AMERICAN CERAMIC SOCIETY
bulletin
emerging ceramics & glass technology
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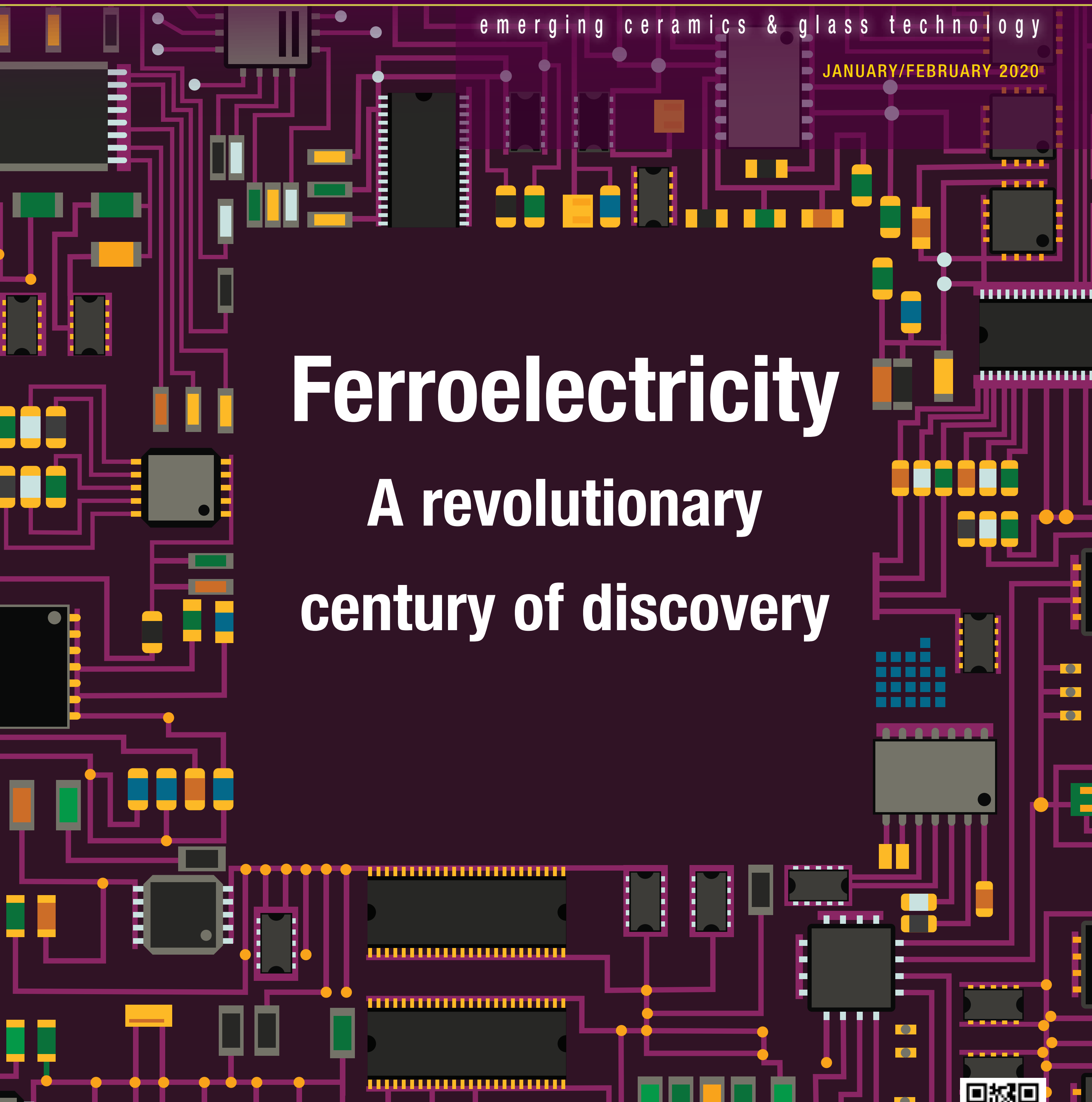

Ferroelectricity
A revolutionary century of discovery

Ceramics Expo 2020 preview | NSF CAREER program–10 years strong | Meet ACerS president

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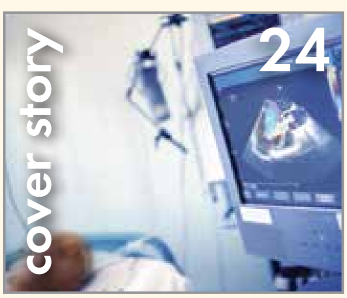
January/February 2020 • Vol. 99 No.1

feature articles

Impact of ferroelectricity

Since the discovery of ferroelectricity 100 years ago, ferroelectric materials are everywhere in our electronics-based society. Learn how they drive a $7 billion industry.

by Susan Trolier-McKinstry



Ferroelectricity—A revolutionary century of discovery

A century after the discovery of ferroelectricity, we look at the physics that makes ferroelectric materials so useful and the research that got us here.

by Geoff Brennecka, Rachel Sherbondy, Robert Schwartz, and Jon Ihlefeld

National Science Foundation CAREER Ceramics Program awardees: Class of 2018 and decadal overview

As an independent federal agency of the United States government, the National Science Foundation (NSF) funds basic research conducted at America's colleges and universities. NSF's Ceramics Program in the Division of Materials Research resides within the Mathematical and Physical Sciences Directorate.

by Lynnette D. Madsen

department

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bulletin

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As seen on *Ceramic Tech Today*...

Credit: ExOne

Government, industry, academia investigate additively manufacturing cemented carbide parts

Additive manufacturing may be an easier way to manufacture cemented carbide parts. The U.S. Army Research Laboratory recently submitted a patent application for a selective laser melting process, and collaborations in industry and academia are investigating binder jetting as well.

Read more at www.ceramics.org/carbideparts

Also see our ACerS journals...

Direct and indirect measurement of large electrocaloric effect in barium strontium titanate ceramics

By G. Dai, S. Wang, G. Huang, et al.
International Journal of Applied Ceramic Technology

Processing and properties of $Bi_{0.98}R_{0.02}FeO_3$ (R = La, Sm, Y) ceramics flash sintered at ~650°C in <5 s

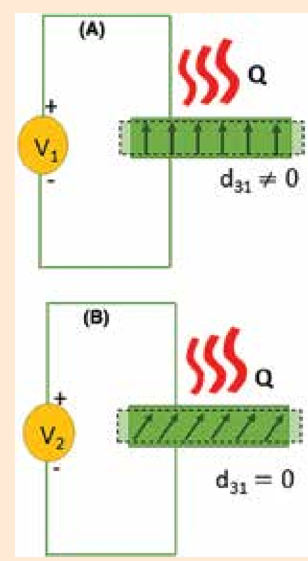
By E. Gil-González, A. Perejón, P. E. Sánchez-Jiménez, et al.
Journal of the American Ceramic Society

Poling tuning: A plausible solution for minimizing microphony and secondary pyroelectric coefficient in ferroelectrics

By R. Kiran, A. Kumar, R. Kumar, and R. Vaisht
International Journal of Applied Ceramic Technology

Dielectric and structural studies of ferroelectric phase evolution in dipole-pair substituted barium titanate ceramics

By V. K. Veerapandiyan, M. Deluca, S. T. Misture, et al.
Journal of the American Ceramic Society



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ACSBA7, Vol. 99, No. 1, pp 1– 48. All feature articles are covered in Current Contents.

news & trends

Labor shortage challenges manufacturing and construction industries

A theme that consistently echoes across diverse markets tied to the construction industry is a familiar concern—labor.

"The generation that is coming into the workforce is less likely to enter the construction market, so there is a gap in labor that is there for all trades—electrical, roofing, insulation, all of it. It's an issue the entire building industry is trying to address," says Matt Gawryla, insulation R&D leader at Owens Corning.

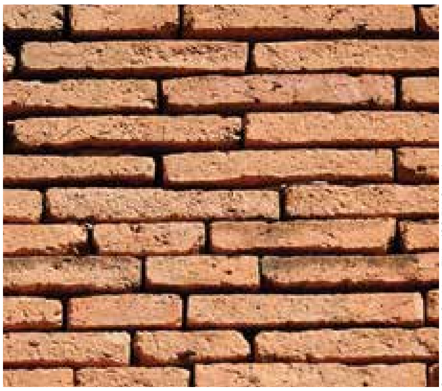
In addition to attracting new young workers, other contributing factors to these labor shortages include the aging current workforce as well as shortages of immigrant workers due to changing governmental practices, especially in the United States.

The brick industry, for examples, faces a shortage of bricklayers and masonry workers, which drives up the cost of brick installation and puts additional pressure on the industry. "So the brickmaker is struggling against increased alternative products plus increased cost to lay brick into the wall, so that's a challenge," says Garth Tayler, retired technical director for Acme Brick (Fort Worth, Texas).

Those challenges extend beyond brick as well, as many other product segments face similar challenges.


Credit: Needpix.com

Many factors—including aging current workforce, attracting new young workers, and shortages of immigrant workers—contribute to a labor shortage in the manufacturing and construction industries.



Credit: Michael Coghlan, Flickr (CC BY-SA 2.0)

Thin bricks are one example of labor-saving materials being used in the construction industry, in part to account for the labor shortage.

"Everyone is looking for long-term solutions to combat the labor shortage that's challenging the manufacturing and construction industries," says Lucas J. Hamilton, manager of applied building science for Saint-Gobain Corp. "Some specific examples of the industry response to workforce issues include a focus on how to properly address energy concerns and stay on top of product innovations, while doing so in a manner that installation is easy and efficient for laborers. We understand the future of construction must be lean, and Saint-Gobain and CertainTeed are becoming more agile to set the example of what lean construction means in North America."

Because much of the labor is required for installation, lean often translates into easier-to-install products that reduce the skill, time, and thus cost of installation. Easy-installation building products are emerging in many markets, including brick, insulation, and roofing.

In the roofing market, for example, labor-saving materials such as roofing membranes with peel-and-stick adhesive backings and insulated metal panels reduce the time and skill required for installation, and they are gaining acceptance. Even some innovations in more traditional materials such as asphalt shingles are directed toward making installation easier, including shingles with more visible reinforced nailing strips.

Similarly, the innovation of thin brick in the brick industry is about more than just consumer options—thin bricks are easier and quicker to install than standard brick, perhaps a creative solution to a shortage of skilled bricklayers.

Many other industries have also developed diverse solutions that all converge on the theme of easier-to-install products, a trend that is likely to continue into the future. ■

Power over Ethernet: The wire(not)less future of smart buildings

Despite Silicon Valley's push for wireless as it aims to realize the Internet of Things (IoT), in the case of smart buildings, Ethernet may be the best way to achieve IoT.

Traditionally, Ethernet is a more reliable (and generally faster) cable-based option to Wi-Fi for computers. But transmitting data is not the only use for Ethernet cables.

Power over Ethernet (PoE) is a networking feature that lets Ethernet cables carry electrical power over an existing data connection.

PoE was first approved for use by IEEE in 2003 via IEEE standard 802.3af. This standard allowed power sourcing equipment to transmit up to 15.4 watts of power to a powered device via twisted pair cabling. In 2009, PoE power increased to 30 watts. Today, many PoE-enabled Ethernet switches provide 60 watts of power, but on Sept. 27, 2018, the latest PoE standard—IEEE 802.3bt—was ratified and approved, which supports 100 watts of power.

PoE offers major advantages to building owners compared to traditional electrical wiring systems, including

- **Reduced installation costs—**Ethernet cables cost less than traditional electrical wiring, and Ethernet is often already installed in buildings.
- **Safer installation—**PoE Type 3 voltages are typically less than 60 volts, and Type 4 less than 90; conduits and metal cladding are not required.
- **Responsive deployment—**An entire network does not need to be brought down to add or subtract devices; PoE devices can be easily moved and reconnected at the switch level.

In addition to these advantages, probably the biggest advantage to PoE is its data-gathering capabilities.

Ethernet gives users the ability to assign an IP address to each connected device. These IP addresses help simplify management, configuration, and maintenance of connected devices, as network

Credit: David Davies, Flickr (CC BY-SA 2.0)

In the case of smart buildings, Ethernet cables may be the best way to achieve the Internet of Things.

administrators and system integrators can immediately see and troubleshoot errors in the system when issues arise.

Recently, The Sinclair, a new luxury lifestyle hotel in Fort Worth, Texas, opened its door to the public on October 31. It is the first hotel in the world to power its lights, window shades, smart mirrors, and minibars with PoE technology.

"With PoE, the Sinclair will power more than 2,000 lights and amenities via an IP address on a computer network," an *Architectural Digest* article explains. "If a light or other PoE device goes out anywhere between the hotel's basement restaurant and the rooftop bar, the Sinclair will be alerted through an immediate notification."

Additionally, vendors were asked to create products that would run on PoE. This request resulted in the motors for window shades, minibars, and smart mirrors being put on PoE; plans to make PoE air-conditioning units and TVs; and in-development exercise machines that would allow guests to power the hotel through 20 minutes or more of cardio workouts. ■

Corporate partner news

Bullen wins Manufacturing Business of the Year

Bullen Ultrasonics was recently named the 2019 Manufacturing Business of the Year by the Dayton Business Journal. The Business of the Year awards program has celebrated the region's best in business for 17 years. ■

Credit: Bullen Ultrasonics

Business news

PLANTS, CENTERS, AND FACILITIES

Schott invests €30M to open new glass-ceramic facility in Germany

Specialty glass manufacturer Schott opened a state-of-the-art CNC competence center for its glass-ceramic Zerodur in Mainz, Germany. The investment amounts to more than €30 million, and up to 70 qualified specialists will be employed at the site. https://optics.org/news

Allied Mineral Products opens second manufacturing facility in Tianjin, China

Allied Mineral Products opened its second manufacturing facility in Tianjin, China. The newly constructed plant measures 19,600 sq.m (210,972 sq.ft) and will provide optimal production space needs, as well as an expansive workspace. https://alliedmineral.com/category/announcements

Groot Glass secures $650 million funding for two glass plants

Namibian company Groot Glass secured $650 million funding for the construction of a glassmaking hub. It plans to construct two separate glass manufacturing factories: one 350tpd Groot Glass Container Factory for the beverages sector, and a 600tpd Groot Glass Float Factory for the construction industries. https://www.glass-international.com/news

ACQUISITIONS AND COLLABORATIONS

Forglass partners with CelSian on mathematical modelling

Polish glass melting technology provider Forglass partnered with Dutch company CelSian Glass & Solar to provide its GTM-x software for computer modelling studies of Forglass' furnace designs. https://www.glass-international.com/news

Rare earths industry welcomes new US-Australian deal to ensure critical minerals supply

A newly signed deal between Australia and the United States focusing on critical minerals could be the push to create a thriving rare earths industry in Australia and, more specifically, central Australia, according to some mineral experts and rare earths industry players. https://www.abc.net.au/news

Magment, Purdue to pursue electric transportation pilot projects at Discovery Park District

Magment Concrete Wireless Power and Purdue University officials announced an innovation partnership to advance electric transportation pilots at Purdue's Discovery Park. They will work on several test cases including micro-mobility scooters, autonomous electric utility vehicle equipment, and robotic shop floor delivery systems. https://www.purdue.edu/newsroom

MARKET TRENDS

New materials in high demand to meet rapid rollout of 5G technology across the globe

In a recent report, Lux Research details the progress made on the rollout of 5G networks and technologies to date, identifies unmet material needs for mmWave technology, and reviews the current technology options and emerging alternatives, with a focus on innovative groups that are already beginning to tackle these challenges. https://prnewswire.com/news-releases

Many glass and glazing materials see only slight changes in October

Many of the prices for materials used in glass and glazing manufacturing changed only slightly in October 2019 or not at all according to the latest Producer Price Index from the U.S. Bureau of Labor Statistics. However, most prices are up year-over-year. https://www.usglassmag.com

Thermal interface materials 2020–2030: Forecasts, technologies, opportunities

In a new report by IDTechEx researchers, they studied thermal interface materials (TIM) markets and technologies and developed a detailed view of the key market trends, for example, how 5G affects TIM requirements and how the energy storage market drives change. https://www.idtechex.com

Gates, Bezos invest in flow battery technology, a potential rival to big bets on lithium-ion

Tesla and GM are betting on lithium-ion batteries for energy storage systems and electric vehicles, but Breakthrough Energy Ventures, the group of private investors led by Bill Gates and fellow billionaires Jeff Bezos, Michael Bloomberg, Richard Branson, and Jack Ma, invested in iron-flow battery maker ESS in November. https://www.cnbc.com ■

Lead-free piezoelectric ceramics market projected to grow at much faster pace through 2024

By Margareth Gagliardi

The global market for piezoelectric devices is estimated to be valued at $25.1 billion in 2019 and projected to expand at a compounded annual growth rate (CAGR) of 6.2% through the next five years. Currently, lead-free piezoelectric ceramics (LFPECs) represent a very small share of this market (an estimated value of $172 million in 2019), but their sales are projected to rise at a CAGR of 20.8% from 2019 to 2024, reaching global revenues of $443 million in 2024.

Electronics and optoelectronics currently account for the largest share of the market, at an estimated 31.4% of the total in 2019. Within this segment, LFPECs are being used primarily for fabrication of inkjet printers and electronic components such as MEMS and surface acoustic wave devices. By comparison, LFPECs for transportation represent a share of 26.7% of the total. This segment has been expanding at a 16.3% CAGR since 2017, mainly driven by the use of LFPECs for production of automotive sensors. In the industrial sector, sales of LFPECs for fabrication of ultrasonic cleaning systems and other ultrasonic equipment are generating revenues of $43 million, corresponding to a 25% share in 2019.

Relevant factors that will contribute to LFPEC market expansion include

- **Stricter environmental and health safety regulations** aimed at limiting the use of lead worldwide,
- **Availability of new ceramic formulations** providing better piezoelectric properties,
- **General good market growth** of industry sectors in which these materials find application,
- **Greater utilization of LFPECs** in energy harvesting technologies as well as in wearable devices, and
- **Growing opportunities** in the field of virtual and augmented reality.

Potassium sodium niobate (KNN) based piezoelectric ceramics represent the largest share of the LFPEC market, at 37.2% of the total in 2019. Currently, these LFPECs find application mainly as sound and vibration sensors, and automotive sensors. Barium sodium titanate (BNT) based piezoelectric ceramics are the second-largest segment of the market at 29.7% of the total in 2019, and these products are primarily used as actuators for inkjet printers and as precision positioning devices. Sales of barium titanate (BT) based piezoelectric ceramics are expanding at a CAGR of 14.6% through 2019. They are being introduced mainly for ultrasonic applications including cleaning, welding, grinding, emulsification, cooling, and drug extraction.

The basic fabrication process of LFPEC materials involves several steps that generally speaking are typical of ceramic manufacturing. Recently, a new forming process was introduced for fabrication of LFPECs consisting of 3D printing by stereolithography. Additive manufacturing is gaining strong interest as a forming technique for rapid prototyping and manufacturing of components with complex shapes.

The leading players in the LFPEC market are sorted in four groups. The first group includes producers of BT-based piezoelectric ceramics, with a total of 16 players. The second group of 15 players includes suppliers of bismuth titanate (BiT) based piezoelectric ceramics, including BNT and modified bismuth titanate formulations. The third group, which supplies KNN-based piezoelectric ceramics, includes 11 suppliers, and the fourth group of five companies supply other types of piezoelectric ceramics, such as bismuth ferrite and niobate-based ceramics (other than KNN), and zinc oxide or aluminum nitride thin films. The total count is 47, rather than 37, because several firms are suppliers of more than one type of piezoelectric material.

Table 1. Global market for lead-free piezoelectric ceramics, by application, through 2024 ($ millions)

Application	2017	2018	2019	2024	CAGR% 2019–2024
Electronics and optoelectronics	39	46	54	148	22.3
Transportation	34	39	46	117	20.5
Industrial	33	37	43	101	18.6
Others	22	25	29	77	21.6
Total	128	147	172	443	20.8

Most U.S. firms (50.0%) produce BT-based piezoelectric ceramics, while European manufacturers specialize primarily in BiT-based products (75.0% of total European firms). In the Asia-Pacific region, KNN-based piezoelectric ceramics are produced by 37.0% of companies.

The Asia-Pacific region currently accounts for the largest share of the market at 36.3% of the total, and it also represents the fastest growing segment with a CAGR of 6.6% during the next five years. This region is projected to generate revenues of $12.5 billion by 2024, or 36.9% of the total. ■

About the author

Margareth Gagliardi is a research analyst for BCC Research. Contact Gagliardi at analysts@bccresearch.com.

