

www.mrs.org/bulletin

SBulletin November 2012 Vol. 37 No. 11

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

Thin-film piezoelectric MEMS



PARTICLE ACCELERATOR SYSTEMS



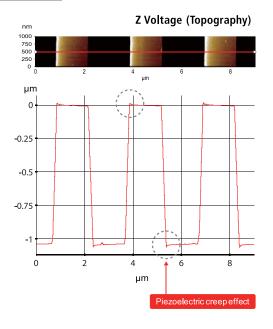
High Voltage Engineering

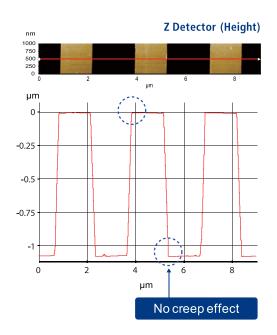
High Voltage Engineering Europa B.V.

P.O. Box 99, 3800 AB Amersfoort, The Netherlands
Tel: 31 33 4619741 • info@highvolteng.com
www.highvolteng.com



ACCURATE AFM TOPOGRAPHY





Sample: 1.020 µm Step Height (9 µm x 1 µm, 2048 pixels x 128 lines)

The World's Most

Accurate AFM

Low Noise Z Detector-based True Sample Topography™

The quality of your data is critical to your work and the success. Key to quality results is accuracy at the nanoscale. Park Systems' innovative NX means the most accurate nanoscale results in a leading-edge atomic force microscope (AFM) at far lower total cost of ownership.

The industry leading low noise Z detector replaces the applied voltage as the topography signal, without the effects of edge overshoot or piezo creep error, unlike other AFM in the market. The low noise Z detector enables the recording of accurate heights of sample surface even during high-speed scanning and provides AFM industry's best and the most accurate sample topography.

The NX technology builds on Park's leadership in AFM data accuracy, and is now available in Park NX10, a premium research-grade small-sample AFM, and Park NX20, a high-end large-sample AFM for failure analysis and quality analysis laboratories of hard disk and semiconductor industries.







MRSBulletin November 2012 Volume 37 Number 11 ISSN: 0883-7694 CODEN: MRSBEA

CONTENTS

THIN-FILM PIEZOELECTRIC MEMS



1007 Thin-film piezoelectric MEMS

Chang-Beom Eom and Susan Trolier-McKinstry, Guest Editors

1018 Meet Our Authors



1022 Giant piezoelectricity in PMN-PT thin films: Beyond PZT

Seung-Hyub Baek, Mark S. Rzchowski, and Vladimir A. Aksyuk



1030 Epitaxial PZT films for MEMS printing applications

Hiroshi Funakubo, Matthijn Dekkers, Alessia Sambri, Stefano Gariglio, Igor Shklyarevskiy, and Guus Rijnders



1039 Piezoelectric MEMS for energy harvesting

Sang-Gook Kim, Shashank Priya, and Isaku Kanno



1051 Piezoelectric aluminum nitride thin films for microelectromechanical systems

Gianluca Piazza, Valeriy Felmetsger, Paul Muralt, Roy H. Olsson III, and Richard Ruby



1062 Piezoelectric PZT MEMS technologies for small-scale robotics and RF applications

Jeffrey S. Pulskamp, Ronald G. Polcawich, Ryan Q. Rudy, Sarah S. Bedair, Robert M. Proie, Tony Ivanov, and Gabriel L. Smith



1071 The piezoelectronic transistor: A nanoactuator-based post-CMOS digital switch with high speed and low power

D.M. Newns, B.G. Elmegreen, X.-H. Liu, and G.J. Martyna

TECHNICAL FEATURE



1079 Opportunities for mesoscale science

G.W. Crabtree and J.L. Sarrao

Energy Quarterly



999 Editorial

The tortoise and the hare M. Stanley Whittingham

1000 Energy Sector Analysis

A capacity for change

Philip Ball

FEATURE EDITOR: Yury Gogotsi

1002 Interview

The materials that make an energy company: BP chief scientist Ellen Williams discusses sustainable energy

Interviewed by Martin Green and Prachi Patel

1004 Regional Initiative

Grid battery storage gets big in the States

Prachi Patel

FEATURE EDITOR: Brian Perusse

1006 Energy Focus

Tim Palucka

www.mrs.org/energy-quarterly Blog: www.materialsforenergy.org



ON THE COVER

Thin-film piezoelectric MEMS. This issue of MRS Bulletin focuses on some of the challenges microelectromechanical systems (MEMS) face as they move to smaller sizes and increased integration density, while requiring fast response and large motions. Advances in the field are being driven by and are prompting advances in heterostructure design and theoretical investigations. On the cover is a notional millimeter-scale robotic system based on PZT MEMS and highly integrated microelectronics. Green regions indicate PZT MEMS actuators, and the stacked "chips" on the body segments represent other required microelectronic subsystems. The robot is a hexapod (six-

legged)-based flight-capable design. See the technical theme that begins on page 1007.

