AR	analytical reagent
AR	aspect ratio
ARPES	angle-resolved photoemission spectroscopy
ASTM	American Society for Testing and Materials
ATQD	*N*-(4-aminophenyl)-*N*′-(4′-(3-triethoxy-silyl-propyl-ureido)phenyl-1,4-quinon-enediimine)
ATP	adenosine-5′-triphosphate
ATRP	atom-transfer radical polymerization
AWWA	American Water Works Association

B

BASF	Badische Anilin und Soda Fabrik
bcc	body-centered cubic
BCF	Burton–Cabrera–Frank
BCP	biphasic calcium phosphate
BDAC	benzyldimethylammoniumchloride
BDNF	brain-derived neurotrophic factor
BEP	Brønsted–Evans–Polanyi relations
BES	Office of Basic Energy Sciences
BET	Brunauer–Emmett–Teller
BF	bright field
BFGF	basic fibroblast growth factor
BG	back-gate
BHJ	bulk heterojunction
bioMEMS	biological microelectromechanical system
BMG	bulk metallic glass
BN	boron nitride
BOM	bubble overlapping mode
BP	buckypaper
BPEA	9,10-bis(phenylethynyl)anthracene
BS	black silicon
BSA	bovine serum albumina
BSI	British Standards Institution
BSPP	bis(*p*-sulfonatophenyl) phenylphosphine dihydrate dipotassium
BT	barium titanate
BT	benzenethiol
BTCP	β-tricalcium phosphate

C

C_{16}TAB	hexadecyl trimethyl ammonium bromide
C-PANI	conductive camphorsulfonic acid-doped emeraldine PANI
C3DT	1,3-Propanedithiol
CA	contact angle
CALPHAD	calculation of phase diagrams
CAM	cluster aggregation mode

CBED	convergent-beam electron diffraction
CBEV	coordination-dependent bond-energy variation
CCDB	Cambridge crystallographic data base
CCG	chemically converted graphene
CCT	correlated color temperature
CCVD	catalytic chemical vapor deposition
CD	cyclodextrin
CFR	continuous flow reactor
CHP	cyclohexylpyrrolidone
CHT	chymotrypsin
CIE	International Commission on Illumination
CIP	current in the plane
CMG	chemically modified graphene
CMOS	complementary metal–oxide–semiconductor
CMP	chemical–mechanical planarization
CNF	carbon nanofiber
CNM	carbon nanotube membrane
CNT	carbon nanotube
CN-TFMBE	1-cyano-trans-1,2-bis(3′,5′-bis-trifluoro-methyl-biphenyl)ethylene
CO	cuboctahedron
COD	1,5-cyclooctadiene
COLI	collagen I
COLIV	collagen IV
COST	Cooperation in Science and Technology
COSY	correlation spectroscopy
COT	1,3,5-cyclooctatriene
cp	close packed
CP	coherent phonon
CP	cross polarization
CPP	conduction perpendicular to plane
CPP	current perpendicular to the plane
CPS	collected photo signal
CS	cross section
CS-PCL	chitosan-graft-PCL
CSA	chemical shift anisotropy
CSP	colloidal silver preparation
CT	charge transfer
CTA^+	cetyl-triamine cation
CTA	cetyltrimethylammonium
CTAB	cetyltrimethylammonium bromide
CV	crystal violet
CV	cyclic voltammetry
CVD	chemical vapor deposition
CW	continuous-wave
CuPC	copper phthalocyanine
CuTCNQ	copper tetracyanoquinodimethane

