Inside: Energy Quarterly

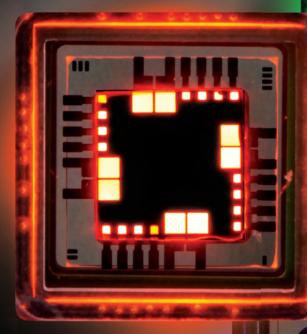
September 2013 Vol. 38 No. 9

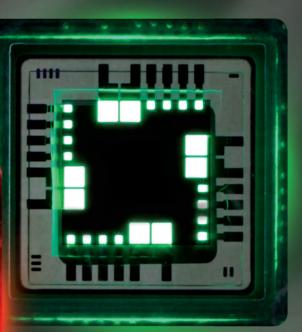
www.mrs.org/bulletin



#### **H**II MRS **MATERIALS RESEARCH SOCIETY** Advancing materials. Improving the quality of life.

## Quantum dot light-emitting devices





# ALSO IN THIS ISSUE Climbing the ladder of density

functional approximations

CAMBRIDGE UNIVERSITY PRESS

## 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 ella a

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

....



# Park NX10 the quickest path to innovative research

#### Better accuracy means better data

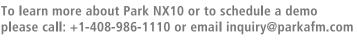
Park NX10 produces data you can trust, replicate, and publish at the highest nano resolution. It features the world's only true non-contact AFM that prolongs tip life while preserving your sample, and flexure based independent XY and Z scanner for unparalleled accuracy and resolution.

#### Better accuracy means better productivity

From sample setting to full scan imaging, measurement, and analysis, Park NX10 saves you time every step of the way. The user friendly interface, easy laser alignment, automatic tip approach, and analysis software allow you to get publishable results faster.

#### Better accuracy means better research

With more time and better data, you can focus on doing more innovative research. And the Park NX10's wide range of measurement modes and customizable design means it can be easily tailored to the most unique projects.



#### www.parkAFM.com





# MRSBulletin September 2013 Volume 38 Number 9 ISSN: 0883-7694 CODEN: MRSBEA

#### QUANTUM DOT LIGHT-EMITTING DEVICES



- 685 Quantum dot light-emitting devices Dmitri V. Talapin and Jonathan Steckel, Guest Editors
- 692 Meet Our Authors



696 **Pure colors from core-shell quantum dots** Ou Chen, He Wei, Axel Maurice, Moungi Bawendi, and Peter Reiss



703 QLEDs for displays and solid-state lighting Geoffrey J. Supran, Yasuhiro Shirasaki, Katherine W. Song, Jean-Michel Caruge, Peter T. Kazlas, Seth Coe-Sullivan, Trisha L. Andrew, Moungi G. Bawendi, and Vladimir Bulović



712 Bright and stable quantum dots and their applications in full-color displays Tae-Ho Kim, Shinae Jun, Kyung-Sang Cho, Byoung Lyong Choi, and Eunjoo Jang



721 Spectroscopic insights into the performance of quantum dot light-emitting diodes Wan Ki Bae, Sergio Brovelli, and Victor I. Klimov



731 Challenges and solutions for high-efficiency quantum dot-based LEDs Deniz Bozyigit and Vanessa Wood



737 **Beyond quantum dot LEDs: Optical gain and laser action in red, green, and blue colors** Cuong Dang and Arto Nurmikko

#### **TECHNICAL FEATURE**



743 Climbing the ladder of density functional approximations 2012 MRS Materials Theory Award John P. Perdew

#### **Energy Quarterly**

677



Editorial With steel, cement, and mortar V.S. Arunachalam

- 678 Energy Sector Analysis A concrete path to sustainability Prachi Patel FEATURE EDITOR: José Fernando Martirena Hernández
- 680 Energy Sector Analysis A test of the steel industry's metal Prachi Patel FEATURE EDITOR: Sridhar Seetharaman
- 682 Interview Dresselhaus recounts work on energy-related materials Interviewed by Steve Yalisove

www.mrs.org/energy-quarterly



#### ON THE COVER

Quantum dot light-emitting devices. This issue of MRS Bulletin covers the application of colloidal quantum dots for use in lighting technologies. Quantum dot lightemitting diodes (QLEDs) represent a technical challenge as well as major

commercial opportunity for display and solid-state lighting applications. Recent developments show that efficiency and brightness of QLEDs can match those of organic LEDs. The cover shows images of red, green, and blue QLEDs. See the technical theme that begins on page **685**.