Resource

M. Gagliardi, "Lead-free piezoelectric ceramics: Technologies and global opportunities" BCC Research Report NAN063A, November 2019. www.bccresearch.com. ■

Meet ACerS president Tatsuki Ohji

By Eileen De Guire


(Credit: ACerS.)

I had the opportunity to talk with president Tatsuki Ohji during the 2019 Annual Meeting about his background and goals for his year at the Society's helm. I hope you enjoy getting to know Ohji as much as I did.

How did you find your way to a career as a ceramic materials researcher?

TO: I am currently a Fellow scientist of the National Institute of Advanced Industrial Science and Technology (AIST), which is one of the biggest national research institutes in Japan. AIST deals with a variety of research fields related to industrial technologies, including energy, environment, bio, IT, materials, chemistry, electronics, manufacturing, geological survey, and metrology.

When I was a graduate student of mechanical engineering, I took a civil service examination of the Japanese government, and I luckily passed it. I was given a list of positions which the government was filling, and one of them was a researcher position on "mechanical property characterization of advanced ceramics" in AIST. It looked very interesting to me because advanced ceramics were called "new dream materials" at that time, so I took it.

How did you learn about ACerS, and what has been your experience as a Society leader?

TO: More than 30 years ago I first submitted my paper to the *Journal of the American Ceramic Society*. When I received the review, I was so amazed and moved to see a lot of valuable, informative, and suggestive comments on my work, and I truly appreciated the kind help of an unknown reviewer, who shared their precious time for an unknown young person outside of the United States like me. I strongly hoped that I would become such a person. Since that time, this Society has been the best "mentor" to me. I have been raised and trained as a scientist by this Society.

> **"I have been raised and trained as a scientist by this Society."**

My first voluntary work for ACerS was organizing a symposium in the Engineering Ceramics Division's International Conference on Advanced Ceramics and Composites, which was held in Cocoa Beach then, but now is in Daytona Beach. ECD people like Jay Singh strongly encouraged and pushed me to do so. I think without their strong encouragement and help, I would not have been able to get involved like I am now, and I am most grateful to them for their encouragement and support. I owe a lot to The American Ceramic Society, and it is my great pleasure to work for this Society and return the favor.

What are your goals for your presidential year?

TO: ACerS strategic plan already provides several goals, but I have some goals upon which I would like to place special importance during my term.

One of the most important matters during my presidency will be MS&T20 and our Annual Meeting, which will be held October 2020 in Pittsburgh. Our goals are to brand ACerS Annual Meeting as a key component of MS&T; create a warm, friendly, and inclusive ACerS community environment; engage Divisions as primary programming units; and encourage Divisions to coorganize symposium with other Divisions and societies.

The next goal is about globalization. As you see from the fact that I have become the president, The American Ceramic Society is truly an international organization representing an international community. It is critically important for us to foster and fortify solidarity and friendship with other ceramic communities worldwide.

Next is about diversity and inclusion. As you know, we are striving to achieve diversity and inclusion in ACerS leadership. When I nominated 33 committee members this May, I worked to create a balance in terms of gender, work sector, and residence place, and I am pleased to let you know that of the 33 appointments, 15 are women, 12 are from abroad, and 16 are from industry. What I have found is we have so many capable members who are willing to serve ACerS's committees.

The last goal that I would like to emphasize is about encouraging volunteering. Volunteering is one of the best ways to get connected with ACerS. I myself was able to create an invaluable worldwide human network through voluntary works for ACerS, and it was possible because I had strong encouragement and support from my friends. I strongly hope that ACerS members, particularly young members, will have similar great opportunities and invaluable experiences volunteering with ACerS and will create their own global human networks.

Please tell us about your life outside the world of ceramics.

TO: My wife's name is Sami. We have two sons. The eldest son is also married and has two kids, a boy and a girl. I am a grandpa.

I make a point of swimming every day in a public swimming pool nearby to my house. I have two purposes. One is to maintain health. The other is to be relaxed. I feel very relaxed after swimming. No matter how busy, I try to swim every day.

My motto is "Do your best." As some know, I am a stammerer. When I was a young child I was a heavy stammerer, but as I grew up, it was gradually cured, at least when speaking Japanese. But in

English my stammer has not yet been cured, particularly when presenting a paper in an international conference. The mechanism of stammering has not yet been well clarified. But, the only solution for not stammering is practice. I have found this has been very useful to me. During such long rehearsal, I can improve the presentation. I can deepen discussion on the results and can prepare answers for various potential questions. I can clarify significance and weakness of that research and identify the next step.

In life there are many obstacles to overcome. I think that trying to do your best for surmounting an obstacle always brings something wonderful to you that you do not get if you do not have that obstacle and do not try to surmount it. ■

Highlights from ACerS 121st Annual Business Meeting

By Lisa McDonald

(Credit all images: ACerS)

Tatsuki Ohji (left) accepts the ACerS presidency from Sylvia Johnson with the transfer of the ceremonial ceramic gavel.

The American Ceramic Society held its 121st Annual Business Meeting, a part of ACerS Annual Meeting at MS&T, in Portland, Ore. ACerS Annual Meeting at MS&T brings together members from the whole Society as the meeting's technical content spans all aspects of ceramic and glass science, from refractories and aerospace to bioceramics and more.

At the Annual Business Meeting, the ACerS president reports on the state of the Society, and the new president outlines plans for the coming year. President Sylvia Johnson reported on the Society's "ongoing process" of promoting diversity and inclusion in the Society, for example, by adding a diversity statement to the ACerS Constitution and implementing new antiharassment and code of conduct policies.

Treasurer Stephen Houseman reported that the Society's financial position is strong, and the Society carries no debt. New officers were sworn-in, and out-going officers were recognized and thanked for their service. Incoming president Tatsuki Ohji outlined his vision and goals for his year as president (see details on previous page). During his opening speech, Ohji noted how his election represents ACerS commitment to diversity. "The fact that I became president shows we are a truly international society," Ohji says.

Iowa State University distinguished professor Steve Martin talks about how climate change is a "catalysis for change" during the comment period following the Annual Business Meeting.

That evening (Sept. 30, 2019), ACerS recognized the achievements of its members at the Annual Awards Banquet, including 20 members elevated to Fellow Status and three members awarded the distinction of Distinguished Life Member.

In addition to the Annual Business Meeting, the nearly week-long Annual Meeting contained various opportunities for updates on different parts of the Society, including meetings of the Board of Directors, division executive committee and business meetings, and meetings of ACerS working committees and subcommittees. The Society's student leadership group, the President's Council of Student Advisors, also holds its annual meeting during that week. This year PCSA includes 42 students from 28 universities, representing five countries.

View images from the many activities that occurred during the Annual Meeting on ACerS Flickr website at http://bit.ly/ACerSAnnualMeeting2019.

ACerS 122nd Annual Meeting at MS&T20 will take place Oct. 4–8, 2020, in Pittsburgh, Pa. ■

SOCIETY, DIVISION, SECTION, AND CHAPTER NEWS

Remembering former president James R. Johnson

Former ACerS president and Distinguished Life Member James Johnson died Oct. 18, 2019, at the age of 96. Johnson earned his Ph.D. in ceramic engineering from The Ohio State University and worked for 3M Company for 23 years, completing his career with 3M as director of physical sciences and executive scientist. He joined the Society in 1947 and was a member of ACerS Basic Science Division, serving as chair 1955–1956. In 1961, Johnson was elevated to Fellow, and he served as president of the Society 1973–1974. In 1981, the Society awarded him Distinguished Life Membership, its highest honor.

A keen researcher, Johnson held 54 patents. John (Jack) Wachtman (also an ACerS Fellow and Distinguished Life Member) recalls meeting Johnson at conferences and discussing future directions for ceramic research and the role of ceramics in technology. "Jim was a strong believer in initiative and creativity and self-reliance," Wachtman recalls. Although the proprietary nature of Johnson's research prevented him from sharing details, he nonetheless "seemed to me to have a broad dedication to the field of ceramic research and a strong sense of dedication to the U.S.A. He was public spirited," says Wachtman.

After retirement, Johnson went on to teach as an adjunct professor at two universities, including the University of Wisconsin–Stout, which awarded him an honorary Ph.D. He was a member of the National Academy of Engineering, belonged to the 3M Carlton Society, and contributed as a board or committee member for numerous nationwide technology organizations.

Johnson's wife, Virginia, survives him, along with five children, 13 grandchildren, and nine great-grandchildren. ■

A cartoon by Johnson from the *Bulletin* Vol. 52 Iss. 8 "President's page" article.

Corporate Partner news

We are pleased to welcome the following Corporate Partners:

- **Object Research Systems, Inc.**
- **Pacific Ceramics, Inc.**

For more details contact Kevin Thompson at 614-794-5894 or kthompson@ceramics.org. ■

Planning to attend an ACerS meeting in 2020?

ACerS members receive discounted rates to attend all ACerS-hosted meetings, which saves you more than the cost of membership. Check your membership status before you register. If you wish to register and renew your membership at the same time, the Registration + Membership Renewal option will allow you to do so with a single payment. Nonmembers will want to join ACerS prior to registering to receive the same membership discounts.

If you are unsure of your current membership status or expiration date, check out your "Personal Snapshot" when you log in to the ACerS website at www.ceramics.org. You may contact customerservice@ceramics.org or call us at 614-890-4700. ■

St. Louis Section/RCD 56th Annual Symposium on Refractories set for March 24–26

The 56th Annual Symposium on Refractories takes place in St. Louis, Mo., at the Hilton St. Louis Airport Hotel on March 24–26, with the theme "Properties and Performance of Refractory Ceramics —A Tribute to Richard C. Bradt." Plan to attend the kickoff event on March 24. Coprogram chairs are Kelley Wilkerson and Jeff Smith (Missouri University of Science & Technology).

For complete details visit http://bit.ly/56thRCDSymposium. Contact Patty Smith at 573-341-6265; fax, 573-341-2071; or psmith@mst.edu with questions. ■

Are you a "webinista"?

ACerS wants you to share your knowledge with your fellow members by participating as a presenter in the 2020 ACerS Webinar Series.

Some of the requested topics include: Learning from Failures in Research; Women in Science: Trials and Tribulations; The Decision to do a Ph.D.; and Public Policy.

If you are interested in presenting on a topic mentioned above—or you have levelled up to 'expert' on a ceramic/glass specific topic—reach out to Yolanda Natividad at ynatividad@ceramics.org to be a potential webinar presenter in 2020. All we ask is that your proposed topic is educational and not promotional in nature.

ACerS members have access to view recordings of past webinars as a benefit of your membership at ceramics.org/webinars. ■

Volunteer Spotlights

ACerS is pleased to announce **Victoria L. Blair** and **Brian Gilmore** have been selected for November and December's Volunteer Spotlight, a program through which we recognize a member who demonstrates outstanding service to The American Ceramic Society through volunteerism.


Blair

Blair received her Ph.D. in ceramics from Alfred University (New York State College of Ceramics) in 2014. She joined the Army Research Lab as a post-doctoral fellow in June 2014 and has conducted research on solid state materials for lithium-air batteries, magnetic field processing of transparent alumina, and synthesis of transparent nanocomposites as a laser host material. Now a staff materials engineer at ARL, Blair focuses on the area of transparent ceramics for Army applications, primarily infrared transparent windows for sensor protection. As a volunteer for ACerS, Blair served in several roles, first as a founding member of the President's Council of Student Advisors and now as the mentor-at-large for the PCSA. She is also the cochair of the Washington DC/Maryland/Northern Virginia Section of ACerS. ■


Gilmore

Gilmore is a staff engineer at Pioneer Natural Resources. He earned a Doctor of Philosophy in ceramic engineering from Missouri University of Science and Technology.

For the past nine years, Gilmore served on the Keramos Professional Fraternity Board of Directors. Additionally, he volunteered to judge the undergraduate student speaking contests and helped organize the student mug drop and disc golf competitions at each ACerS Annual Meeting at MS&T. He also participated in the ACerS Education Integration Committee (EIC) and Education and Professional Development Council (EPDC) over the past five years.

We extend our deep appreciation to Blair and Gilmore for their service to our Society! ■

In memoriam

Edna Dancy	*Joanna McKittrick*
James R. Johnson	*Fred Stover*
Burton Kushner	*Victor Tennery*

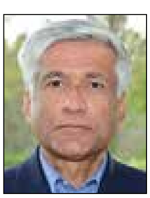
Some detailed obituaries can be found on the ACerS website, www.ceramics.org/in-memoriam.

Society, Division, Section, and Chapter news (continued)

Names in the news

Credit: AZU

Alexandra Navrotsky joined the faculty of Arizona State University and celebrated the opening of the new Navrotsky Eyring Center for Materials of the Universe in October 2019.

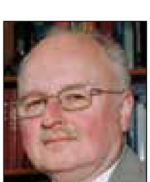


Choudhary

Manoj Choudhary delivered the prestigious Atma Ram Memorial Lecture at the Central Glass and Ceramic Research (CGCRI) Institute in Kolkata, India, on Oct. 15, 2019. CGCRI is the national research institute under the Council of Scientific and Industrial Research (CSIR), India.

Richardson

Kathleen A. Richardson received the 2020 SPIE Maria J. Yzuel Educator Award for outstanding contributions to optics education by a SPIE instructor or an educator in the field.



Tuller

Harry Tuller received the Thomas Egleston Medal this past May 30, 2019, from Columbia University Engineering Alumni Engineering Association. The Medal recognizes distinguished achievement in engineering or applied science. ■

AWARDS AND DEADLINES

Last call for 2020 award nominations

Nominations for most ACerS Society awards, including Distinguished Life Member, Morgan Medal and Global Distinguished Doctoral Dissertation, Kingery, Du-Co Ceramics Young Professional, Jeppson, Coble, Corporate Achievement, Spriggs, Friedberg, and Fulrath, are due **Jan. 15, 2020**.

For more information, visit www.ceramics.org/awards or contact Erica Zimmerman at ezimmerman@ceramics.org.

Please note that the 2020 Purdy Award will be for papers published in 2018. Nomination details can be found at: ceramics.org/awards. ■

Art, Archaeology & Conservation Science Division announces new award

The Anna O. Shepard Award honors pioneering work in the analysis and description of pottery and ceramics from 1930 to 1973. The award is presented to an individual(s) who has made outstanding contributions to materials science applied to art, archaeology, architecture, or cultural heritage. The contributions could be an artistic creation, an archaeological study, or significant materials research. The deadline for nominations is **Jan. 15, 2020**. For more information visit http://bit.ly/AnnaOShepardAward. ■

ECD best poster winners from ICACC 2019

The Engineering Ceramics Division has announced the best poster winners from the ICACC 2019 meeting held last January in Daytona Beach, Fla. The awards will be presented during the plenary session at ICACC 2020. Congratulations to the authors of these award-winning posters.

2019 Best Poster Awards

First place

Preparation and characterization of cation substituted Na_3SbS_4 electrolyte with Na^+ ion conductivity

N. Masuzawa, **S. Yubuchi**, **A. Sakuda**, **A. Hayashi**, and **M. Tatsumisago**

Second place

Diamond-ceramic composites by reactive hot-pressing

J. LaSalvia, **K. D. Behler**, **A. A. DiGiovanni**, **T. Shoulders**, **S. D. Walck**, and **L. Vargas**

Joint third place

Residual stress free joining of liquid-phase sintered SiC ceramics using a SiC tape

Y. Kim and **Y. Kim**

Using AE energy and frequency analysis to characterize damage in SiC/SiC minicomposites

A. J. Gorven, **A. S. Almansour,** and **J. D. Kiser**

Trustee Award

Preparation of nanoceramic materials by needleless electrospinning

I. Shepa, **E. Mudra**, **M. Vojtko**, **J. Dusza**, and **V. Medvecka** ■

2018–2019 Global ambassador awardees

The Global Ambassador Program recognizes dedicated ACerS volunteers worldwide who demonstrate exceptional leadership and/or service that benefits the Society, its members, and the global ceramics and glass community.

ACerS 2018–2019 president Sylvia Johnson selected the following nine volunteers for the Global Ambassador Award:

– **Dileep Singh**, Argonne National Laboratory
– **Toshihiro Ishikawa**, Tokyo University of Science
– **Henry Colorado**, Universidad de Antioquia
– **Steven Tidrow**, Alfred University
– **Jon Binner**, University of Birmingham
– **Kyoung Il Moon**, Korea Institute of Industrial Technology
– **Marissa Reigel**, Savannah River National Laboratory
– **Dana Goski**, Allied Mineral Products, Inc.
– **Kristen Brosnan**, GE Global Research Center ■

STUDENTS AND OUTREACH

Attention students and young professionals: Going to ICACC20 or EMA20? Don't miss these events, especially for you

Make sure to attend the student and young professional activities being offered at the Electronic Materials and Applications (EMA 2020) conference and the 44th International Conference and Expo on Advanced Ceramics and Composites (ICACC 2020).

EMA 2020 student events

• Student and Young Professional Networking Mixer, Jan. 23, 5:30 – 6:30 p.m.

• Journal Workshop: Expand your impact, Jan. 22, 12:30 p.m. – 1:30 p.m. Preregistration is requested.

• We hope to offer the Lunch with a Pro program again this year. Keep an eye out for more information delivered to your inboxes and posted on social media.

• Finally, be sure to connect with fellow attendees by indicating your attendance via the EMA Facebook event page. Search "EMA 2020" on Facebook to find the event.

See: https://ceramics.org/student-events-ema20

ICACC 2020 student events

• Student and Young Professional Networking Mixer, Jan. 27, 7:30 – 9 p.m.

• Journal Workshop: Expand your impact, Jan. 28, Noon – 1 p.m. Preregistration is requested.

• Shot Glass Competition (organized by ACerS PCSA), Jan. 28, 6:45 – 8 p.m.

• Student and Industry Failure Trials (SIFT) Competition (organized by ACerS PCSA), Jan. 29, 5:30 – 7:30 p.m.

• The Lunch with a Pro program will be offered on Monday, Jan. 27 at noon, and Wednesday, Jan. 29 at noon. Register to participate.

• Share your comments, photos, videos, selfies, and other shareworthy content on Facebook or Twitter using the hashtag #ICACC20 and you will be entered to win a $50 gift card! We will give away one per day (Jan. 27–29).

• Finally, be sure to connect with fellow attendees by indicating your attendance via the ICACC Facebook event page. Search "ICACC 2020" on Facebook to find the event.

See: https://ceramics.org/student-events-icacc20 ■

Student and Outreach (continued)

Register today for ACerS Annual Winter Workshop

ACerS Winter Workshop, sponsored by The Ceramic and Glass Industry Foundation, is being held in conjunction with the 44th International Conference and Expo on Advanced Ceramics and Composites, Jan. 24–28, 2020, in Daytona Beach, Fla. The Winter Workshop provides a combination of technical and professional development sessions designed specifically for students and young professionals. Find out more or register at https://ceramics.org/winter-workshop-2020. Students attending EMA20 are welcome to attend. Contact Belinda Raines at braines@ceramics.org for information. ■

ACerS GGRN for young ceramic and glass researchers

Global Graduate Researcher Network (GGRN) aims to help graduate students

- Engage with The American Ceramic Society (ACerS),
- Build a network of peers and contacts within the ceramic and glass community, and
- Have access to professional development tools.

Are you a current graduate student who could benefit from additional networking within the ceramic and glass community? Visit www.ceramics.org/ggrn to learn what GGRN can do for you, or contact Yolanda Natividad at ynatividad@ceramics.org. ■

Post-MS&T19 Conference students tour national laboratory

ACerS 2019 Student Tour attendees on the grounds of the Pacific Northwest National Laboratory (PNNL) alongside PNNL staff, including Suresh Baskaran, director of research partnerships (left).

After a successful ACerS Annual Meeting at MS&T19, 18 undergraduate and graduate students participated in a tour organized by the ACerS President's Council of Student Advisors at the Pacific Northwest National Laboratory (PNNL) located in Richland, Wash. The students, representing 11 universities from across the country, were welcomed by Suresh Baskaran, director of research partnerships at PNNL, along with PNNL scientists who represent diverse fields of cutting-edge research. The students were introduced to PNNL's interdisciplinary, collaborative culture, as well as career opportunities, internships, and the Distinguished Graduate Research Programs where graduate students can conduct part of their dissertation research in collaboration with PNNL.

