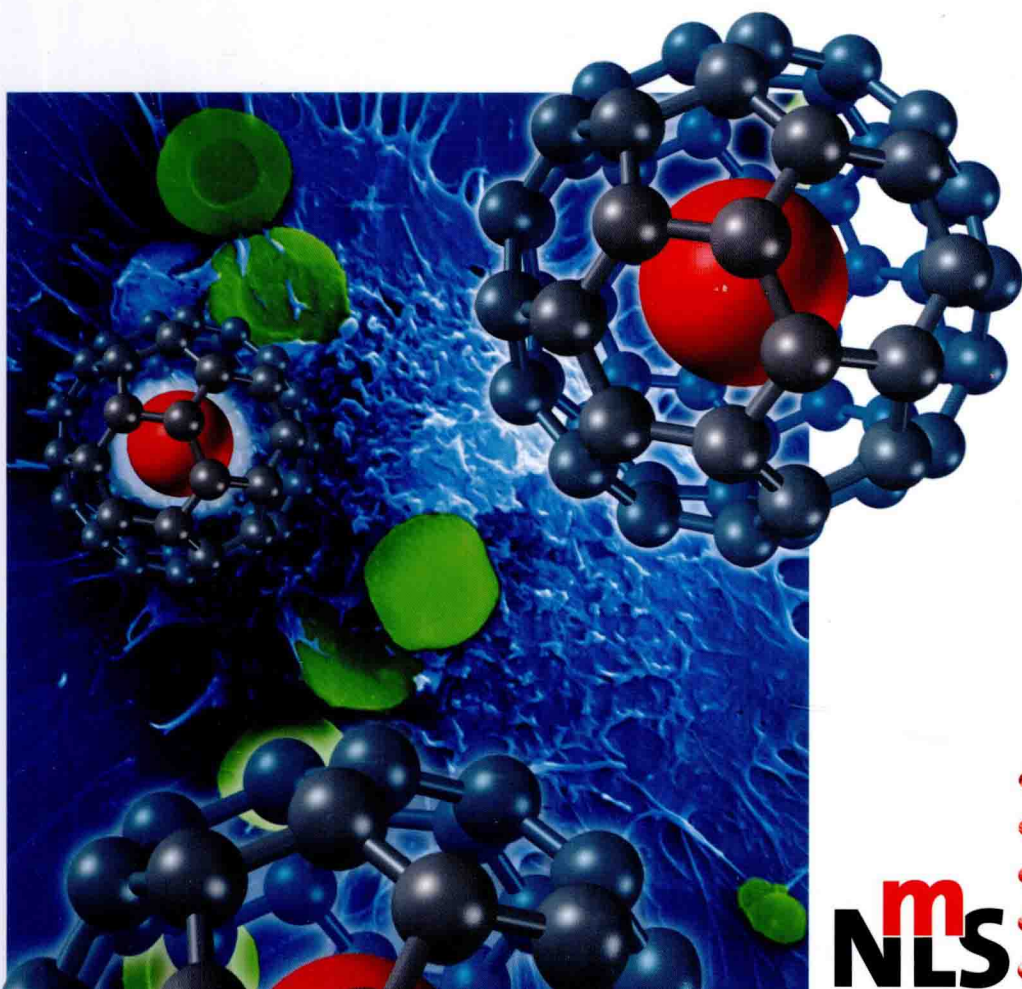


Edited by Challa Kumar

 WILEY-VCH

Biomimetic and Bioinspired Nanomaterials



m
NLS 

Nanomaterials for the Life Sciences
Volume 7

**Biomimetic and
Bioinspired Nanomaterials**

Edited by
Challa S. S. R. Kumar



WILEY-VCH Verlag GmbH & Co. KGaA

The Editor

Dr. Challa S. S. R. Kumar

CAMD

Louisiana State University

6980 Jefferson Highway

Baton Rouge, LA 70806

USA

Cover Picture

As we all know, science is developing step-wise – periods of steady-state growth are interrupted by fast transformations caused by new experimental evidence or/and NEW IDEAS. Truly new ideas use to emerge as some “unlogical” steps related to “cross-terms” with other fields of science and even art. Each researcher always has his own “picture” behind any new model or theory. To have such ideas one should go beyond common way of thinking for a while.