www.mrs.org/bulletin

#### DEPARTMENTS

#### NEWS & ANALYSIS

#### 670 Materials News

- Single atoms imaged in situ with environmental STEM Emily Lewis
- Crystalline reflectors enable ultralow-thermal-noise optical cavities Colin McCormick
- Hard talk to stem cells for new bone growth Lukmaan A. Bawazer
- LuMnO<sub>3</sub> thin films reveal ferromagnetic and antiferromagnetic properties simultaneously
- Li-ion microbattery fabricated by 3D printing

#### 673 Science Policy

- Universities prepare next-generation workforce to benefit from the Materials Genome Initiative Ashley A. White
- EU and industry join forces to invest €22 billion in research and innovation

#### $\diamond$

#### FEATURES

- 675 Beyond the Lab Bruce Clemens teaches materials science online Interviewed by Piper Klemm
- 759 **Posterminaries Toying with science** Robin Selinger

#### 751 SOCIETY NEWS

 Survey on Big Data gathers input from materials community Lori A. Wilson

#### 👩 754 CAREER CENTRAL

#### ADVERTISERS IN THIS ISSUE Page No.

Aldrich Materials Science	684
American Elements	Outside back cover
American Scientific Publishers	
Angstrom Engineering, Inc	711
CRAIC Technologies, Inc	742
High Voltage Engineering	Inside front cover
Hindawi Publishing Corporation	Inside back cover
Janis Research Company, LLC	730
MMR Technologies, Inc	720
National Electrostatics Corp	691
Park Systems, Inc	665
Rigaku Corporation	750
Strem Chemicals, Inc	702
ULVAC Technologies, Inc	695



#### www.mrs.org/bulletin MRS members—access MRS Bulletin online

www.mrs.org/energy-quarterly Access Energy Quarterly online

www.mrs.org/mymrs MRS Publications Alert receive advance Table of Contents by email

http://journals.cambridge.org/ mrsbulletin-rss Subscribe TODAY to the *MRS Bulletin* RSS Feed

Design images used under license from Shutterstock.com

#### 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 encompassing approximately 125 topical symposia, 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 MRS Foundation helps the Society advance its mission by supporting various projects and initiatives

MRS publishes MRS Bulletin, MRS Communications, the MRS Online Proceedings Library, Journal of Materials Research, MRS Energy & Sustainability, and books and textbooks with its publishing partner, Cambridge University Press.

#### 2013 MRS BOARD OF DIRECTORS

President Orlando Auciello, University of Texas at Dallas, USA Immediate Past President Bruce M. Clemens, Stanford University, USA Vice President and President-Elect Tia Benson Tolle, The Boeing Company, USA

Secretary Sean J. Hearne, Sandia National Laboratories, USA Treasurer Michael R. Fitzsimmons, Los Alamos National Laboratory, USA Executive Director Todd M. Osman, Materials Research Society, USA

Ana Claudia Arias, University of California–Berkeley, USA Shenda Baker, Synedgen, Inc./Harvey Mudd College, USA David Cahen, Weizmann Institute of Science, Israel Duane B. Dimos, Sandia National Laboratories, USA Steve Eglash, Stanford University, USA Chang-Beom Eom, University of Wisconsin-Madison, USA Susan Ermer, Lockheed Martin Advanced Technology Center, USA Eric Garfunkel, Rutgers University, USA Sossina M. Haile, California Institute of Technology, USA Andrea M. Hodge, University of Southern California, USA Oliver Kraft, Karlsruhe Institute of Technology, Germany Hideki Matsumura, Japan Advanced Institute of Science and Technology, Japan Fiona C. Meldrum, University of Leeds, UK Eric A. Stach, Brookhaven National Laboratory, USA Stephen Streiffer, Argonne National Laboratory, USA Susan E. Trolier-McKinstry, The Pennsylvania State University, USA