DEPARTMENTS



► OPINION

983 Letter from the President

MRS serves the global materials community Bruce M. Clemens



NEWS & ANALYSIS

987 Research/Researchers

- Room-temperature terahertz detectors fabricated using graphene field-effect transistors Steven Trohalaki
- Smallest ice crystal revealed
- Germanium lasers may close Moore's Gap

991 Science Policy

- NRC recommends optics and photonics research priorities
- Global uranium supply ensured for long term



FEATURES

996 Beyond the Lab

A gift of glass

Zenzile Brooks

1098 Books

Polymer processing and characterization: Advances in materials science, Volume 1 Sabu Thomas, Deepalakshmi Ponnamma, and Ajesh K. Zachariah, Editors Reviewed by N. Balasubramanian

1112 Posterminaries

Materials research and white-knuckle air travel Steve Moss



1089 SOCIETY NEWS

- MRS reports election results for 2013
- MRS and SMM held International Materials Research Congress 2012 in Cancún



1099 CAREER CENTRAL

ADVERTISERS IN THIS ISSUE	Page No
* Advanced Research Systems, Inc	1088
* Agilent Technologies	992
* Aldrich Materials Science	998
American ElementsOutsic	de back cover
* Bruker981; Insid	de back cover
* Goodfellow Corporation	993
High Voltage EngineeringInsid	le front cover
* HORIBA Scientific	994
* Hysitron, Inc	989
* International Centre	
for Diffraction Data (ICDD)	1078
* Janis Research Company, LLC	1061
* JEOL USA, Inc	986
* Kurt J. Lesker Company	982
* Lake Shore Cryotronics, Inc	1029
* MMR Technologies, Inc	1021
National Electrostatics Corp	1038
* Park Systems, Inc	977
* RSC Publishing	995
* Strem Chemicals, Inc	1076
* ULVAC Technologies, Inc	1050
* Wafer World, Inc	1028
* J.A. Woollam Company, Inc	985

*Please visit us at the Exhibit, November 27-29, during the 2012 MRS Fall Meeting in Boston.

www.mrs.org/bulletin

MRS members—access MRS Bulletin online

www.mrs.org/energy-quarterly

Access Energy Quarterly online

www.materialsforenergy.org

Join the conversation in the Materials for Energy blog

www.mrs.org/mymrs

MRS Publications Alertreceive advance Table of Contents by email

http://journals.cambridge.org/ mrsbulletin-rss

Subscribe TODAY to the MRS Bulletin RSS Feed





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

About the Materials Research Society

The Materials Research Society (MRS), a not-for-profit scientific association founded in 1973, promotes interdisciplinary goal-oriented basic research on materials of technological importance. Membership in the Society includes almost 16,000 scientists, engineers, and research managers from industrial, government, and university research laboratories in the United States and over 80 countries.

The Society's interdisciplinary approach differs from that of single-discipline professional societies because it promotes information exchange across the many technical fields touching materials development. MRS sponsors 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 in local geographic regions through Sections and University Chapters.

MRS participates in the international arena of materials research through the International Union of Materials Research Societies (IUMRS). MRS is a member of the Alliance for Science & Technology Research in America and is an affiliate of the American Institute of Physics.

MRS publishes The MRS Online Proceedings Library, MRS Bulletin, Journal of Materials Research, MRS Communications, and other publications related to current research activities.

2012 MRS BOARD OF DIRECTORS

President Bruce M. Clemens, Stanford University, USA

Immediate Past President James J. De Yoreo, Lawrence Berkeley National Laboratory, USA

Vice President and President-Elect Orlando Auciello, University of Texas at Dallas, 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

Wade Adams, Rice University, USA Ana Claudia Arias, University of California-Berkeley, USA

Shenda Baker, Synedgen, Inc./Harvey Mudd College, USA Tia Benson Tolle, U.S. Air Force Research Laboratory, USA Duane B. Dimos, Sandia National Laboratories, USA Chang-Beom Eom, University of Wisconsin-Madison, USA

Eric Garfunkel, Rutgers University, USA

J. Murray Gibson, Argonne National Laboratory, USA

Oliver Kraft, Karlsruhe Institute of Technology, Germany Hideki Matsumura, Japan Advanced Institute of Science and Technology, Japan

Stephen K. Streiffer, Argonne National Laboratory, USA James C. Sturm, Princeton University, USA

Susan E. Trolier-McKinstry, The Pennsylvania State University, USA Pierre Wiltzius, University of California-Santa Barbara, 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, U.S. Naval Research Laboratory, USA Meetings Committee David S. Ginley, National Renewable Energy Laboratory, USA

