## Nanostructure Science and Technology

Series Editor: David J. Lockwood, FRSC National Research Council of Canada Ottawa, Ontario, Canada

More information about this series at http://www.springer.com/series/6331

Anatoli Korkin • Stephen Goodnick Robert Nemanich Editors

# Nanoscale Materials and Devices for Electronics, Photonics and Solar Energy



*Editors* Anatoli Korkin Nano and Giga Solutions, Inc. Gilbert, AZ, USA

Robert Nemanich Department of Physics Arizona State University Tempe, AZ, USA Stephen Goodnick Engineering Research Center Arizona State University Tempe, AZ, USA

ISSN 1571-5744 ISSN 2197-7976 (electronic) Nanostructure Science and Technology ISBN 978-3-319-18632-0 ISBN 978-3-319-18633-7 (eBook) DOI 10.1007/978-3-319-18633-7

Library of Congress Control Number: 2015945943

Springer Cham Heidelberg New York Dordrecht London © Springer International Publishing Switzerland 2015

This work is subject to copyright. All rights are reserved by the Publisher, whether the whole or part of the material is concerned, specifically the rights of translation, reprinting, reuse of illustrations, recitation, broadcasting, reproduction on microfilms or in any other physical way, and transmission or information storage and retrieval, electronic adaptation, computer software, or by similar or dissimilar methodology now known or hereafter developed.

The use of general descriptive names, registered names, trademarks, service marks, etc. in this publication does not imply, even in the absence of a specific statement, that such names are exempt from the relevant protective laws and regulations and therefore free for general use.

The publisher, the authors and the editors are safe to assume that the advice and information in this book are believed to be true and accurate at the date of publication. Neither the publisher nor the authors or the editors give a warranty, express or implied, with respect to the material contained herein or for any errors or omissions that may have been made.

Printed on acid-free paper

Springer International Publishing AG Switzerland is part of Springer Science+Business Media (www.springer.com)

### Preface

The Nano and Giga Challenges (NGC) conference series has had a long tradition of tutorial lectures given by world-renowned researchers. As early as the first forum in Moscow, Russia, in 2002, the organizers realized that publication of the lectures notes from NGC2002 would be a valuable legacy of the meeting and a significant educational resource and knowledge base for students, young researchers, and experts alike. Our first book was published by *Elsevier* and named after the meeting itself—*Nano and Giga Challenges in Microelectronics* [1]. Our subsequent books based on the tutorial lectures of the NGCM2004 [2], NGC2007 [3], NGC2009 [4], NGC2011 [5], and the current book derived from the NGC2014 conference have been published by Springer in the *Nanostructure Science and Technology* series.

Energy and information are essential elements for the development of human society, which are interconnected. Processing and storage of information requires energy consumption, while the efficient use and access to new energy sources requires new information (ideas and expertise) and the design of novel systems such as photovoltaic devices, fuel cells, and batteries. Semiconductor physics creates the knowledge base for the development of information (computers, cell phones, etc.) and energy (photovoltaics) technologies. The exchange of ideas and expertise between these two technologies is critical and expands beyond semiconductors. Efficient use of solar energy requires development of novel energy storage devices while biosystems provide new paradigms for the development of materials and devices for information (processing and storage) and energy (e.g., biofuel and artificial photosynthesis) technologies and biomedical applications (sensors and diagnostics).

Progress in information and renewable energy technologies requires miniaturization of devices and reduction of costs, energy, and material consumption. The latest generation of electronic devices is now approaching nanometer scale dimensions; new materials are being introduced into electronics manufacturing at an unprecedented rate; and alternative technologies to mainstream CMOS are evolving. The low cost of natural energy sources has created economic barriers to the development of alternative and more efficient solar energy systems, fuel cells, and batteries. However, there is emergent understanding that the sustainable development of human society requires use of new alternate sources of energy to natural gas and oil.

Nanotechnology is widely accepted as a source of potential solutions in securing future progress for information and energy technologies. Our conference series is an interdisciplinary forum in education, research, and innovations in the development of new materials, devices, and systems for these key technologies. The NGC2014 conference (the sixth Nano and Giga Forum) invited academic and industrial researchers to present tutorial and original research papers dedicated to solving scientific and technological problems in the following areas of electronics, photonics, and renewable energy: atomic scale materials design, bio- and molecular electronics, high frequency electronics, fabrication of nanodevices, magnetic materials and spintronics, materials and processes for integrated and subwave optoelectronics, nanoCMOS, new materials for FETs and other devices, nanoelectronics system architecture, nano-optics and lasers, non-silicon materials and devices, chemical and biosensors, quantum effects in devices, nanoscience and technology applications in the development of novel solar energy devices, and fuel cells and batteries. We also invited inventors, entrepreneurs, and business leaders to explore the unique opportunity provided by our interdisciplinary forum for technical due diligence and potential commercialization of emerging new technologies.

The success of the NGC2014 conference [6], which resulted in the publication of this book, would have not been possible without generous support from many sponsors and research institutions. We gratefully acknowledge contributions and support of Arizona State University (host of the conference), Springer Publisher, National Institute of Health (NIH), and many other local, national, and international organizations and individual supporters.

