

Nanotechnology

Understanding Small Systems

THIRD EDITION

Ben Rogers
Jesse Adams
Sumita Pennathur

Nanotechnology

Understanding Small Systems

THIRD EDITION

Ben Rogers

Jesse Adams

Sumita Pennathur



CRC Press

Taylor & Francis Group

Boca Raton London New York

CRC Press is an imprint of the
Taylor & Francis Group, an **informa** business

CRC Press
Taylor & Francis Group
6000 Broken Sound Parkway NW, Suite 300
Boca Raton, FL 33487-2742

© 2015 by Taylor & Francis Group, LLC
CRC Press is an imprint of Taylor & Francis Group, an Informa business

No claim to original U.S. Government works

Printed and bound in India by Replika Press Pvt. Ltd.

Printed on acid-free paper
Version Date: 20140725

International Standard Book Number-13: 978-1-4822-1172-6 (Hardback)

This book contains information obtained from authentic and highly regarded sources. Reasonable efforts have been made to publish reliable data and information, but the author and publisher cannot assume responsibility for the validity of all materials or the consequences of their use. The authors and publishers have attempted to trace the copyright holders of all material reproduced in this publication and apologize to copyright holders if permission to publish in this form has not been obtained. If any copyright material has not been acknowledged please write and let us know so we may rectify in any future reprint.

Except as permitted under U.S. Copyright Law, no part of this book may be reprinted, reproduced, transmitted, or utilized in any form by any electronic, mechanical, or other means, now known or hereafter invented, including photocopying, microfilming, and recording, or in any information storage or retrieval system, without written permission from the publishers.

For permission to photocopy or use material electronically from this work, please access www.copyright.com (<http://www.copyright.com/>) or contact the Copyright Clearance Center, Inc. (CCC), 222 Rosewood Drive, Danvers, MA 01923, 978-750-8400. CCC is a not-for-profit organization that provides licenses and registration for a variety of users. For organizations that have been granted a photocopy license by the CCC, a separate system of payment has been arranged.

Trademark Notice: Product or corporate names may be trademarks or registered trademarks, and are used only for identification and explanation without intent to infringe.

Library of Congress Cataloging-in-Publication Data

Rogers, Ben, 1977-
Nanotechnology : understanding small systems, / Ben Rogers, Jesse Adams, Sumita Pennathur. --
Third edition.
pages cm
Includes bibliographical references and index.
ISBN 978-1-4822-1172-6
1. Nanotechnology--Textbooks. I. Adams, Jesse, 1974- II. Pennathur, Sumita, 1978- III. Title.

T174.7.R64 2015
620'.5--dc23

2014027324

Visit the Taylor & Francis Web site at
<http://www.taylorandfrancis.com>

and the CRC Press Web site at
<http://www.crcpress.com>

Nanotechnology

Understanding Small Systems

THIRD EDITION

Mechanical Engineering Series

Frank Kreith, Series Editor

Alternative Fuels for Transportation

Edited by Arumugam S. Ramadhas

Computer Techniques in Vibration

Edited by Clarence W. de Silva

Distributed Generation: The Power Paradigm for the New Millennium

Edited by Anne-Marie Borbely and Jan F. Kreider

*Elastic Waves in Composite Media and Structures: With Applications to Ultrasonic
Nondestructive Evaluation*

Subhendu K. Datta and Arvind H. Shah

Elastoplasticity Theory

Vlado A. Lubarda

Energy Audit of Building Systems: An Engineering Approach

Moncef Krarti

Energy Conversion

Edited by D. Yogi Goswami and Frank Kreith

Energy Management and Conservation Handbook

Edited by Frank Kreith and D. Yogi Goswami

The Finite Element Method Using MATLAB®, Second Edition

Young W. Kwon and Hyochoong Bang

Fluid Power Circuits and Controls: Fundamentals and Applications

John S. Cundiff

Fundamentals of Environmental Discharge Modeling

Lorin R. Davis

Handbook of Energy Efficiency and Renewable Energy

Edited by Frank Kreith and D. Yogi Goswami

Heat Transfer in Single and Multiphase Systems

Greg F. Naterer

Heating and Cooling of Buildings: Design for Efficiency, Revised Second Edition

Jan F. Kreider, Peter S. Curtiss, and Ari Rabl

Intelligent Transportation Systems: Smart and Green Infrastructure Design, Second Edition