Science for authors (and we believe, for many others) is fun, and they would like to share this fun with readers! Working over our simple models of complex phenomena, we sometimes managed to find reasonable solutions by using the analogies between reactions in solid state and in surrounding nature and art. May be naively, we decided to illustrate this principle from the very beginning – at the cover picture, using kind permission of their international authors – King Ning Tu (USA), Chen Zhong (Singapore), Oksana Bortz (Russia), Juern Schmelzer (Germany). In remaining photos the principle of analogy is applied:

Tin-lead solder bump – sun “bump”,

Cu₆Sn₅ scallops in Flux Driven Ripening – natural rocks “scallop”,

Morphology of reaction zone between electroless nickel and solder – “reaction zone” of waterfall,

Diffusion zone with emerging intermediate phases layers and islands in MC simulation – diffused transition zone between night and day with emerging intermediate foggy “phases”.

Unexpected nucleation of rainbow between clouds and earth is actually of the same type, but it is simultaneously a logical center of all collection, analogical couples going clockwise.

All books published by Wiley-VCH are carefully produced. Nevertheless, authors, editors, and publisher do not warrant the information contained in these books, including this book, to be free of errors. Readers are advised to keep in mind that statements, data, illustrations, procedural details or other items may inadvertently be inaccurate.

Library of Congress Card No.: applied for

British Library Cataloguing-in-Publication Data

A catalogue record for this book is available from the British Library.

Bibliographic information published by the Deutsche Nationalbibliothek

The Deutsche Nationalbibliothek lists this publication in the Deutsche Nationalbibliografie; detailed bibliographic data are available on the Internet at <<http://dnb.d-nb.de>>.

© 2010 WILEY-VCH Verlag GmbH & Co. KGaA, Boschstr. 12, 69469 Weinheim

All rights reserved (including those of translation into other languages). No part of this book may be reproduced in any form – by photoprinting, microfilm, or any other means – nor transmitted or translated into a machine language without written permission from the publishers. Registered names, trademarks, etc. used in this book, even when not specifically marked as such, are not to be considered unprotected by law.

Composition Toppan Best-set Premedia Ltd., Hong Kong

Printing and Binding betz-druck GmbH, Darmstadt

Cover Design Schulz Grafik-Design, Fußgönheim

Printed in the Federal Republic of Germany
Printed on acid-free paper

ISBN: 978-3-527-32167-4

*Nanomaterials for the
Life Sciences*
Volume 7
**Biomimetic and
Bioinspired Nanomaterials**

Edited by
Challa S. S. R. Kumar

Related Titles

Kumar, C. S. S. R. (ed.)

Nanotechnologies for the Life Sciences

10 Volume Set

ISBN: 978-3-527-31301-3

Kumar, C. S. S. R. (Ed.)

Nanomaterials for the Life Sciences (NmLS)

Book Series, 10 Volumes

Vol. 6

Semiconductor Nanomaterials

2010

ISBN: 978-3-527-32166-7

Vol. 7

Biomimetic and Bioinspired Nanomaterials

2010

ISBN: 978-3-527-32167-4

Vol. 8

Nanocomposites

2010

ISBN: 978-3-527-32168-1

Vol. 9

Carbon Nanomaterials

2011

ISBN: 978-3-527-32169-8

Vol. 10

Polymeric Nanomaterials

2011

ISBN: 978-3-527-32170-4

Preface

Nature continues to teach us and inspire us. It is therefore not surprising that Nature is far advanced in utilizing Nanomaterials and nanotechnology principles than us. It is awe inspiring to learn these tools from Nature and to apply them to build materials that are useful in our day to day life. We have seen a dramatic increase in the number of investigation focusing on these approaches aptly termed as “biomimetic” or “bioinspired.” The concept of biomimetics, though, emerged only in the 1960s, it has been developing rapidly in enhancing the functions of materials and devices ranging from biomedicine to energy. This advancement came about mainly due to progress in nano- and biotechnologies. Here within this book we have the first opportunity to summarize these advances with special reference to life sciences. I am pleased to present to you the seventh volume in the NmLS series that is dedicated to capturing these investigations and organizing them in such a way as to provide information in an easy and free flowing manner. The book is aptly titled, Biomimetic and Bioinspired Nanomaterials for Life Sciences, and has fourteen chapters describing in depth various aspects of nanomaterials derived from or inspired by Nature ranging from plant and animal kingdom. This is judiciously interspersed with chapters covering tools developed for understanding the nanoscale phenomenon in nature and applying the lessons to design materials in the laboratory.