Gilbert, AZ, USA	Anatoli Korkin
Tempe, AZ, USA	Stephen Goodnick
Tempe, AZ, USA	Robert Nemanich

#### References

- 1. Nano and Giga Challenges in Microelectronics, ed. by J. Greer, A. Korkin, J. Labanowski (Elsevier, Amsterdam, Netherlands, 2003)
- 2. Nanotechnology for Electronic Materials and Devices, ed. by A. Korkin, E. Gusev, J. Labanowski, S. Luryi (Springer, New York, 2007)
- 3. Nanoelectronics and Photonics: From Atoms to Materials, Devices, and Architectures, ed. by A. Korkin, F. Rosei (Springer, New York, 2008)
- 4. Nanotechnology for Electronics, Photonics, and Renewable Energy, ed. by A. Korkin, P. Krstic, J. Wells (Springer, New York, 2010)

- 5. Nanoscale Applications for Information and Energy Systems, ed. by A. Korkin, D.J. Lockwood (Springer, New York, 2013)
- Nano and Giga Challenges in Electronics, Photonics and Renewable Energy: From Materials to Devices to System Architecture, Symposium and Spring School (Tutorial Lectures), Phoenix, Arizona, 10–14 March 2014; http://www.nanoandgiga.com/ngc2014

# Contents

1	<b>Ultralow-Power Device Operation</b>	1
2	Ultralow-Power Pseudospintronic Devices via Exciton Condensation in Coupled Two-Dimensional Material Systems Xuehao Mou, Leonard Franklin Register, and Sanjay Kumar Banerjee	31
3	<b>Graphene-Based Photonics and Plasmonics</b>	93
4	Materials Challenges for Concentrating Solar Power Dominic F. Gervasio, Hassan Elsentriecy, Luis Phillipi da Silva, A.M. Kannan, Xinhai Xu, and K. Vignarooban	127
5	Atomistic Simulations of Electronic and Optical Properties of Semiconductor Nanostructures	149
6	What Happens When Molecules Meet Nanostructures:The Convergence of Chemistry and Electronicsat the NanoscaleStuart Lindsay	217
7	<b>Terahertz Wave Generation Using Graphene</b> <b>and Compound Semiconductor Nano-Heterostructures</b> Taiichi Otsuji, Victor Ryzhii, Stephane Boubanga Tombet, Akira Satou, Maxim Ryzhii, Vyacheslav V. Popov, Wojciech Knap, Vladimir Mitin, and Michael Shur	237

8	Optics of Hybrid Nanomaterials in the Strong		
	Coupling Regime	263	
	Adam Blake and Maxim Sukharev		
In	dex	275	

## Contributors

Francis Balestra IMEP-LAHC, Grenoble INP-Minatec, Grenoble, France

Sanjay Kumar Banerjee University of Texas at Austin, Austin, TX, USA

**Oleg L. Berman** Physics Department, New York City College of Technology, The City University of New York, Brooklyn, NY 11201, USA

Adam Blake Department of Physics, Arizona State University, Tempe AZ 85281, USA

**Hassan Elsentriecy** Department of Chemical and Environmental Engineering, University of Arizona, Tucson, AZ 85281, USA

**Dominic F. Gervasio** Department of Chemical and Environmental Engineering, University of Arizona, Tucson, AZ 85281, USA

**A.M. Kannan** Fulton School of Engineering, Arizona State University, Mesa, AZ, USA

Roman Ya. Kezerashvili Physics Department, New York City College of Technology, The City University of New York, Brooklyn, NY 11201, USA

**Wojciech Knap** LC2-Laboratory, CNRS-Universite Montpellier 2, Montpellier, France

**Marek Korkusinski** Quantum Theory Group, Security and Disruptive Technologies, National Research Council, Ottawa, ON, Canada

**Stuart Lindsay** Department of Physics, Biodesign Institute, Arizona State University, Tempe, AZ 85287, USA

Department of Chemistry and Biochemistry, Biodesign Institute, Arizona State University, Tempe, AZ 85287, USA

**Yurii E. Lozovik** Institute of Spectroscopy, Russian Academy of Sciences, 142190 Troitsk, Moscow Region, Russia

MIEM at National Research University HSE, 109028 Moscow, Russia

Vladimir Mitin Department of EE, University at Buffalo, SUNY, Buffalo, NY, USA

Xuehao Mou University of Texas at Austin, Austin, TX, USA

Taiichi Otsuji RIEC, Tohoku University, Sendai, Japan

**Vyacheslav V. Popov** Kotelnikov Institute of Radio Engineering and Electronics, Saratov, Russia

Leonard Franklin Register University of Texas at Austin, Austin, TX, USA

Maxim Ryzhii Department of CSC, University of Aizu, Aizu-Wakamatsu, Japan

Victor Ryzhii RIEC, Tohoku University, Sendai, Japan

Akira Satou RIEC, Tohoku University, Sendai, Japan

**Michael Shur** Department of ECSC, Rensselaer Polytechnic Institute, Troy, MI, USA

Luis Phillipi da Silva Department of Chemical and Environmental Engineering, University of Arizona, Tucson, AZ 85281, USA

Maxim Sukharev Science and Mathematics Faculty, College of Letters and Sciences, Arizona State University, Mesa AZ 85212, USA

Stephane Boubanga Tombet RIEC, Tohoku University, Sendai, Japan

**K. Vignarooban** Fulton School of Engineering, Arizona State University, Mesa, AZ, USA

**Xinhai Xu** Department of Chemical and Environmental Engineering, University of Arizona, Tucson, AZ 85281, USA