Inside: Energy Quarterly



June 2018 Vol. 43 No. 6

www.mrs.org/bulletin

RSBuletin

MRS MATERIALS RESEARCH SOCIETY® Advancing materials. Improving the quality of life.

Materials for nonreciprocal photonics

ALSO IN THIS ISSUE

The Materials Genome Initiative and artificial intelligence

CAMBRIDGE

CUSTOMIZED PRODUCTION ION IMPLANTERS

- Beam energies from 10 keV up to several 10s of MeV
- Beam currents from 100 micro-amps up to several milliamps
- Ion species, including H, He, B, P, As and others
- Single wafer or batch processing of wafers up to and including 300 mm
- In-air or in-vacuum cassette-to-cassette wafer handling
- Electrostatic and/or mechanical wafer clamping

High Voltage Engineering

.

•

a da .

High Voltage Engineering Europa B.V. P.O. Box 99, 3800 AB Amersfoort, The Netherlands Tel: 31 33 4619741 • info@highvolteng.com www.highvolteng.com

.

.

MRS ENERGY **SUSTAINABILITY**

Now indexed in the Web of Science, **Emerging Sources Citation Index** (ESCI)

science 🛇 technology 🛇 socio-economics 🛇 policy



SSOCIATE

David S. Ginley TORS-IN-CHIEF National Renewable Energy Laboratory, USA

David Cahen Weizmann Institute of Science, Israel

Elizabeth A. Kócs University of Illinois at Chicago, USA

Kristen Brown EDITORS Commonwealth Edison Company, USA

Sydney Kaufman Office of Sen. Tom Begich, Alaska State Senate. USA

Pabitra K. Nayak University of Oxford, United Kingdom

www.mrs.org/energy-sustainability-journal



CAMBRIDGE

MRSBulletin June 2018 Volume 43 Number 6 ISSN: 0883-7694 CODEN: MRSBEA

MATERIALS FOR NONRECIPROCAL PHOTONICS



408 Materials for nonreciprocal photonics Lei Bi, Guest Editor



13 Monolithic magneto-optical oxide thin films for on-chip optical isolation Qingyang Du, Takian Fakhrul, Yan Zhang, Juejun Hu, and Caroline A. Ross



419 Optical nonreciprocal devices for silicon photonics using wafer-bonded magnetooptical garnet materials Tetsuya Mizumoto, Roel Baets, and John E. Bowers



425 Plasmonic isolator for photonic integrated circuits Hiromasa Shimizu and Vadym Zayets



430 Sputter-deposited magneto-optical garnet for all-mode (transverse electric/transverse magnetic) Faraday rotators Bethanie J.H. Stadler and David C. Hutchings



436 Artificial nonreciprocal photonic materials at GHz-to-THz frequencies Andrea Alù and Harish Krishnaswamy



443 Nonreciprocity in synthetic photonic materials with nonlinearity Weijian Chen, Daniel Leykam, Y.D. Chong,

and Lan Yang

TECHNICAL FEATURE

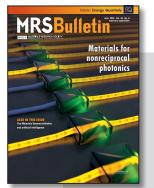


452 The Materials Genome Initiative and artificial intelligence James A. Warren

Energy Quarterly



- Editorial Water, energy, and materials science N. Balasubramanian
- 404 Energy Sector Analysis Crises and opportunities at the energy-water interface Eva Karatairi FEATURE EDITOR: Seth B. Darling
- 406 Energy Sector Analysis Will next-generation membranes rise to the water challenge? Prachi Patel FEATURE EDITOR: Laura Biedermann



ON THE COVER

Materials for nonreciprocal photonics. For photonic systems, breaking reciprocity using nonreciprocal materials is a challenge and opportunity. It allows for both the development of key photonic components as well as provides revolutionary ways to transport and process data in photonic systems. In this issue of *MRS Bulletin*, research directions toward realizing integrated nonreciprocal photonic materials and devices are discussed. On the cover

are optical isolators, the optical equivalent of electrical diodes, which are ubiquitous components on research benches and in fiber-optic systems. However, they remain the "missing link" in photonic-integrated circuits. The novel nonreciprocal materials presented in this issue are about to change that. Credit: Nathan Lindquist, Bethel University, Minnesota. See the technical theme that begins on page **408**.



www.mrs.org/bulletin

DEPARTMENTS

NEWS & ANALYSIS

397 Materials News

- Research Highlights: Perovskites Prachi Patel FEATURE EDITOR: Pabitra K. Nayak
- Cryo-transmission electron microscopy reveals protein nucleation pathways Tianyu Liu
- Detoxifying the oceans by using reused polystyrene Rahim Munir
- Origami-shaped conducting polymer stretches like an accordion Alex Klotz