Who have not heard of Geckos, small to average sized lizards belonging to the family Gekkonidae, and well known for their adhesion? The book begins with a chapter on Gecko-inspired Nanomaterials by Christian Greiner. It discusses the physical origin of gecko adhesion and how to mimic its abilities. Moving from Gecko to humans, the second chapter offers a brief review of teeth with reference to bio-mineralization systems and in vitro strategies to synthesize similar materials. The chapter by Janet Moradian-Oldak zeroes in on enamel and dentin as nanocomposite materials, their unique structures and common molecular mechanisms involved in their formation. From more specific nanocomposites to general tissue engineering, the third chapter by Peter Ma describes extracellular matrix (ECM) scaffold for tissue regeneration and explains fabrication techniques viz electro spinning, self-assembly, and phase separation for nano-fibrous scaffolds and their applications to tissue engineering. Such ECM-mimicking nano-structured biomaterials have been shown to actively regulate many biological

effects and cellular responses including adhesion, proliferation, and differentiation thereby demonstrating the significance of biomimetic nanomaterials for tissue engineering and regeneration. In the next chapter, nature-inspired nanomachines and their significance with respect to Nano-Electro-Mechanical-Systems are presented. Covering several biological molecular machines, including Myosin, Kinesin, ATPase, and DNA, the author Tony Jun Huang continues the discussion to include several biomimetic molecular machines, such as rotaxanes, catenanes, pseudorotaxanes, nanocars, polyelectrolyte brushes, and light-driven molecular motors. This chapter in combination with chapter eight provides a comprehensive review on nature inspired nanomachines. Unlike the chapter four, the chapter eight covers advances in biomimetic distributed nanosensors and nanoactuators (BNN) made with nanocomposites of ion-containing polymers, polyelectrolytes and conductive materials and networks. In addition, the chapter by Mohsen Shahinpoor shares phenomenological model of the underlying sensing and actuation mechanisms in these sensors.

The peptide nanostructures have remarkable features such as rigidity, thermal stability, chemical stability and high versatility that allow tailor-made chemical and biological modifications. In the fifth chapter, Francesco Pampaloni's commentary on Biomimetic and Bio-inspired Self-assembled Peptide Nanostructures reiterates the importance of several types of peptide nanostructures ranging from nanotubes, wires, rods, particles to thin films in a number of applications related to life sciences. In the sixth chapter entitled, Bio-inspired Layered Nanomaterials in Medical Therapy, Jin-Ho Choy introduces structure and chemical features of biocompatible layered nanomaterials and the intercalative hybrid nanomaterials for medical therapy. The chapter is also valuable as it presents information from the point of view of clinical toxicology. Offering the possibility for drugs to be intercalated into layered materials, these nanostructures act as biomolecular reservoirs or drug delivery systems with superior drug pharmacokinetics.

While biomimetic nanostructures are intriguing and provide new opportunities for designing novel nanomaterials with unique properties and applications, a different line of investigations is related to the increasing interest and emphasis on developing cleaner and more sophisticated methods for preparation of nanomaterials using bio-templates by mimicking biological processes. In the seventh chapter, Jim Yang Lee argues that the synthesis of nanoparticles by organisms or biomolecules is ideal from the viewpoint of a reduced environmental footprint. Substantiating this point of view, the chapter summarizes the current progress in biological and biomimetic synthesis of metal nanoparticles (using nanogold and nanosilver as examples), emphasizing on their major differentiating features from conventional chemical synthesis and some understanding of the fundamental principles involved. The chapter "Biomimetic Nanotechnology" reviews current status on bio-mineralization processes; covering the growth of bio-crystals, their morphological control and site-selective immobilization using bio-mimetic approaches. The role of molecular recognition is also stressed. In this chapter by Takahiro Ishizaki, the emphasis is on the products of bio-mineralization, that is,

bio-minerals, controlling their crystallo-chemical properties through molecular recognition at an inorganic-organic interface.

