Thermoelectric Power Generation

MATERIALS RESEARCH SOCIETY
SYMPOSIUM PROCEEDINGS VOLUME 1044

Thermoelectric Power Generation

Symposium held November 26–29, 2007, Boston, Massachusetts, U.S.A.

EDITORS:

Timothy P. Hogan
Michigan State University
East Lansing, Michigan, U.S.A.

Jihui Yang
General Motors R&D Center
Warren, Michigan, U.S.A.

Ryoji Funahashi
National Institute of Advanced Industrial
Science and Technology
Osaka, Japan

Terry M. Tritt
Clemson University
Clemson, South Carolina, U.S.A.

Materials Research Society
Warrendale, Pennsylvania

CAMBRIDGE UNIVERSITY PRESS
Cambridge, New York, Melbourne, Madrid, Cape Town,
Singapore, São Paulo, Delhi, Mexico City

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

Published in the United States of America by Cambridge University Press, New York

www.cambridge.org
Information on this title: www.cambridge.org/9781558999879

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

First published 2008
First paperback edition 2013

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

CODEN: MRSPDH

ISBN 978-1-558-99987-9 Hardback

This work was supported in part by the Office of Naval Research under Grant Number N00014-07-1-1187. The United States Government has a royalty-free license throughout the world in all copyrightable material contained herein.

CONTENTS

*Invited Paper

POSTER SESSION

CHALCOGENIDES I

BULK THERMOELECTRICS I

*Invited Paper

NANOCOMPOSITES III AND BULK THERMOELECTRICS II

CHALCOGENIDES II:
THIN FILMS AND THERMIONICS

POSTER SESSION

*Invited Paper

THIN FILMS AND DEVICES

NEW AND EMERGING MATERIALS AND STANDARDS

*Invited Paper

PREFACE

Symposium U, "Thermoelectric Power Generation," held November 26–29 at the 2007 MRS Fall Meeting in Boston, Massachusetts, was the eighth in a series of thermoelectric materials research symposia related to new thermoelectric materials and devices [see MRS Proceedings volumes: 234, 478, 545, 626, 691, 793, 886]. In this symposium there were 135 contributed presentations including 11 invited talks and 63 posters. A steady and growing interest in the field of thermoelectric materials is evidenced by the continual increase in the number of submitted abstracts throughout the series of symposia. Even with the narrowed focus on thermoelectric power generation, this symposium was no exception having the highest number of contributions in the series.

The efficiency, η, of a thermoelectric power generator can be written as the product of a Carnot efficiency component, η_c, given as the ratio of the temperature gradient over the hot side temperature, and a thermoelectric component, η_{ZT}, such that $\eta = \eta_c \cdot \eta_{ZT}$. The thermoelectric component, η_{ZT}, is a function of the unitless figure of merit, ZT, and rapidly increases at low ZT values then asymptotically approaches a value of one in the limit. Higher efficiencies can therefore be achieved with large temperature gradients, and through improvements in ZT (commonly used materials have $ZT \approx 1$). This figure of merit is based on the material properties as $ZT = \alpha^2\sigma T/\kappa$, where α is the thermopower, σ the electrical conductivity, and κ is the thermal conductivity of the material. It is a challenging task to find materials with high electrical conductivity while simultaneously exhibiting high thermopower, and low thermal conductivity. Promising materials are often brittle and significant research in the processing of these materials is also of interest. Some results of current research in these areas are contained in these proceedings, and it is the hope of the organizers of this symposium that these proceedings will provide a concise reference for the current state of the field of thermoelectric materials research and development.