Students received an overview of materials science at PNNL and toured several laboratories located on campus. One of the laboratories visited was the Wasteform Development Lab, the key to the nation's quest for the safe, long-term storage of nuclear waste. The students also toured the Environmental Molecular Sciences Laboratory, the Atomic Force Microscopy, and Advanced Battery Facility.

Throughout the day, the students learned about advanced equipment used by PNNL scientists as well as the unique environment where these tools are used to characterize a variety of materials from inorganic nanoparticles and battery materials to biological samples.

For many, this tour was their first visit to a national laboratory. The visit was organized in partnership with The American Ceramic Society. ■

"The tour offered students the chance to see the national laboratory's cutting-edge scientific instrumentation and unique facilities for research and development on advanced batteries, solid oxide fuel cells, glass and ceramic wasteforms, and more"

— Suresh Baskaran, PNNL, director of research partnerships

CERAMICANDGLASSINDUSTRY FOUNDATION

ACerS members volunteer for teacher outreach


A teacher is wowed by a materials science demo.

The Ceramic and Glass Industry Foundation (CGIF) recently participated as an exhibitor at the National Science Teaching Association (NSTA) Regional Conference which took place Nov. 14–16, 2019, in Cincinnati, Ohio. We are grateful for the following ACerS members who volunteered their time and expertise at the event:

Tom Arbanas (Du-Co Ceramics), **Stephanie Chapman** (Emerson Electric), **Jake Wieland** and **Paul Kramer-Arndts** (AluChem), **Victor Arulapppan Pushparaj** (Wright State University), **Ian Prendergast** (retiree), and **Tulsi Patel** (Air Force Research Lab).


Left to right: Tulsi Patel, Tom Arbanas, and Victor Arulapppan Pushparaj.

The volunteers helped teachers understand ceramic and glass scientific concepts and demonstrated lab activities from the CGIF's Materials Science Classroom Kit at the conference.

The CGIF appreciates the dedication of these volunteers who share our commitment to student and teacher outreach, as we all strive to encourage more students to become involved in ceramic and glass science and engineering.

Similar volunteer opportunities will be available in April 2020: the NSTA National Conference in Boston (April 2–5) and the USA Science and Engineering Festival in Washington, DC (April 24–26). If you think you may be interested in participating, contact Belinda Raines at braines@ceramics.org. ■

Paul Kramer-Arndts, left, and Jake Wieland, right.

ceramics in the environment

Optical fibers for earthquake monitoring head undersea

Lawrence Berkeley National Laboratory researchers have now taken their research using optical fibers to monitor seismic quakes undersea.

In February, Berkeley Lab researchers led by Jonathon Ajo-Franklin reported on using "dark fibers," installed fiber-optic cables that currently lay unused, to detect earthquakes on land. Specifically, they investigated using dark fibers for distributed acoustic sensing (DAS), a sensing system that measures strain by relying on fiber-optic cables' high sensitivity to deformations.

The results from that experiment were promising. However, monitoring seismic quakes on land is only part of constructing a robust seismographic network. "One of the blank spots in the seismographic network worldwide is in the oceans," Ajo-Franklin says in a recent University of California, Berkeley press release.

Marine waters cover more than 70% of the Earth's surface, and some of the largest tsunamis are caused by subduction of tectonic plates far away from land. In some cases, land-based seismometers monitoring these regions are more than 100 miles away, hindering prediction speed and accuracy, according to Columbia University professor Spahr Webb in an article in *The Atlantic*.

Monitoring seismic quakes caused by plate tectonics closer to the source would greatly improve tsunami prediction. But "it is challenging to put instruments like seismometers at the bottom of the sea," UC Berkeley professor Michael Manga says in the press release. Fortunately, just as fiber-optic cables detect seismic waves on land, fiber-optic cables could be used for DAS underwater as well.

Ajo-Franklin (now a professor at Rice University) and his colleagues Nathaniel Lindsey (graduate student under Manga, UC Berkeley) and T. Craig Dawe (technical support manager, Monterey Bay Aquarium Research Institute) employed 20 km (12.4 mi) of a 52-km undersea fiber-optic cable as a seismic array to study the fault zones under Monterey Bay. The cable normally supports the Monterey Accelerated Research System, but it was off during a four-day maintenance period in March 2018.

As explained in the press release, the researchers "were able to measure a broad range of frequencies of seismic waves from a magnitude 3.4 earthquake that occurred 45 kilometers inland near Gilroy, California, and map multiple known and previously unmapped submarine fault zones, part of the San Gregorio Fault system." They also detected steady-state ocean waves and storm waves, and their measurements matched those gathered by buoy and land seismic monitors.

"This research shows the promise of using existing fiber-optic cables as arrays of sensors to image in new ways," Manga says.

Credit: Official U.S. Navy Page, Flickr (CC BY 2.0)

United States Navy personnel remove corroded zinc anodes from an undersea cable. Traditionally used to transmit data, undersea cables could offer a way to monitor underwater seismic quakes closer to the source.

While using dark fibers for seismic monitoring holds a lot of potential, Ajo-Franklin and Lindsey hope to take the research a step further by using lit fiber-optic cables for seismography.

Lit fiber-optic cables refer to fiber-optic cables actively used for data transmission. To use lit fiber-optic cables for seismic monitoring, laser pulses need to be able to travel through one channel in the fiber without interfering with other channels carrying independent data packets.

Ajo-Franklin and Lindsey are conducting experiments now with lit fibers, and they also plan to conduct fiber-optic monitoring of seismic events in a geothermal area south of Southern California's Salton Sea, in the Brawley seismic zone.

The paper, published in *Science*, is "Illuminating seafloor faults and ocean dynamics with dark fiber distributed acoustic sensing" (DOI: 10.1126/science.aay5881). ■

research briefs

Developing sturdier bioglass capsules for RFID tracking devices

Researchers from Florida A&M University took on the challenge of understanding the causes of the high failure rates of trackers implanted in blackbuck antelopes at a local wildlife preserve.

The trackers are based on radio frequency identification (RFID) technology. RFID devices are widely used in data storage applications, as they have larger memories than barcodes. In RFID devices, a transponder receives power via electromagnetic radio waves emitted by an electronic reader, and then the transponder sends back the requested information to the reader.

For tracking highly active animals, RFID devices are implanted into the animals. Not only must the implanted container protect the device from physical damage and corrosion, it must also be biocompatible to prevent harming the animal.

Bioglass meets these requirements, and bioglass encapsulated RFID devices have been successfully deployed in pets for quite some time. But the brittleness of bioglass is a serious shortcoming when implanted into animals that butt heads for dominance, like sheep and oxen.

The Florida A&M researchers chose three-point bending for failure testing the bioglass-encapsulated RFID devices. Even with specially designed clamps and static loading, they noted a wide variation in flexural strength of the bioglass capsules.

With the flexural strength of the capsule, and the peak forces produced by the antelope while fighting, the researchers used finite element analysis to stress maxima within the capsules. They used three different force distribution models to represent possible force modes in the animals:

- Three-point bending for a single point of external contact on a capsule perched on two bones,
- Forces distributed across both sides for broad contact on a capsule laying on a flat spot, and
- Force distributed on one side against two contact points to simulate a mixture of the other two situations.

Not surprising, all models show that stresses in the capsule exceeded the flexural failure strength when the maximum fight-


Credit: Godwingk, YouTube

Bioglass-encapsulated RFID devices used for tracking animals that butt heads may be less brittle in the future, based on research published in a recent ACerS journal.

Research News

A record-setting transistor

University of Delaware researchers created a high-electron mobility transistor, a device that amplifies and controls electrical current, using gallium nitride with indium aluminum-nitride as the barrier on a silicon substrate. Among devices of its type, this transistor has record-setting properties, including record low gate leakage current (a measure of current loss), a record high on/off current ratio (the magnitude of the difference of current transmitted between the on state and off state), and a record high current gain cutoff frequency (an indication of how much data can be transmitted with a wide range of frequencies). For more information, visit https://www.udel.edu/udaily/research. ■

ing force is applied. Interestingly, all three models also showed stress concentration at the ends of the capsules where the tube meets the hemispherical cap. However, the capsules broke more toward the middle of the capsule than at the ends, which is predicted by the distributed force models.

The researchers proposed and tested several new designs for the capsules to improve reliability by reducing the internal stresses. One design emerged that met the dimensional requirements for the transponder while reducing stresses to below the failure strength limits.

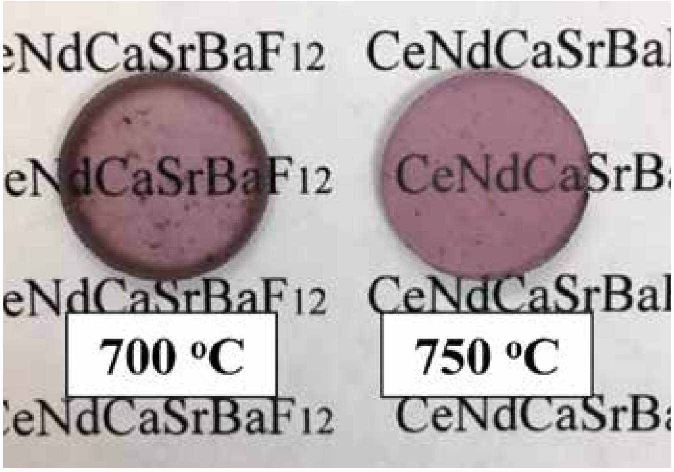
The open-access paper, published in the *International Journal of Ceramic Engineering & Science*, is "Understanding the failure of Bioglass 8625 transponder capsules used in tracking blackbuck antelopes" (DOI: 10.1002/ces2.10027).

High-entropy transparent ceramics hold high potential

A paper recently published by two Alfred University researchers in the *Journal of the American Ceramic Society* reports the development of a transparent high-entropy fluoride ceramic for the first time, which has great potential application as a laser material.

High-entropy materials (HEMs) are defined as solid solutions that consist of five or more elements of approximately equimolar composition. A solid solution is a multicomponent system in which all components remain in a single homogeneous phase. In the case of HEMs, the elements remain in one phase because the structure is "entropy stabilized," that is, HEM structure is stable due to entropy (a measure of disorder).

In studies, HEMs exhibit unique mechanical, physical, and chemical properties. However, the optical properties of HEMs have not been explored and studied fundamentally yet. So Xianqiang Chen and Yiquan Wu, post-doctoral researcher and professor, respectively, at Alfred University, explored optical properties in their study.



High-entropy fluoride-based transparent ceramics, sintered at 700°C and 750°C by vacuum hot pressing.

They chose to investigate high-entropy fluoride-based ceramics due to the advantages fluoride ceramics offer to optical applications, including their nonhygroscopic nature (does not readily absorb/retain moisture), relative ease of machining and polishing, high thermal conductivity, and high doping concentration. Already, "fluoride materials see application in such areas as lasers, scintillators, windows, and ultraviolet (UV) and vacuum ultraviolet (VUV) lenses," they add in the paper.

In an email, Wu says that single-phase fluoride ceramics have been investigated before, but not high-entropy fluoride ceramics, making this study the first investigation of high-entropy fluoride ceramic characteristics.

To create the first high-entropy fluoride transparent ceramic, Chen and Wu synthesized $CeNdCaSrBaF_{12}$ nanopowders via a coprecipitation method using commercially sourced products. The resulting powder was then consolidated under a vacuum hot-pressing method to reach full densification. Then, the researchers measured the ceramic's optical properties.

"The work shows that the $CeNdCaSrBaF_{12}$ transparent ceramics possess broad excitation bands in the visible and NIR regions, which are advantageous for its application as a laser material and will reduce its dependency on pumping wavelengths which, in turn, reduce the need for temperature control of the laser diodes," Wu says. "This [property] will make the high-entropy laser ceramic an attractive candidate for developing miniaturized laser devices."

In the future, Wu says they plan to investigate the atomic level microstructures of the high-entropy laser ceramics to understand the local atom environments of the dopant and the host materials.

The paper, published in *Journal of the American Ceramic Society*, is "High-entropy transparent fluoride laser ceramics" (DOI: 10.1111/jace.16842).

Research News

Researchers develop an optical fiber made of cellulose

Researchers from the VTT Technical Research Centre of Finland were able to transmit light in wood-based fiber. The core of the new optical fiber is made of cellulose, modified for the purpose using ionic solvents developed by VTT. A cladding made out of cellulose acetate surrounds the core. Cellulose-based fiber will not compete with glass-based optical fibers in telecommunications applications but is best suited for sensors that benefit from the biodegradability of the material. The R&D is still in its initial phases, so the researchers do not yet know all the applications for the new optical fiber. For more information, visit https://www.vttresearch.com/media/news.

Graphene: Softer through bending

In a recent paper, researchers from the University of Illinois at Urbana-Champaign and the National Institute for Materials Science in Japan aimed to understand what factors determine bending stiffness in graphene.

Since Andre Geim, Konstantin Novoselov, and their collaborators unambiguously produced and identified graphene in 2004, major advances have been made in both how the material is studied and how it is produced. Yet some of graphene's most fundamental properties—like bending stiffness—still are not completely understood.

"The bending stiffness of a material is one of its most fundamental mechanical properties," Edmund Han, materials science and engineering graduate student at the University of Illinois at Urbana-Champaign (UIUC), says in a university press release. "Even though we have been studying graphene for two decades, we have yet to resolve this very fundamental property."

The reason for this uncertainty comes from the fact that different research groups have come up with different values for bending stiffness—values that span across orders of magnitude.

"For monolayer graphene, literature values for its bending stiffness range from 0.83 to 10,000 eV," write Han and his collaborators in the paper. "Furthermore, the reported bending stiffness of bilayer graphene ranges across two orders of magnitude, from 3.4 to 160 eV, while values for trilayer graphene range from 7 to 690 eV."

In the paper, the researchers aimed to understand why such discrepancies in bending stiffness measurements exist. To do so, they fabricated heterostructures of few-layer graphene and draped it over atomically sharp steps of hexagonal boron nitride, which allowed them to systematically vary the thickness and degree of curvature in the graphene.

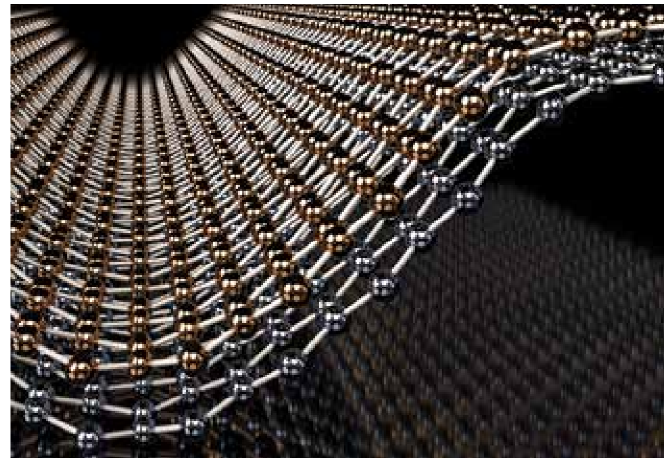
Through testing numerous curvature configurations and building atomic-scale models, they discovered why previous research efforts disagreed on bending stiffness. "They were either bending the material a little or bending it a lot," Jaehyung Yu, mechanical science and engineering graduate student at UIUC, says in the press release. "But we found that graphene behaves differently in these two situations."

"When you bend multilayer graphene a little, it acts more like a stiff plate or a piece of wood," Yu continues. "When you bend it a lot, it acts like a stack of papers where the atomic layers can slide past each other."

In the press release, UIUC professor Arend van der Zande explains how exciting it is that despite the supposed disagreements, the results show everyone was actually correct. "Every group was measuring something different," he says. "What we have discovered is a model to explain all the disagreement by showing how they all relate together through different degrees of bending."

In the paper's conclusion, the researchers note that though they focused on the properties of graphene, their conclusions should generalize to other van der Waals-bonded materials. Additionally, "these results will be important for the design of new classes of highly curved nanosystems such as nanoelectromechanical systems, stretchable electronics and origami structures made from 2D materials," they add.

The paper, published in *Nature Materials*, is "Ultrasoft slip-mediated bending in few-layer graphene" (DOI: 10.1038/s41563-019-0529-7). ■



Credit: Blanka Janicek (Pinshane Huang Lab), University of Illinois

Researchers from the U.S. and Japan found bending stiffness of graphene depends on how much you bend it.

Cold sintering offers financial, environmental benefits to ceramic manufacturing

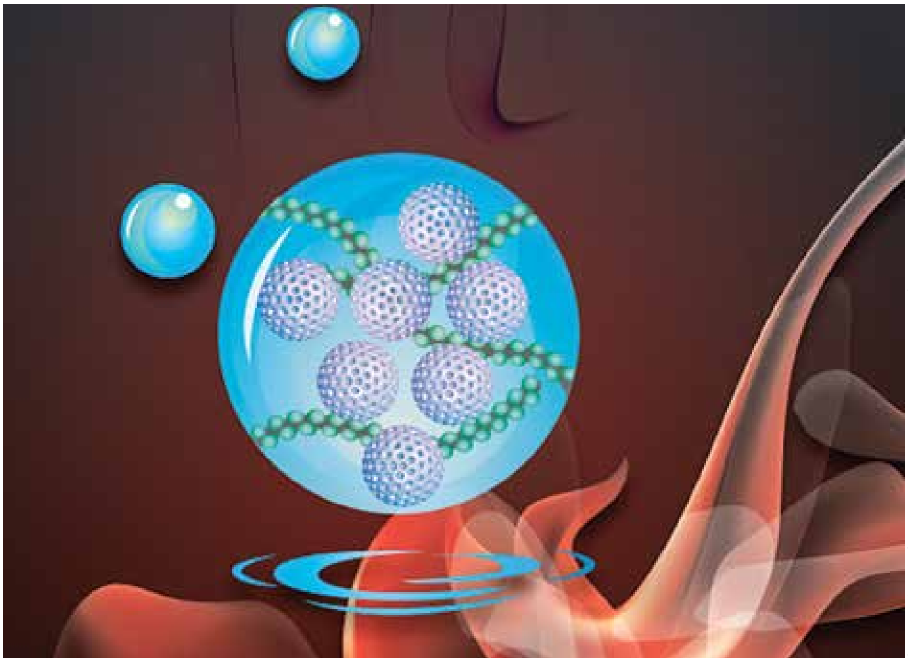
In an open-access paper coauthored by researchers from The Pennsylvania State University and colleagues in the United Kingdom, Norway, and Malaysia, the advantages the cold sintering process (CSP) offers to industry both financially and environmentally are investigated.

CSP is a dual-process technology that significantly reduces energy use in ceramic manufacturing by combining heat, pressure, and water to lower temperatures required to produce ceramics from more than 1,000°C to less than 300°C. Penn State researchers, led by ACerS Fellow Clive Randall, developed CSP in 2016. They and other groups have continued to refine CSP over the past few years.

In the paper, the researchers explain their reason for the study. "Despite the upsurge in research interests relating to developing low temperature sintering process, techno-economic analyses of CSP alongside existing sintering techniques such as traditional and spark plasma sintering (SPS) is lacking," they write in the paper. "Understanding the potential techno-economic impact of sintering techniques, manufacturing routes and materials composites is essential, ... [and] This research need is addressed in this paper using a robust techno-economic analysis framework derived from ranking mechanisms of marginal abatement cost curve (MACC) and Pareto optimisation."

The researchers considered three functional ceramics in their analysis: zinc oxide (ZnO), lead zirconate titanate (PZT), and barium titanate ($BaTiO_3$). Data for the duration of sintering operations and manufacturing routes for each ceramic under different sintering techniques were obtained from published research articles; capital costs and power ratings of equipment for each sintering technique were estimated based on current market prices as well as a mix of literature and heuristic information.

"By using pounds per tonne of CO_2 saved as a figure of merit to measure the cost-effectiveness of each sintering technique at the level of the laboratory, it was established that CSP is the most economically attractive sintering technique, indicating lower capital costs, best return on investment and a considerable reduction in CO_2 emissions ... even under projected mass production scenarios," the researchers conclude.



An artistic interpretation of cold sintering of ceramic particles (white) and polymer strands (green) using low heat to evaporate added water molecules (blue).

The researchers do note that transitioning CSP from laboratory to industry faces some challenges, including requiring hugely different facilities and instrumentation as well as relevant property/performance validation. However, based on the results of this analysis, the researchers urge industry to consider adoption.

"We find that there are clear financial and environmental benefits if the ceramics industry was to take the cold sintering process out of labs and into commercial manufacturing," Taofeeq Ibn-Mohammed, first author and assistant professor at the University of Warwick, says in a University of Warwick press release.