Self-assembly is the most sought after and reliable approach that Nature has been using from the time immemorial. We have learnt a lot about self-assembly from Nature and bio molecular and bio mimetic self-assembly has emerged as an appealing and promising route for fabrication of materials and devices with most desirable functions. In the tenth chapter by Bo Liedberg, an overview of current progress on bio mimetic approaches for self-assembly of nanomaterials, with a particular focus on *de novo* designed polypeptides and their uses as scaffolds and tools for self-assembly of functional nano-architectures and hybrid materials is presented. This analysis reveals that bio mimetic self-assembly designs from Nature are far more advanced than most manmade materials and possess many attractive physical and chemical properties. With specific reference to self assembly related to surfaces, the next chapter teaches the reader about artificial nanostructured surfaces resulting from both mimicking and being inspired by nature. The chapter by Emmanuel Stratakis also reviews different approaches that have been employed so far for the fabrication of bio-inspired artificial nano structured surfaces in addition to delineating existing limitations and discussing emerging possibilities and future prospects. The twelfth chapter, Natural and Modified Nanomaterials for Environmental Applications, is a contribution from Guodong Yuan. In this chapter, the author describes natural aluminosilicate nanomaterials and more specifically the actual and potential applications of two well-studied nanosize aluminosilicates, notably montmorillonite and allophane, and their modified forms. The chapter provides an overview of various facets of environmental functions of natural nanomaterials ranging from adsorbents, filters, membranes, catalysts, antimicrobial agents, sensors, and finally as carriers of chemicals.

Among the biopolymers, S-layer proteins are one of the most common and their structure, genetics, chemistry, morphogenesis and function have been under investigations for more than 30 years. Pointing out the importance of scanning force microscopy as an important tool for imaging and probing the surface properties of native and genetically modified S-layer proteins, the thirteenth chapter provides an overall description of native and genetically modified S-layer proteins, their reassembly on solid surfaces and patterning by lithographical methods and their structural investigations using single molecule recognition force spectroscopy. The author Dietmar Pum focused the discussion towards rendering silicon surfaces hydrophilic or hydrophobic utilizing S-layer proteins. The final chapter contributed by Himadri S. Gupta is entitled, Nanoscale Deformation Mechanisms in Biological Tissues. In this chapter, the author highlights the importance of cooperative and multi-scale processes activated during deformation of biological materials and highlights some unifying common principles in nanoscale deformation behavior that emerge, when considering a whole range of materials. The author also recommends utilization of high resolution experimental tools like in-situ synchrotron testing and single molecule mechanical spectroscopy for discovering and discriminating between the relevant deformation mechanisms.

I do hope that the information that has been painstakingly accumulated by several researchers in this book will help in furthering better understanding of the nanosystems derived from Nature leading to newer biomimetic materials with never foreseen applications. I am very grateful to all the authors for their excellent presentations of their topics, providing timely inputs and corrections in making this unique book a reality. I am always thankful to my employer, family, friends and Wiley VCH publishers for their continued support and encouragement. Finally, my special thanks to you, the readers, for making attempts to utilize the knowledge base provided in this book. I look forward to receiving your comments and suggestions.

Challa S.S.R. Kumar

List of Contributors

Daniel Aili

Linköping University
Department of Physics
Chemistry and Biology (IFM)
581 83 Linköping
Sweden

and

Imperial College
Department of Materials and
Institute of Biomedical
Engineering
Exhibition Road
London SW7 2AZ
UK

Soo-Jin Choi

Seoul Women's University
Department of Food Science and
Technology
Seoul 139-774
Korea

Jin-Ho Choy

Ewha Womans University
Department of Bioinspired
Science and Department of
Chemistry and Nano Science
Center for Intelligent NanoBio
Materials
Division of Nano Science BK21
Seoul 120-750
Korea

Yuwei Fan

Louisiana State University Health
Science Center
School of Dentistry
1100 Florida Ave
New Orleans, LA 70119
USA

Christian Greiner

University of Pennsylvania
Department for Mechanical
Engineering and Applied
Mechanics
112 Towne Building
220 South 33rd St.
Philadelphia, PA 19104
USA

Himadri S. Gupta

Queen Mary University of
London
School of Engineering and
Materials Science
Mile End Road
London E1 4NS
UK

Peter Hinterdorfer

Johannes Keppeler University
Institute for Biophysics
4040 Linz
Austria

Tony Jun Huang

Pennsylvania State University
Department of Engineering
Science and Mechanics
University Park, PA 16801
USA

Takahiro Ishizaki

National Institute of Advanced
Industrial Science and
Technology (AIST)
2266-98 Anagahora,
Shimoshidami, Moriyama-ku
Nagoya 463-8560
Japan

