

Fundamentals of Low-Dimensional Carbon Nanomaterials

**MATERIALS RESEARCH SOCIETY
SYMPOSIUM PROCEEDINGS VOLUME 1284**

Fundamentals of Low-Dimensional Carbon Nanomaterials

Symposium held November 29–December 3, Boston, Massachusetts, U.S.A.

EDITORS

John J. Boeckl

Air Force Research Laboratory
Wright-Patterson AFB, Ohio, U.S.A.

Mark Rummeli

Leibniz Institute, IFW Dresden
Dresden, Germany

Weijie Lu

Fisk University
Nashville, Tennessee, U.S.A.

Jamie Warner

University of Oxford
Oxford, United Kingdom



Materials Research Society
Warrendale, Pennsylvania



CAMBRIDGE UNIVERSITY PRESS

Cambridge, New York, Melbourne, Madrid, Cape Town,
Singapore, São Paulo, Delhi, Tokyo, Mexico City

Cambridge University Press
32 Avenue of the Americas, New York, NY 10013-2473, USA

www.cambridge.org
Information on this title: www.cambridge.org/9781605112619

Materials Research Society
506 Keystone Drive, Warrendale, PA 15086, USA
<http://www.mrs.org>

© Materials Research Society 2011

This publication is in copyright. Subject to statutory exception
and to the provisions of relevant collective licensing agreements,
no reproduction of any part may take place without the written
permission of Cambridge University Press.

This book has been registered with Copyright Clearance Center, Inc.
For further information please contact the Copyright Clearance Center,
Salem, Massachusetts, USA

First published 2011

Printed in the United States of America

This work was supported in part by the
AFOSR/AOARD (Air Force Office of Scientific
Research/Asian Office of Aerospace Research and
Development). AFOSR/AOARD support is not intended
to express or imply endorsement by the U.S. federal government.

Single article reprints from this publication are available through
University Microfilms Inc., 300 North Zeeb Road, Ann Arbor, MI 48106

CODEN: MRSPDH

ISBN: 978-1-605-11261-9 Hardback

Cambridge University Press has no responsibility for the persistence or
accuracy of URLs for external or third-party Internet Web sites referred to
in this publication and does not guarantee that any content on such Web sites
is, or will remain, accurate or appropriate.

CONTENTS

Preface xi

Materials Research Society Symposium Proceedings xiii

GROWTH OF GRAPHENE/SUBSTRATE STRUCTURES

* Graphene Growth on SiC and Other Substrates Using Carbon Sources. 3

W.C. Mitchel, J.H. Park, Howard E. Smith,
L. Grazulis, S. Mou, D. Tomich, K. Eyink,
and Said Elhamri

CVD Growth of Graphene on Three Types of Epitaxial
Metal Films on Sapphire Substrate 11

Katsuya Nozawa, Nozomu Matsukawa,
Kenji Toyoda, and Shigeo Yoshii

LOW-DIMENSIONAL GRAPHITIZATION AND STRUCTURAL TRANSFORMATIONS

Low Temperature CVD Growth of Graphene Nano-Flakes
Directly on High K Dielectrics 19

Mark H. Rummeli, Alicja Bachmatiuk,
Arezoo Dianat, Andrew Scott, Felix Börrnert,
Imad Ibrahim, Shasha Zhang, Ewa Borowiak-Palen,
Gianaurelio Cuniberti, and Bernd Büchner

On the Carbo-Thermal Reduction of Silica for Carbon
Nano-Fibre Formation via CVD. 25

Alicja Bachmatiuk, Felix Börrnert,
Imad Ibrahim, Bernd Büchner,
and Mark H. Rummeli

A Fully Atomistic Reactive Molecular Dynamics Study
on the Formation of Graphane from Graphene
Hydrogenated Membranes 31

Pedro A.S. Autreto, Marcelo Z. Flores,
Sergio B. Legoas, Ricardo P.B. Santos,
and Douglas S. Galvao

*Invited Paper

**POSTER SESSION: MECHANISM, GROWTH, AND PROCESSES
OF LOW-DIMENSIONAL CARBON NANOSTRUCTURES**

**Metal-Catalyzed Graphitization in Ni-C Alloys
and Amorphous-C/Ni Bilayers** .39
Katherine L. Saenger, Christian Lavoie,
Roy Carruthers, Ageeth A. Bol, Timothy J. McArdle,
Jack O. Chu, James C. Tsang, and Alfred Grill