Sumit Ghosh and Tony S. Lee

Introduction to Biofuels

David M. Mousdale

Introduction to Precision Machine Design and Error Assessment

Edited by Samir Mekid

Introductory Finite Element Method

Chandrakant S. Desai and Tribikram Kundu

Large Energy Storage Systems Handbook

Edited by Frank S. Barnes and Jonah G. Levine

Machine Elements: Life and Design

Boris M. Klebanov, David M. Barlam, and Frederic E. Nystrom

- Mathematical and Physical Modeling of Materials Processing Operations*
Olusegun Johnson Ilegbusi, Manabu Iguchi, and Walter E. Wahnsiedler
- Mechanics of Composite Materials*
Autar K. Kaw
- Mechanics of Fatigue*
Vladimir V. Bolotin
- Mechanism Design: Enumeration of Kinematic Structures According to Function*
Lung-Wen Tsai
- Mechatronic Systems: Devices, Design, Control, Operation and Monitoring*
Edited by Clarence W. de Silva
- The MEMS Handbook, Second Edition (3 volumes)*
Edited by Mohamed Gad-el-Hak
MEMS: Introduction and Fundamentals
MEMS: Applications
MEMS: Design and Fabrication
- Multiphase Flow Handbook*
Edited by Clayton T. Crowe
- Nanotechnology: Understanding Small Systems, Third Edition*
Ben Rogers, Jesse Adams, and Sumita Pennathur
- Nuclear Engineering Handbook*
Edited by Kenneth D. Kok
- Optomechatronics: Fusion of Optical and Mechatronic Engineering*
Hyungsuck Cho
- Practical Inverse Analysis in Engineering*
David M. Trujillo and Henry R. Busby
- Pressure Vessels: Design and Practice*
Somnath Chattopadhyay
- Principles of Solid Mechanics*
Rowland Richards, Jr.
- Principles of Sustainable Energy*
Frank Kreith
- Thermodynamics for Engineers*
Kau-Fui Vincent Wong
- Vibration and Shock Handbook*
Edited by Clarence W. de Silva
- Vibration Damping, Control, and Design*
Edited by Clarence W. de Silva
- Viscoelastic Solids*
Roderic S. Lakes

Preface

THIS IS THE THIRD EDITION of this book. But from the first edition, we knew we did not want this to be a book that glosses over the nitty-gritty stuff, assuming you already know everything, nor a book that uses “hand-waving” to magically skirt around real explanations of the complex stuff. The tone of the book is intended to make it more readable—which is to say that it is not too “textbook-y.” Having used hundreds of textbooks ourselves, we knew how we did not want this one to be, and that was stodgy.

This book is about nanotechnology, a gigantic topic about small things. It is a book that is intended to excite, inspire, and challenge you. We want to uncover the most important things about nanotechnology and give you the tools you need to dig deeper on your own. We want you to enjoy learning (maybe even laugh) and for you to find out a lot in a short time. There will be plenty of rigorous scientific support, but concepts will be conveyed in clear, simple language that you can digest and apply immediately. We do “back-of-the-envelope” calculations together throughout the process so that you get a good feeling for the numbers of nanotechnology. Creative problem sets (Homework Exercises) follow each chapter to test your understanding of new concepts.

Nanotechnology represents a convergence of many sciences and technologies at the nanometer scale. In fact, it is becoming its own discipline altogether. It requires the ability to apply various scientific principles to system-level design and analysis. The multidisciplinary nature of nanotechnology—which draws from physics, chemistry, biology, medicine, and engineering—has the inherent challenge of teaching students with backgrounds in different knowledge domains.

And because the synthesis of disciplines is at the core of nanotechnology, we focus on *systems* in this book. A system is a set of interacting, interrelated, or interdependent elements that are put together to form a complex whole. We discuss nanotechnology on a system-by-system basis to foster both an appreciation and an understanding of this multifaceted topic.