D

D4R	double four ring
DAAQ	1,5-diaminoanthraquinone
DAFC	direct alcohol fuel cell
DAPI	4′,6-diamidino-2-phenylindole
DAPRAL	copolymer of maleic anhydride and α-olefin
DBR	distributed Bragg mirror
DC	dendritic cell
DC	direct current
DCE	1,2-dichloroethane
DD-PTCDI	N,N'-di(dodecyl)-perylene-3,4,9,10-tetracarboxylic diimide
DDA	discrete dipole approximation
DDAB	didecyldimethylammonium bromide
DDC	N,N'-dicyclohexylcarbodiimide
DEFC	direct ethanol fuel cell
DEG	diethylene glycol
DF	defluoridation capacity
DF	density function
DFAC	direct formic acid fuel cell
DFT	density functional theory
DFTB	density functional tight binding
DGU	density-gradient ultracentrifugation
DI	deionized
DIC	differential interference contrast
DLC	diamond-like carbon
DLS	dynamic light scattering
DLVO	Derjaguin–Landau–Verwey–Overbeek
DMA	dimethylamide
DMEU	1,3-dimethyl-2-imidazolidinone
DMF	dimethylformamide
DMFC	direct methanol fuel cell
DMPO	5,5-dimethyl-pyrroline N-oxide
DMSA	dimercaptosuccinic acid
DMSO	dimethyl sulfoxide
DNA	deoxyribonucleic acid
DND	detonation nanodiamond
DOS	density of states
DOX	doxorubicin
dpa	displacements per atom
DPPTE	1,2-dipalmitoyl-*sn*-glycero-3-phospho-thioethanol
DQ	double quantum
DR	draw ratio
DRG	dorsal root ganglion
DRIFT	diffuse reflectance infrared Fourier-transform
DSC	differential scanning calorimetry
DT	decanethiol
DTAB	dodecyltrimethylammonium bromide
DTE	desaminotyrosyl-tyrosine ethyl ester
DWCNT	double-walled carbon nanotube
DWNT	double-walled nanotubes
Dox	doxorubicin

E

ECD	electrochemical deposition
ECDL	electrochemical double layer

ECELL	environmental cell
ECM	extracellular matrix
ECP	electronically conducting polymer
ECSA	electrochemically active surface area
ED	electrodialysis
ED	electron diffraction
EDAX	energy dispersive analysis
EDC	1-ethyl-3-(3-dimethylaminopropyl)-carbodiimide
EDL	electrical double layer
EDLC	electric double-layer capacitor
EDS	energy-dispersive x-ray spectroscopy
EDTA	ethylenediaminetetraacetic acid
EDX	energy-dispersive x-ray spectroscopy
EELS	electron energy-loss spectroscopy
EFM	electrostatic force microscopy
EG	evaporated gold
EIS	electrochemical impedance spectroscopy
EL	electroluminescence
ELISA	enzyme-linked immuno sorbent assay
EM	electromagnetic
EMI	electromagnetic interference
EOF	electroosmotic flow
EPA	Environmental Protection Agency
EPR	electron paramagnetic resonance
EPS	extracellular polymeric substance
EQE	external quantum efficiency
ESC	embryonic stem cell
ESR	electron spin resonance
ESR	equivalent series resistance
ETEM	environmental TEM
EXAFS	extended x-ray absorption fine structure
ElAP(S)O	element aluminophosphosilicate
EPITH	epithelial cells

F

f-SWCNT	functionalized SWCNT
FABMS	fast atom bombardment mass spectroscopy
FBI	Federal Bureau of Investigation
FBR	fluidized bed reactor
fcc	face-centered cubic
fct	face-centered tetragonal
FDA	Food and Drug Administration
FEB	ferrocene/ethanol/benzylamine
FES	fluctuation-enhanced sensing
FESEM	field emission scanning electron microscope
FET	field-effect transistor
FF	fill factor
FFT	fast Fourier transform
FGO	functionalized GO
FIB	fibrinogen
FIB	focused ion beam
FIPOS	full isolation by porous oxidized silicon
FIT	fluctuation-induced tunneling
FITC	fluorescein isothiocyanate
FLG	few-layer graphene
FMR	ferromagnetic resonance
FN	fibronectin
FND	fluorescent carboxylated HPHT ND
FND	fluorescently enhanced ND
fpRFDR	finite-pulse radio frequency-driven recoupling