**Hole or Electron Doped C₆₀ Polymer Using Free
Electron Laser Irradiation** .45
Nobuyuki Iwata, Daiki Koide, Syouta Katou,
Eri Ikeda, and Hiroshi Yamamoto

**Comparison of Epitaxial Graphene on Si-Face
and C-Face 6H-SiC** .51
Shin Mou, J.J. Boeckl, L. Grazulis, B. Claffin,
Weijie Lu, J.H. Park, and W.C. Mitchel

***CNTs GROWTH, EXPLORING NOVEL CNT GROWTH TECHNIQUES
AND GROWTH MECHANISMS I***

**Growth of Diameter-Modulated Single-Walled Carbon
Nanotubes through Instant Temperature Modulation
in Laser-Assisted Chemical Vapor Deposition** .61
M. Mahjouri-Samani, Y.S. Zhou, W. Xiong,
Y. Gao, M. Mitchell, and Y.F. Lu

A CMOS Compatible Carbon Nanotube Growth Approach69
Daire Cott, Masahito Sugiura,
Nicolo Chiodarelli, Kai Arstila,
Philippe M. Vereecken, Bart Vereecke,
Sven Van Elshocht, and Stefan De Gendt

***CNTs GROWTH, EXPLORING NOVEL CNT GROWTH TECHNIQUES
AND GROWTH MECHANISMS II***

**On the Formation of Carbon Nanotube Serpentes:
Insights from Multi-Million Atom Molecular
Dynamics Simulation** .79
Leonardo D. Machado, Sergio B. Legoas,
Jaqueline S. Soares, Nitzan Shadmi, Ado Jorio,
Ernesto Joselevich, and Douglas S. Galvao

*ELECTRONIC, OPTICAL, AND MAGNETIC PROPERTIES
OF CARBON NANOMATERIALS I*

- Graphene for Magnetoresistive Junctions**87
J. Inoue, T. Hiraiwa, R. Sato, A. Yamamura,
S. Honda, and H. Itoh
- Room Temperature Superparamagnetism Observed
in Foam-like Carbon Nanomaterials**93
Shunji Bandow, Hirohito Asano,
Susumu Muraki, Takahiro Mizuno,
Makoto Jinno, and Sumio Iijima

STRUCTURAL CHARACTERIZATION

- In-situ* Observations of Restructuring Carbon Nanotubes
via Low-Voltage Aberration-Corrected Transmission
Electron Microscopy**101
Felix Börrnert, Alicja Bachmatiuk,
Sandeep Gorantla, Jamie H. Warner,
Bernd Büchner, and Mark H. Rummeli

OPTICAL PROBES

- A Fully Automated Remote Controllable Microwave-Based
Synthesis Setup for Colloidal Nanoparticles with Integrated
Absorption and Photoluminescence Online Analytics**109
Simon Einwächter and Michael Krüger

*ELECTRONIC, OPTICAL, AND MAGNETIC PROPERTIES
OF CARBON NANOMATERIALS II*

- Band Gap Opening of Graphene after UV/Ozone
and Oxygen Plasma Treatments**117
Adrianus I. Aria, Adi W. Gani,
and Morteza Gharib

**POSTER SESSION: CHARACTERIZATIONS AND PROPERTIES
OF LOW-DIMENSIONAL NANOCARBON STRUCTURES**

**Thermal, Chemical and Radiation Treatment Influence
on Hydrogen Adsorption Capability in Single Wall
Carbon Nanotubes**125
Michail Obolensky, Andrew Kravchenko,
Vladimir Beletsky, Yuri Petrusenko,
Valeriy Borysenko, Sergey Lavrynenko,
Andrew Basteev, and Leonid Bazyma

Electrogenerated Chemiluminescence from Carbon Dots131
L. Sun, T.-H. Teng, Md. H. Rashid,
M. Krysmann, P. Dallas, Y. Wang,
B.-R. Hyun, A.C. Bartnik, G.G. Malliaras,
F.W. Wise, and E.P. Giannelis

**Far Infrared Characterization of Single and Double
Walled Carbon Nanotubes**137
S.G. Chou, Z. Ahmed, G.G. Samsonidze,
J. Kong, M.S. Dresselhaus, and D.F. Plusquellic