We start with an overview treatment of nanotechnology, with special emphasis on the history, key personalities, and early milestones. Then onto the issues, promises, and fundamentals of nanotechnology. In fact, Chapter 1, “Big Picture and Principles of the Small World,” stands alone as a comprehensive introduction, intended to answer your first questions as to what nanotechnology really is and could be. This chapter is self-contained and comprehensive; there is enough information for a freshman or general public course. It

includes a discussion of the effects this new industry could have on human life, careers, education, and the environment.

Chapter 2 discusses scaling laws, giving us intuition about the physical ramifications of miniaturization. (While we think this is a useful chapter, be warned: it could bore you. If so, feel free to skip or skim it and use it as a reference.)

Then we dive headlong into nanotechnology. We begin with an “Introduction to Nanoscale Physics” (Chapter 3). Then we tackle the eight main disciplines: nanomaterials (Chapter 4), nanomechanics (Chapter 5), nanoelectronics (Chapter 6), nanoscale heat transfer (Chapter 7), nanophotonics (Chapter 8), nanoscale fluid mechanics (Chapter 9), nanobiotechnology (Chapter 10), and nanomedicine (Chapter 11). In these “nano” chapters, we provide the specific, fundamental differences between macroscale and nanoscale phenomena and devices, using applications to teach key concepts.

Welcome!

Acknowledgments

FOR THEIR HELP IN BRINGING this book to life and making it better along the way, the authors thank the National Science Foundation, Melodi Rodrigue, David Bennum, Jonathan Weinstein, Joe Cline, Jeff LaCombe, Michael Hagerman, Seyfollah Maleki, Palma Catravas, Roop Mahajan, Frank Kreith, Daniel Fletcher, Katherine Chen, Todd Sulchek, Nevada Nanotech Systems, Inc., Nevada Ventures, Robb Smith, Stuart Feigin, Chris Howard, Ian Rogoff, Ralph Whitten, David Burns, the Davidson Academy, and the University of Nevada, Reno—especially the Library Department, the College of Engineering, and the Department of Mechanical Engineering.

We would also like to make specific acknowledgments.

For their nurturing and support, I thank the love of my life, Jill; my daughters, Sydney and Quinn; my parents, Jim and Sandra; my brothers, Judd and Tyler; and the rest of my family, as well as my friends, all of whom continue to cheer and steer me. Finally, I thank all my teachers over the years, from preschool to graduate school. I, like this book, was a team effort.

Ben Rogers

Thanks to all my family, friends, and mentors. You are all the best and this is dedicated to your hard work.

Jesse Adams

I thank Anthony T. Chobot III, Anthony T. Chobot IV, and Zofia Lakshmi Chobot for their undying love and support, and for allowing me the opportunity to be a part of this work. Additionally, I thank all my educators throughout the years for giving me the guidance and motivation to contribute to such a textbook.

Sumita Pennathur

AN INVITATION

One more thing. We put a lot of work into making this book useful for you. So, we invite every reader to comment on this book and tell us how we can make it even better. We want your suggestions for future editions and corrections to any errors you may discover. Please e-mail suggestions, questions, comments, and corrections to michael.slaughter@taylorandfrancis.com. We list the names of helpful readers here, in this section.

Here are those who have already contributed to this ever-improving book: Ongi Englander, Ed Hodkin, Morteza Mahmoudi, Aaron S. Belsh, Eva Wu, Brett Pearson, John C. Bean, Darryl Wu, Lia Hankla, and Alec Hendricks.

That said, let us get started!

Authors

Ben Rogers is a writer and an engineer (BS 2001; MS 2002, University of Nevada, Reno). He has done research at Nanogen, the Oak Ridge National Laboratory, and NASA's Jet Propulsion Laboratory, and published many technical papers, as well as fictional works and essays (which can be found at <http://readrogers.com/>). He is currently the principal engineer at NevadaNano and lives in Reno with his wife and two daughters.

Jesse Adams (BS 1996, University of Nevada; MS 1997 and PhD 2001, Stanford University) is the vice president and CTO of NevadaNano. He is working to bring multifunctional microsensor technology to the chemical sensing market space.