G

GMR	giant magnetoresistance
GN	gold nanoparticle
GNC	gold nanoparticle cluster
GNP	gold nanoparticle
GNP	graphite nanoplatelet
GNR	gold nanorod
GNR	graphene nanoribbon
GO	graphene oxide
GOX	glucose oxidase
GSH	glutathione
GTBMD	generalized tight-binding molecular dynamics

H

HA	humic acid
HAADF	high-angle annular dark field
HATU	2-(7-aza-1*H*-benzotriazole-l-yl)-1,1,3,3,-tetramethyluronium hexafluorophosphate
HAZ	heat-affected zone
HC	hexagonal channel
HCCN	highly curved carbon nanostructure
HCI	highly charged ion
hcp	hexagonal close packed
HDA	hexadecylamine
HDD	1,2-hexadecanediol
HDDR	hydrogenation–decomposition–desorption–recombination
HDS	hydrodesulfurization
HDT	hexadecanethiol
HEPES	4-(2-hydroxyethyl)-1-piperazineethane-sulfonic acid
HEV	hybrid electric vehicle
HF	hydrofluoric acid
HG	hydrazinium graphene
HIV	human immunodeficiency virus
HL60	human promyelocytic leukemia
HMDA	hexamethylenediamine
HMO	hydrous manganese dioxide
HMOG	heavy metal oxide glass
HMTA	hexamethylenetetramine
HNS	hot neutron source

HOMO	highest occupied molecular orbital
HOPG	highly oriented pyrolytic graphite
HP	Hall–Petch
HPA	hexylphosphonic acid
HPC-Py	pyrene-labeled hydroxypropyl cellulose
HPHT	high-pressure high-temperature
HPMC	Hydroxypropylmethyl cellulose
HPSMAP	poly(styrene-co-maleic anhydride) carrying pyrene
HSMA	hydrolyzed poly(styrene-co-maleic) anhydrite
h-PSMA	hydrolyzed-poly(styrene-*alt*-maleic anhydride)
HREM	high-resolution electron microscopy
HRN	helical rosette nanotube
HRP	horseradish peroxidase
HRSEM	high-resolution scanning electron microscope
HRTEM	high-resolution transmission electron microscopy
HSA	human serum albumin
hSKMC	human skeletal muscle cell
HTT	heat treatment temperature
HWHM	half-width at half-maximum
HiPCO	high-pressure carbon monoxide

I

IANH	International Alliance for NanoEHS (environment, health, safety)
IC	integrated circuit
ICP	inductively coupled plasma
ICP-MS	inductively coupled plasma mass spectrometry
IE	immersion–electrodeposition
IF	immunofluorescence
IF	inorganic fullerene-like nanoparticle
iFF	isotactic polypropylene
IFSS	interfacial shear strength
Ig	immunoglobulin
IgG	immunoglobulin G
Ih	icosahedron
IKVAV	laminin derived self-assembling peptide
IKVAV-PA	IKVAV polyacrylamide
IL	interleukin
IL	ionic liquid
IMR	intramolecular rotation
INCO	International Nickel Company
INT	inorganic nanotube
IP	iminopyrrole
IPCE	incident photon to charge carrier efficiency
iPSC	induced pluripotent stem cell
IR	infrared
ipr	isolated pentagon rule
ISO	International Standards Organization
ITO	indium tin oxide
IZA	International Zeolite Association

K

KE	Kirkendall effect
KK	Kramers–Kronig

L

LA	longitudinal acoustic
LAM	laminin
LB	Langmuir–Blodgett technique
LB94	van Leeuwen–Baerends
LBL	layer-by-layer
LCD	liquid-crystal display
LDA	local density approximation
LDOS	local density of states
LED	light-emitting diode
LEED	low energy electron diffraction
LIB	lithium-ion battery
LMP	Larson–Miller plot
LN	less noble
LPM	large-pore mordenite
LPS	lipopolysaccharide
LSC	limbal stem cells
LSP	longitudinal surface plasmon
LSPR	localized surface plasmon resonance
LTA	Linde type A
LUMO	lowest unoccupied molecular orbital
LYM	lymphocytes