#### MRS OPERATING COMMITTEE CHAIRS

Academic Affairs M. Stanley Whittingham, SUNY-Binghamton, USA Awards C. Barry Carter, University of Connecticut, USA Government Affairs Nabil Bassim, US Naval Research Laboratory, USA Meetings Committee David S. Ginley, National Renewable Energy Laboratory, USA

Member Engagement Yves Chabal, The University of Texas at Dallas, USA Public Outreach Aditi Risbud, University of Utah in Salt Lake City, USA Publications Paul McIntyre, Stanford University, USA

#### MRS OFFICE OF PUBLIC AFFAIRS

Ron Kelley 499 South Capitol St. SW, Suite 600, Washington, DC 20003

# **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

Guest Editors

Special Consultants

Energy Quarterly

Anke Weidenkaff

M. Stanley Whittingham,

Advertising/Sponsorship

Member Subscriptions

Michelle Judt, judt@mrs.org

Non-Member Subscriptions

and Steve M. Yalisove

David Cahen (Chair),

Dmitri V. Talapin and Jonathan Steckel

Anshu Bharadwaj, Russell R. Chianelli,

Philip Purnell and Karen Scrivener

George Crabtree, Sabrina Sartori,

Mary E. Kaufold, kaufold@mrs.org

Donna L. Watterson, watterson@mrs.org

subscriptions\_newyork@cambridge.org

#### Editor

Gopal R. Rao, rao@mrs.org Managing Editor

Judy Meiksin, meiksin@mrs.org

**Technical Editor** Lori A. Wilson, lwilson@mrs.org

**Editorial Assistants** Graeme Lister Ben Moriarty, moriarty@mrs.org Mary Wilmoth

Associate Technical Editor B. Reeja Jayan

Production/Design Andrea Pekelnicky, Rebecca Yokum,

and TNQ Production Editor

Catherine Paduani Science News Editor Tim Palucka

Principal Development Editor Elizabeth L. Fleischer

**Director of Communications** Eileen Kiley Novak

#### EDITORIAL BOARD

Paul S. Drzaic (Chair), Apple, Inc., USA V.S. Arunachalam, Center for Study of Science, Technology & Policy, India Marie-Isabelle Baraton, University of Limoges, France Hanns-Ulrich Habermeier, Max Planck Institute for Solid State Research, Germany Igor Lubomirsky, Weizmann Institute, Israel Fiona C. Meldrum, University of Leeds, UK Amit Misra, Los Alamos National Laboratory, USA Steven C. Moss, Aerospace Corporation, USA Julie A. Nucci, Cornell University, USA Linda J. Olafsen, Baylor University, USA Carol Trager-Cowan, University of Strathclyde, UK Eric Werwa, Washington, DC, USA Steve M. Yalisove, University of Michigan, USA

#### VOLUME ORGANIZERS

- 2014 Deborah E. Leckband, University of Illinois at Urbana-Champaign, USA Yuri Suzuki, Stanford University, USA Enrico Traversa, King Abdullah University of Science and Technology, Saudi Arabia Yonhua Tzeng, National Cheng Kung University, Taiwan
- 2013 Mark T. Lusk, Colorado School of Mines, USA Eva Olsson, Chalmers University of Technology, Sweden Birgit Schwenzer, Pacific Northwest National Laboratory, USA James W. Stasiak, Hewlett-Packard Co., USA
- 2012 Lei Jiang, Chinese Academy of Sciences, China Sergei V. Kalinin, Oak Ridge National Laboratory, USA Stéphanie P. Lacour, EPFL, Switzerland Steven C. Moss, Aerospace Corporation, USA