Within this symposium, there were sessions on nanocomposite materials including an excellent overview given by Millie Dresselhaus (MIT) on the use of "self assembled," and "force-engineered" nanocomposites in bulk samples. Jian He (Clemson) described the coating of pulverized *p*-type Bi_2Te_3 powders followed by hot pressing into bulk samples. Mercouri Kanatzidis (Northwestern U.) showed $ZT > 1.4$ for self assembled nanostructured PbTe-based bulk materials. George Nolas (U. of South Florida) described efforts in material systems including group IV clathrates, nanostructured chalcogenides, and antiflourite compounds and the use of powder processing techniques for the fabrication of bulk samples. Thallium telluride, and gallium telluride materials with extremely low thermal conductivity of below 0.5 (W/m·K) were presented by Shinsuke Yamanaka (Osaka U.). Theoretical studies of oxide thermoelectrics were presented by David Singh (ORNL) using conventional Boltzmann transport and showing the origin of the desired bandstructures coming from the bonding topology. Wataru Koshibae (Sendai National College of Technology) presented theoretical analysis on strongly correlated electron systems, and S.D. Mahanti (Michigan State U.) presented theoretical studies of the $AgPb_mSbTe_{m+2}$ material system. Mahanti showed self assembled nanostructuring in these materials can be understood through clustering and ordering of Ag, Sb, and Pb ions, and the temperature dependent electrical conductivity is dominated by the temperature dependence of the relaxation time rather than its energy dependence. Qiang Li (Brookhaven National Lab) described modeling and fabrication efforts toward materials with high power factors, and Holger Kleinke (U. of Waterloo) presented several new interesting compounds including $Mo_3(Sb,Te)_7$, $Nb_3(Sb,Te)_7$, and $Re_3(E,As)_7$ (with E = Si, Ge, Sn). Filling of the voids with nickel gave the compound $Ni_{0.06}Mo_3Sb_{5.4}Te_{1.6}$ as a degenerate *p*-type semiconductor that reaches $ZT = 0.96$ at 750°C. The symposium focused not only on the preparation and properties of new materials, but also included several talks on the processing of these new materials into devices, and the mechanical properties of thermoelectric compounds. In addition, the development status for the use of several advanced thermoelectric materials in radioisotope thermal generators for space applications was given by Thierry Caillat (JPL). Continued interest in the area of thermoelectrics was evidenced by the

number of outstanding presentations received, and the excellent level of attendance throughout the symposium.

The greatest returns come from investments in human capital through training and research of future scientists. As with previous thermoelectrics related symposia, there were a large number of graduate student presentations. Through the generous support of sponsors for this symposium, six graduate student oral presentation awards, and five graduate student poster awards were given. These students included:

Oral Presentations

Xiaofeng Qiu (Case Western Reserve University) "Synthesis and Characterization of Novel Thermoelectric Nanomaterials"

Bo Zhang (Clemson University) "PbTe Nanocomposites Fabricated by a Nano Surface Coating Technique"

Fei Ren (Michigan State University) "Mechanical Characterization of PbTe-based Thermoelectric Materials"

Vladimir Jovovic (Ohio State University) "Galvanomagnetic Measurements of Neodymium Doped Lead Telluride"

Matt Beekman (University of South Florida) "Synthesis and Characterization of Inorganic Clathrate-II Materials"

Joseph R. Sootsman (Northwestern University) "Transport Behavior, Thermal Conductivity Reduction, and Improved Thermoelectric Performance in the Composite System PbTe – Pb – Sb"

Poster Presentations

Ann I. Persson (University of Oregon) "Thermal Conductivity Measurements of Epitaxially Grown Nanowire Arrays Using TDTR"

Sabah Bux (University of California) "Synthesis and High Temperature Thermoelectric Properties of Nano Bulk Silicon and Silicon-Germanium Semiconductors"

Masataka Fukano (Tokyo University of Science) "Crystal Growth of Mg_2Si by the Vertical Bridgman Method and the Doping Effect of Bi and Al on Thermoelectric Characteristics"

Yoriko Mune (Nagoya University) "Origin of Giant Seebeck Coefficient for High Density 2DEGs Confined in the $SrTiO_3/SrTi_{0.8}Nb_{0.2}O_3$ Superlattices"

Yohei Oguni (Tokyo University of Science) "Formation of Transition-metal-based Ohmic Contacts to n-Mg_2Si by Plasma Activated Sintering"

The organizers are most grateful for the very gracious support of the Science and Technology Division of the Office of Naval Research, General Motors Corporation, Marlow Industries, Quantum Design Incorporated, Tellurex Corporation, ULVAC Technologies Incorporated, and the Materials Research Society. Their support enabled the large number of student awards and allowed for travel funds to help support contributing presenters.