The open-access paper, published in *Journal of the European Ceramic Society*, is "Decarbonising ceramic manufacturing: A techno-economic analysis of energy efficient sintering technologies in the functional materials sector" (DOI: 10.1016/j.jeurceramsoc.2019.08.011). ■

Using sucrose as binder for MgO-C refractories

Researchers from China University of Geosciences and Hunan University of Humanities, Science and Technology in China investigated using a sucrose solution instead of phenolic resin as binder in MgO-C refractories.

Magnesium oxide is a widely used refractory material in furnaces and kilns due to its high melting point and strong corrosion resistance to alkaline slag. However, because of its large thermal expansion coefficient, MgO refractory products exhibit poor thermal shock stability.

To make MgO refractory products less susceptible to cracking, MgO is often combined with graphite to form MgO-C, a refractory material with improved porosity and thermal shock resistance.

Phenolic resin is a commonly used

Credit: David Goehring, Flickr (CC BY 2.0)

Sucrose may be an environmentally friendly alternative to phenolic resin binders in MgO-C refractories.

binder for MgO-C refractories. However, during the heat treatment process, phenolic resin releases pollutant gases, such as methyl aldehyde and phenols, which have harmful effects on both health and the environment.

Replacing phenolic resin with an environmentally friendly binder would be ideal, and sucrose is a possible option.

The researchers created refractories using fused magnesia and flake graphite as the main raw materials and added metal aluminum powder as an antioxidant. They prepared refractories with both phenolic resin and sucrose as binders to compare.

The researchers first studied the carbonization behavior of the sucrose binder using infrared spectroscopy and differential thermogravimetry.

"[I]t is known that free water and some easily decomposable substances in sucrose are decomposed in the temperature range from room temperature to 320°C; sucrose decomposes into CO_2 and H_2O in the temperature range from 320 to 800°C, and thermogravimetric curves are basically stable in the temperature range from 800 to 1400°C, indicating that sucrose has been decomposed, and carbonization completely produces a stable carbon structure in this temperature range," they write.

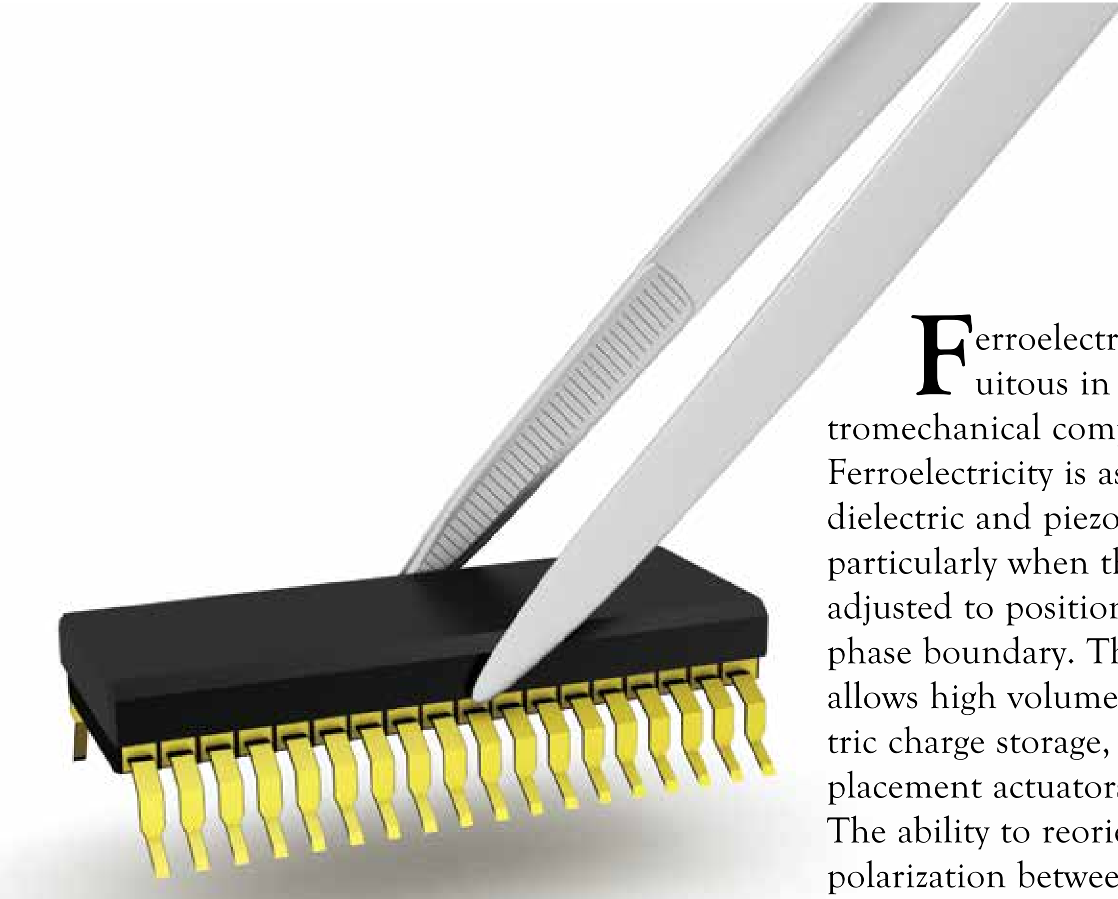
Knowing this information helped them understand flexural strength and compressive strength measurements. Specifically, sucrose-bonded MgO-C refractories showed higher flexural (5.59 MPa) and compressive (44.50 MPa) strengths when heat-treated at 180°C, lower strengths when heat-treated at 1,000°C, and increased flexural (4.51 MPa) and compressive (37.00 MPa) strengths when heat-treated at 1,500°C.

The researchers then compared flexural and compressive strengths of sucrose-bonded MgO-C refractories to refractories bonded with phenolic resin.

"Comparing the flexural strength and compressive strength of MgO-C refractories prepared with phenolic resin as binder, it can be seen that the flexural strength and compressive strength of the specimens obtained with phenolic resin as binder are slightly higher than those obtained with sucrose as binder after curing at lower temperature," the researchers write, "but overall, the difference was not large."

"Therefore, it is feasible to substitute phenolic resin with low-cost and environmentally friendly sucrose solution as binder for MgO-C refractories," they conclude.

The open-access paper, published in *IOP Conference Series: Materials Science and Engineering*, is "Preparation and properties of MgO-C refractories using sucrose as binder" (DOI: 10.1088/1757-899X/678/1/012092). ■



Impact of ferroelectricity

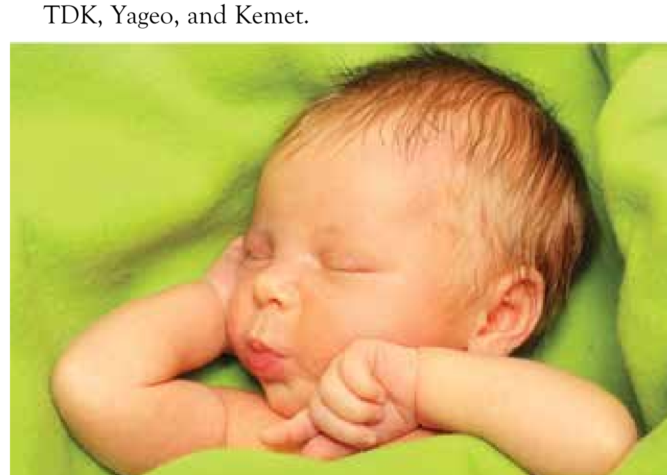
By Susan Trolier-McKinstry

Since the discovery of ferroelectricity 100 years ago, ferroelectric materials are everywhere in our electronics-based society. Learn how they drive a $7 billion industry.

Ferroelectric materials are ubiquitous in electrical and electromechanical components and systems. Ferroelectricity is associated with large dielectric and piezoelectric coefficients, particularly when the composition is adjusted to position the solid near a phase boundary. This characteristic allows high volumetric efficiency dielectric charge storage, as well as high displacement actuators at modest voltages. The ability to reorient the spontaneous polarization between crystallographically-defined states is essential in allowing poling of ceramic materials to obtain net piezoelectric or pyroelectric responses.

Capacitors

The largest industrial use of ferroelectric materials is in multilayer ceramic capacitors. The poor availability of mica-based crystals during World War II spurred development of air- and moisture-stable, high volumetric efficiency dielectrics. The subsequent dawn of the electronics age led to production of several trillion $BaTiO_3$-based capacitors around the world on an annual basis, with hundreds to thousands used in each current generation smart phone or computer. The size of this market is approximately $6 billion. Among the major capacitor suppliers around the world are Murata, Taiyo Yuden, Samsung Electromechanics, Kyocera (AVX), TDK, Yageo, and Kemet.



Medical ultrasound is the second most widely adopted imaging modality in medicine. It works thanks to ferroelectric materials.

The relatively closely-spaced ferroelectric phase transitions in $BaTiO_3$ enable a high relative permittivity over a broad temperature range. Equally important is the processing science that fostered progressive miniaturization of the dielectric layers thickness over the last several decades—the so-called Moore's law of capacitors—which has helped enable miniaturization of many electronic devices, including cellular phones.

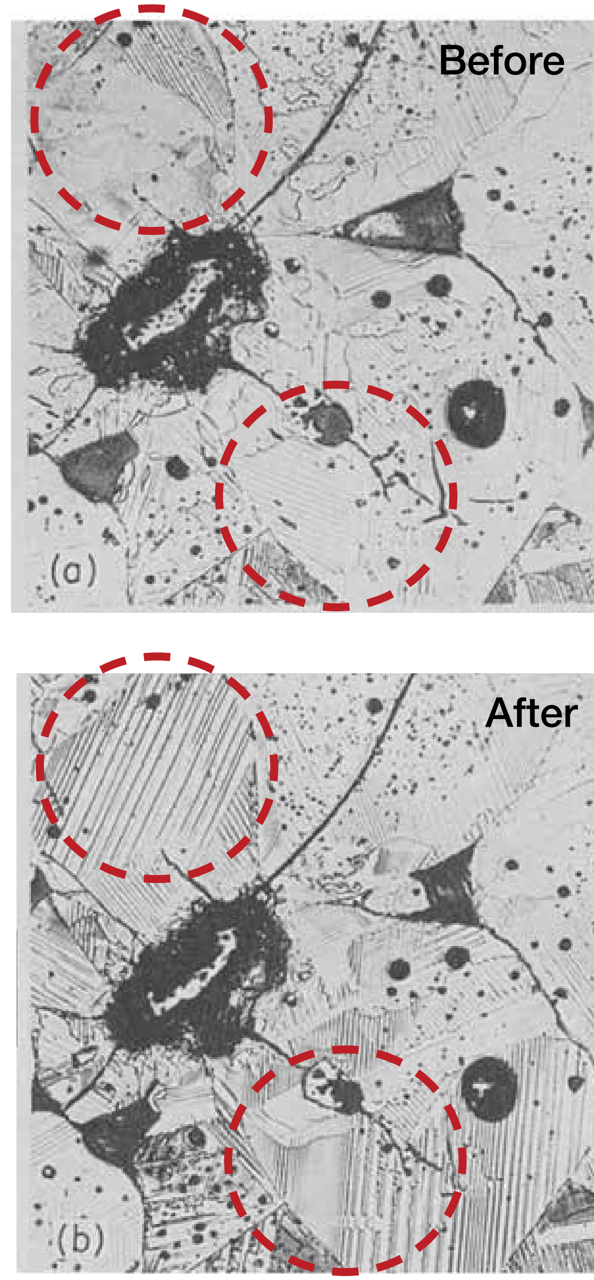
Industrial production is dominated by tape casting, electroding, and lamination to produce multilayer components at progressively decreasing case sizes. At present, commercial parts with layer thicknesses less than one micron with thin, highly-conductive nickel metal layers are readily available, with projected future miniaturization down to dielectric thicknesses of about 0.3 micron. The rich defect chemistry of these systems allows production of high reliability parts, even in the case where low oxygen partial pressure firing induces a high concentration of oxygen vacancies.

Piezoelectric applications

A second major use of ferroelectric materials is in piezoelectric ceramics, single crystals, and composites for actuators, sensors, and transducers. In the future, it is possible that ferroelectric piezoelectrics will also be widely adopted for kinetic energy harvesting systems for distributed low-power systems, including emplaced sensors for the Internet of Things. The world-wide piezoelectric ceramics market is approximately $1B annually. This market is dominated by lead zirconate titanate-based (PZT) materials; numerous formulations are utilized to tailor the piezoelectric responses, the coupling coefficients, and the field-induced hysteresis.

Among the main uses of these piezoelectrics are precise positioners, sonar systems, fish finders, medical ultrasound transducers, fluid flow meters, ultrasound systems for nondestructive testing, high precision accelerometers, transformers, and many other applications. Of these, medical ultrasound is the second most widely adopted imaging modality in medicine and offers tremendous capability in high resolution imaging of subsurface features without necessitating ionizing radiation (see image of infant). At this point, an enormous number of lives have been saved through the use of medical ultrasound employing ferroelectric–polymer composite transducers. Notably, the diversity of form factors and compositions needed for this range of applications of piezoelectric materials means that production for any given component in the piezoelectrics markets tend to be smaller. There are numerous suppliers of piezoelectric ceramics, including Channel Technologies, Murata, American Piezoceramics, Piezo Kinetics, Meggitt (Ferroperm), Morgan Electroceramics, TDK, PI Ceramics, Sinocera, and many others. In other cases, ferroelectric single crystals are used for domain engineered high strain piezoelectrics, or for surface acoustic wave devices.

While capacitors and piezoelectrics comprise two of the largest uses of ferroelectric materials, many other electrooptic components are also of commercial importance, e.g., $LiNbO_3$ for frequency doublers, optical modulators, and more; positive temperature coefficient of resistance thermistors for self-limiting heaters; pyroelectric based room occupancy sensors and fire detectors; and computing memory elements (including PZT and $SrBi_2Ta_2O_9$).



Microstructure of barium titanate (a) before and (b) after application of an electric field. The ferroelectric response of barium titanate causes reorientation of its domain structure, most easily seen in the circled areas.

Credit: DeVRIES, R.C. and BURKE, J.E. (1957), Microstructure of barium titanate ceramics. *Journal of the American Ceramic Society*, 40: 200-206. doi:10.1111/j.1151-2916.1957.tb12603.x

About the author

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Prenatal ultrasound (left) and cardiac ultrasound (above).

Ferroelectricity—A revolutionary century of discovery

By Geoff Brennecka, Rachel Sherbondy, Robert Schwartz, and Jon Ihlefeld

A century after the discovery of ferroelectricity, we look at the physics that makes ferroelectric materials so useful and the research that got us here.

Imagine a young couple that has just "seen" their infant still in the womb for the first time after a routine ultrasound scan. What joy! This news is worth sharing, so they click an image of the monitor on their smartphones and send it to grandparents, family, friends, and their entire social media networks.

Meanwhile, across the medical campus, a recent retiree undergoes a cardiac procedure guided with real-time ultrasound scans to repair a blockage discovered, also with ultrasound. What relief! This patient just found out he will be a grandfather and now confidently awaits that day with anticipation.

Capsule summary

A SALTY START

University of Minnesota graduate student Joseph Valasek gave the first presentation on ferroelectricity in Rochelle salt in 1920. He could scarcely have predicted how his careful measurements would end up playing a fundamental role in many of today's technologies.

VERSATILE USES

The switchable spontaneous polarization that defines ferroelectricity directly enables applications such as nonvolatile ferroelectric random access memory, but many other applications, such as multilayer ceramic capacitors, are enabled by ferroelectric materials even without directly using the switchable polarization.

FUTURE FERRO

In the past 10 years, two new structural classes—including fluorite-structured HfO_2 and wurzite-structured (Al,Sc)N—joined the ferroelectric family and bring with them some potential technological superiority to traditional materials.

These routine activities of modern life are possible because of piezoelectric ultrasound transducers, many thousands of ferroelectric multilayer ceramic capacitors, and a host of other electronics, sensors, actuators, and devices based on ferroelectric materials.

Ferroelectrics have intrigued materials scientists since their first report in 1920 and first publication the following year.[1] The label "ferroelectric" can be slightly misleading, as only a small fraction of ferroelectric compositions contain iron. Rather, the nomenclature was adopted in recognition of the parallels between the newly discovered phenomenon of ferroelectricity and the already-familiar ferromagnetism, which originally was thought to be tied exclusively to iron.

The defining characteristic of a ferroelectric material is the existence of spontaneous dipoles within its crystal structure whose direction can be reoriented by the application of an electric field. In other words, all materials belonging to a polar point group are potentially ferroelectric, but it takes a demonstrated polarization reversal for the material to earn the title.[2] (See sidebar, "Genesis of hysteresis..."). This strict definition highlights an important conundrum: a variety of phenomena can produce polarization-vs-field measurements that suggest ferroelectricity, but they are instead artifacts masquerading as polarization reversal.[3] At the same time, only a small fraction of the applications enabled by ferroelectric materials directly take advantage of the switchable polarization. Instead, as summarized here, the tremendous utility of ferroelectric materials in modern life typically arises from phenomena associated with, but not necessarily directly leveraging, the full reorientation of this spontaneous dipole.

Discovery and early developments

In 1919, Joseph Valasek began his Ph.D. work at the University of Minnesota under professor W.F.G. Swan, who suggested that Valasek investigate the curious crystals of Rochelle salt ($KNaC_4H_4O_6{\cdot}4H_2O$). These crystals were relatively straightforward to grow and were already known to be piezoelectric, pyroelectric, and optically active. Annoyingly, they were also very sensitive to humidity, and nearly all of their interesting properties seemed to depend on everything, including temperature, electric field, and previous history.

Valasek's first task was to develop sensitive measurements that could finally pin down the properties of this mischievous Rochelle salt. Valasek's thesis and the associated publications are a veritable treatise on crystal physics and careful measurements. It is interesting to note that of Valasek's five papers in *Physical Review* on Rochelle salt, he is the sole author on four of them, and the seminal paper[1] reporting the first ever ferroelectric hysteresis loop received just over 200 citations in the ensuing century. The scientific enterprise certainly has changed!

Reading Valasek's papers, it is clear he imagined this new phenomenon would lead to new functionality and new devices, but he could scarcely have predicted how his care-

FERROELECTRIC TIMELINE

In the ferroelectrics community

1912
THE PREDICTION
Erwin Schroedinger proposes the word "ferroelectric" ("ferroelektrisch" in German) as the analogy of ferromagnetism for spontaneous electrifying of liquids when cooling

1920
THE DISCOVERY
Joseph Valasek, graduate student at the University of Minnesota, gives first presentation on ferroelectricity in Rochelle salt at the Meeting of the American Physical Society on April 23

1944–1946
PEROVSKITES ENTER
T. Ogawa and S. Waku (Japan, 1944), B. Wul and J.M. Goldman (Russia, 1945), and A. von Hippel (U.S., 1946) investigate ferroelectricity in $BaTiO_3$; R.B. Gray (U.S., 1945) showcases first operating poled $BaTiO_3$ transducer

1950–1955
PZT
Groups, including those of Shirane, Takeda, and Sawaguchi in Japan, explore the $PbTiO_3$:$PbZrO_3$ solid solution system

1952
FERAM PROPOSED
Ferroelectric random access memory (FeRAM) is proposed in Dudley Allen Buck's master's thesis

1971
HIGH VALUE PZT
B. Jaffe's group explains the importance of phase transitions in $PbTiO_3$:$PbZrO_3$

2000s
LEAD-FREE
Interest in identifying lead-free piezoelectric materials increases across the globe

In the world

1900
COMMERCIAL RADIO
Radio receivers become more practical and radio becomes a household item

1914–1918
WWI
World War I stretches from July 28, 1914, to Nov. 11, 1918

1939–1945
WWII
World War II stretches from Sept. 1, 1939, to Sept. 2, 1945, stimulating spending for the military sector

1942
DIGITAL COMPUTERS
The first digital computer (as recognized by the U.S. Patent office) is completed. The Atanasoff-Berry computer (ABC) is started in 1937 and work continues until 1942

1947
TRANSISTORS
Bell Laboratories successfully demonstrates the first transistor on December 23

1969
ARPANET DEBUT
The Advanced Research Projects Agency Network (ARPANET) debuted in the United States and made the technical foundation for the internet. Thus began the race for semiconductors and optics technology

1996
HANDHELD COMPUTERS
The first handheld computer (Palm Pilot) is available for purchase

2000
FLASH DRIVES
USB flash drives become an alternative to the floppy disc and CD for portable data storage

Figure 1. Timeline presenting development of ferroelectric materials alongside global advances at the time.

ful measurements of nonlinear dielectric response of finicky Rochelle salt crystals would end up playing such a fundamental role in so many technologies a century later. Figure 1 presents an approximate timeline of the development of ferroelectric materials from prediction in 1912 to discovery in 1920 to the first ceramic transducer in 1945 through to the present time's search for eco-friendly compositions. This history, juxtaposed against global advances at the time, gives interesting context to the significance of ferroelectric devices to the evolution of digital technology.

