Nanoscale Thermoelectric Materials: Thermal and Electrical Transport, and Applications to Solid-State Cooling and Power Generation

MATERIALS RESEARCH SOCIETY
SYMPOSIUM PROCEEDINGS VOLUME 1543

Nanoscale Thermoelectric Materials: Thermal and Electrical Transport, and Applications to Solid-State Cooling and Power Generation

Symposia held April 1–5, 2013, San Francisco, California U.S.A.

EDITORS

Scott P. Beckman
Iowa State University
Ames, Iowa, U.S.A.

Harald Böttner
Fraunhofer-Institut für Physikalische Messtechnik IPM
Freiburg. Germany

Yann Chalopin
Ecole Centrale Paris
Chatenay Malabry, France

Christopher Dames
University of California, Berkeley
Berkeley, California, U.S.A.

P. Alex Greaney
Oregon State University
Corvallis, Oregon, U.S.A.

Patrick Hopkins
University of Virginia
Charlottesville, Virginia, U.S.A.

Baowen Li
National University of Singapore
Singapore, Singapore

Tako Mori
National Institute for Materials Science
Tsukuba, Japan

Takeshi Nishimatsu
Tohoku University
Sendai, Japan

Kevin Pipe
University of Michigan
Ann Arbor, Michigan, U.S.A.

Rama Venkatasubramanian
Johns Hopkins University
Laurel, Maryland, U.S.A.

Materials Research Society
Warrendale, Pennsylvania

CAMBRIDGE UNIVERSITY PRESS

Shaftesbury Road, Cambridge CB2 8EA, United Kingdom

One Liberty Plaza, 20th Floor, New York, NY 10006, USA

477 Williamstown Road, Port Melbourne, VIC 3207, Australia

314–321, 3rd Floor, Plot 3, Splendor Forum, Jasola District Centre, New Delhi – 110025, India

103 Penang Road, #05–06/07, Visioncrest Commercial, Singapore 238467

Cambridge University Press is part of Cambridge University Press & Assessment, a department of the University of Cambridge.

We share the University's mission to contribute to society through the pursuit of education, learning and research at the highest international levels of excellence.

www.cambridge.org
Information on this title: www.cambridge.org/9781605115207

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

First published 2013

CODEN: MRSPDH

A catalogue record for this publication is available from the British Library

ISBN 978-1-605-11520-7 Hardback

CONTENTS

*Invited Paper

LAYERED STRUCTURES

NANOSTRUCTURED BULK AND COMPOSITES

*Invited Paper

NANOSCALE TRANSPORT PHENOMENA

PREFACE

At the Material Research Society Spring 2013 meeting, held in San Francisco April 1-5, 2013, three symposia were held that focused on thermal-to-electric energy conversion and thermal transport: Symposium H: Nanoscale Thermoelectrics—Materials and Transport Phenomena – II, Symposium I: Materials for Solid-State Refrigeration, and Symposium V: Nanoscale Heat Transport—From Fundamentals to Devices. Although each technical session was focused on a different aspect of this subject, the intellectual commensurability of these symposia warranted the publication of their proceedings in a single volume.

The sessions in symposium H covered the latest approaches and results in nanoscale thermoelectric materials and their devices for thermal-to-electric conversion, energy harvesting as well as for high-performance cooling and thermal management. Recent advances, including nanoscale materials to reduce lattice thermal conductivity without significantly affecting electronic transport, resonant states, delta-doping, topological insulators, energy filtering to control the flow of desirable heat-transporting carriers and organic/molecular structures were discussed. The sessions, which included several invited talks from leading experts, highlighted the fundamentals of nanoscale materials synthesis and first-principles calculations aimed at understanding the nanoscale physics of transport. The proceedings of the symposium is a collection of papers that highlight the multidisciplinary nature of the materials research, including measurement methods and characterization tools for thermal and electrical interfaces.