**Curvature-Induced Symmetry Lowering
and Anomalous Dispersion of Phonons in Single-Walled
Carbon Nanotubes**143
Jason Reppert, Ramakrishna Podila,
Nan Li, Codruta Z. Loebick,
Steven J. Stuart, Lisa D. Pfefferle,
and Apparao M. Rao

**Properties Modeling of Low-Dimensional Carbon
Nanostructures**149
Andrew Basteev, Leonid Bazyma,
Mykhaylo Ugryumov, Yuriy Chernishov,
and Margarita Slepicheva

DOPING, DEFECTS AND SURFACE CHEMISTRY

**Effect of Sidewall Fluorination on the Mechanical
Properties of Catalytically Grown Multi-Wall
Carbon Nanotubes**157
Yogeeswaran Ganesan, Cheng Peng, Lijie Ci,
Valery Khabashesku, Pulickel M. Ajayan,
and Jun Lou

***NOVEL STRUCTURES AND PROPERTIES OF LOW DIMENSIONAL
CARBON NANOSTRUCTURES***

Nonlinear Mechanical Properties of Graphene Nanoribbons165
Qiang Lu and Rui Huang	
Dynamics of Graphene Nanodrums173
Gustavo Brunetto, Sergio B. Legoas, Vitor R. Coluci, Liacir S. Lucena, and Douglas S. Galvao	
A Novel Method for Sorting Single Wall Carbon Nanotubes by Length179
Shigekazu Ohmori, Takeshi Saito, Bikau Shukla, Motoo Yumura, and Sumio Iijima	
Author Index185
Subject Index187

PREFACE

Symposium C, “Fundamentals of Low-Dimensional Carbon Nanomaterials,” was held Nov. 29–Dec. 3 at the 2010 MRS Fall Meeting in Boston, Massachusetts. This resultant proceedings volume comprises 27 manuscripts with topics including growth techniques for CNTs and graphene, structural characterization, novel properties, and interface & surface structures. This was the first symposium at the MRS meeting which was devoted solely to fundamental issues of low-dimensional carbon nanomaterials. Device applications of carbon nanostructures were excluded from this symposium.

Low-dimensional carbon nanostructures exhibit a rich structural diversity from zero-dimensional C60, one-dimensional carbon nanotubes (CNTs), and two-dimensional graphene and graphite oxides. These low-dimensional carbon nanostructures are at the forefront of materials science and provide a platform for understanding the growth mechanisms and properties of nanostructures in general. They exhibit novel properties with endless potential applications from high-speed electronics to high-performance composites.

Although low-dimensional carbon nanomaterials have attracted great interest in the research community, the applications and commercialization of graphene and CNTs have, to date, not been as successful as anticipated. The need for significant improvements in material quality and structural uniformity exists. Other areas that need further understanding include the atomic scale growth mechanisms, structural control of various graphitic nanostructures, the chemistry of graphitic hexagonal structures, and graphitization engineering in low dimensions. Without comprehending the basic growth mechanisms and techniques to control atomic structure, the promise of future applications will be difficult to achieve.

The editors would like to thank the authors of the manuscripts. MRS meetings have become one of the most important forums for carbon nanomaterials. The challenges in fundamental issues of low-dimensional carbon nanomaterials have a great impact not only on carbon material science but also on the general fields of nanoscience and nanoengineering. This volume is a useful resource to share interests within this broad research community.