One thing that has not changed significantly since Valasek's time is that much of the funding devoted to development of new materials is driven by potential military applications. In Valasek's case, the interest was in detection of submarines. To this day, needs for improved materials for sonar remain a strong driver of ferroelectric and piezoelectric materials development. In fact, World War II spurred development of $BaTiO_3$, $Pb(Zr,Ti)O_3$, and $Bi_4Ti_3O_{12}$ based ferroelectrics roughly simultaneously in isolated groups in the United States, Japan, and Russia. This development, discussed in more detail below, is an excellent example of how the phenomenon of ferroelectricity enables otherwise unachievable performance even when the switchable polarization itself is only indirectly related to the application.

In the century since Valasek first discovered the ferroelectric effect, enormous research effort went into understanding these extraordinary materials and how to make them better, controlling their properties precisely, shrinking the size of components, and deploying them in new and novel applications. Much of that research was—and continues to be—reported in ACerS publications. The sidebar "Historically significant ferroelectrics papers" highlights key papers over the years that advanced the science and art that led to the implementation of ferroelectric components in devices we enjoy today.

It is worth noting that ferroelectric polymers, most notably polyvinylidene fluoride, do exist and find significant application. However, in this article we focus on inorganic, nonmetallic (i.e., ceramic) ferroelectrics, which are both more numerous and more widely used than their squishier counterparts.

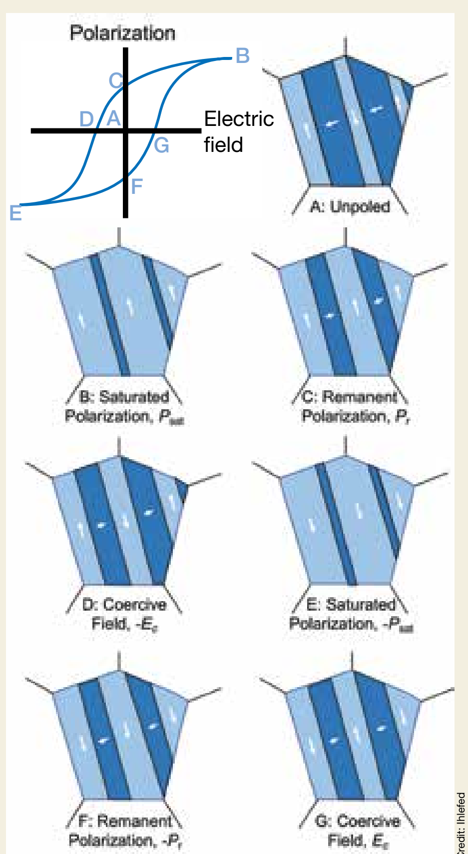
Fundamentals of ferroelectric ceramics

One of the most significant characteristics of ferroelectric ceramics is their ability to exhibit single crystal-like behavior even when fabricated as polycrystalline ceramics. In addition to typically being significantly less costly and easier to produce than single crystals, fabrication of polycrystalline ceramics also introduces opportunities for microstructure engineering and formation of complex shapes. Use of polycrystalline ceramics as piezoelectrics depends upon the ability to break full isotropic symmetry through the application of a poling field and thus relies on extrinsic effects (domain wall motion) in ferroelectrics. The sidebar "What does symmetry have to do with it" reviews the importance of crystallographic symmetry to piezoelectricity and ferroelectricity.

Intrinsic piezoelectricity is linear under small fields, so applying a +5 V field in one direction will produce equal and opposite strain to applying –5 V in the same direction. In a typical sintered polycrystalline ceramic, even if each of the billions of individual grains is piezoelectric, they all collectively cancel out their neighbors, and the net result is zero macroscopic piezoelectric response. This fact is why quartz piezoelectrics, such as those used for timekeeping in watches, must be single crystals.

Therefore, to use polycrystalline materials as piezoelectrics, the macroscopic

Genesis of hysteresis in ferroelectric materials



Polarization reversal is the defining characteristic of ferroelectric materials, and the hysteretic response is often represented as a plot of polarization vs. electric field, as shown schematically here. Diagrams A-G show how the domain structure responds to applied field in a single grain at different stages on the hysteresis loop. The colored regions represent domains in which all of the unit cells are collectively polarized in the direction of the arrow. In the initial unpoled state (A), the domain structure forms to minimize total energy, balancing charge, strain, and the energy penalty associated with formation of domain walls themselves. Application of an electric field gradually aligns domains (B) via the motion of domain walls to increase the volume of material polarized along with the external field; this maximum polarization is known as the saturated polarization (P_{sat}). When the external field is removed, the material relaxes (C) and some of the domain volume reorients to minimize strain and charge, but some residual net polarization is retained and is referred to as the remanent polarization (P_r). When an external field of the opposite polarity is applied, some volume of the domains reorient accordingly.The point at which the net polarization on the sample is zero (D) is the coercive cield, E_c, referring to the field required to coerce the sample into switching. Further increases in this polarity of field lead to a P_{sat}, and removal of the applied field lands the polarization at a value of $–P_r$. Subsequent field reversal will trace out an approximately symmetric hysteresis loop without ever returning to a stable net zero polarization unless, or until, the sample is 'depoled,' for example, by heating above the Curie temperature.

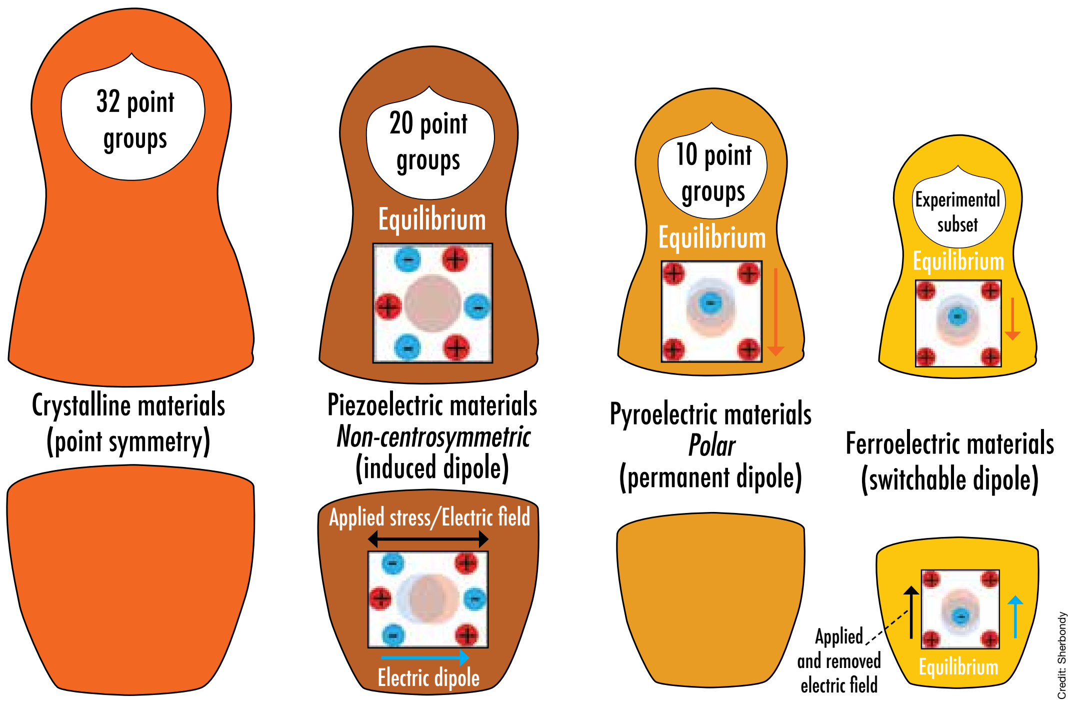


Figure 2. Of the crystalline or polycrystalline materials that exhibit piezoelectric behavior, some are pyroelectric, and of those, some are ferroelectric. Materials are classified into these categories based on the symmetry of their unit cell, which in turn dictates how they interact with thermal, electrical, and mechanical energies.

random symmetry of the grains must be broken in some way. One option is to force the grains to all (or at least mostly) grow in a coordinated direction. This approach is used for AlN thin films in MEMS resonators and clever ceramic processing approaches such as templated grain growth.[4] Another option is to start with a crystallographically random polycrystalline ceramic sample and break the macroscopic symmetry in some way, such as with the application of a large electric field. The applied field aligns crystallographic dipoles, and this "poling" process is enabled by the field-induced alignment of spontaneous dipoles, in other words, ferroelectricity (Fig. 2).

The outstanding properties of ferroelectric materials for piezoelectric and charge storage applications arise from a combination of intrinsic and extrinsic contributions. Ceramics based on barium titanate ($BaTiO_3$) dominate the capacitor market while lead zirconate titanate ($Pb(Zr,Ti)O_3$, PZT) based ceramics are the most widely used piezoelectric ceramic for more than six decades, finding applications in medical ultrasound transducers, sonar, micropositioners, and more. These materials are cubic and thus nonferroelectric at temperatures above T_C (the Curie temperature) and transform to a lower symmetry polar state below this temperature. Figure 3 shows how the ferroelectric phase transition occurs in the prototypic ferroelectric, $BaTiO_3$ (Fig. 3).

Historically significant ferroelectrics papers

H. Jaffe, (1958) Piezoelectric Ceramics, *JACerS*, **41**(11), 494–498.

H.A. Sauer and J.R. Fisher, (1960) Processing of positive temperature coefficient thermistors, *JACerS*, **43**(6), 297–301.

G.H. Haertling and C.E. Land, (1971) Hot-pressed $(Pb,La)(Zr,Ti)O_3$ ferroelectric ceramics for electroopic applications, *JACerS*, **54**(1), 1–11.

R.B. Atkin and R.M. Fulrath, (1971) Point defects and sintering of lead zirconate titanate, *JACerS*, **54**(5), 265–270.

K.A. Klicker, J.V. Biggers, and R.E. Newnham, (1981) Composites of PZT and epoxy for hydrostatic transducer applications, *JACerS*, **64**(1), 5–9.

N.H. Chan, R.K. Sharma, and D.M. Smyth, (1981) Non-Stoichiometry in undoped $BaTiO_3$, *JACerS*, **64**(9), 556-562.

A.I. Kingon and J.B. Clark, (1983) Sintering of PZT Ceramics 1: Atmosphere Control, *JACerS*, **66**(4), 253–256.

S.L. Swartz, T.R. Shrout, W.A. Schulze, and L.E. Cross, (1984) Dielectric properties of lead-magnesium niobate ceramics, *JACerS*, **67**(5), 311–315.

Y. Sakabe, (1987) Dielectric materials for base-metal multilayer ceramic capacitors, *ACerS Bulletin*, **66**(9), 1338–1341.

W. Pan, Q. Zhang, A. Bhalla, and L.E. Cross, (1989) Field-forced antiferroelectric-to-ferroelectric switching in modified lead zirconate titanate stannate ceramics, *JACerS*, **72**(4), 571–578.

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C.A. Randall, N. Kim, J.P. Kucera, W.W. Cao, and T.R. Shrout, (1998) Intrinsic and extrinsic size effects in fine-grained morphotropic-phase-boundary lead zirconate titanate ceramics *JACerS*, **81**(3), 677–688.

D. Damjanovic, (2005) Contributions to the piezoelectric effect in ferroelectric single crystals and ceramics, *JACerS*, **88**(10), 2663–2676.

J. Rödel, W. Jo, K.T.P. Seifert, E.M. Anton, T. Granzow, and D. Damjanovic, (2009) Perspective on the development of lead-free piezoceramics, *JACerS*, **92**(6), 1153–1177.

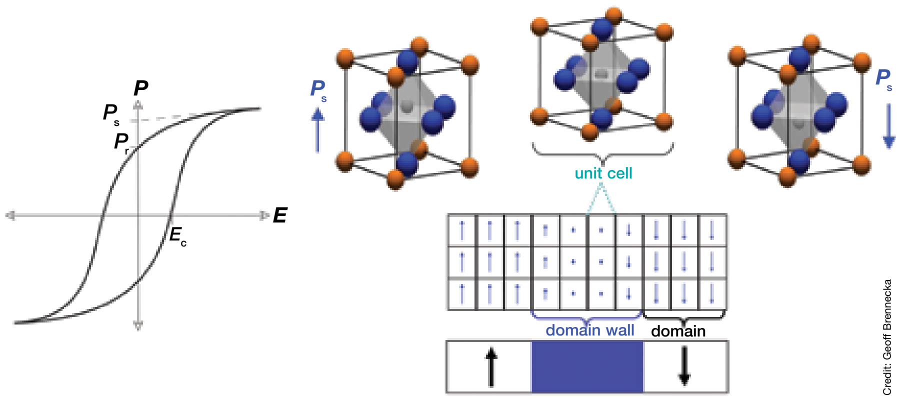


Figure 3. During the phase transition that results upon cooling through the Curie temperature, the $BaTiO_3$ unit cell expands by roughly 1% in the polar direction while shrinking accordingly in the two perpendicular directions. Displacement of the cation species (the Ba^{2+} and Ti^{4+}) and anion species (O^{2-}) in opposing directions results in a polar (tetragonal) crystal structure and the presence of a small electrical dipole, a spontaneous polarization, within each unit cell. While the dimensional changes associated with this phase transition are relatively small (about 0.1 Å), the lower symmetry is the key to enabling ferroelectricity and its derivative properties.

The change in shape and the resulting spontaneous polarization along the (by definition) *c*-axis occurs in every unit cell in the sample, and of course each unit cell is influenced by those around it. Having all of the unit cells transition in the same direction would be both a tremendous coincidence and a higher energy state than having some disorder. Thermodynamic free energy minimization drives the formation of domains to reduce both elastic (strain) and electrostatic (charge) energies. Domain sizes and distributions depend on boundary conditions and defects, but the ability to configure and reconfigure these domains by applying electric fields is both the defining property of ferroelectrics and the source of extrinsic contributions that often dominate the properties.

It is worth noting that in recent decades, researchers have found that electrically driving single crystal piezoelectrics along nonpolar directions can produce very large extrinsic contributions to electromechanical strain, taking advantage of similar mechanisms to those described here for polycrystalline ceramics.

Some of the same factors that enable large piezoelectric responses in ferroelectrics also contribute to large permittivities, which is of great importance for charge storage in capacitors. Relative permittivity (also referred to as dielectric constant, though it is anything but constant in the materials discussed here) is proportional to the change in polarization with an applied electric field. When a small electric field is applied to a ferroelectric, the intrinsic response discussed above results in a change in polarization that is typically much larger than in linear dielectrics, such as silica or alumina. This change in polarization leads to a large relative permittivity and a high volumetric capacitance. Additional extrinsic effects, small motions of domain walls, lead to even larger changes in polarization and even higher relative permittivities. These attributes make ferroelectrics well-suited for many capacitor applications. For example, the relative permittivity of $BaTiO_3$-based dielectrics in the multilayer ceramic capacitors (MLCC, Fig. 4) that are present in our cell phones, computers, and other electron-

What does symmetry have to do with it?

Differences in atomic packing and bonding in different crystallographic directions influence a material's mechanical, thermal, electrical, magnetic, and optical properties, all of which can be direction-dependent. The symmetry principles that govern the categorization of crystalline materials into seven crystal systems and 32 point groups also reflect in the symmetry of the material's properties. This simple but powerful concept that the properties of a crystalline material must exhibit at least the same symmetry as the underlying crystal structure is Neumann's principle.[S1]

All crystalline substances, neglecting quasicrystals, belong to one of 32 crystallographic point groups. Eleven of those point groups possess an inversion center, which means that for any point (x,y,z) in the crystal, the corresponding point ($-x$,$-y$, $-z$) is completely identical. In other words, if you pick any point in space and turn the crystal "inside out" through that point, it will look and behave exactly the same as when you started. Of the remaining 21 point groups, 20 are piezoelectric (the combination of other symmetry operators prohibits piezoelectricity in point group 432), which simply means that applying a stress to the crystal will create a net separation of positive and negative charges in the crystal, hence the name piezoelectric, which translates simply to pressure-electric. This polarization results in the buildup of charges at the crystal surface. The converse is also true: applying an electric field to pull the positive and negative charges apart will produce a net strain in a piezoelectric material. It is this intrinsic coupling of electrical and mechanical energies that makes piezoelectricity such a useful phenomenon.

Of the 20 piezoelectric point groups, 10 are spontaneously polarized, meaning they have a built-in (spontaneous) dipole even without the presence of an applied field. These are the polar point groups, and because the magnitude of the spontaneous dipole changes with temperature, such polar materials are also known as pyroelectric (temperature-electric) materials. If the direction of this spontaneous dipole can be reoriented through the application of an electric field, the material is a ferroelectric. This fact means that ferroelectrics are an experimental subset of pyroelectric materials. If a material undergoes dielectric breakdown (essentially a lightning bolt) before the applied electric field is sufficient to reverse its polarization, it is not ferroelectric, or at least it was not, before you and your lightning bolt destroyed it.

Therefore, all ferroelectric materials are pyroelectrics, and all pyroelectrics are piezoelectric, but not all piezoelectric materials are pyroelectric, and not all pyroelectrics are ferroelectric. If that is confusing, just remember that all squares are rectangles, but not all rectangles are squares.

S1. Neumann's principle. Online Dictionary of Crystallography. http://reference.iucr.org/dictionary/Neumann's_principle. Accessed Dec. 2, 2019.

ics, is greater (often much greater) than 1,000. For comparison, silica has a relative permittivity value of just 3.9.

Abundant applications

Sophisticated ceramic processing and microstructure engineering enabled scaling of ferroelectric-containing MLCCs, such that today our electronics operate with dielectric layer thicknesses far less than one micron packaged into capacitors with more than 100 active layers. Packaged MLCC devices today can be many times smaller than a grain of salt. In fact, MLCC scaling over the past 50 years rivaled—and often outpaced—the aggressive transistor scaling of the semiconductor industry known as Moore's Law.

As discussed in the sidebar "What does symmetry...", polar crystals exhibit the pyroelectric effect, or a change in polarization magnitude with a change in temperature. While all polar materials possess this property, ferroelectrics may have pyroelectric coefficients that are much larger than their nonferroelectric counterparts, often in the proximity of a ferroelectric phase transition. This property makes ferroelectric pyroelectrics particularly well-suited for thermal sensors. A wide variety of ferroelectrics are used for pyroelectric sensors, but some of the most common are single crystal $LiNbO_3$ or $LiTaO_3$ owing to their combination of high pyroelectric coefficient, low losses, and low relative permittivity, which increases the measurable voltage for a given amount of charge produced.

$LiNbO_3$ and $LiTaO_3$ single crystals also find tremendous use in the optics sector, often in the form of periodically poled lithium niobate (PPLN) and periodically poled lithium tantalate (PPLT), structures for waveguides, phase matching, difference frequency generation, and many others. This periodic poling takes advantage of the nearly strain-free 180-degree domain walls in these crystals as well as their large coercive fields. In fact, the coercive fields of as-grown $LiNbO_3$ and $LiTaO_3$ crystals at room temperature are often very close to the breakdown strengths of the crystals, so the pure materials are often poled as they are pulled from a melt or at temperatures approaching their Curie temperature where the coercive fields are lower. Doping with magnesium reduces the coercive field and increases the laser damage threshold of $LiNbO_3$ and $LiTaO_3$ by compensating for the lithium deficiency inherent in melt-grown $LiNbO_3$ and $LiTaO_3$ crystals. Creating an array of inverted domains with periodicity related to the wavelength of an incident laser beam enables a variety of clever manipulations of the beam as it passes through the PPLN or PPLT crystal, and the high coercive fields ensure that once the material is poled, it will stay that way during operation, even under large optical powers and occasionally large applied electric fields.