Sumita Pennathur is an associate professor of mechanical engineering at the University of California, Santa Barbara (BS 2000, MS 2001, Massachusetts Institute of Technology; PhD 2005, Stanford University). She has been actively contributing to the fields of nanofluidics and nanoelectromechanical systems (NEMS), and has spent some time at both Sandia National Laboratories in Livermore, California, and the University of Twente MESA+ research facility in the Netherlands. When not enveloped in her research work, she can be found either spending time with her husband and two kids or at a local club wailing on her saxophone.

Also by these authors: *Nanotechnology: The Whole Story* (CRC Press, 2013), a general audience take on the best-selling, award-winning book, *Nanotechnology: Understanding Small Systems* (CRC Press, 2014).

Contents

Preface, xv

Acknowledgments, xvii

Authors, xix

CHAPTER 1 ■ Big Picture and Principles of the Small World	1
1.1 UNDERSTANDING THE ATOM: <i>EX NIHILO NIHIL FIT</i>	3
1.2 NANOTECHNOLOGY STARTS WITH A DARE: FEYNMAN'S BIG LITTLE CHALLENGES	9
1.3 WHY ONE-BILLIONTH OF A METER IS A BIG DEAL	15
1.4 THINKING IT THROUGH: THE BROAD IMPLICATIONS OF NANOTECHNOLOGY	16
1.4.1 Gray Goo	19
1.4.2 Environmental Impact: Risks to Ecosystems and Human Health	19
1.4.3 The Written Word	23
1.5 THE BUSINESS OF NANOTECH: PLENTY OF ROOM AT THE BOTTOM LINE TOO	24
1.5.1 Products	26
HOMEWORK EXERCISES	27
REFERENCES	29
RECOMMENDATIONS FOR FURTHER READING	30

CHAPTER 2 ■ Introduction to Miniaturization	31
2.1 BACKGROUND: THE SMALLER, THE BETTER	31
2.2 SCALING LAWS	32
2.2.1 The Elephant and the Flea	32
2.2.2 Scaling in Mechanics	35
2.2.3 Scaling in Electricity and Electromagnetism	38
2.2.4 Scaling in Optics	41

2.2.5	Scaling in Heat Transfer	43
2.2.6	Scaling in Fluids	45
2.2.7	Scaling in Biology	48
2.3	ACCURACY OF THE SCALING LAWS	49
	HOMEWORK EXERCISES	51
	RECOMMENDATIONS FOR FURTHER READING	55
CHAPTER 3 ■ Introduction to Nanoscale Physics		57
3.1	BACKGROUND: NEWTON NEVER SAW A NANOTUBE	57
3.2	ONE HUNDRED HOURS AND EIGHT MINUTES OF NANOSCALE PHYSICS	57
3.3	THE BASICS OF QUANTUM MECHANICS	58
3.3.1	Atomic Orbitals (Not Orbits)	59
3.3.2	EM Waves	62
3.3.2.1	<i>How EM Waves Are Made</i>	64
3.3.3	The Quantization of Energy	66
3.3.4	Atomic Spectra and Discreteness	67
3.3.5	The Photoelectric Effect	69
3.3.6	Wave–Particle Duality: The Double-Slit Experiment	73
3.3.6.1	<i>Bullets</i>	73
3.3.6.2	<i>Water Waves</i>	74
3.3.6.3	<i>Electrons</i>	75
3.3.7	The Uncertainty Principle	77
3.3.8	Particle in a Well	79
3.4	SUMMARY	83
	HOMEWORK EXERCISES	84
	REFERENCES	87
	RECOMMENDATIONS FOR FURTHER READING	87
CHAPTER 4 ■ Nanomaterials		89
4.1	BACKGROUND: MATTER MATTERS	89
4.2	BONDING ATOMS TO MAKE MOLECULES AND SOLIDS	89
4.2.1	Ionic Bonding	90
4.2.2	Covalent Bonding	93
4.2.3	Metallic Bonding	93
4.2.4	Walking through Waals: van der Waals Forces	94