M

M	metalloid
MA	mechanical alloying
MAE	magnetic anisotropy energy
MALDI-TOF	matrix-assisted laser desorption/ionization-time of flight
MAPO	metalaluminophosphate
MAPSO	metalaluminophosphosilicates
MAS	magic angle spinning
MBE	molecular beam epitaxy
MC	metal cluster
MCFC	molten carbonate fuel cell
MCL	maximum contamination limit
MCS	ethylene glycol monomethyl ether
MD	molecular dynamics
MDA	malondialdehyde
MDA	mercaptodecanoic acid
MEA	membrane electrode assembly
MEMS	microelectromechanical system
MF	mesoflower
MF	microfiltration

MFC	microbial fuel cell
MFI	melt–flow index
MFM	magnetic force microscopy
MGM	metal-graphite multilayer
MHAP	micron particulate hydroxyapatite
ML	monolayer
MN	more noble
MNM	manufactured nanomaterials
MNPM	metallic nanoporous material
MO	methyl orange
MOCVD	metalorganic chemical vapor deposition
MOF	metal-organic framework
MOKE	magneto-optical Kerr effect
MPB	morphotropic phase boundary
MPC	monolayer-protected cluster
MPCF	mesophase pitch-based carbon fiber
MPS	mercaptopropyltrimethoxysilane
MPTMS	mercaptopropyltrimethoxysilane
MR	magnetic resonance
MRAM	magnetic random-access memory
MRI	magnetic resonance imaging
mRNA	messenger RNA
MRR	material removal rate
MRSw	magnetic relaxation switching
MSA	mercaptosuccinic acid
MSC	mesenchymal stem cell
MSE	mercurous sulfate electrode
MTBD	[7-methyl-1,5,7-triazabicyclo[4.4.0]dec-5-ene][bis(perfluoroethylsulfonyl)imide]
MWCNT	multiwalled carbon nanotube
MWNT	multiwalled nanotubes

N

NaBBS	sodiumbutylbenzene sulfonate
NaDDBS	sodium dodecylbenzene sulfonate
NADH	nicotinamide adenine dinucleotide
NaOBS	sodium octylbenzene sulfonate
NaPSS	polystyrene sulfonate sodium salt
NBE	near-band-edge
NC	nanocrystalline
nc-AFM	noncontact AFM
ND	nanodiamond
NDO	ozone-modified nanodiamond
ND-PTCDI	N,N'-di(nonyldecyl)-perylene-3,4,9,10-tetracarboxylic diimide
NEMS	nanoelectromechanical system
NEUT	neutrophils
NEXAFS	near-edge x-ray absorption fine structure
NF	nanofeatures
NF	nanofiltration
NFA	nanostructured ferritic alloy
NG	natural highly-oriented pyrolytic graphite
NGF	nerve growth factor
NHAP	nanohydroxyapatite
nHAp	nanohydroxyapatite particle
n-HApC	nanohydroxyapatite/chitosan
NHS	*N*-hydroxysuccinimidyl ester
NIOSH	National Institute for Occupational Safety and Health
NIR	near infrared
NM	noble metal
NMP	*N*-methyl-pyrrolidone
Nmpd	*N*-methylpyridinium
Nmpr	*N*-methylpyrrole
NMR	nuclear magnetic resonance
NO-IF	nanooctahedra-IF
NP	nanoparticle
NPG	nanoporous graphite
NPG/GC	NPG supported by glassy carbon electrode
NPGC	nanoporous gold composite
NPM	nanoporous metal
NPNT	nanoporous nanotube
NPS	nanoporous silver
NR	nanorod
NSC	neural stem cell
NSM	nanostructured materials
NT	nanotube
NTS	nanostructured transformable steel
NV	nitrogen-vacancy
NW	nanowire