401 Science Policy

- US Air Force supports high-flying science research in Asia—and around the world
 William G. Schulz
- EC's Horizon 2020 funds development of organ-on-chip technology

SOCIETY NEWS

458 Fifteen years on the road—Strange Matter continues its journey

FEATURES 460 Beyond the Lab WE ARE for Science advocates for diversity and inclusion in science 461 Book Reviews Cellulose Nanocrystals: Properties, Production and Applications Wadood Y. Hamad Reviewed by Walid M. Daoush

- Crystal Chemistry: From Basics to Tools for Materials Creation Gérard Férey Reviewed by M. Stanley Whittingham
- 3D Printing: Technology, Applications, and Selection Rafiq Noorani Reviewed by Jeffery Aguiar
- 464 Image Gallery Look Again



463 CAREER CENTRAL

ADVERTISERS IN THIS ISSUE	Page No.
American Elements	.Outside back cover
High Voltage Engineering	Inside front cover
Janis Research Company, LLC	418
Rigaku Corporation	

www.mrs.org/bulletin www.mrs.org/energy-quarterly www.mrs.org/mymrs http://journals.cambridge.org mrsbulletin-rss

https://doi.org/10.1557/mrs.2018.144 Published online by Cambridge University Press

MATERIALS RESEARCH SOCIETY® MRS Advancing materials. Improving the quality of life.

About the Materials Research Society

The Materials Research Society (MRS), a not-for-profit scientific association founded in 1973 and headquartered in Warrendale, Pennsylvania, USA, promotes interdisciplinary materials research. Today, MRS is a growing, vibrant, member-driven organization of over 16,000 materials researchers spanning over 80 countries, from academia, industry, and government, and a recognized leader in the advancement of interdisciplinary materials research.

The Society's interdisciplinary approach differs from that of single-discipline professional societies because it promotes information exchange across many scientific and technical fields touching materials development. MRS conducts three major international annual meetings and also sponsors numerous single-topic scientific meetings. The Society recognizes professional and technical excellence and fosters technical interaction through University Chapters. In the international arena, MRS implements bilateral projects with partner organizations to benefit the worldwide materials community. The Materials Research Society Foundation helps the Society advance its mission by supporting various projects and initiatives.

2018 MRS BOARD OF DIRECTORS

President Sean J. Hearne, Sandia National Laboratories, USA Immediate Past President Susan Trolier-McKinstry,

The Pennsylvania State University, USA Vice President and President-Elect Michael R. Fitzsimmons. Oak Ridge National Laboratory and The University of Tennessee, USA Secretary Eric A. Stach, University of Pennsylvania, USA Treasurer David J. Parrillo, The Dow Chemical Company, USA

Executive Director Todd M. Osman, Materials Research Society, USA Griselda Bonilla, IBM T.J. Watson Research Center, USA Li-Chyong Chen, National Taiwan University, Taiwar Matt Copel, IBM T.J. Watson Research Center, USA Paul S. Drzaic, Apple, Inc., USA Dawnielle Farrar-Gaines, Johns Hopkins University, USA Yury Gogotsi, Drexel University, USA Claudia Gutiérrez-Wing, Instituto Nacional de Investigaciones Nucleares, Mexico Young-Chang Joo, Seoul National University, South Korea Lincoln J. Lauhon, Northwestern University, USA Paul C. McIntyre, Stanford University, USA Christopher A. Schuh, Massachusetts Institute of Technology, USA Rachel A. Segalman, University of California, Santa Barbara, USA Magaly Spector, The University of Texas at Dallas, USA Molly M. Stevens, Imperial College London, UK Ehrenfried Zschech, Fraunhofer Institute for Ceramic Technologies and Systems, Germany

MRS OPERATING COMMITTEE CHAIRS

Academic Affairs Bruce M. Clemens, Stanford University, USA Awards Albert Polman, FOM Institute AMOLF, The Netherlands Government Affairs David P. Norton, University of Florida, USA Meetings Terry Aselage, Sandia National Laboratories, USA Member Engagement Sossina M. Haile, Northwestern University, USA Public Outreach Elizabeth Kupp, The Pennsylvania State University, USA Publications Shefford P. Baker, Cornell University, USA

MRS HEADQUARTERS

Todd M. Osman, Executive Director J. Ardie Dillen, Director of Finance and Administration Damon Dozier, Director of Government Affairs Patricia Hastings, Director of Meetings Activities Eileen M. Kiley, Director of Communications

RSBulletin

EDITORIAL OFFICE 506 Keystone Drive, Warrendale, PA 15086-7573 USA Bulletin@mrs.org tel 724.779.2747 fax 724.779.8313 www.mrs.org