4.2.4.1	<i>Dispersion Force</i>	95
4.2.4.2	<i>Repulsive Forces</i>	96
4.2.4.3	<i>van der Waals Force versus Gravity</i>	97
4.3	CRYSTAL STRUCTURES	100
4.4	STRUCTURES SMALL ENOUGH TO BE DIFFERENT (AND USEFUL)	102
4.4.1	Particles	103
4.4.1.1	<i>Colloidal Particles</i>	107
4.4.2	Wires	107
4.4.3	Films, Layers, and Coatings	109
4.4.4	Porous Materials	111
4.4.5	Small-Grained Materials	113
4.4.6	Molecules	116
4.4.6.1	<i>Carbon Fullerenes and Nanotubes</i>	117
4.4.6.2	<i>Dendrimers</i>	121
4.4.6.3	<i>Micelles</i>	123
4.5	SUMMARY	124
	HOMEWORK EXERCISES	124
	RECOMMENDATIONS FOR FURTHER READING	129
CHAPTER 5	■ Nanomechanics	131
5.1	BACKGROUND: THE UNIVERSE MECHANISM	131
5.1.1	Nanomechanics: Which Motions and Forces Make the Cut?	132
5.2	A HIGH-SPEED REVIEW OF MOTION: DISPLACEMENT, VELOCITY, ACCELERATION, AND FORCE	133
5.3	NANOMECHANICAL OSCILLATORS: A TALE OF BEAMS AND ATOMS	136
5.3.1	Beams	136
5.3.1.1	<i>Free Oscillation</i>	137
5.3.1.2	<i>Free Oscillation from the Perspective of Energy (and Probability)</i>	140
5.3.1.3	<i>Forced Oscillation</i>	142
5.3.2	Atoms	148
5.3.2.1	<i>Lennard-Jones Interaction: How an Atomic Bond Is Like a Spring</i>	148
5.3.2.2	<i>Quantum Mechanics of Oscillating Atoms</i>	152
5.3.2.3	<i>Schrödinger Equation and Correspondence Principle</i>	156

5.3.2.4	<i>Phonons</i>	161
5.3.3	Nanomechanical Oscillator Applications	163
5.3.3.1	<i>Nanomechanical Memory Elements</i>	164
5.3.3.2	<i>Nanomechanical Mass Sensors: Detecting Low Concentrations</i>	168
5.4	FEELING FAINT FORCES	172
5.4.1	Scanning Probe Microscopes	172
5.4.1.1	<i>Pushing Atoms around with the Scanning Tunneling Microscope</i>	172
5.4.1.2	<i>Skimming across Atoms with the Atomic Force Microscope</i>	175
5.4.1.3	<i>Pulling Atoms Apart with the AFM</i>	177
5.4.1.4	<i>Rubbing and Mashing Atoms with the AFM</i>	180
5.4.2	Mechanical Chemistry: Detecting Molecules with Bending Beams	183
5.5	SUMMARY	187
	HOMEWORK EXERCISES	187
	REFERENCE	192
	RECOMMENDATIONS FOR FURTHER READING	192
CHAPTER 6 ■ Nanoelectronics		193
6.1	BACKGROUND: THE PROBLEM (OPPORTUNITY)	193
6.2	ELECTRON ENERGY BANDS	193
6.3	ELECTRONS IN SOLIDS: CONDUCTORS, INSULATORS, AND SEMICONDUCTORS	196
6.4	FERMI ENERGY	199
6.5	DENSITY OF STATES FOR SOLIDS	201
6.5.1	Electron Density in a Conductor	203
6.6	TURN DOWN THE VOLUME! (HOW TO MAKE A SOLID ACT MORE LIKE AN ATOM)	204
6.7	QUANTUM CONFINEMENT	205
6.7.1	Quantum Structures	207
6.7.1.1	<i>Uses for Quantum Structures</i>	208
6.7.2	How Small Is Small Enough for Confinement?	209
6.7.2.1	<i>Conductors: The Metal-to-Insulator Transition</i>	211
6.7.2.2	<i>Semiconductors: Confining Excitons</i>	213
6.7.3	Band Gap of Nanomaterials	215