Membership 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

Editor

Gopal R. Rao, rao@mrs.org

Managing Editor

Judy Meiksin, meiksin@mrs.org

Technical Editor

Lori A. Wilson, lwilson@mrs.org

Fditorial Assistants

Ben Moriarty, moriarty@mrs.org Mary Wilmoth

Associate Technical Editor

Carol Tseng

Art Director

Kasia M. Bruniany

Production/Design

Andrea Pekelnicky, Rebecca Yokum, and TNO

Production Editor

Catherine Paduani

Science News Editor

Tim Palucka

Principal Development Editor Elizabeth L. Fleischer

Director of Communications

Eileen Kiley Novak

Guest Editors

Chang-Beom Eom and Susan Trolier-McKinstry

Special Consultants

Babu Chalamala and Alexandra K. Duncan

Energy Quarterly

David Cahen (Chair), Anshu Bharadwaj, Russell R. Chianelli, George Crabtree, 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

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

Robert C. Cammarata, Johns Hopkins University, USA Laura Fornaro, University of Uruguay, Uruguay

Hanns-Ulrich Habermeier, Max Planck Institute for Solid State Research, Germany Fiona C. Meldrum, University of Leeds, UK

Amit Misra, Los Alamos National Laboratory, USA

Julie A. Nucci, Cornell University, USA Linda J. Olafsen, Baylor University, USA

David N. Seidman, Northwestern University, USA

Carol Trager-Cowan, University of Strathclyde, UK Julia R. Weertman. Northwestern University, USA

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 Ramamoorthy Ramesh, University of California-Berkeley, USA Enrico Traversa, Xi'an Jiaotong University, China 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

2011 Kyoung-Shin Choi, Purdue University, USA Reuben T. Collins, Colorado School of Mines, USA Sean E. Shaheen, University of Denver, USA

MRS Bulletin (ISSN: 0883-7694, print: ISSN 1938-1425, online) is published 12 times a year by the Materials Research Society, 506 Keystone Drive, Warrendale, PA 15086-7573, Copyright © 2012, 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 Nyack, NY 10994-2113, USA. Printed in the U.S.A.

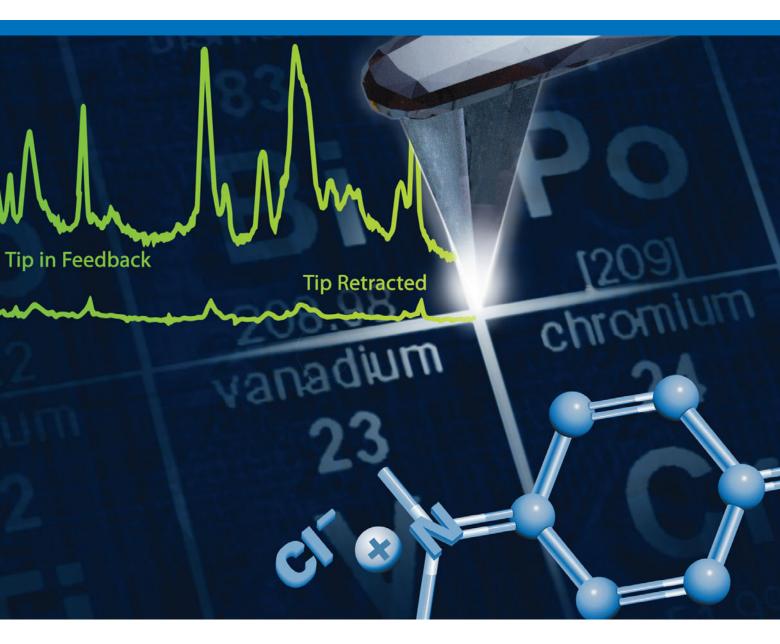
Membership in MRS is \$115 annually for regular members, \$30 for students. Dues include an allocation of \$29 (\$17 for students) to a subscription to MRS Bulletin. Indi-

vidual member subscriptions are for personal use only. Non-member subscription rates are \$363 for one calendar year (12 issues) within North America and \$436 elsewhere. Requests from subscripters for 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*/Phspineering, Computing, and Technology; Current Contents*/Phspineering, 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.

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





Taking the quality of material characterization to a new level.

- IRIS models provide proven tip-enhanced Raman spectroscopy (TERS) integration
- Co-located models integrate highest performance, largesample atomic force microscopy with uncompromised confocal micro-Raman spectroscopy
- Flexibility of analysis with every detail considered
- Easy-to-use AFMs for spectroscopy in materials research and life sciences
- Highest performance, most complete AFM capabilities
- True nanoscale spectroscopy targeted to your application

Visit www.bruker.com/AFM-Raman or contact us today at +1.805.967.1400/800.873.9750 or productinfo@bruker-nano.com to learn more about Bruker's ideal AFM-Raman solutions.

Innovation with Integrity

Atomic Force Microscopy



Fuel Your Research

All Things Vacuum

KJLC® offers the most comprehensive inventory of pure elements, alloys, advanced metal oxides, precious metals and compounds fabricated to meet the most demanding physical vapor deposition process requirements.

- · Largest Target and Evaporation Materials Inventory
- · On-Site Advanced Ceramics Manufacturing
- In-House Indium Bonding
- Unmatched Service and Technical Support