Timothy P. Hogan
Jihui Yang
Ryoji Funahashi
Terry M. Tritt

April 2008

MATERIALS RESEARCH SOCIETY SYMPOSIUM PROCEEDINGS

Volume 1024E —Combinatorial Methods for High-Throughput Materials Science, D.S. Ginley, M.J. Fasolka, A. Ludwig, M. Lippmaa, 2008, ISBN 978-1-60511-000-4
Volume 1025E —Nanoscale Phenomena in Functional Materials by Scanning Probe Microscopy, L. Degertekin, 2008, ISBN 978-1-60511-001-1
Volume 1026E —Quantitative Electron Microscopy for Materials Science, E. Snoeck, R. Dunin-Borkowski, J. Verbeeck, U. Dahmen, 2008, ISBN 978-1-60511-002-8
Volume 1027E —Materials in Transition—Insights from Synchrotron and Neutron Sources, C. Thompson, H.A. Dürr, M.F. Toney, D.Y. Noh, 2008, ISBN 978-1-60511-003-5
Volume 1029E —Interfaces in Organic and Molecular Electronics III, K.L. Kavanagh, 2008, ISBN 978-1-60511-005-9
Volume 1030E —Large-Area Processing and Patterning for Active Optical and Electronic Devices, V. Bulović, S. Coe-Sullivan, I.J. Kymissis, J. Rogers, M. Shtein, T. Someya, 2008, ISBN 978-1-60511-006-6
Volume 1031E —Nanostructured Solar Cells, A. Luque, A. Marti, 2008, ISBN 978-1-60511-007-3
Volume 1032E —Nanoscale Magnetic Materials and Applications, J-P. Wang, 2008, ISBN 978-1-60511-008-0
Volume 1033E —Spin-Injection and Spin-Transfer Devices, R. Allenspach, C.H. Back, B. Heinrich, 2008, ISBN 978-1-60511-009-7
Volume 1034E —Ferroelectrics, Multiferroics, and Magnetoelectrics, J.F. Scott, V. Gopalan, M. Okuyama, M. Bibes, 2008, ISBN 978-1-60511-010-3
Volume 1035E —Zinc Oxide and Related Materials—2007, D.P. Norton, C. Jagadish, I. Buyanova, G-C. Yi, 2008, ISBN 978-1-60511-011-0
Volume 1036E —Materials and Hyperintegration Challenges in Next-Generation Interconnect Technology, R. Geer, J.D. Meindl, R. Baskaran, P.M. Ajayan, E. Zschech, 2008, ISBN 978-1-60511-012-7
Volume 1037E —Materials, Integration, and Technology for Monolithic Instruments II, D. LaVan, 2008, ISBN 978-1-60511-013-4
Volume 1038— Nuclear Radiation Detection Materials, D.L. Perry, A. Burger, L. Franks, M. Schieber, 2008, ISBN 978-1-55899-985-5
Volume 1039— Diamond Electronics—Fundamentals to Applications II, R.B. Jackman, C. Nebel, R.J. Nemanich, M. Nesladek, 2008, ISBN 978-1-55899-986-2
Volume 1040E —Nitrides and Related Bulk Materials, R. Kniep, F.J. DiSalvo, R. Riedel, Z. Fisk, Y. Sugahara, 2008, ISBN 978-1-60511-014-1
Volume 1041E —Life-Cycle Analysis for New Energy Conversion and Storage Systems, V.M. Fthenakis, A.C. Dillon, N. Savage, 2008, ISBN 978-1-60511-015-8
Volume 1042E —Materials and Technology for Hydrogen Storage, G-A. Nazri, C. Ping, A. Rougier, A. Hosseinmardi, 2008, ISBN 978-1-60511-016-5
Volume 1043E —Materials Innovations for Next-Generation Nuclear Energy, R. Devanathan, R.W. Grimes, K. Yasuda, B.P. Uberuaga, C. Meis, 2008, ISBN 978-1-60511-017-2
Volume 1044 — Thermoelectric Power Generation, T.P. Hogan, J. Yang, R. Funahashi, T. Tritt, 2008, ISBN 978-1-55899-987-9
Volume 1045E —Materials Science of Water Purification—2007, J. Georgiadis, R.T. Cygan, M.M. Fidalgo de Cortalezzi, T.M. Mayer, 2008, ISBN 978-1-60511-018-9