Bala Krishna Juluri

Pennsylvania State University
Department of Engineering
Science and Mechanics
University Park, PA 16801
USA

Hyun Jung

Dongguk University
Advanced Functional Nanohybrid
Materials Laboratory
Department of Chemistry
Seoul 100-715
Korea

Aitan Lawit

Pennsylvania State University
Department of Engineering
Science and Mechanics
University Park, PA 16801
USA

Jim Yang Lee

National University of Singapore
4 Engineering Drive 3
Department of Chemical and
Biomolecular Engineering
Singapore-MIT Alliance
10 Kent Ridge Crescent
Singapore 119260
Singapore

SunHyung Lee

Shinshu University
Faculty of Engineering
Nagano 380-8553
Japan

Bo Liedberg

Linköping University
Department of Physics
Chemistry and Biology (IFM)
581 83 Linköping
Sweden

Andrew P. Loeffler

The University of Michigan
Department of Biomedical
Engineering
Ann Arbor, MI 48109
USA

Peter X. Ma

The University of Michigan
Department of Biomedical
Engineering
Ann Arbor, MI 48109
USA

The University of Michigan
Department of Biologic and
Materials Sciences
Ann Arbor, MI 48109
USA

The University of Michigan
Macromolecular Science and
Engineering Center
Ann Arbor, MI 48109
USA

Andrea Masotti

IRCCS-Children's Hospital
Bambino Gesù
Gene Expression – Microarrays
Laboratory
P.za S.Onofrio 4
00165 Rome
Italy

Yoshitake Masuda

National Institute of Advanced
Industrial Science and
Technology (AIST)
2266-98 Anagahora,
Shimoshidami, Moriyama-ku
Nagoya 463-8560
Japan

Janet Moradian-Oldak

University of Southern California
Center for Craniofacial Molecular
Biology
2250 Alcazar Street
Los Angeles, CA 90033
USA

Jae-Min Oh

Yonsei University
College of Science and
Technology, Department of
Chemistry and Medical Chemistry
Wonju
Gangwon-Do 220-710
Korea

Francesco Pampaloni

European Molecular Biology
Laboratory (EMBL)
Cell Biology & Biophysics Unit
Meyerhofstrasse 1
69117 Heidelberg
Germany

Dietmar Pum

Universität für Bodenkultur Wien
Department of
Nanobiotechnology
1190 Vienna
Austria

Nagahiro Saito

Nagoya University
EcoTopia Science Institute
Furo-cho, Chikusa-ku
Nagoya 464-8603
Japan

Mohsen Shahinpoor

University of Maine
Mechanical Engineering
Department
Biomedical Engineering
Laboratory
Orono, ME 04469
USA

Uwe B. Sleytr

Universität für Bodenkultur Wien
Department of
Nanobiotechnology
1190 Vienna
Austria

Emmanuel I. Stratakis

Institute of Electronic Structure
and Lasers (IESL)
Foundation for Research and
Technology Hellas (FORTH)
Nikolaou Plastira 100
71003 Voutes Heraklion Crete
Greece
University of Crete, Hellas
Department of Materials Science
and Technology
Nikolaou Plastira 100
71003 Voutes Heraklion Crete
Greece

Osamu Takai

Nagoya University
Department of Materials, Physics
and Energy Engineering
Graduate School of Engineering
Furo-cho, Chikusa-ku
Nagoya 464-8603
Japan

Yen Nee Tan

National University of Singapore
Singapore-MIT Alliance
4 Engineering Drive 3
Singapore 117576
Singapore

Jilin Tang

Changchun Institute of Applied
Chemistry
Changchun
130021
China

Katsuya Teshima

Shinshu University
Department of Environmental
Science and Technology
Faculty of Engineering
Nagano 380-8553
Japan

Jose-Luis Toca Herrera

CIC BiomaGUNE
Biosurfaces Unit
20009 San Sebastian
Spain

Jianping Xie

National University of Singapore
Singapore-MIT Alliance
4 Engineering Drive 3
Singapore 117576
Singapore

Guodong Yuan

Landcare Research
Palmerston North
PB 11052
New Zealand

Vassilia Zorba

Lawrence Berkeley National
Laboratory
Environmental Energy
Technologies Division
Laser Spectroscopy and Applied
Materials Group
1 Cyclotron Road, MS 70R108B
Berkeley, CA 94720
USA