The sessions in symposium I covered the latest approaches in materials used for solid-state refrigeration technologies. The development of this symposium was in part driven by interests in technologies to replace the existing vapor-compression cycle devices, which are notoriously inefficient. It was also motivated by recent interest in technologies aimed at micro-scale refrigeration devices, e.g., cooling on a chip. In addition to presentations on thermoelectric solid-state technologies, which have experienced recent advances due to the development of nanostructured materials, presentations about new approaches were given including devices based on the magnetocaloric effect, the electrocaloric effect, and the elastocaloric effect. There are also common challenges to solid-state refrigeration that are shared by all phenomenological approaches; for example, the control and optimization of thermal conductivity at and around the operating region. These issues were also discussed in this session. By creating sessions that included researchers from diverse backgrounds we hoped to stimulate discussions across fields and provide a receptive forum for new concepts in refrigeration.

The sessions in symposium V covered the latest approaches in heat transport within nanostructured materials, nanoscale devices, and lithographically-defined nanostructures, where structural length scales overlap with intrinsic phonon and electron length scales, leading to the strong modification of thermal transport mechanisms. Topics of invited and contributed presentations included phonon barriers and superlattices, nanowires, graphene, carbon nanotubes and carbon nanotube composites, electron-phonon

interactions, organic and hybrid materials, thermal radiation, microfluidics, and phase change materials. Emerging measurement and simulation techniques were highlighted, as well as applications to medical therapies, thermoelectric energy conversion, and energy storage. Profs. Ali Shakouri and Alan McGaughey, from Purdue University and Carnegie Mellon University respectively, gave well-attended tutorials on experimental and computational methods for studying nanoscale heat transport.

Scott P. Beckman
Harald Böttner
Yann Chalopin
Christopher Dames
P. Alex Greaney
Patrick Hopkins
Baowen Li
Tako Mori
Takeshi Nishimatsu
Kevin Pipe
Rama Venkatasubramanian

September 2013

Materials Research Society Symposium Proceedings

Volume 1536 — Film Silicon Science and Technology, 2013, P. Stradins, A. Boukai, F. Finger, T. Matsui, N. Wyrsch, ISBN 978-1-60511-513-9

Volume 1537E — Organic and Hybrid Photovoltaic Materials and Devices, 2013, S.W. Tsang, ISBN 978-1-60511-514-6

Volume 1538 — Compound Semiconductors: Thin-Film Photovoltaics, LEDs, and Smart Energy Controls, 2013, M. Al-Jassim, C. Heske, T. Li, M. Mastro, C. Nan, S. Niki, W. Shafarman, S. Siebentritt, Q. Wang, ISBN 978-1-60511-515-3

Volume 1539E — From Molecules to Materials—Pathways to Artificial Photosynthesis, 2013, J.-H. Guo, ISBN 978-1-60511-516-0

Volume 1540E — Materials and Integration Challenges for Energy Generation and Storage in Mobile Electronic Devices, 2013, M. Chhowalla, S. Mhaisalkar, A. Nathan, G. Amaratunga, ISBN 978-1-60511-517-7

Volume 1541E — Materials for Vehicular and Grid Energy Storage, 2013, J. Kim, ISBN 978-1-60511-518-4

Volume 1542E — Electrochemical Interfaces for Energy Storage and Conversion—Fundamental Insights from Experiments to Computations, 2013, J. Cabana, ISBN 978-1-60511-519-1

Volume 1543 — Nanoscale Thermoelectric Materials, Thermal and Electrical Transport, and Applications to Solid-State Cooling and Power Generation, 2013, S.P. Beckman, H. Böttner, Y. Chalopin, C. Dames, P.A. Greaney, P. Hopkins, B. Li, T. Mori, T. Nishimatsu, K. Pipe, R. Venkatasubramanian, ISBN 978-1-60511-520-7