MATERIALS RESEARCH SOCIETY SYMPOSIUM PROCEEDINGS

Volume 1046E —Forum on Materials Science and Engineering Education for 2020, L.M. Bartolo, K.C. Chen, M. Grant Norton, G.M. Zenner, 2008, ISBN 978-1-60511-019-6
Volume 1047 — Materials Issues in Art and Archaeology VIII, P. Vandiver, F. Casadio, B. McCarthy, R.H. Tykot, J.L. Ruvalcaba Sil, 2008, ISBN 978-1-55899-988-6
Volume 1048E—Bulk Metallic Glasses—2007, J. Schroers, R. Busch, N. Nishiyama, M. Li, 2008, ISBN 978-1-60511-020-2
Volume 1049 — Fundamentals of Nanoindentation and Nanotribology IV, E. Le Bourhis, D.J. Morris, M.L. Oyen, R. Schwaiger, T. Staedler, 2008, ISBN 978-1-55899-989-3
Volume 1050E —Magnetic Shape Memory Alloys, E. Quandt, L. Schultz, M. Wuttig, T. Kakeshita, 2008, ISBN 978-1-60511-021-9
Volume 1051E —Materials for New Security and Defense Applications, J.L. Lenhart, Y.A. Elabd, M. VanLandingham, N. Godfrey, 2008, ISBN 978-1-60511-022-6
Volume 1052 — Microelectromechanical Systems—Materials and Devices, D. LaVan, M.G. da Silva, S.M. Spearing, S. Vengallatore, 2008, ISBN 978-1-55899-990-9
Volume 1053E —Phonon Engineering—Theory and Applications, S.L. Shinde, Y.J. Ding, J. Khurgin, G.P. Srivastava, 2008, ISBN 978-1-60511-023-3
Volume 1054E —Synthesis and Surface Engineering of Three-Dimensional Nanostructures, O. Hayden, K. Nielsch, N. Kovtyukhova, F. Caruso, T. Veres, 2008, ISBN 978-1-60511-024-0
Volume 1055E —Excitons and Plasmon Resonances in Nanostructures, A.O. Govorov, Z.M. Wang, A.L. Rogach, H. Ruda, M. Brongersma, 2008, ISBN 978-1-60511-025-7
Volume 1056E —Nanophase and Nanocomposite Materials V, S. Komarneni, K. Kaneko, J.C. Parker, P. O'Brien, 2008, ISBN 978-1-60511-026-4
Volume 1057E —Nanotubes and Related Nanostructures, Y.K. Yap, 2008, ISBN 978-1-60511-027-1
Volume 1058E —Nanowires—Novel Assembly Concepts and Device Integration, T.S. Mayer, 2008, ISBN 978-1-60511-028-8
Volume 1059E —Nanoscale Pattern Formation, W.J. MoberlyChan, 2008, ISBN 978-1-60511-029-5
Volume 1060E —Bioinspired Polymer Gels and Networks, F. Horkay, N.A. Langrana, A.J. Ryan, J.D. Londono, 2008, ISBN 978-1-60511-030-1
Volume 1061E —Biomolecular and Biologically Inspired Interfaces and Assemblies, J.B.-H. Tok, 2008, ISBN 978-1-60511-031-8
Volume 1062E —Protein and Peptide Engineering for Therapeutic and Functional Materials, M. Yu, S-W. Lee, D. Woolfson, I. Yamashita, B. Simmons, 2008, ISBN 978-1-60511-032-5
Volume 1063E —Solids at the Biological Interface, V.L. Ferguson, J.X-J. Zhang, C. Stoldt, C.P. Frick, 2008, ISBN 978-1-60511-033-2
Volume 1064E —Quantum-Dot and Nanoparticle Bioconjugates—Tools for Sensing and Biomedical Imaging, J. Cheon, H. Mattoussi, C.M. Niemeyer, G. Strouse, 2008, ISBN 978-1-60511-034-9
Volume 1065E —Electroactive and Conductive Polymers and Carbon Nanotubes for Biomedical Applications, X.T. Cui, D. Hoffman-Kim, S. Luebben, C.E. Schmidt, 2008, ISBN 978-1-60511-035-6

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