Editor Gopal R. Rao, rao@mrs.org

Managing Editor Lori A. Wilson, lwilson@mrs.org

News Editor Judy Meiksin, meiksin@mrs.org

Technical Editor Lisa C. Oldham, oldham@mrs.org

Editorial Assistants Michelle S. Raley, raley@mrs.org Mary Wilmoth

Associate Technical Editor Tobias Lockwood

Production/Design Michael P. Moran, Rebecca Tokarczyk, Felicia Turano, and TNQ

Associate Production Editor Katie Wurtzel

Principal Development Editor Elizabeth L. Fleischer

Director of Communications Eileen M. Kiley

Guest Editors Lei Bi and Zheng Wang

Special Consultant Angelika Veziridis

Energy Quarterly

Andrea Ambrosini (Chair). Monika Backhaus, Kristen Brown, David Cahen, Russell R. Chianelli, George Crabtree, Elizabeth A. Kócs, Shirley Meng, Sabrina Sartori, Anke Weidenkaff, M. Stanley Whittingham, and Steve M. Yalisove

Advertising/Sponsorship Mary E. Kaufold, kaufold@mrs.org Donna L. Watterson, watterson@mrs.org

Member Subscriptions Michelle Judt, judt@mrs.org

Non-Member Subscriptions subscriptions_newyork@cambridge.org

EDITORIAL BOARD

Fiona C. Meldrum (Chair), University of Leeds, UK Ilke Arslan, Pacific Northwest National Laboratory, USA V.S. Arunachalam, Center for Study of Science, Technology & Policy, India N. (Balu) Balasubramaniam, Bangalore, India (retired) Christopher J. Bettinger, Carnegie Mellon University, USA Tommie Kelley, 3M, USA Igor Lubomirsky, Weizmann Institute, Israel Amit Misra, University of Michigan, USA Steven C. Moss, The Aerospace Corporation, USA (retired) Julie A. Nucci, Cornell University, USA Linda J. Olafsen, Baylor University, USA Boaz Pokroy, Technion-Israel Institute of Technology, Israel Zhiwei Shan, Xi'an Jiaotong University and Hysitron, China James W. Stasiak, HP Inc., USA Carol Trager-Cowan, University of Strathclyde, UK Eric Werwa, Washington, DC, USA M. Stanley Whittingham, Binghamton University, The State University of New York, USA Steve M. Yalisove, University of Michigan, USA

VOLUME ORGANIZERS

- 2018 Karsten Albe, Technische Universität Darmstadt, Germany Hiroshi Funakubo, Tokyo Institute of Technology, Japan Michael Hickner, The Pennsylvania State University, USA Bethanie Stadler, University of Minnesota, USA
- 2019 Craig B. Arnold, Princeton University, USA Claus Daniel, Oak Ridge National Laboratory and The University of Tennessee, Knoxville, USA Seung Min Han, Korea Advanced Institute of Science and Technology, Republic of Korea Gabriel Montaño, Los Alamos National Laboratory/Northern Arizona University, USA
- 2020 Hongyou Fan, Sandia National Laboratories, USA Oleg Gang, Brookhaven National Laboratory, USA Seokwoo Jeon, Korea Advanced Institute of Science and Technology, Republic of Korea Tae-Woo Lee, Seoul National University, South Korea

MRS Bulletin (ISSN: 0883-7694, print; ISSN 1938-1425, online) is published monthly by the Materials Research Society, 506 Keystone Drive, Warrendale, PA 15086-7573. © 2018 Materials Research Society. Permission required to reproduce content. Periodical postage paid at New York, NY, and at additional mailing offices. POSTMASTER: Send address changes to MRS Bulletin in care of the Journals Department, Cambridge University Press, 100 Brook Hill Drive, West Nyzek, NY 10994-2113, USA. Printed in the U.S.A. Membership in MRS is \$130 annually for regular members, \$252 for students, and includes an electronic subscription to MRS Bulletin. Print subscriptions are available to MRS members for an additional \$25. Individual member subscriptions are for personal use only. Non-member subscription rates are \$560 (USD) for one calendar year (12 issues). Requests from subscribers

Tor missing journal issues will be honored without charge only if received within six months of the issue's actual date of publication. *MRS Bulletin* is included in Current Contents®/Engineering, Computing, and Technology; Current Contents®/Physical, Chemical, and Earth Sciences, the SciSearch® online database, Research Alert®, Science Citation Index®, and the Materials Science Citation Index™. Back volumes of *MRS Bulletin* are available on microfiche through University Microfilms Inc.,

300 North Zeeb Road, Ann Arbor, MI 48106, USA,

Authors of each technical article appearing in MRS Bulletin are solely responsible for all content in their article(s), including accuracy of the facts, statements, and citing resources. Facts and opinions are solely the personal statements of the respective authors and do not necessarily represent the views of the editors, the Materials Research Society, or Cambridge University Press.

.....

Send Letters to the Editor to Bulletin@mrs.org. Include your name, affiliation, and full contact information.