One technology that utilizes the full switching of polarization, the very hallmark of ferroelectricity, is ferroelectric random access memory, FeRAM. In this technology, the polarization of the ferroelectric represents a binary bit of information (i.e., 1 or 0). When coupled in series with a transistor, the amount of current flowing through the channel when the transistor is activated allows differentiation of the positive or negative polarization (memory) state of the ferroelectric capacitor. A voltage pulse is then used to set the polarization of the ferroelectric for the next stored bit. The result is a nonvolatile memory that can maintain its state for timescales up to 45 years.[5] FeRAM has advantages over other memory technologies in terms of the number of read/write cycles possible and the energy required for each switching event, though its physical scaling into the tens of nanometer range remains a significant challenge.

While ferroelectric and related materials dominate the high strain piezoelectric technologies of sonar, ultrasound, and micro- and nano-positioners, these technologies rely on bulk ceramics or single crystals fabricated into specific geometries for best performance. To affect technologies at smaller size scales, such as millimeter-scale robotics, RF switches, and actuators for inkjet printers, the device sizes must also decrease. This requirement has driven significant efforts into development of ferroelectric piezoelectric thin films and micro-electromechanical systems (MEMS) devices that can perform at reduced dimensions—a field known as piezoMEMS. Figure 5 shows an example piezoMEMS device designed to imitate dragonfly flight.[6] The most broadly studied material for piezoMEMS is PZT. In approximately 30 years of piezoMEMS study, the piezoelectric performance of PZT thin films substantially improved through advances in processing and understanding of the roles of mechanical boundary conditions.

While PZT and other lead-based ferroelectric piezoelectrics demonstrate the most utility for electro-mechanical applications, the looming European Union Restriction on Hazardous Substances (ROHS) requirements drive the search for reduced lead in materials and has also led to the study of lead-free piezoelectric ceramics and films. The piezoelectric coefficients of the lead-free materials, such as $(K,Nb)NbO_3$ and $Bi_{0.5}Na_{0.5}TiO_3$-$Bi_{0.5}K_{0.5}TiO_3$ to date lag behind those of lead-based systems and represent a large area of current and future study and growth.

Frontiers of ferroelectricity

In the first 90 years of ferroelectrics research, attention focused on a few

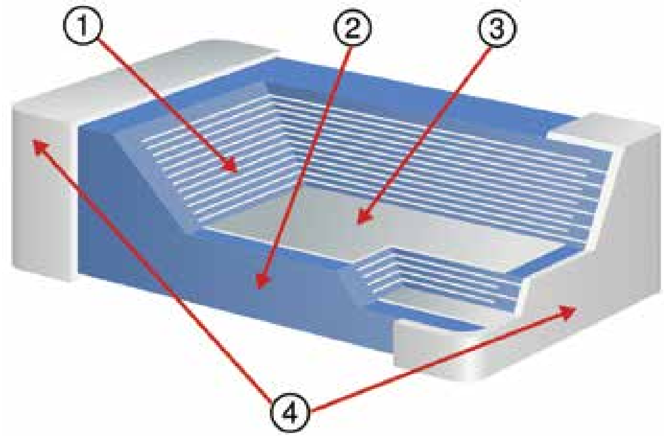
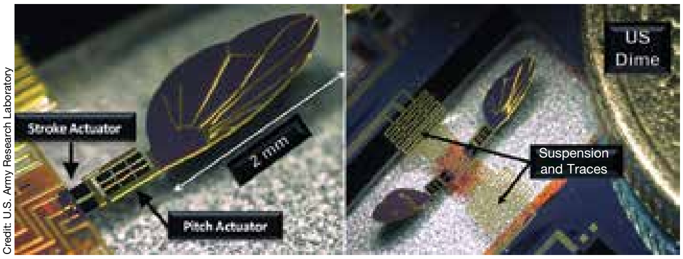


Figure 4. Schematic structure of a multilayer ceramic capacitor. Layers are (1) dielectric ceramic, (2) outer ceramic layer, (3) electrode, and (4) contact surface.



Credit: U.S. Army Research Laboratory

Figure 5. U.S. Army Research Laboratory's prototype PZT piezoMEMS dragonfly with stroke and pitch actuated wing design. The image on the right shows a platform suspended on the dragonfly between individually controllable wings.[7]

primary crystal structures and materials populating those structures at the forefront for commercial applications. These include the perovskite ferroelectrics $LiNbO_3$ and $LiTaO_3$ described previously; layered structures, such as $SrBi_2Ta_2O_9$; and dihydrogen phosphates, such as KH_2PO_4. However, in the past 10 years, two new structural classes have joined the ferroelectric family and bring with them some potential technological superiority to traditional materials on the basis of chemical compatibility with dominant semiconductor technologies. These include fluorite-structured HfO_2 and wurzite-structured (Al,Sc)N.

In 2011, Boscke et al. first reported ferroelectricity in fluorite-structured silicon-doped HfO_2 thin films.[7] The observation of a switchable polarization in this material surprised the community and generated a great deal of excitement. This excitement was driven largely by the inherent silicon compatibility of hafnia and the fact that the first observation of ferroelectric response in HfO_2 occurred in films that were only 10 nm thick just shortly after HfO_2-based gate dielectrics emerged in commercial integrated circuits. HfO_2-based ferroelectrics are poised to enable scaling of existing ferroelectrics-based technologies, such as FeRAM, to even smaller dimensions. In addition to demonstrated and commercialized ferroelectric thin film technologies, the integrated circuit process compatibility of HfO_2 positions it to enable other new devices, such as negative differential capacitance field effect transistors (NC-FETs) and ferroelectric-FETs, which may offer continued performance increases to silicon based integrated circuits.

All of the commercially relevant ferroelectric ceramics discussed so far are oxides, but recent efforts have identified promising nitride ferroelectrics. Primary among them is (Al,Sc)N.[8] MEMS resonators based on AlN thin films dominate the wireless communications market since the early 2000s, and in recent years, such resonators showed improved piezoelectric response via alloying with ScN or other transition metal nitrides. Increasing the concentration of scandium in (Al,Sc)N reduces the *c/a* ratio of the polar AlN wurtzite structure, gradually pushing the unit cell closer to the nonpolar hexagonal BN-type structure in which the cation sits in the same plane as the anions. At sufficiently high scandium contents, the amount of electric field required to switch the polarity of this structure can be less than the breakdown strength of the sample, and the material is ferroelectric. In large part due to the size of the MEMS industry already established around AlN thin films for radio frequency communications, ferroelectric (Al,Sc)N films and their derivatives have attracted tremendous attention for a number of integrated devices, but the enormous driving force for phase separation makes reliable fabrication rather challenging.

Recent predictions suggest ferroelectric behavior in nitride perovskites, including $LaWN_3$.[9] Calculations point to a polar structure with a sufficiently low energy barrier between anti-aligned polarities to make it a strong candidate for ferroelectricity,[10] but these await experimental confirmation. Similarly, ferroelectricity reported in several of hybrid halide perovskites took the photovoltaic world by storm, though the veracity of the genuine ferroelectric nature and the potential role(s) of the spontaneous polarization on the properties of these materials remains controversial.

We will not pretend to know exactly what lies ahead for the second century of ferroelectricity, but it is a safe bet that ferroelectrics will continue to play the role of enabler, quietly operating behind the scenes, facilitating critical functions and systems.

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National Science Foundation CAREER Ceramics Program awardees: Class of 2018 and decadal overview

By Lynnette D. Madsen

The National Science Foundation's Faculty Early Career Development (CAREER) program supports junior faculty who exemplify their roles as teacher–scholars through excellent research and education. The NSF CAREER award series[1–9] gives visibility to these junior professors and their work in the ceramics and glass community and inspires academic careers of ceramic researchers and educators. Incoming junior faculty sustain and grow the field—they are indeed the future as well as the guardians of the future work force.

Quite often, the CAREER award represents the launch of support for these young faculty researchers.

In recognition of the 10th year of this series, this article includes an overview, which has a snapshot of where they are now in their academic careers (Table 1). For the most part, Ceramics Program CAREER awardees do not move institutions until after completion of their CAREER awards; several of them have picked up joint appointments with other departments and/or senior leadership roles in addition to progressing in the faculty ranks.

FY 2018 CAREER grantees

It is my honor to present the four 2018 CAREER awardees from the Ceramics Program of the Division of Materials Research at NSF.

CAREER: Confining magnetism to two-dimensions in transition metal oxide atomic layers

Divine P. Kumah, North Carolina State University (Figure 1) — NSF Award 1751455

This research seeks a comprehensive understanding of the fundamental interactions that occur at the interfaces between atomically-thin magnetic oxide films and other polar and nonpolar perovskite materials in order to establish a link between the observed interactions and the physical properties of these systems (Figure 2). A combination of first principles theory, high-resolution electron microscopy and temperature-dependent magnetic, transport, and element-specific synchrotron X-ray magnetic dichroism measurements is used to design novel oxide heterointerfaces for achieving the confinement of ferromagnetism in two-dimensional oxide layers. This information is needed to understand why some oxide materials lose their useful magnetic properties when their thicknesses are reduced to a few atomic layers.[10]

Broader impacts include:

- Exciting applications for design of novel materials and devices for information processing, quantum computing and low-powered sensors.
- Education of undergraduate and graduate students in the development of next generation of advanced nanoscale materi-

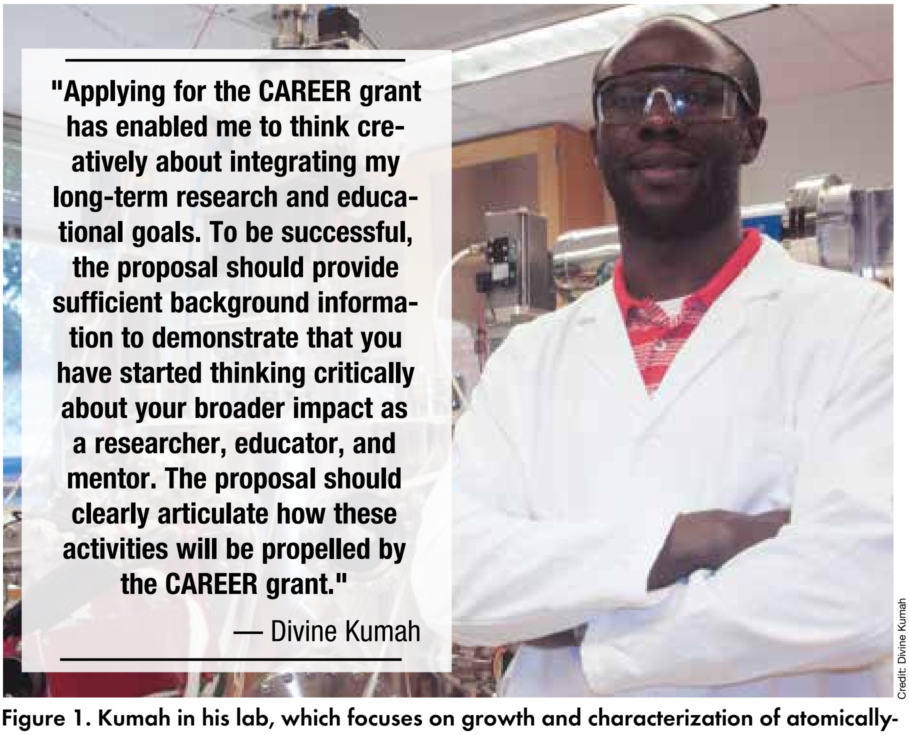

Figure 1. Kumah in his lab, which focuses on growth and characterization of atomically-thin magnetic complex oxide films.

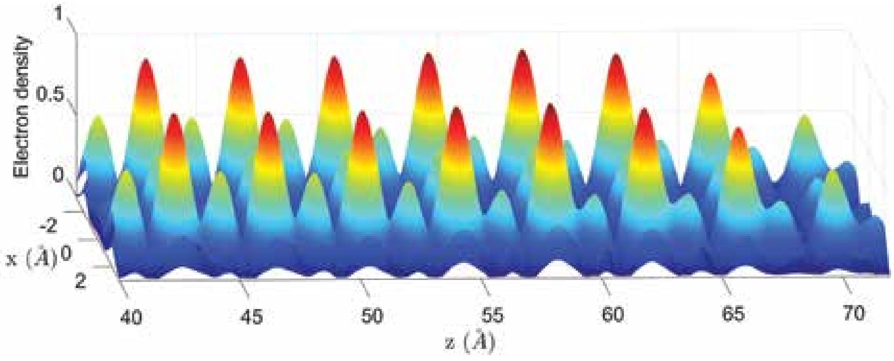

Figure 2. High-resolution electron density profile of a crystalline oxide film obtained from synchrotron X-ray diffraction. Combining crystalline atomic layers of transition metal oxide materials allows for the formation of heterointerfaces with novel electronic, magnetic, and orbital phases. Using synchrotron X-ray based diffraction and spectroscopy combined with first-principles theory, the novel interfacial phases are probed to understand their physical origin and identify pathways for designing heterostructures with specific magnetic and electronic properties for device applications.

als is enhanced through exposure to a wide range of cutting-edge research tools such as the state-of-the-art synchrotron X-ray facilities at the Argonne National Laboratory and the Berkeley National Laboratory.

- Providing low-cost tools for visualizing complex atomic and electronic structures and abstract concepts related to crystallography for classroom instruction and public outreach to K-12 schools and fostering the public's understanding of new technologically-relevant crystalline materials.

Companies with a potential interest: Sector of advanced computing and information storage devices.

CAREER: Controlling two-dimensional heterointerface in layered oxides for electrodes with advanced electrochemical properties

Ekaterina Pomerantseva, Drexel University (Figure 3) — NSF Award 1752623

This research focuses on understanding how face-to-face heterostructured interfaces can be created and controlled in layered materials (Figure 4). The aim is to produce 2D oxide-based heterostructures with high electron and ion transport leading to greater energy storage capabilities in Li-ion, Na-ion, and K-ion batteries. Layered transition metal oxides show high redox activity in intercalation reactions and relatively high working potentials, making them especially attractive for use as cathodes in energy storage devices. However, the low electronic conductivity of most oxides limits their performance. To overcome this limitation, layered oxides are combined in unique heterostructured architectures with electronically conductive 2D compounds by controllably alternating atomically thick layers of different individual materials. The 2D heterostructure electrodes are constructed using a sol-gel assisted transition metal oxide synthesis process through (1) chemical pre-intercalation of organic molecules followed by pyrolysis, or (2) addition of solid nanoflakes of conducting phases (graphene or MXene) during the sol-gel process. Combining

"When writing this proposal, I was inspired by outstanding research published by my mentors and colleagues. With so many talented scientists in the field of energy storage, I feel privileged to be selected to shed more light on the ways to solve one of the biggest issues of oxide electrodes—their poor electronic conductivity.

My passion is to make new materials that potentially can facilitate intercalation. So, when you think about crystal structures of the materials, the structures that favor intercalation properties the most are so-called layered structures. We have layers of the host materials that are separated by these two-dimensional channels. This is the channel that is available for ion intercalation. It seems favorable to have these layers being expanded, because we can put more ions in, and the capacity will be higher.

What's most interesting for me in this research is that two-dimensional oxide heterostructures with controlled order of the layers have never been synthesized before for large scale production of cathode materials necessary for energy storage applications."

— Ekaterina Pomerantseva

Figure 3: Pomerantseva assembling an autoclave for the hydrothermal synthesis of two-dimensional oxide heterostructured materials for use as electrodes in intercalation batteries.

layered metal oxides and carbon-based compounds in high quality layer-by-layer architecture offers an opportunity to discover and investigate new phenomena occurring at interfaces.[11]

Broader impacts include:

• Tailored 2D heterointerfaces make the design of new ceramic materials with tunable structures and compositions possible. Synthesized materials will exhibit high ion storage capability, rapid electron and ion transport, and enhanced electrochemical stability. There is potential to create batteries with improved energy and power capabilities. The materials and methods developed in this work are also relevant to a wider range of applications, including electrochromics (responsible for reversible changes of color), sensing, actuation (or control of movement), and water treatment.

• Integration of synthesis and properties of 2D structures into the

Table 1. Ten years of CAREER awardees in the NSF Ceramics Program, Division of Materials Research.

Class Year	Name	Position/Title*	Current Organization	Organization Changed?
2009	Tabbetha Dobbins	Associate professor	Rowan University	yes
2009	Robert Klie	Professor	University of Illinois at Chicago	no
2009	Haiyan Wang**	Basil S. Turner Professor	Purdue University	yes
2010	Shriram Ramanathan	Professor	Purdue University	yes
2010	Erica Corral	Distinguished Scholar Associate Professor	University of Arizona	no
2010	Javier Garay	Professor	University of California, San Diego	yes
2011	Miladin Radovic	Professor	Texas A&M University	no
2011	Ricardo H.R. Castro	Professor	University of California, Davis	no
2011	Bilge Yildiz	Professor	Massachusetts Institute of Technology	no
2011	Matthew Dawber	Associate professor	State University of New York at Stony Brook	no
2011	Ying Shirley Meng	Zable Endowed Chair Professor	University of California, San Diego	no
2011	Junqiao Wu**	Professor	University of California, Berkeley	no
2012	Steven J. May	Professor	Drexel University	no
2012	Jennifer S. Andrew	Associate professor	University of Florida	no
2012	Brady Gibbons	Professor	Oregon State University	no
2012	Jie Lian	Professor	Rensselaer Polytechnic Institute	no
2012	Lane W. Martin**	Professor	University of California, Berkeley	yes
2013	Nazanin Bassiri-Gharb	Harris Saunders, Jr. Chair and Professor	Georgia Institute of Technology	no
2013	Shen J. Dillon	Associate professor	University of Illinois at Urbana-Champaign	no
2013	Liping Huang	Professor	Rensselaer Polytechnic Institute	no
2013	Alexander Orlov	Associate professor	State University of New York at Stony Brook	no
2013	Xueyan Song	Professor	West Virginia University	no
2014	Corinne Packard	Associate professor	Colorado School of Mines	no
2014	James LeBeau**	Associate professor	Massachusetts Institute of Technology	yes
2015	Hui (Claire) Xiong	Associate professor	Boise State University	no
2015	William Chueh	Associate professor	Stanford University	no
2016	Yiquan Wu	Professor	Alfred University	no
2016	Claire White	Associate professor	Princeton University	no
2016	Wei Lai	Associate professor	Michigan State University	no
2016	Candace Chan	Associate professor	Arizona State University	no
2016	Geoff Brennecka	Associate professor	Colorado School of Mines	no
2017	Matthew McDowell**	Assistant professor	Georgia Institute of Technology	no
2017	Luiz G. Jacobsohn	Associate professor	Clemson University	no
2017	Jessica A. Krogstad	Assistant professor	University of Illinois at Urbana-Champaign	no
2018	Divine P. Kumah	Assistant professor	North Carolina State University	
2018	Ekaterina Pomerantseva	Associate professor	Drexel University	
2018	Min Hwan Lee	Associate professor	University of California, Merced	
2018	Nicholas C. Strandwitz	Associate professor	Lehigh University	

* Joint/cross and leadership appointments not listed

** Presidential Early Career Award for Scientists and Engineers (PECASE) nominated by NSF and other Federal agencies

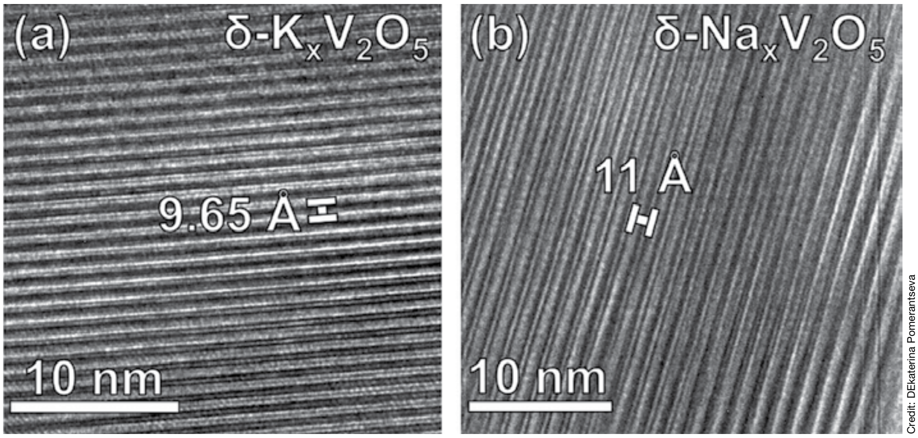

Figure 4. Transmission electron microscopy images of layered oxide materials synthesized in Pomerantseva's group demonstrating an ability to tune interlayer distance by controlling synthesis conditions. These materials were obtained via chemical preintercalation of potassium (a) and sodium (b) ions into the interlayer region of bilayered vanadium oxide, a high-capacity cathode material in intercalation batteries.

engineering curriculum. Creation of educational videos on synthesis and electrochemical properties of materials enrich outreach programs.