6.8	TUNNELING	216
6.8.1	Electrons Tunnel	216
6.9	SINGLE ELECTRON PHENOMENA	220
6.9.1	Two Rules for Keeping the Quantum in Quantum Dot	221
6.9.1.1	<i>Rule 1: The Coulomb Blockade</i>	221
6.9.1.2	<i>Rule 2: Overcoming Uncertainty</i>	224
6.9.2	Single-Electron Transistor	225
6.10	MOLECULAR ELECTRONICS	228
6.10.1	Molecular Switches and Memory Storage	230
6.11	SUMMARY	232
	HOMEWORK EXERCISES	232
	REFERENCE	236
	RECOMMENDATIONS FOR FURTHER READING	236
CHAPTER 7	■ Nanoscale Heat Transfer	237
7.1	BACKGROUND: HOT TOPIC	237
7.2	ALL HEAT IS NANOSCALE HEAT	237
7.2.1	Boltzmann's Constant	238
7.3	CONDUCTION	238
7.3.1	Thermal Conductivity of Nanoscale Structures	242
7.3.1.1	<i>Mean Free Path and Scattering of Heat Carriers</i>	242
7.3.1.2	<i>Thermoelectrics: Better Energy Conversion with Nanostructures</i>	245
7.3.1.3	<i>Quantum of Thermal Conduction</i>	247
7.4	CONVECTION	248
7.5	RADIATION	249
7.5.1	Increased Radiation Heat Transfer: Mind the Gap!	250
7.6	SUMMARY	252
	HOMEWORK EXERCISES	253
	RECOMMENDATIONS FOR FURTHER READING	254
CHAPTER 8	■ Nanophotonics	255
8.1	BACKGROUND: THE LYCURGUS CUP AND THE BIRTH OF THE PHOTON	255
8.2	PHOTONIC PROPERTIES OF NANOMATERIALS	256
8.2.1	Photon Absorption	256
8.2.2	Photon Emission	257

8.2.3	Photon Scattering	258
8.2.4	Metals	259
8.2.4.1	<i>Permittivity and the Free Electron Plasma</i>	260
8.2.4.2	<i>The Extinction Coefficient of Metal Particles</i>	262
8.2.4.3	<i>Colors and Uses of Gold and Silver Particles</i>	265
8.2.5	Semiconductors	266
8.2.5.1	<i>Tuning the Band Gap of Nanoscale Semiconductors</i>	266
8.2.5.2	<i>The Colors and Uses of Quantum Dots</i>	268
8.2.5.3	<i>Lasers Based on Quantum Confinement</i>	269
8.3	NEAR-FIELD LIGHT	272
8.3.1	The Limits of Light: Conventional Optics	272
8.3.2	Near-Field Optical Microscopes	274
8.4	OPTICAL TWEEZERS	277
8.5	PHOTONIC CRYSTALS: A BAND GAP FOR PHOTONS	277
8.6	SUMMARY	278
	HOMEWORK EXCERCISE	279
	RECOMMENDATIONS FOR FURTHER READING	282
CHAPTER 9 ■ Nanoscale Fluid Mechanics		283
9.1	BACKGROUND: BECOMING FLUENT IN FLUIDS	283
9.1.1	Treating a Fluid the Way It Should Be Treated: The Concept of a Continuum	283
9.1.1.1	<i>Fluid Motion, Continuum Style: The Navier–Stokes Equations</i>	284
9.1.1.2	<i>Fluid Motion: Molecular Dynamics Style</i>	290
9.2	FLUIDS AT THE NANOSCALE: MAJOR CONCEPTS	292
9.2.1	Swimming in Molasses: Life at Low Reynolds Numbers	292
9.2.1.1	<i>Reynolds Number</i>	292
9.2.2	Surface Charges and the Electrical Double Layer	294
9.2.2.1	<i>Surface Charges at Interfaces</i>	295
9.2.2.2	<i>Gouy–Chapman–Stern Model and Electrical Double Layer</i>	296
9.2.2.3	<i>Electrokinetic Phenomena</i>	299
9.2.3	Small Particles in Small Flows: Molecular Diffusion	301
9.3	HOW FLUIDS FLOW AT THE NANOSCALE	304
9.3.1	Pressure-Driven Flow	305