Contents

Preface XV

List of Contributors XIX

1	Gecko-Inspired Nanomaterials	1
	<i>Christian Greiner</i>	
1.1	The Gecko and Its Adhesion Capabilities	1
1.1.1	What are Setae?	1
1.1.2	Walking on the Ceiling	3
1.2	The Physics of Gecko Adhesion	4
1.2.1	Contact Splitting	4
1.2.2	Adhesion Design Maps	6
1.3	Fabrication Methods for Gecko-Inspired Adhesives	8
1.3.1	Soft-Molding	8
1.3.2	Nanostructured Adhesive Surfaces	11
1.3.2.1	Hot Embossing	11
1.3.2.2	Filling Nanoporous Membranes	11
1.3.2.3	Electron-Beam Lithography	12
1.3.2.4	Carbon Nanotubes	13
1.3.2.5	Drawing Polymer Fibers	13
1.3.2.6	Hierarchical Adhesive Surfaces	14
1.3.2.7	3-D Structured Adhesive Surfaces	16
1.3.2.8	Switchable Adhesive Surfaces Made from Responsive Materials	17
1.4	Measuring Adhesion	17
1.4.1	What Actually is Measured?	17
1.4.2	How is Adhesion Measured?	20
1.5	What Have We Learned About Fibrillar Adhesives?	22
1.5.1	Contact Splitting	22
1.5.2	Aspect Ratio	23
1.5.3	Tip Geometry	24
1.5.4	Young's Modulus	25
1.5.5	Backing Layer	25
1.5.6	Tilt Angle	26
1.5.7	Hierarchy	27

1.5.8	Experimental Parameters that Influence Measurements	28
1.5.8.1	Adhesion Tests: Indentation versus Peeling	28
1.5.8.2	Indenter Geometry	29
1.5.8.3	Humidity	29
1.5.9	Other Approaches and Factors	30
1.6	Applications in the Life Sciences	30
1.7	Summary and Future Perspectives	33
	References	34
2	Tooth-Inspired Nanocomposites	41
	<i>Janet Moradian-Oldak and Yuwei Fan</i>	
2.1	Introduction	41
2.1.1	Biologically Formed Nanocomposites	42
2.1.2	Nanocomposite Synthesis	44
2.2	Enamel	45
2.2.1	Enamel Hierarchical Structure	46
2.2.2	Molecular Mechanisms in Amelogenesis (Enamel Formation)	47
2.2.2.1	Amelogenin	48
2.2.2.2	Other Enamel Proteins	50
2.2.3	Synthesis of Enamel-Like Organized Apatite Crystals	52
2.2.4	Amelogenin-Based Nanocomposites	54
2.2.4.1	Controlled Crystallization of Apatite by Amelogenin	54
2.2.4.2	Biomimetic Coatings Using Simulated Body Fluid	56
2.2.4.3	Amelogenin-Apatite Coatings Using Electrodeposition (ELD)	57
2.2.4.4	Bioinspired Remineralization of Enamel	61
2.3	Dentin	64
2.3.1	Types of Dentin	65
2.3.2	Dentin Hierarchical Structure	65
2.3.3	Molecular Mechanisms in Dentinogenesis (Dentin Formation)	66
2.3.3.1	Collagen	67
2.3.3.2	Noncollagenous Extracellular Matrix Proteins	67
2.3.4	Collagen–Calcium Phosphate Nanocomposites	69
2.3.4.1	Biomimetic Collagen Mineralization Using SBF	69
2.3.4.2	Bioinspired Mineralization of Collagen	71
2.3.4.3	Collagen-Apatite Coating in Modified SBF	73
2.3.4.4	Collagen-Apatite Coating by Electrodeposition	73
2.3.5	Dentin Remineralization	75
2.4	Summary and Future Perspective	76
	Acknowledgments	77
	Abbreviations	77
	References	78
3	Bioinspired Nanomaterials for Tissue Engineering	89
	<i>Andrew P. Loeffler and Peter X. Ma</i>	
3.1	Introduction	89
3.2	Biomimetic Material Properties	91