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, Copyright © 2013 MRS builetin (ISSN: U883-7694, print; ISSN 1938-1425, online) is published monthly by the Materials Research Society, 5ub Reystone Drive, Warrendale, PA 15086-7673. Copyright © 2013 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 Builetin in care of the Journals Department, Cambridge University Press, 100 Brook Hill Drive, West Nyack, NY 10994-2113, USA. Printed in the U.S.A. Membership in MRS is \$115 annually for regular members, \$30 for students. Dues include an allocation of \$29 (\$17 for students) to a subscription to MRS Builetin. Indi-vidual member subscriptions are for personal use only. Non-member subscription rates are \$394 for one calendar year (12 issues) within North America and \$479 elsewhere. Requests from subscribers for missing journal issues will be honored without charge only if received within six months of the issue's actual date of publication. MRS Builetin is included in Current Contents®/Engineering, Computing, and Technology; Current Contents®/Engiscal, Chemical, and Earth Sciences, the SciSearch® online data-base, Research Alert<sup>®</sup>, Science Citation Index<sup>®</sup>, and the Materials Science Citation Index<sup>®</sup>. Back volumes of MRS Builetin are available on microfiche through University Microfilms Inc., 200 horth Zeeb Pand, hon Acher, M 48106, USA.

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

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



## SCIENTIFIC

www.aspbs.com

## ENCYCLOPEDIA OF NANOSCIENCE AND NANOTECHNOLOGY 25-Volume Set

#### **KEY FEATURES**

- The 25 volume set is a landmark reference that contains the largest number of research articles in the world
- Most up-to-date reference work ever published drawing on the past two decades of pioneering research
- ▶ 710 review chapters (ca. 20,000 pages) contributed by nearly 2,000 of the world's leading scientists
- All entries organized alphabetically in an A-Z order, browsing capabilties within different categories
- Edited and written by internationally known authoritative experts familiar with current technologies
- Truly international: authors from 40 countries
- Approximately 150,000 bibliographic citations providing extensive cross-referencing in each article
- About 15,000 figures, 1,400 tables and hundreds of chemical structures and equations
- Timely, authoritative and most comprehensive
- Extensive cross-referencing in each article provides reader with broader range of knowledge
- Available Online Edition allowing multiple users and fully searchable text
- Essential source for students, scientists, college and university professors, professionals, investors
- Multidisciplinary reference source for researchers spanning from science to engineering to medicine

Editor Dr. Hari Singh Nalwa, USA

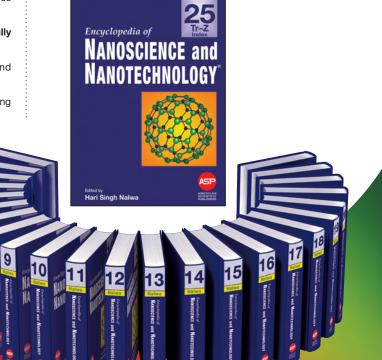
Editor-in-Chief Journal of Nanoscience and Nanotechnology www.aspbs.com/jnn www.aspbs.com/enn

The first edition of the Encyclopedia of Nanoscience and Nanotechnology, 10-Volume Set, (Foreword by Professor Richard E. Smalley, Nobel Prize Laureate, Endorsed by Professor Jean-Marie Lehn, Nobel Prize Laureate) that appeared in 2004 received the "Best Reference Work Award" of the American Society for Engineering Education and "Outstanding Academic Title" by the CHOICE magazine from the American Library Association.

With the addition of new 15 volumes (vols. 11-25) in 2011, the entire 25-volume set contains the largest number of articles ever published in the field of nanotechnology in the world. It is the most useful reference for all academic and research libraries.

- ► Volume 1-10, ISBN: 1-58883-001-2 (2004)
- ► Volume 11-25, ISBN: 1-58883-159-0 (2011)
- 25% Loyalty Discount on 15-volume set to customers who own volumes 1-10 set!

Available in Print & Online Editions





#### **ORDER FROM**

American Scientific Publishers 26650 The Old Road, Suite 208 Valencia, California 91381, USA

Tel. 661-799-7200 Fax: 661-799-7230 order@aspbs.com www.aspbs.com