Volume 1544E — *In-Situ* Characterization Methods in Energy Materials Research, 2014, J.D. Baniecki, P.C. McIntyre, G. Eres, A.A. Talin, A. Klein, ISBN 978-1-60511-521-4

Volume 1545E — Materials for Sustainable Development, 2013, R. Pellenq, ISBN 978-1-60511-522-1

Volume 1546E — Nanoparticle Manufacturing, Functionalization, Assembly and Integration, 2013, H. Fan, T. Hyeon, Z. Tang, Y. Yin, ISBN 978-1-60511-523-8

Volume 1547 — Solution Synthesis of Inorganic Functional Materials—Films, Nanoparticles and Nanocomposites, 2013, M. Jain, Q.X. Jia, T. Puig, H. Kozuka, ISBN 978-1-60511-524-5

Volume 1548E — Nanomaterials in the Subnanometer-Size Range, 2013, J.S. Martinez, ISBN 978-1-60511-525-2

Volume 1549 — Carbon Functional Nanomaterials, Graphene and Related 2D-Layered Systems, 2013, P.M. Ajayan, J.A. Garrido, K. Haenen, S. Kar, A. Kaul, C.J. Lee, J.A. Robinson, J.T. Robinson, I.D. Sharp, S. Talapatra, R. Tenne, M. Terrones, A.L. Elias, M. Paranjape, N. Kharche, ISBN 978-1-60511-526-9

Volume 1550E — Surfaces of Nanoscale Semiconductors, 2013, M.A. Filler, W.A. Tisdale, E.A. Weiss, R. Rurali, ISBN 978-1-60511-527-6

Volume 1551 — Nanostructured Semiconductors and Nanotechnology, 2013, I. Berbezier, J-N. Aqua, J. Floro, A. Kuznetsov,ISBN 978-1-60511-528-3

Volume 1552 — Nanostructured Metal Oxides for Advanced Applications, 2013, A. Vomiero, F. Rosei, X.W. Sun, J.R. Morante, ISBN 978-1-60511-529-0

Volume 1553E — Electrical Contacts to Nanomaterials and Nanodevices, 2013, F. Léonard, C. Lavoie, Y. Huang, K. Kavanagh, ISBN 978-1-60511-530-6

Volume 1554E — Measurements of Atomic Arrangements and Local Vibrations in Nanostructured Materials, 2013, A. Borisevich, ISBN 978-1-60511-531-3

Volume 1556E — Piezoelectric Nanogenerators and Piezotronics, 2013, X. Wang, C. Falconi, S-W. Kim, H.A. Sodano, ISBN 978-1-60511-533-7

Volume 1557E — Advances in Scanning Probe Microscopy for Imaging Functionality on the Nanoscale, 2013, S. Jesse, H.K. Wickramasinghe, F.J. Giessibl, R. Garcia, ISBN 978-1-60511-534-4

Volume 1558E — Nanotechnology and Sustainability, 2013, L. Vayssieres, S. Mathur, N.T.K. Thanh, Y. Tachibana, ISBN 978-1-60511-535-1

Volume 1559E — Advanced Interconnects for Micro- and Nanoelectronics—Materials, Processes and Reliability, 2013, E. Kondoh, M.R. Baklanov, J.D. Bielefeld, V. Jousseaume, S. Ogawa, ISBN 978-1-60511-536-8

Volume 1560E — Evolutions in Planarization—Equipment, Materials, Techniques and Applications, 2013, C. Borst, D. Canaperi, T. Doi, J. Sorooshian, ISBN 978-1-60511-537-5

Volume 1561E — Gate Stack Technology for End-of-Roadmap Devices in Logic, Power and Memory, 2013, S. Banerjee,ISBN 978-1-60511-538-2

