Nanotechnology

A Crash Course

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Tutorial Texts in Optical Engineering
Volume TT86

SPIE PRESS
Bellingham, Washington USA

Library of Congress Cataloging-in-Publication Data

Martín-Palma, Raúl J.
Nanotechnology : a crash course / Raúl J. Martín-Palma and Akhlesh Lakhtakia.
p. cm. – (Tutorial texts in optical engineering ; v. TT 86)
Includes bibliographical references and index.
ISBN 978-0-8194-8075-0
1. Nanotechnology. I. Lakhtakia, A. (Akhlesh), 1957- II. Title.
T174.7.M358 2010
620'.5–dc22

2010009455

Published by

SPIE
P.O. Box 10
Bellingham, Washington 98227-0010 USA
Phone: +1 360.676.3290
Fax: +1 360.647.1445
Email: Books@spie.org
Web: http://spie.org

Printed in the United States of America.

DEDICATION

To such wonderful megawords in the English language as

antidisestablishmentarianism
honorificabilitudinitatibus
nanobioinfocognotechnology
pneumonoultramicroscopicsilicovolcanoconiosis
and
supercalifragilisticexpialidocious

Introduction to the Series

Since its inception in 1989, the Tutorial Texts (TT) series has grown to more than 85 titles covering many diverse fields of science and engineering. The initial idea for the series was to make material presented in SPIE short courses available to those who could not attend and to provide a reference text for those who could. Thus, many of the texts in this series are generated by augmenting course notes with descriptive text that further illuminates the subject. In this way, the TT becomes an excellent stand-alone reference that finds a much wider audience than only short course attendees.

Tutorial Texts have grown in popularity and in the scope of material covered since 1989. They no longer necessarily stem from short courses; rather, they are often generated independently by experts in the field. They are popular because they provide a ready reference to those wishing to learn about emerging technologies or the latest information within their field. The topics within the series have grown from the initial areas of geometrical optics, optical detectors, and image processing to include the emerging fields of nanotechnology, biomedical optics, fiber optics, and laser technologies. Authors contributing to the TT series are instructed to provide introductory material so that those new to the field may use the book as a starting point to get a basic grasp of the material. It is hoped that some readers may develop sufficient interest to take a short course by the author or pursue further research in more advanced books to delve deeper into the subject.

The books in this series are distinguished from other technical monographs and textbooks in the way in which the material is presented. In keeping with the tutorial nature of the series, there is an emphasis on the use of graphical and illustrative material to better elucidate basic and advanced concepts. There is also heavy use of tabular reference data and numerous examples to further explain the concepts presented. The publishing time for the books is kept to a minimum so that the books will be as timely and up-to-date as possible. Furthermore, these introductory books are competitively priced compared to more traditional books on the same subject.

When a proposal for a text is received, each proposal is evaluated to determine the relevance of the proposed topic. This initial reviewing process has been very helpful to authors in identifying, early in the writing process, the need for additional material or other changes in approach that would serve to strengthen the text. Once a manuscript is completed, it is peer reviewed to ensure that chapters communicate accurately the essential ingredients of the science and technologies under discussion.

It is my goal to maintain the style and quality of books in the series and to further expand the topic areas to include new emerging fields as they become of interest to our reading audience.

James A. Harrington
Rutgers University

Contents

To the Reader

Suppose that you recently graduated with a B.S. degree in science or engineering and will commence your first professional employment tomorrow. Earlier this afternoon, your manager called to ask if you know something about nanotechnology, so that tomorrow you can begin developing an internal proposal for your division. But either your college did not offer a course on nanotechnology or you decided not to take one. You need a crash course in nanotechnology, just to get you off the ground.

Suppose that you are a doctoral student in a department whose candidacy examination requires you to write a 5–10-page research proposal on an emerging topic assigned by the faculty committee. Suppose that your assigned topic intersects with nanotechnology, but all that you know about nanotechnology came from a couple of hour-long graduate seminars that you attended the previous semester. You need a crash course in nanotechnology, not only to write an impressive introduction but also to acquaint yourself with terminology to conduct efficient searches on Google Scholar, Web of Science, Scopus, etc.

Suppose that you are a post-doctoral researcher at either an academic or an industrial research institution. Your supervisor has asked you to advise a shining undergraduate student for a summer project in nanotechnology, although the focus of your own research is elsewhere. You need a crash course in nanotechnology, to start the student off in a promising direction.

Suppose that you are a new assistant professor. Your departmental head advises that your research proposal to a government program to assist new faculty members in beginning research programs lacks that "wow" factor that would virtually guarantee success. "Put in a nano angle," you are told. You need a crash course in nanotechnology, to clothe your proposal in the glory of "nano."

Suppose that you are a middle-aged professor undergoing a midlife crisis. Instead of changing your family or lifestyle, you may choose to change your research focus to an emerging research area. You need a crash course in nanotechnology, to assess your current resources and future needs.

With your particular need in mind, we persuaded SPIE Press to publish our short and readable introduction to nanotechnology. While *Nanotechnology: A Crash Course* is unlikely to convert you overnight into a nanostar, it would meet your immediate need and very likely help you steer your professional life in a new direction.