John J. Boeckl
Mark Rummeli
Weijie Lu
Jamie Warner

February 2011

MATERIALS RESEARCH SOCIETY SYMPOSIUM PROCEEDINGS

- Volume 1275— Structural and Chemical Characterization of Metals, Alloys and Compounds, R. Pérez Campos, A. Contreras Cuevas, R.A. Esparza Muñoz, 2011, ISBN 978-1-60511-252-7
- Volume 1276— Advanced Structural Materials—2010, H.A. Calderon, A. Salinas Rodriguez, H. Balmori-Ramirez, 2010, ISBN 978-1-60511-253-4
- Volume 1277E—Biomaterials—2010, S.E. Rodil, A. Almaguer-Flores, K. Anselme, 2010, ISBN 978-1-60511-254-1
- Volume 1278E—Composite, Hybrid Materials and Ecomaterials, R. Bernal, C. Cruz Vazquez, L.E. Rendon Diaz Miron, V.M. Castaño, 2010, ISBN 978-1-60511-255-8
- Volume 1279— New Catalytic Materials, J.A. Wang, J. Manuel Dominguez, 2010, ISBN 978-1-60511-256-5
- Volume 1280E—Nanomaterials for Biomedical Applications, L. Zhang, T.J. Webster, A. Salinas Rodriguez, 2010, ISBN 978-1-60511-257-2
- Volume 1282— Diamond Electronics and Bioelectronics—Fundamentals to Applications IV, P. Bergonzo, J.E. Butler, C.E. Nebel, M. Nesladek, A.T.S. Wee, 2011, ISBN 978-1-60511-259-6
- Volume 1283E—Carbon-Based Electronic Devices—Processing, Performance and Reliability, M. Chhowalla, R.R. Keller, M. Meyyappan, W.J. Ready, 2011, ISBN 978-1-60511-260-2
- Volume 1284— Fundamentals of Low-Dimensional Carbon Nanomaterials, J.J. Boeckl, L. Dai, W. Lu, M.H. Rummeli, J. Warner, 2011, ISBN 978-1-60511-261-9
- Volume 1285E—Challenges in Roll-to-Roll (R2R) Fabrication for Electronics and Other Functionalities, T. Blaudeck, G. Cho, J.H. Daniel, M.R. Dokmeci, 2011, ISBN 978-1-60511-262-6
- Volume 1286E—Molecular and Hybrid Materials for Electronics and Photonics, J. Liu, 2011, ISBN 978-1-60511-263-3
- Volume 1287E—Low-Temperature-Processed Thin-Film Transistors, E. Fortunato, 2011, ISBN 978-1-60511-264-0
- Volume 1288E—Novel Fabrication Methods for Electronic Devices, P. Andrew, 2011, ISBN 978-1-60511-265-7
- Volume 1289E—Controlling Material Properties and Charge-Carrier Interactions with Quantum-Dot Coupling, 2011, ISBN 978-1-60511-266-4
- Volume 1290E—Magnetism and Correlated Electronic Structure of Nitrides—Rare-Earth and Transition Metals as Constituents and Dopants, W.R.L. Lambrecht, A. Ney, K. Smith, H.J. Trodahl, 2011, ISBN 978-1-60511-267-1
- Volume 1291E—Integrated Nonreciprocal Photonics—Materials, Phenomena and Devices, V. Fratello, M. Levy, B. Stadler, M. Vanwolleghem, 2011, ISBN 978-1-60511-268-8
- Volume 1292— Oxide Nanoelectronics, H. Hwang, J. Levy, P. Makysymovych, G. Medeiros-Ribeiro, R. Waser, 2011, ISBN 978-1-60511-269-5
- Volume 1293E—Liquid-Crystal Materials—Beyond Displays, N.L. Abbott, D.J. Broer, T. Kato, T.J. White, 2011, ISBN 978-1-60511-270-1
- Volume 1294E—Resonant Optical Antennas—Sensing and Shaping Materials, K.B. Crozier, N. Engheta, G. Ju, R. Quidant, R. Zia, 2011, ISBN 978-1-60511-271-8
- Volume 1295— Intermetallic-Based Alloys for Structural and Functional Applications, M. Palm, B. Bewlay, S. Kumar, K. Yoshimi, 2011, ISBN 978-1-60511-272-5
- Volume 1296E—New Methods in Steel Design—Steel Ab Initio, Y. Adachi, R. Dronskowski, D. Raabe, P.E.A. Turchi, 2011, ISBN 978-1-60511-273-2
- Volume 1297— Deformation Mechanisms, Microstructure Evolution and Mechanical Properties of Nanoscale Materials, J.R. Greer, D.S. Gianola, B.G. Clark, T. Zhu, A.H.W. Ngan, 2011, ISBN 978-1-60511-274-9
- Volume 1298— Advanced Materials for Applications in Extreme Environments, T.S. Byun, R. Smith, M. Li, 2011, ISBN 978-1-60511-275-6
- Volume 1299— Microelectromechanical Systems—Materials and Devices IV, M.P. de Boer, F.W. DelRio, C. Eberl, E.P. Gusev, 2011, ISBN 978-1-60511-276-3
- Volume 1300E—Bulk Metallic Glasses and their Applications, K.F. Yao, 2011, ISBN 978-1-60511-277-0