• A variation on the gameshow Family Feud focused on electrochemistry is being used to attract more students to science, technology, engineering, and mathematics (STEM) fields.

Companies with an interest: Because limited charge storage capacity of the cathode materials remains a barrier that does not allow achieving breakthrough improvements in battery performance, Pomerantseva's research on creating two-dimensional oxide-based cathode heterostructures is of interest to multiple national and global companies that require portable power.

CAREER: Probing oxygen-mediated electrochemical processes of oxides at high spatial and temporal resolution

Min Hwan Lee, University of California, Merced (Figure 5) — NSF Award 1753383

Solid oxide fuel cells—devices that produces electricity directly from oxidizing a fuel—offer clean and efficient energy conversion. The performance of SOFCs and electrolyzers are largely affected by the kinetics of oxygen electrochemical reduction/evolution reactions (ORR/OER). While each elementary process of the reaction is intrinsically a nanoscale phenomenon dictated by local material properties and geometry, the electrochemical properties have been mostly analyzed through bulk (volume-averaged) measurements. To obtain a breakthrough in electrode design, a more thorough understanding of the underpinning mechanisms of the reactions at the nanoscale is needed. This research[12–13] stands to advance the understanding of ORR/OER processes through in situ nanoscale observations by leveraging a novel scanning probe-based setup with a microscale heater (Figure 6). There are three significant aspects: 1) demonstrating a new high temperature scanning probe-based approach for in situ nanoscale characterizations of electrochemical surface reaction and charge transport kinetics under operating oxygen activities; 2) pioneering novel time-resolved nanoscale characterization of thermally-activated processes; and 3) providing deeper insight regarding the ORR/OER and related charge transport at the nanoscale.

Broader impacts include:

• Extensive research opportunities for graduate and undergraduate students (including underrepresented minority students) for their future employment in the energy technology sector.

• Curricula enhanced by incorporating research into seminars and courses.

• Effective education for K-12 students from the local and surrounding rural communities in the Central Valley through the on-campus Engineering Service Learning.

Companies with a possible interest include those in the energy sector.

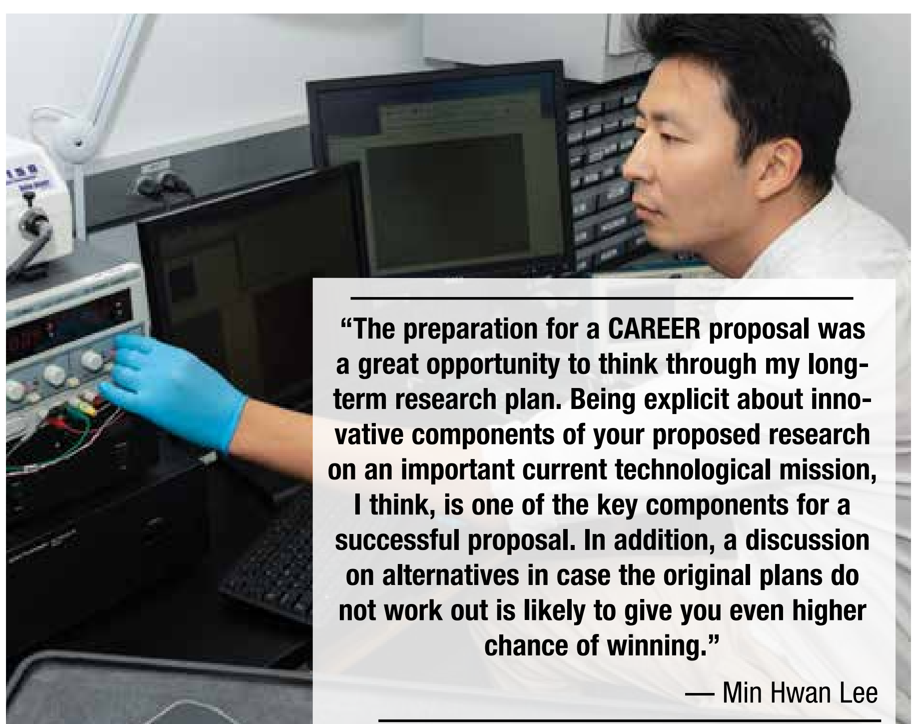

Figure 5. Lee performs a nanoscale electrochemical measurement on a solid oxide-based cell in front of an atomic force microscopy system located in his laboratory at the University of California, Merced.

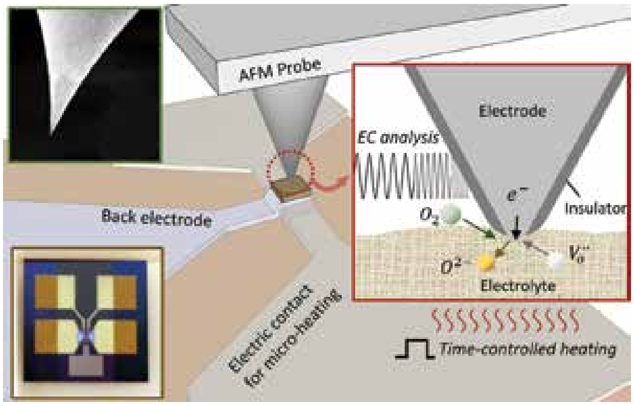

Figure 6. Conceptual drawing of scanning probe-based setup for in situ observations of oxygen-mediated electrochemical reactions at true nanoscale. Microheater embedded half cells and custom-made all-Pt tips are integrated into a scanning probe system of controlled gas environment. Insets show a custom-fabricated all-Pt tip (upper left) and a micro-heater embedded half cell (lower left).

CAREER: Probing crystallization of atomic layers using in situ electron

Nicholas C. Strandwitz, Lehigh University (Figure 7) — NSF Award 1752956

In these studies, the fundamental transformations that occur during atomic layer deposition (ALD) and annealing are elucidated by utilizing in situ reflection high energy electron diffraction (RHEED). Current ALD processes are often limited in terms of the structural control available (due to the precursor decomposition at high temperatures), which presents a significant barrier to precisely controlled three-dimensional epitaxial architectures that are integral to next generation electronics. Therefore, this work sets out to separate the precursor chemisorption steps (ALD component) (Figure 8) that result in amorphous layers from thermal processing that provides energy needed to induce crystallization in the model material system gallium oxide. Importantly, electron diffraction is probing in real time the structural transformations that occur to reveal the effect of ambient atmosphere, substrate structure, and orientation with adlayer thicknesses in the range of 0.5–10 nm. Analytical electron microscopy is providing precise structural and compositional details of the films and film-substrate interfaces including defect characteristics. This research captures a slow-motion picture of the structural changes that occur during many traditional thin film epitaxy techniques and yields new relationships that control crystallization of ultrathin layers and thus impacts the thin film/epitaxy communities.

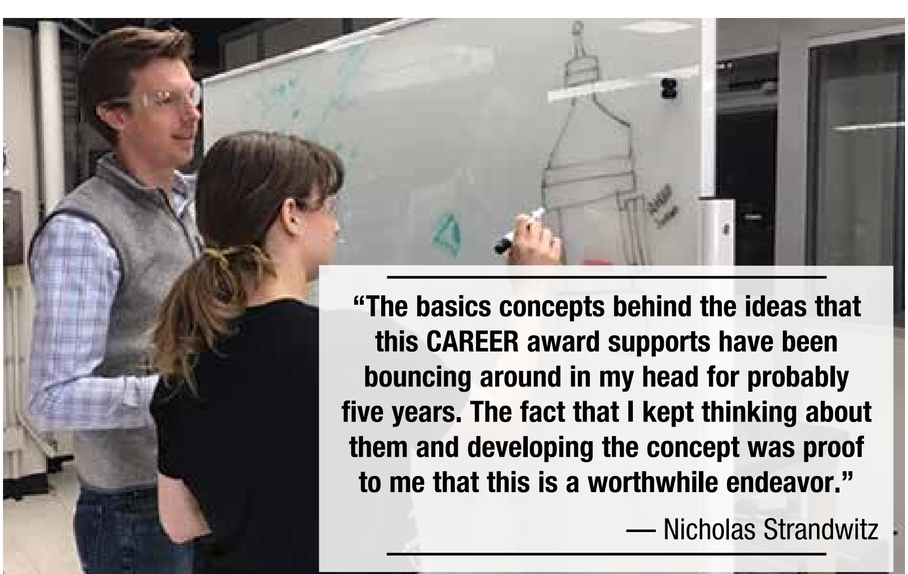

Figure 7. Strandwitz and Ph.D. student Alexandra Howzen discuss reactor design and the challenges and opportunities associated with integrating RHEED and ALD.

Broader impacts include:

- Control of atomic scale structure in ultra-thin films on nonplanar substrates is critical to next generation optical, electrical, biological, and magnetic materials and devices. In particular, nanoscale control of materials is essential to enable further decreases in the feature sizes and growth of materials in three-dimensional (nonplanar) architectures in development for applications such as logic circuitry, memories, and photovoltaics.
- Research findings are integrated into a university-level thin film course, a hands-on equipment laboratory, and an industrial outreach effort.
- Mentorship and outreach are conducted through the Booth Scholarship Program, Mountaintop Experience, and a local science center.

Companies with a possible interest in this research include those in the semiconductor manufacturing sector.

Experience speaks—Advice from senior researchers

On-going success at getting research support is critical to surviving in U.S. academia at research-intensive universities. Accordingly, I reached out to three senior investigators to hear their advice.

Jonathan Stebbins, Stanford University, has received 24 NSF awards to date, including those for instrumentation and research awards in ceramics and geosciences (reflecting his dual appointment on campus). Stebbins intentionally keeps his research program small, which helps him stay close to the action. "Due to the incredible support of our research, we've been able to focus on studies that seem fundamental to long-standing questions involving silicate and oxide materials important to a wide range of scientific problems but have kept our programs relatively small. That way I've been able to stay closely involved with all of the work in our labs, from sample syntheses to data collection to paper and proposal writing. This has continued to make the research personally rewarding. Big, multidisciplinary programs are important and exciting, but 'small' can be very 'beautiful', too!," he says.

Himanshu Jain, Lehigh University, has received 17 NSF awards as PI so far. His awards have come from DMR, the

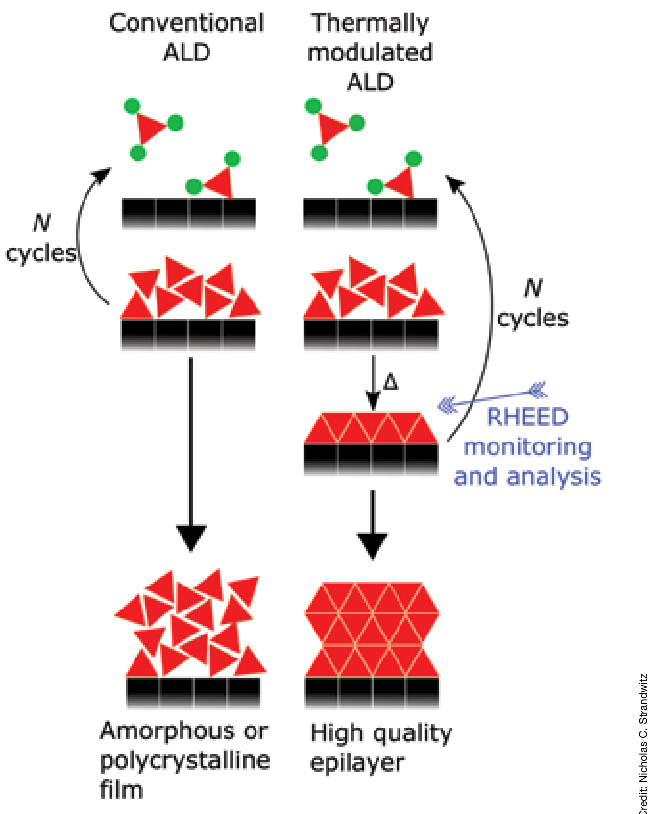

Figure 8. Schematic of (left) conventional ALD, where cyclic deposition of precursors results in films lacking long range order due to insufficient thermal energy for atomic motion of chemisorbed species and (right) thermally modulated ALD where heating steps are inserted in between ALD growth cycles and the structural rearrangements probed using RHEED.

Engineering Directorate, the Education and Human Resources Directorate, and the Office of International Science and Engineering. Jain encourages proposal writers to let their curiosity and enthusiasm show. "For someone at the beginning of a career in curiosity-driven scientific research, there is probably no better organization than US National Science Foundation where one can expect a fair evaluation of one's ideas. The difficult part for many young researchers is getting the message of their proposal at the level that the reviewer can appreciate readily and get excited about it. Reviewers get excited about innovative and transformative ideas, but it does not mean that everyone needs to run after what is 'fashionable' at a given time. A well-articulated, novel solution to a long-standing problem can generate just as much excitement," he says.

Katherine Faber, California Institute of Technology, is recipient of 20 awards to date from NSF today with the majority coming from DMR. However, her topics cover a significant range from microcracking, to SiC-based ceramics, to composites. Her advice is to allow yourself to be open to the unexpected. "One of the beauties of NSF support is the flexibility afforded by awards. If research results take an unexpected turn, follow your nose to a new area. There is no penalty for moving in a different direction as research evolves. Cross-program opportunities also abound," she says.

These senior researchers provided some overlapping advice: "Try to submit your ideas to a program that has just started; the competition can become stiffer with the age of the program," and "Collaboration with experts outside your field is intellectually rewarding and enriching. Of course, you must become world's expert on some topic first, so that others would want to collaborate with you."

Success begins with the solicitation. My advice for applying to NSF is to read the solicitation carefully and seek guidance when needed. Additional details are provided in a previous article.[14]

About the author

Lynnette D. Madsen has served as program director, Ceramics, at NSF since 2000. Contact her at lmadsen@nsf.gov.

Acknowledgements

This article would not have been possible without input from Profs. Faber, Jain, Kumah, Lee, Pomerantseva, Stebbins and Strandwitz; their contributions are gratefully acknowledged.

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2020 GLASS & OPTICAL MATERIALS DIVISION ANNUAL MEETING

www.ceramics.org/gomd2020

Hotel Monteleone
New Orleans, La.
May 17–21, 2020

Join ACerS's Glass & Optical Materials Division for GOMD 2020, May 17–21, 2020, in New Orleans, La., for a program featuring four symposia: Fundamentals of the Glassy State, Optical and Electronic Materials and Devices, Glass Technology and Cross-Cutting Topics, and a brand-new symposium on glass and water, Aging and Degradation of Amorphous Materials. Technical sessions consisting of both oral and poster presentations led by technical leaders from industry, national laboratories, and academia will provide an open forum for glass scientists and engineers from around the world to present and exchange findings on recent advances in various aspects related to glass science and technology.

Students are encouraged to enter their presentations in the annual student poster competition for professional recognition and cash awards. Students attending GOMD 2020 are also invited to attend a career roundtable discussion with scientists from industry, national laboratories, and academia about career opportunities and other topics in a casual environment. GOMD 2020 will provide a unique opportunity for students to learn, interact, and win!

Hotel Monteleone is located right in the French Quarter of New Orleans, among a variety of specialty shops selling art and antiquities from around the world, and restaurants serving authentic New Orleans Cajun cuisine. Tourist attractions are located just steps from the hotel, including Jackson Square, Bourbon Street, the French Market, and the Riverwalk. New Orleans itself is steeped in European traditions and Caribbean influences. The Big Easy offers visitors sweet sounds and savory aromas fueled by three hundred years of history.

The GOMD Executive Committee, program chairs, and volunteer organizers sincerely hope you will join us in New Orleans for GOMD 2020 to find new collaborative opportunities and to exchange ideas in the international glass community.

We look forward to seeing you in New Orleans!

PROGRAM CHAIRS:

Jessica Rimsza
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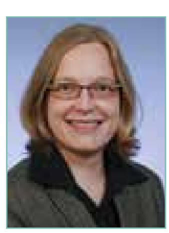
jrimsza@sandia.gov



Delia Brauer
Otto Schott Institute of Materials Research
Friedrich Schiller University
Jena, Germany
delia.brauer@uni-jena.de

Preliminary Schedule	
Sunday, May 17, 2020	
Registration	4 – 7 p.m.
Welcome reception	6 – 8 p.m.
Monday, May 18, 2020	
Registration	7 a.m. – 5:30 p.m.
Stookey Lecture of Discovery	8 – 9 a.m.
Concurrent sessions	9:20 a.m. – 5:40 p.m.
Lunch on own	Noon – 1:20 p.m.
GOMD general business meeting	5:45 – 6:30 p.m.
Poster session and student poster competition	6:30 – 8:30 p.m.
Tuesday, May 19, 2020	
Registration	7:30 a.m. – 5:30 p.m.
George W. Morey Award lecture	8 – 9 a.m.
Concurrent sessions	9:20 a.m. – 6 p.m.
The Norbert J. Kreidl Award for Young Scholars	Noon – 1 p.m.
Lunch on own	Noon – 1:30 p.m.
Conference banquet	7 – 10 p.m.
Wednesday, May 20, 2020	
Registration	7:30 a.m. – 5 p.m.
Darshana and Arun Varshneya Frontiers of Glass Science lecture	8 – 9 a.m.
Concurrent sessions	9:20 a.m. – 5:40 p.m.
Lunch on own	Noon – 1:30 p.m.
Thursday, May 21, 2020	
Registration	7:30 a.m. – Noon
Darshana and Arun Varshneya Frontiers of Glass Technology lecture	8 – 9 a.m.
Concurrent sessions	9:20 a.m. – Noon

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Reserve your room by April 20, 2020 to secure the negotiated conference rate.

Visit the hotel and travel page at ceramics.org/GOMD2020 to reserve your room today.

Advanced ceramics: Enabling a clean, efficient, and electrified future

May 5–6, 2020 • I-X Center, Cleveland, Ohio, USA

Ceramics Expo returns to Cleveland, Ohio, for its 6th year, bringing the entire advanced ceramic industry together to source cutting-edge innovations in materials and manufacturing, learn the latest trends in processes and applications, and network with more than 3,000 professionals from across the supply chain.

Backing for Ceramics Expo 2020 has been boosted by participation from several modern powerhouse manufacturing industries—industries that are innovating at a tremendous pace and on which the more traditional sectors increasingly rely.

It is the reason that ***Enabling a clean, efficient, and electrified future*** is right there on the masthead for 2020—it is an affirmation of the extremely close relationship that has been forged between the producers that keep clean energy flowing and that create dynamic, alternative modes of transport for land, air, and sea, and the ceramic component innovators that make it all possible. Our future harnessing of energy and low carbon footprint existence rely at every step on the high performance, reliability, durability, green credentials, and ability to adapt offered by advanced ceramics.

ENERGY HARVESTING AND STORAGE

Advanced ceramics and glasses will continue to be pivotal in the effective delivery of this industry sector and there will be no shortage of examples, demos, and conference sessions in Cleveland to prove the point.

Clean energy and alternative power generation strategies lay down a marker for ceramic innovators and Ceramics Expo is where we can expect to get the big reveal. Ceramics are proven in fuel cells, battery systems, solar energy, wind power, hydropower, and power distribution, supply, and transmission generally.

The actual products vary greatly as they are called upon to solve engineering challenges in everything from generators, turbines, and reactors to supercapacitors, insulators, thermal energy storage units, and e-mobility.

Many leading names at the cutting edge will demonstrate just how wide the expertise is in this area, with organizations such as **3M**, **Superior Graphite**, **STC**, **Kerafol**, **Blasch**, **FineWay Ceramics**, **Haiku Tech**, **Höganäs**, **Oasis Materials**, **Mo-Sci**, and **Precision Ceramics** already assured for the Expo.

ELECTRONIC PACKAGING AND ASSEMBLY

These elements lie at the beating heart of systems without which our interconnected world would cease very quickly to function. Consumer electronics, of course, but also knowledge, telecommunications, energy, motion, and heating/cooling networks that are crucial for space/aerospace technology, the automotive industry, measurement and control, the medical field, and optoelectronics, to name but a few.

A variety of advanced ceramics and glasses play a crucial role due to their dielectric characteristics (capacitors and inductors, for instance), as insulators, and offer special sealing, heat sink, and wider thermal management properties. Some of the commonly found materials are modified alumina and low temperature cofired ceramics (substrates), silicon carbide, silicon nitride, glass fiber, and borosilicates.