O

O/F	oxidant-to-fuel
OCP	open-circuit potential
OCT	optical coherence tomography
ODA	octadecylamine
ODE	octadecene
ODF	orientation distribution function
ODPA	octadecylphosphonic acid
ODS	octadecyltrimethoxysilane
ODS	oxide dispersion strengthened
OER	oxygen evolution reaction
OFET	organic field-effect transistor
Oh	octahedron
OL	optical-limiting
OLC	onion-like carbon
OLED	organic light-emitting diode
OPD	O-phenylenediamine
OPH	organophosphorus hydrolase
OPS	oxidized PS
OPV	organic photovoltaic
ORR	oxygen reduction reaction
OSN	organic solvent nanofiltration
OTM	one-temperature model

P

P3HT	poly(3-hexylthiophene)
P3OT	poly(3-octylthiophene)
PA	peptide amphiphile
PA-6	prepared a nylon-6
PAA	poly(acrylic acid)
PABS	polyaminobenzene sulfonic acid
PAFC	phosphoric acid fuel cell
PAGE	polyacrylamide gel electrophoresis
PAH	polycyclic aromatic hydrocarbon
PAN	polyacrylonitrile
PANI	polyaniline
PATS	polythiophene derivatives
PBO	poly(*p*-phenylene benzobisoxazole)
PBS	phosphate buffered saline
PC	pentagonal column
PC	photonic crystal
PC	polycarbonate
PC	principal component
PCA	principal component analysis
PCB	polychlorinated biphenyl
PCE	power conversion efficiency
PCF	photonic crystal fiber
PCL	poly(ε-caprolactone)
PCL-G	PCL-gelatin
PDDA	poly(diallyldimethyl)ammonium chloride
PDDP	1-phenyl-3-((dimethylamino)styryl)-5-((dimethylamino)phenyl)-2-pyrazoline
PDEAEMA	poly(2-diethylaminoethyl methacrylate)
PDGF	platelet-derived growth factor
PDLC	polymer-dispersed liquid-crystal
PDMS	polydimethylsiloxane
PDOS	phonon density of states
PE	photoelectron
PE	polyethylene
PEC	photoelectrochemical
PECVD	plasma-enhanced CVD
PEDOT	poly(3,4-ethylenedioxythiophene)
PEEk	produced poly(ether ether ketone)
PEG	polyethylene glycol
PEI	polyethyleneimine
PEL	permissible occupational exposure limit
PEMFC	proton exchange membrane fuel cell
PEN	Project on Emerging Nanotechnologies
PEO	poly(ethylene oxide)
PES	potential energy surface
PET	polyethylene terephthalate
PFG	pulsed-field-gradient
PFM	piezoelectric force microscopy
PG	PCL–gelatin
PG	proteoglycan
PGA	poly(glycolic acid)
PGLA	copolymer of PGA and PLLA
PGM	platinum group metal
pIh	polyicosahedron
PIPAAm	responsive poly(*N*-isopropylacrylamide)
PL	photoluminescence
PL-PEG	phospholipid polyethylene glycol
PLA	poly-ethylene oxide
PLA	pulsed laser ablation
PLE	photoluminescence excitation
PLGA	poly(lactic-co-glycolic) acid
PLLA	poly(L-lactic) acid
PM	dipropylene glycol monomethylether
PMMA	poly-methyl methacrylate
PMN-PT	$PbMg_{1/3}Nb_{2/3}O_3$-$PbTiO_3$
PmPV	poly(*m*-phenylenevinylene-co-2,5-dioctoxy-*p*-phenylenevinylene)
PN	phosphorus-nitrogen
PNIPAm	poly(*N*-isopropyl acrylamide)
PNP	plasmonic
PP	polypropylene
pp	peak-to-peak
PPCP	1,2,3,4,5-pentaphenyl-1,3-cyclopentadiene
PT	$PbTiO_3$
PPE	poly-*p*-phenyleneethynylene
PPF	propylene fumarate
PPTA	poly phenylene terephthalamide
PPV	poly-*p*-phenylenevinylene
PPy	polypyrrole
PRR	pattern recognition receptor
PS	polystyrene
PS	porous silicon
PS-PFS	poly(styrene-b-ferrocenyldimethylsilane)
PSD	photo signal detector
PSS	poly(sodium 4-styrenesulfonate)
PSS	polystyrene sulfonate
PSU	polysulfonate
PSU	polysulfone
PSVPh	poly(styrene-*co*-vinyl phenol)
Pt-NPG	platinum-decorated nanoporous gold
Pt-NPGL	platinum-plated nanoporous gold leaf
PTCDI	N,N'-di(propoxyethyl)perylene-3,4,9,10-tetracarboxylic diimide
PTCE	track-etched polycarbonate
PTFE	polytetrafluoroethylene
PU	polyurethane
PV	pervaporation
PV	photovoltaic
PVA	polyvinyl alcohol
PVC	polyvinylchloride
PVD	physical vapor deposition
PVDF	polyvinyldifluoride
PVP	polyvinyl pyrrolidone
PW	plane wave
pzc	point of zero charge