MATERIALS RESEARCH SOCIETY SYMPOSIUM PROCEEDINGS

- Volume 1301— Soft Matter, Biological Materials and Biomedical Materials—Synthesis, Characterization and Applications, A.J. Nolte, K. Shiba, R. Narayan, D. Nolte, 2011, ISBN 978-1-60511-278-7
- Volume 1302E—Nanowires—Growth and Device Assembly for Novel Applications, 2011, ISBN 978-1-60511-279-4
- Volume 1303— Nanomaterials Integration for Electronics, Energy and Sensing, D. E. Perea, Y. Jung, J. B. Hannon, M. A. Reed, S. T. Picraux, 2011, ISBN 978-1-60511-280-0
- Volume 1304E—Hierarchical Materials and Composites—Combining Length Scales from Nano to Macro, J.H. Moon, G.M. Odegard, M.S.P. Shaffer, B.L. Wardle, 2011, ISBN 978-1-60511-281-7
- Volume 1305E—Group IV Semiconductor Nanostructures and Applications, L. Dal Negro, 2011, ISBN 978-1-60511-282-4
- Volume 1306E—Aerogels and Aerogel-Inspired Materials, S. Brock, G. Gould, A. Roig, D. Rolison, 2011, ISBN 978-1-60511-283-1
- Volume 1307E—Boron and Boron Compounds—From Fundamentals to Applications, M. Dudley, J.H. Edgar, M. Kuball, 2011, ISBN 978-1-60511-284-8
- Volume 1308E—Artificially Induced Crystalline Alignment in Thin Films and Nanostructures, A.T. Findikoglu, R. Huehne, T. Shimada, J.Z. Wu, 2011, ISBN 978-1-60511-285-5
- Volume 1309— Solid-State Chemistry of Inorganic Materials VIII, K-S. Choi, S.J. Clarke, P.S. Halasyamani, D.G. Mandrus, 2011, ISBN 978-1-60511-286-2
- Volume 1310E—Magneto Calorics and Magnetic Cooling, A. Fujita, K. Gschneidner Jr., O. Gutfleisch, K.G. Sandeman, A. Yan, 2011, ISBN 978-1-60511-287-9
- Volume 1311— Next-Generation Fuel Cells—New Materials and Concepts, T. He, K. Swider-Lyons, B. Park, P.A. Kohl, 2011, ISBN 978-1-60511-288-6
- Volume 1312— Polymer-Based Materials and Composites—Synthesis, Assembly, Properties and Applications, V. Bharti, M. Chipara, D. Venkataraman, 2011, ISBN 978-1-60511-289-3
- Volume 1313— Materials for Advanced Lithium Batteries, G.-A. Nazri, J-M Tarascon, D. Guyomard, A. Yamada, 2011, ISBN 978-1-60511-290-9
- Volume 1314E—Thermoelectric Materials for Solid-State Power Generation and Refrigeration, Y. Grin, G.S. Nolas, J. Sharp, T.M. Tritt, 2011, ISBN 978-1-60511-291-6
- Volume 1315— Transparent Conducting Oxides and Applications, J.J. Berry, E. Fortunato, J. Medvedeva, Y. Shigesato, 2011, ISBN 978-1-60511-292-3
- Volume 1316E—Nanofunctional Materials, Nanostructures and Nanodevices for Biomedical Applications II, R. Rao, 2011, ISBN 978-1-60511-293-0
- Volume 1317E—Interdisciplinary Approaches to Safe Nanotechnologies, C. Chaneac, S. Harper, G.V. Lowry, R.I. MacCuspie, 2011, ISBN 978-1-60511-294-7
- Volume 1318— Advances in Spectroscopy and Imaging of Surfaces and Nanostructures, J. Cumings, J. Guo, F.M. Granozio, O.V. Kolosov, 2011, ISBN 978-1-60511-295-4
- Volume 1319— Materials Issues in Art and Archaeology IX, P.B. Vandiver, C.L. Reedy, J.L. Ruvalcaba Sil, W. Li, 2011, ISBN 978-1-60511-296-1
- Volume 1320— Materials Education Development and Outreach—From K—Grad, D. Bahr, K. Jones, M. Glass, E. Allen, 2011, ISBN 978-1-60511-297-8

Prior Materials Research Society Symposium Proceedings available by contacting Materials Research Society