3.2.1	Scaffold Surface and Pore Structure	91
3.2.2	Scaffold Biodegradability	92
3.2.3	Scaffold Mechanical Properties	93
3.2.4	Scaffold Biocompatibility and Cellular Interactions	94
3.3	Nanofiber Scaffold Fabrication Methods	94
3.3.1	Electrospinning	95
3.3.2	Self-Assembly	97
3.3.3	Phase Separation	99
3.3.3.1	Predesigned Macropores	100
3.3.3.2	Solid Freeform Fabrication	101
3.4	Modification of Nanofibrous Scaffolds	103
3.4.1	Scaffold Surface Modifications	104
3.4.2	Inorganic Composite Scaffolds	105
3.4.3	Factor Delivery Scaffolds	107
3.5	Biological Effects of Nanofibers	110
3.5.1	Cell Attachment and Morphology	110
3.5.2	Proliferation	112
3.5.3	Differentiation and Tissue Formation	113
3.6	Conclusions	115
	References	116

4 Nature-Inspired Molecular Machines 125 *Aitan Lawit, Bala Krishna Juluri, and Tony Jun Huang*

4.1	Introduction	125
4.2	Biological Molecular Machines	125
4.2.1	Kinesin and Myosin	126
4.2.2	ATPase	132
4.2.3	DNA	134
4.3	Biomimetic Molecular Machines	136
4.3.1	Rotaxanes, Catenanes, and Pseudorotaxanes	137
4.3.2	Nanocars	142
4.3.3	Polyelectrolyte Brushes	143
4.3.4	Light-Driven Molecular Motors	145
4.4	Conclusions	146
4.5	Future Perspective	147
	References	147

5 Biomimetic and Bioinspired Self-Assembled Peptide Nanostructures 151 *Francesco Pampaloni and Andrea Masotti*

5.1	Introduction	151
5.1.1	Some Key Principles of Biological Self-Assembly	151
5.1.2	Biological Self-Assembly in Nanotechnology	152
5.2	Peptide-Based Self-Assembling Nanomaterials	152
5.2.1	Alpha-Helical Coiled-Coil	153
5.2.1.1	Self-Assembly Mechanism of Coiled-Coils	153

5.2.1.2	De Novo-Designed α -Helix Coiled-Coil Nanofibers	154
5.2.2	β -Sheet Structures	158
5.2.2.1	Amyloid Fibrils	158
5.2.2.2	De Novo-Designed β -Sheet Materials	160
5.2.2.3	Collagen-Based Assemblies	162
5.3	Matrices for Tissue Engineering and Regenerative Medicine	164
5.3.1	Peptide–Amphiphile Nanofiber Matrices	166
5.3.1.1	Molecular Structure	166
5.3.1.2	Self-Assembly and Physical–Biochemical Properties	166
5.3.1.3	Applications in 3-D Cell Cultures	168
5.3.1.4	Applications in Regenerative Medicine	169
5.3.2	Beta-Sheet Nanofiber Matrices (“Designer Peptides”)	170
5.3.2.1	Molecular Structure	170
5.3.2.2	Self-Assembly Mechanism and Biophysical Properties	172
5.3.2.3	Applications in 3-D Cell Cultures	172
5.3.2.4	Applications in Regenerative Medicine	173
5.3.2.5	Local Delivery of Molecules	174
5.3.3	Beta-Hairpin Peptides	175
5.3.3.1	Molecular Structure	175
5.3.3.2	Self-Assembly Mechanism and Biophysical Properties	176
5.3.3.3	Applications in 3-D Cell Cultures	177
5.3.3.4	Applications in Regenerative Medicine	177
5.4	Virus-Based and Virus-Inspired Nanomaterials	177
5.4.1.1	Nanomechanical Properties of Virus Capsids	178
5.4.2	Applications of Viruses in Nanotechnology	180
5.4.2.1	Virus-Based Nanostructures and Self-Organizing Assemblies	181
5.4.2.2	Virus-Like Particles Encapsulating Non-Genetic Molecular Cargos	185
5.4.2.3	Synthetic Viruses	187
5.4.2.4	Functionalization of Virus Capsids	189
5.4.2.5	Viruses as Templates for Programmed Synthesis of Nanomaterials	193
5.5	Biomimetic Nanotubes	194
5.5.1	Properties of Nanotubes	194
5.5.2	Peptide and Protein Nanotubes	195
5.5.3	Cellular Microtubules	198
5.5.3.1	Self-Assembly and Structure of Microtubules	198
5.5.3.2	Microtubule Bundles	199
5.5.3.3	Prospect: Insights from MT for Nanotechnology	199
	Acknowledgments	200
	Abbreviations	200
	References	202