Materials Research Society Symposium Proceedings

Volume 1562E — Emerging Materials and Devices for Future Nonvolatile Memories, 2013, Y. Fujisaki, P. Dimitrakis, D. Chu, D. Worledge, ISBN 978-1-60511-539-9
Volume 1563E — Phase-Change Materials for Memory, Reconfigurable Electronics, and Cognitive Applications, 2013, R. Calarco, P. Fons, B.J. Kooi, M. Salinga, ISBN 978-1-60511-540-5
Volume 1564E — Single-Dopant Semiconductor Optoelectronics, 2014, M.E. Flatté, D.D. Awschalom, P.M. Koenraad, ISBN 978-1-60511-541-2
Volume 1565E — Materials for High-Performance Photonics II, 2013, T.M. Cooper, S.R. Flom, M. Bockstaller, C. Lopes, ISBN 978-1-60511-542-9
Volume 1566E — Resonant Optics in Metallic and Dielectric Structures—Fundamentals and Applications, 2013, L. Cao, N. Engheta, J. Munday, S. Zhang, ISBN 978-1-60511-543-6
Volume 1567E — Fundamental Processes in Organic Electronics, 2013, A.J. Moule, ISBN 978-1-60511-544-3
Volume 1568E — Charge and Spin Transport in Organic Semiconductor Materials, 2013, H. Sirringhaus, J. Takeya, A. Facchetti, M. Wohlgenannt, ISBN 978-1-60511-545-0
Volume 1569 — Advanced Materials for Biological and Biomedical Applications, 2013, M. Oyen, A. Lendlein, W.T. Pennington, L. Stanciu, S. Svenson, ISBN 978-1-60511-546-7
Volume 1570E — Adaptive Soft Matter through Molecular Networks, 2013, R. Ulijn, N. Gianneschi, R. Naik, J. van Esch, ISBN 978-1-60511-547-4
Volume 1571E — Lanthanide Nanomaterials for Imaging, Sensing and Optoelectronics, 2013, H. He, Z-N. Chen, N. Robertson, ISBN 978-1-60511-548-1
Volume 1572E — Bioelectronics—Materials, Interfaces and Applications, 2013, A. Noy, N. Ashkenasy, C.F. Blanford, A. Takshi, ISBN 978-1-60511-549-8
Volume 1574E — Plasma and Low-Energy Ion-Beam-Assisted Processing and Synthesis of Energy-Related Materials, 2013, G. Abrasonis, ISBN 978-1-60511-551-1
Volume 1575E — Materials Applications of Ionic Liquids, 2013, D. Jiang, ISBN 978-1-60511-552-8
Volume 1576E — Nuclear Radiation Detection Materials, 2014, A. Burger, M. Fiederle, L. Franks, D.L. Perry, ISBN 978-1-60511-553-5
Volume 1577E — Oxide Thin Films and Heterostructures for Advanced Information and Energy Technologies, 2013, G. Herranz, H-N. Lee, J. Kreisel, H. Ohta, ISBN 978-1-60511-554-2
Volume 1578E — Titanium Dioxide—Fundamentals and Applications, 2013, A. Selloni , ISBN 978-1-60511-555-9
Volume 1579E — Superconducting Materials—From Basic Science to Deployment, 2013, Q. Li, K. Sato, L. Cooley, B. Holzapfel, ISBN 978-1-60511-556-6
Volume 1580E — Size-Dependent and Coupled Properties of Materials, 2013, B.G. Clark, D. Kiener, G.M. Pharr, A.S. Schneider, ISBN 978-1-60511-557-3
Volume 1581E — Novel Functionality by Reversible Phase Transformation, 2013, R.D. James, S. Fähler, A. Planes, I. Takeuchi, ISBN 978-1-60511-558-0
Volume 1582E — Extreme Environments—A Route to Novel Materials, 2013, A. Goncharov, ISBN 978-1-60511-559-7
Volume 1583E — Materials Education—Toward a Lab-to-Classroom Initiative, 2013, E.M. Campo, C.C. Broadbridge, K. Hollar, C. Constantin, ISBN 978-1-60511-560-3

Prior Materials Research Symposium Proceedings available by contacting Materials Research Society