PZN-PT	$PbZn_{1/3}Nb_{2/3}O_3$-$PbTiO_3$
PZT	$Pb(Zr,Ti)O_3$

Q

QC	quantum cluster
QD	quantum dot
QEXAFS	quick EXAFS
QHE	quantum Hall effect

R

R6G	rhodamine 6G
RA	right angle
RBM	radial breathing mode
RCF	rabbit corneal fibroblast
RE	rare-earth
rebar	reinforcement bar
REDOR	rotational echo double resonance
RF	radio frequency
RFDR	radiofrequency-driven recoupling
RFID	radiofrequency identification
RGB	red green blue
RGD	Arg-Gly-Asp
RGO	reduced graphene oxide
rhBMP-2	recombinant human bone morphogenic protein-2
RHE	reversible hydrogen electrode
RIA	radioimmuno assay
RIE	reactive-ion etching
RIR	restriction of intramolecular rotation
RJS	rotary jet spinning
RKKY	Rudermann–Kittel–Kasuya–Yosida
RM	reactive milling
RMS	microscale surface roughness
RNA	ribonucleic acid
RO	reverse osmosis
ROS	reactive oxygen species
RPC	retinal progenitor cells
RRR	redox replacement reaction
RRS	resonant Raman scattering
RT	room temperature
RT-PCR	real-time polymerase chain reaction
R&D	research and development

S

S–W	Stone–Wales
S/L	solid/liquid
SA	sliding angle
SA	solar ablation
SAED	selected-area electron diffraction
SAM	self-assembled monolayer
SANS	small -angle neutron scattering
SAPO	silicoaluminophosphate
SAXS	small-angle x-ray scattering
SBU	secondary building unit
SC	simple cubic
SC	sodium cholate
SCC	stress corrosion cracking
SCE	saturated calomel electrode
SCR	space-charge region
SD	standard deviation
SDBS	sodium dodecylbenzene sulfate
SDCH	samaria-doped ceria
SDS	sodium dodecyl sulfate
SEC	size exclusion chromatography
SEI	solid–electrolyte interphase
SEIRA	surface-enhanced infrared absorption
SEM	scanning electron microscopy
SES	scanning electron spectroscopy
SERS	surface-enhanced Raman scattering
SET	single-electron transistor
SF	silk fibroin
SFF	solid freedom fabrication
SFG	sum-frequency generation
SFM	scanning force microscopy
SGS	spaced superconducting electrode
SHE	standard hydrogen electrode
SIM	structured illumination microscopy
SIMS	secondary-ion mass spectrometry
siRNA	silenced RNA
SL	superlattice
SLS	solution–liquid–solid
SMA	shape-memory alloy
SMAD	solvated metal atom dispersion
SNR	signal-to-noise ratio
SOCT	sodium octanoate
SOFC	solid oxide fuel cell
SOI	silicon-on-insulator
SP	surface plasmon
SP-STM	spin-polarized scanning tunneling microscopy
SPM	scanning probe microscopy
SPM	small-pore mordenite
SPP	surface plasmon polariton
SPR	surface plasmon resonance
SPS	spark plasma sintering
SQ	single quantum
SQUID	superconducting quantum interference device
SRNF	solvent resistant nanofiltration
SS	stainless steel
SSA	specific surface area
SSNMR	solid-state nuclear magnetic resonance
STEM	scanning transmission electron microscopy
STM	scanning tunneling microscopy
STORM	stochastic optical reconstruction microscopy
STS	scanning tunneling spectroscopy
SWCNT	single-walled carbon nanotube