Suppose that you simply have some time on your hands and wish to enrich your mind. But your financial health does not permit you to travel to a remote part of our planet or to buy an audio or video course on an ancient civilization. You, too, may like to read *Nanotechnology: A Crash Course*. Borrow it from a public library, buy yourself a hard copy, or purchase it as an eBook from the SPIE Digital Library.

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Acknowledgments

Nanotechnology encompasses so many traditional disciplines that numerous mentors, colleagues, and students are indirectly responsible for our selection and treatment of topics in *Nanotechnology: A Crash Course.* To all of these ladies and gentlemen: Thank you.

We were successful in persuading a few technoscientists to read early versions of this book and provide us feedback. The first two among them are Russell Messier (The Pennsylvania State University), whose knowledge and understanding of thin-film morphology is legendary, and Carlo Pantano (The Pennsylvania State University), who has his finger on the pulse of materials research. Next come Fei Wang (Micron Technologies, Inc.) and Ginés Lifante (Universidad Autónoma de Madrid), both of whom have surveyed nanotechnology for various projects. Finally, we thank Muhammad Faryad (The Pennsylvania State University) for providing us the perspective of a graduate student. Unhappy readers are requested to lob rotten eggs and tomatoes at us, but not at these fine gentlemen whose only fault is that they allowed us to befriend them.

Two reviewers, both unknown to us, kindly went through a draft. We were able to incorporate most of their invaluable suggestions, but noted the remainder for another book that we may write—not for another 10 years, however.

We thank Leah Budin for redrawing several figures for this book. At SPIE Press, Tim Lamkins encouraged us to write this book, Beth Kelley assisted in obtaining the permissions for reprinted figures, and Dara Burrows shepherded its publication, including going through the manuscript with a fine-tooth comb. We acknowledge our debt of gratitude to all three of them.

Nomenclature

A	cross-sectional area of a conducting strip
a_{cc}	carbon–carbon bond length for graphene
A_n	coefficients of expansion
$\vec{a}_1, \vec{a}_2$	basis vectors of graphene lattice
B_0	magnitude of applied magnetic field
(B_x, B_y, B_z)	Cartesian components of the magnetic field
c	speed of light in vacuum
C	capacitance
$\vec{c}$	chiral (or wrapping) vector of a carbon nanotube
d	average grain diameter
e	charge of an electron (= 1.602×10^{-19} C)
E	energy
E_F	Fermi energy level
E_g	energy across a bandgap
E_M	energy levels
E_n	eigenenergy
E_{ex}	binding energy of an exciton
E_{exc}	exciting electric field
$(E_{n_x}, E_{n_y}, E_{n_z})$	eigenenergies of quantum wells, wires, and dots
(E_x, E_y, E_z)	Cartesian components of the electric field
G	electrical conductance
g_0	thermal conductance quantum
G_0	conductance quantum
h	Planck constant (= 6.626×10^{-34} J s)
$\hbar$	reduced Planck constant (= $h/2\pi$)
$H(\vec{r}, t)$	Hamiltonian
i	$\sqrt{(-1)}$
I	electric current (Chapter 3)
I	nuclear spin (Chapter 5)
k	wave number
$\vec{k}$	wave vector
k_B	Boltzmann constant
K_{HP}	constant in Hall–Petch relation
k_x	particle momentum along the x axis

l	length of a conducting strip
(L_x, L_y, L_z)	dimensions of a reduced-dimensionality structure along the x, y, and z axes
m	mass
m^*	effective mass
m_0	rest mass of an electron (= 9.109×10^{-31} kg)
n	quantum number
N	number of electrons
N_c	number of channels available for transport
(n, m)	dual index to specify the structure of a carbon nanotube shell
(n_x, n_y, n_z)	principal quantum numbers
P	polarization
R_K	von Klitzing constant (= 25812.8 Ω)
R_0	resistance quantum
R_{mn}	cross-sectional radius of a carbon nanotube
$\vec{r} = (x, y, z)$	position vector
t	time
T	temperature
$\mathbf{U}$	single-electron charging energy
V	potential
w	width of a conducting strip
Z	acoustic impedance
α	fine structure constant
γ	gyromagnetic ratio
γ_0	carbon–carbon interaction energy
ε_0	permittivity of vacuum (= 8.854×10^{-12} F m^{-1})
λ	free-space wavelength
λ_{DB}	de Broglie wavelength
λ_e	mean free path of electron
λ_F	Fermi wavelength
μ_B	Bohr magneton
ρ_s	surface charge density
ρ_{xx}	longitudinal resistivity
ρ_{xy}	Hall resistivity
σ	electric conductivity
σ_{xy}	Hall conductivity
σ_0	frictional stress
σ_y	yield strength
τ	relaxation time
ψ	wavefunction
$(\psi_{n_x}, \psi_{n_y}, \psi_{n_z})$	eigenfunctions in quantum wells, wires, and dots
ω	angular frequency
ω_p	plasma frequency
ω_{lspr}	local-surface-plasmon-resonance frequency