SWNH single-wall nanohorn
SWNT single-walled nanotube
SXRD surface x-ray diffraction
ShdH Shubnikov–de Haas
Si-MEMS silicon microelectromechanical system
Si-nc silicon nanocrystal

T

TA thioctic acid
TA transverse acoustic
TAMRA tetramethylrhodamine
TASA template-assisted self-assembly
TCNQ tetracyanoquinodimethane
TCO transparent conductive oxide
TDABr tetradodecylammonium bromide
TDDFT time-dependent density-functional-theory
TDPA tetradecylphosphonic acid
TE transition metal element
TEG tetra(ethylene glycol)
TEM transmission electron microscopy
TEOS tetraethyl orthosilicate
TEP thermoelectric power
TFT thin-film transistor
TG top gate
TGA thermogravimetric analysis
TGA thioglycolic acid
TGF-β transforming growth factor
THF tetrahydrofuran
THPC tetrakismethyl)phosphonium chloride
TIC toxic industrial chemical
TIPS thermally induced phase separation
TL transition-metal element
TMAH tetramethylammonium hydroxide
TMR tunnel magnetoresistance
TNF-α tumor necrosis factor
TNT 2-methyl-1,3,5-trinitrobenzene
TO truncated octahedron
TOAB tetraoctylammonium bromide
TOF turnover frequency
TOP trioctylphosphine
TOPO trioctylphosphine oxide
TPA tetrapropylammonium
TPD temperature programmed desorption
TPI 2,4,5-triphenylimidazole
TPL two-photon luminescence
TPP 1,3,5-triphenyl-2-pyrazoline
TSP transverse surface plasmon
TSW Thrower–Stone–Wales
TTCP tetracalcium phosphate
TWC three-way catalyst
ThT thioflavin T

U

UF ultrafiltration
UHP ultrahigh pressure
UHV ultrahigh vacuum
UNCD ultrananocrystalline diamond
UPD underpotential deposition
UV ultraviolet
UV-VIS ultraviolet-visible
UVR ultraviolet radiation

V

vdW van der Waals
VGCF vapor-grown carbon fiber
VHS van Hove singularity
VLS vapor–solid–liquid
VPC vacuum pyrolysis/carbothermal
VRH variable range hopping
VS vapor–solid
VSFG vibrational sum-frequency generation
VSM vibrating sample magnetometry
VSS vapor–solid–solid
Van vancomycin

W

WAXD wide angle x-ray diffraction
WC tungsten carbide
WG waveguide
WHO World Health Organization

X

XANES x-ray absorption near-edge spectroscopy
XAS x-ray absorption spectroscopy
xc exchange–correlation
XPS x-ray photoelectron spectroscopy
XRD x-ray diffraction

Y

YAB $YAl_3(BO_3)_4$
YAM $Y_4Al_2O_9$
Y-CNT Y-shaped carbon nanotube

Z

ZAP zone axis pattern
ZHDS hydroxydodecylsulfate
ZHS zinc hydroxysulfate
ZLC zero-length-column
ZSM zeolite sieve of molecular porosity