Every type of operation, from niche players through to multinationals, gets involved in helping to map the future for ceramics in this sector and names such as **Kyocera**, **Corning**, **Johnson Matthey**, **Saint-Gobain**, **Cerix**, **Materion**, **QSIL**, **Skyworks Solutions**, and **YJC** are already confirmed to be at Ceramics Expo 2020.

There will be much to discuss, not least the continuing transition from silicon to silicon carbide (SiC) technology—which is important in supporting the growing electric vehicle, 4G/5G mobile and industrial markets, and the announcement in the past few weeks of the construction in the United States of the world's largest SiC device manufacturing facility.

CERAMIC COATINGS

There are many areas where advanced ceramic coatings find an

application: everything from auto body and marine craft protection; enhanced wear and corrosion resistance in harsh industrial environments (steel production, oil and gas exploration, chemical pumping, and more); battery coatings for electric vehicles; special steel plate coating (in boilers, for instance); and ultrahydrophobic nanoceramic glass coating, such as found on solar panels. A Market Research Future report says it expects a CAGR of 7.6% for global ceramic coatings, resulting in sales hitting over $18 billion in 2023.

Ceramic coatings generally bring with them benefits in terms of superior hardness, corrosion protection, wear resistance, thermal shock resistance, durability, low friction, and can offer high electrical resistivity. Several materials will be featured prominently, including alumina, titania, zirconia, alumina-magnesia, hafnia, silicon carbide, silicon nitride, boron nitride, and boron carbide.

Ceramics Expo exhibitors are pushing these specialty materials to the next level, widening the potential for industrial adoption, and raising the performance bar at the same time. Typical of this approach is the new boron nitride (BN) CeraGlide coatings from Saint-Gobain, developed with the aim of solving challenges related to lubrication, protection, and mold release, particularly under high temperature conditions. BN coatings are used to coat parts, launders, troughs, ladles, and spoons, among others, during operations such as casting, pressing, forging, and extrusion. Other uses are in superplastic and quick plastic forming, or anywhere high temperature protection, lubrication, and release are paramount.

JOIN US IN CLEVELAND – MAY 2020

The exhibition and conference are free to attend—register for your free pass at http://www.ceramicsexpousa.com. If you would like to showcase your products and services and meet new buyers, book one of the last remaining spaces at the exhibition. If you are an ACerS Corporate member, take advantage of the exclusive $200 discount on booth space—contact the team at info@ceramicsexpousa.com to find out more. ■

Electronic Materials and Applications (EMA 2020)

Organized by the ACerS Electronics and Basic Science Divisions

EMA 2020 is designed for researchers, engineers, technologists, and students interested in basic science, engineering, and applications of electroceramic materials. Speakers include an international mix of university, industrial, and federal laboratory participants exchanging information and ideas on the latest developments in theory, experimental investigation, and applications of electroceramic materials.

Students are highly encouraged to participate in the meeting. Prizes will be awarded for the best oral and poster student presentation.

Please join us in Orlando, Fla, to participate in this unique experience!

PLENARY SPEAKERS

WEDNESDAY, JANUARY 22
8:30 AM | ROOM: ORANGE A

Rijnders

A.J.H.M. (Guus) Rijnders

Professor, MESA+ Institute for Nanotechnology, University of Twente, Netherlands

Title: ***Novel functionalities in atomically controlled oxide heterostructures by pulsed laser deposition***

Abstract: Complex oxides of the transition metals are of great importance and interest both from a fundamental science as well as a technological point of view. With regards to fundamental science, complex oxides show an interplay between strong electron correlations, band behaviour, as well as a rich repertoire of ordering phenomena in the spin and orbital sectors making them an enduring focus of theoretical and experimental investigation.

Recent progress in epitaxy-based thin film growth approaches has added a dimension to complex oxide research, providing opportunities to improve experimental control over the properties of the system. We now possess a number of tools that can be used to design novel functionalities in complex oxides.

We have demonstrated recently that strong oxygen octahedral coupling at interfaces transfers the octahedral rotation from one oxide into the other at the interface region. As a result, we possess control of magnetic and electronic properties by atomic scale design of the oxygen octahedral rotation. In this contribution I will highlight recent work on magnetic anisotropy in manganites, as well as the control of the metal-to-insulator transition temperature in nickelate heterostructures and superlattices.

I will furthermore highlight some recent new insights in the "physics" of pulsed laser deposition of complex oxides, as well as the large-scale integration of epitaxial oxides on silicon-wafers up to 200 mm in diameter.

THURSDAY, JANUARY 23
8:30 AM | ROOM: ORANGE A

Dickey

Elizabeth Dickey

Professor, Kyocera Professor, associate head of Department of Materials Science and Engineering, North Carolina State University, USA

Title: ***Defect disorder and dynamics in functional oxides***

Abstract: Lattice defects play an important role in the dielectric and conductivity properties of ceramic materials, and thus great effort is expended on controlling point defect equilibria via doping, oxygen activity, and temperature control during processing. In device applications, because lattice defects are typically charged, applied electric fields provide a strong driving force for defect migration, and their spatio-temporal redistribution depends on the electric potential distribution and the interfacial exchange kinetics. Ultimately this process leads to spatially varying conductivity profiles and often a concomitant macroscopic increase in leakage current in many dielectric materials. While this leakage current enhancement is detrimental in devices such as capacitors, the phenomenon can be utilized to form novel functional behaviors such as resistive switching in metal-oxides. Furthermore, the use of electric fields in processing ceramic materials, e.g., flash sintering, can lead to analogous electromigration processes resulting in long-range chemical and microstructural gradients. This talk will review our current understanding and implications of point defect electromigration in important electroceramic materials.

ACERS JOURNAL WORKSHOP: EXPAND YOUR IMPACT (ORGANIZED BY ACERS JOURNALS TEAM)

WEDNESDAY, JANUARY 22 | 12:30 – 1:30 P.M. |

This workshop discusses methods for improving the reach of your publications, including options for sharing your work. Furthermore, the workshop provides insight on the need for and hands-on experience with formulating societal impact language.

Lunch will be provided.

Please register to attend so we have enough for everyone!

ACERS STUDENT AND YOUNG PROFESSIONAL NETWORKING MIXER

THURSDAY, JANUARY 23 | 5:30 – 6:30 P.M. |

Join us to meet up and network with fellow students and young professionals!

LUNCH WITH A PRO (ORGANIZED BY THE ACERS YOUNG PROFESSIONALS NETWORK (YPN))

SCHEDULE OF EVENTS

TUESDAY, JANUARY 21, 2020

Conference registration	5 – 6:30 p.m.

WEDNESDAY, JANUARY 22, 2020

Conference registration	7:30 a.m. – 6 p.m.
Plenary session 1	8:30 – 9:30 a.m.
Coffee break	9:30 – 10 a.m.
Concurrent technical sessions	10 a.m. – 5:30 p.m.
Poster session set up	12:30 – 5 p.m.
Lunch on own	12:30 – 2 p.m.
Coffee break	3:30 – 4 p.m.
Poster session & reception	5:30 – 7:30 p.m.
Basic Science Division tutorial	7:40 – 8:45 p.m.

THURSDAY, JANUARY 23, 2020

Conference registration	7:30 a.m. – 6 p.m.
Plenary session 2	8:30 – 9:30 a.m.
Coffee break	9:30 – 10 a.m.
Concurrent technical sessions	10 a.m. – 5:30 p.m.
Lunch on own	12:30 – 2 p.m.
Coffee break	3:30 – 4 p.m.
Student & young professionals reception	5:30 – 6:30 p.m.
Conference dinner	7 – 9 p.m.

FRIDAY, JANUARY 24, 2020

Conference registration	7:30 a.m. – 4 p.m.
Concurrent technical sessions	8:30 a.m. – 5 p.m.
Coffee break	10 – 10:30 a.m.
Lunch on own	12:30 – 2 p.m.
Failure: The greatest teacher	5 – 6 p.m.

TECHNICAL PROGRAM

- **S1** Characterization of Structure-Property Relationships in Functional Ceramics
- **S2** Advanced Electronic Materials: Processing Structures, Properties, and Applications
- **S3** Frontiers in Ferroic Oxides: Synthesis, Structure, Properties, and Applications
- **S4** Complex Oxide Thin Film Materials Discovery: From Synthesis to Strain/Interface Engineered Emergent Properties
- **S5** Mesoscale Phenomena in Ferroic Nanostructures: Beyond the Thin-Film Paradigm
- **S6** Complex Oxide and Chalcogenide Semiconductors: Research and Applications
- **S7** Superconducting and Magnetic Materials: From Basic Science to Applications
- **S8** Structure-property Relationships in Relaxor Ceramics
- **S9** Ion-Conducting Ceramics
- **S10** Point Defects and Transport in Ceramics
- **S11** New Directions in Sintering and Microstructure Control for Electronic Applications
- **S12** Electronic Materials Applications in 5G Telecommunications
- **S13** Thermal Transport in Functional Materials and Devices
- **S14** Agile Design of Electronic Materials: Aligned Computational and Experimental Approaches and Materials Informatics
- **S15** Functional Materials for Biological Applications
- **S16** Molecular, Inorganic, and Hybrid Ferroelectrics for Optoelectronic and Electronic Applications

44TH INTERNATIONAL CONFERENCE AND EXPOSITION ON ADVANCED CERAMICS AND COMPOSITES

#ICACC20

January 26 – 31, 2020 | Hilton Daytona Beach Oceanfront Resort, Daytona Beach | Florida, USA

The 44th International Conference and Exposition on Advanced Ceramics and Composites (ICACC) continues a strong tradition as the leading international meeting on advanced structural and functional ceramics, composites, and other emerging ceramic materials and technologies.

Award and Plenary Speakers

JAMES I. MUELLER AWARD

Weber

William J. Weber, Governor's Chair Professor, University of Tennessee, USA

Title: *Ion-beam modification and nanostructure evolution in ceramics*

BRIDGE BUILDING AWARD

Ishikawa

Toshihiro Ishikawa, vice president, Tokyo University of Science, Japan

Title: *Development of precursor ceramics using organic silicon polymer*

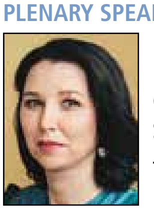
PLENARY SPEAKER

Gray

George T. (Rusty) Gray III, Laboratory Fellow, Los Alamos National Laboratory, USA

Title: *Developing a pathway to microstructure-aware predictive capability for the shock / dynamic response of materials*

PLENARY SPEAKER



Balázsi

Katalin Balázsi, Head of Thin Film Physics Department, Institute for Technical Physics and Materials Science, Centre for Energy Research, Hungarian Academy of Sciences, Budapest, Hungary

Title: *Ceramic biomaterials: From traditional technologies to novel applications*

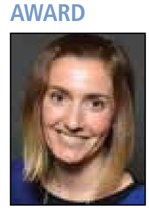
GLOBAL YOUNG INVESTIGATOR AWARD

Mhin

Sungwook Mhin, senior researcher, Korea Institute of Industrial Technology (KITECH), Korea

Title: *Advantageous crystalline–amorphous phase boundary for water oxidation*

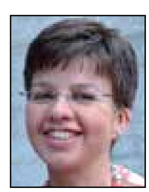
ENGINEERING CERAMICS DIVISION JUBILEE GLOBAL DIVERSITY AWARD



Tallon

Carolina Tallon, Department of Materials Science and Engineering and Advanced Manufacturing Team, Virginia Polyechnic Institute and State University, USA

Title: *EMulti-scale thermal protective systems for extreme environments: Design, processing, properties and modeling*



Casalegno

Valentina Casalegno, Institute of Materials Physics and Engineering, Politecnico di Torino (POLITO), Italy

Title: *Ceramic and composite joints for nuclear applications*

Yun

Hui-suk Yun, Materials Processing Innovation Research Division, Korea Institute of Materials Science (KIMS), Korea

Title: *Current technological advances in multi-ceramic additive manufacturing*

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Exhibit hours

Tuesday, Jan. 28, 2020, 5–8 p.m.

Wednesday, Jan. 29, 2020, 5–7:30 p.m.

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Exhibit space is filling up fast. To reserve your booth, visit www.ceramics.org/icacc2020 or contact **Mona Thiel** at mthiel@ceramics.org or 614-794-5834.

STOP BY any vendor booth in our ICACC 2020 Expo and receive a raffle ticket for a drawing to win the following exciting prizes:

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Phase Equilibria Diagrams PC Database, Version 4.4 USB single license ($1,095 value)

Second prize

ICACC 2021 free registration ($730 value)

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"Engineered Ceramics: Current Status and Future Products" technical book ($175 value)

Turn your raffle tickets in during exhibit hours at the ACerS booth in the exhibit hall. You may turn in as many tickets as you gather from exhibitors, so the more you visit with our vendors, the better your odds to win! The prizes will be drawn at 6:30 p.m., Wednesday, Jan. 29, at the ACerS booth. You need not be present to win. This raffle is a great opportunity to collaborate with potential business partners and walk away with something useful for your business or career. It can be a win-win, literally.

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AVS, Inc.	307
Centorr Vacuum Industries	200
Ceramics Expo	311
Cincinnati Testing Labs	314
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EAG Laboratories	317
FCT Systeme GmbH	319
Fraunhofer Institute for Ceramic Technologies and Systems IKTS	117
Fritsch Milling & Sizing, Inc.	219
Gasbarre	203
Haiku Tech	208
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Mechanical Properties of Ceramics and Glass 2020 Short Course*

Thursday, January 30 | 8:30 a.m. – 5:00 p.m.

Friday, January 31 | 8:30 a.m. – 5:00 p.m.

Location: Hilton – Coquina Salon C (North Tower)

Instructor: **George D. Quinn**, NIST

Additional registration fee is required.

Calendar of events

January 2020

22–24 EMA2020: Electronic Materials and Applications — DoubleTree by Hilton Orlando at Sea World Conference Hotel, Orlando, Fla.; www.ceramics.org/ema2020

26–31 ICACC20: 44th Int'l Conference and Expo on Advanced Ceramics and Composites — Daytona Beach, Fla.; www.ceramics.org/icacc20

March 2020

25–26 56th Annual St. Louis Section/Refractory Ceramics Division Symposium on Refractories — Hilton St. Louis Airport Hotel, St. Louis, Mo.; https://ceramics.org/event/56th-annual-st-louis-section

April 2020

13–17 2020 MRS Spring Meeting & Exhibit — Phoenix, Ariz.; www.mrs.org/spring2020

May 2020

5–6 6th Ceramics Expo — I-X Center, Cleveland, Ohio.; https://ceramics.org/event/6th-ceramics-expo

6–7 Ceramic Manufacturing Solutions Conference — I-X Center, Cleveland, Ohio; https://ceramics.org/event/ceramic-manufacturing-solutions-conference

17–21 2020 Glass and Optical Materials Division Annual Meeting — Hotel Monteleone, New Orleans, La.; www.ceramics.org/gomd2020

June 2020

7–10 ➨ Ultra-high Temperature Ceramics: Materials for Extreme Environment Applications V — The Lodge at Snowbird, Snowbird, Utah; http://bit.ly/5thUHTC

July 2020

19–23 Pan American Ceramics Congress and Ferroelectrics Meeting of the Americas (PACC-FMAs 2020) — Hilton Panama, Balboa Avenida Aquilino de la Guardia, Panama City, Panama; www.ceramics.org/PACCFMAs

August 2020

2–7 ➨ Solid State Studies in Ceramics, Gordon Research Conference — Mount Holyoke College, South Hadley, Mass.; https://www.grc.org/solid-state-studies-in-ceramics-conference/2020

16–21 Materials Challenges in Alternative & Renewable Energy 2020 (MCARE2020) combined with the 4th Annual Energy Harvesting Society Meeting (AEHSM 2020) — Hyatt Regency, Bellevue, Wash.; www.ceramics.org/mcare2020

23–27 ➨ International Congress on Ceramics (ICC8) — Bexco, Busan, Korea; www.iccs.org

October 2020

4–8 MS&T20 combined with ACerS 122nd Annual Meeting — David L. Lawrence Convention Center, Pittsburgh, Pa.; www.matscitech.org

November 2020

8–13 7th Int. Conference on Electrophoretic Deposition (EPD 2020) — Santa Fe, New Mexico; http://www.engconf.org/conferences/materials-science-including-nanotechnology/electrophoretic-deposition-vii-fundamental-and-applications

29–Dec. 3 2020 MRS Fall Meeting & Exhibit — Boston, Mass.; www.mrs.org/fall2020

January 2021

20–22 EMA2021: Electronic Materials and Applications — DoubleTree by Hilton Orlando at Sea World Conference Hotel, Orlando, Fla.; www.ceramics.org

24–29 45th International Conference and Expo on Advanced Ceramics and Composites (ICACC2021) — Hilton Daytona Beach Oceanfront Resort, Daytona Beach, Fla.; www.ceramics.org

March 2021

27-31 ➨ The Int'l Conference on Sintering 2021 — Nagaragwa Convention Center, Gifu, Japan; https://www.sintering2021.org

May 2021

23–28 14th Pacific Rim Conference on Ceramic and Glass Technology (PACRIM 14) — Hyatt Regency Vancouver, Vancouver, British Columbia, Canada; www.ceramics.org

September 2021

14–17 20th Biennial Worldwide Congress Unified International Technical Conference on Refractories — Hilton Chicago, Chicago, Ill.; www.ceramics.org

October 2021

17–21 ACerS 123rd Annual Meeting with Materials Science & Technology 2021 — Greater Columbus Convention Center, Columbus, Ohio; www.ceramics.org

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Entries in **BLUE** denote ACerS events.

➨ denotes meetings that ACerS cosponsors, endorses, or otherwise cooperates in organizing.

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A regular column offering the student perspective of the next generation of ceramic and glass scientists, organized by the ACerS Presidents Council of Student Advisors.

Daniel Drury
Guest columnist

Ferroelectric nitrides for communications technologies

Ferroelectric materials exhibit a permanent charge separation, or dipole, that is reorientable under an applied electric field, making them useful for applications such as nonvolatile memory. In addition, because ferroelectrics are a subset of piezoelectrics, which couple electrical and mechanical energies to either produce a charge when stressed or a mechanical strain when an electric field is applied, these same materials can also be useful for microelectromechanical systems.

With fifth generation (5G) wireless communications slowly rolling out, many believe ferroelectrics can assist in overcoming some technological challenges. The 5G standard encompasses several key new features, including low latency, multiple-input and multiple-output, and directional beamforming, as well as an unprecedentedly wide frequency range designated as 5G (F1) and 5G (F2) (Fig. 1a).

Historically, the telecommunications industry embraced the piezoelectric AlN system, and only recently began to alloy AlN and ScN for enhanced piezoelectric response. This material is used to construct film bulk acoustic resonators (FBARs) due to the high quality factor (low losses) and ease of integration (Fig. 1b). An FBAR acts as frequency filter when sending and receiving data by mechanically oscillating at a set frequency under an applied electric field; signals incident to the device that match the frequency can pass through. For communication devices to operate over a range of frequencies, they contain hundreds of these fixed-frequency filters to minimize interference from nearby emitters. However, manufacturing high quality and reliable films is a difficult and costly task when increasing scandium content, so state-of-the-art AlN compositions possess less than 10 at% scandium.

There are active demands for materials that can operate at higher frequencies with increased energy efficiency. The biggest issues are that current high-performance piezoelectric materials such as $Al_{1-x}Sc_xN$ (x=0.06) are unable to meet these demands and that ferroelectric oxides are inherently weak contenders due to wafer compatibility issues and low mechanical quality factors. A recent report of ferroelectricity in the $Al_{1-x}Sc_xN$ system at high scandium contents (x>0.30) sparked interest in potential multifunctional devices that could feasibly offer the combined flexibility of ferroelectrics with the superior high-frequency resonator performance of AlN.[1]

Finding a method to stabilize the ferroelectric phase of $Al_{1-x}Sc_xN$ with x>0.30 will be a challenging undertaking but one with a potentially enormous payoff. As a fab-compatible ferroelectric material that also offers the possibility of efficient piezoelectric performance, $Al_{1-x}Sc_xN$ will offer tunability and memory functionality as well as enable a number of other device architectures. The search for 5G-enabling materials is heating up, with a variety of AlN-based and ferroelectric HfO_2-based materials receiving the majority of interest for integrated devices.[2,3]

As a member of the Functional Ceramics group at Colorado School of Mines led by Dr. Geoff Brennecka, I aim to answer what role ferroelectric nitrides will play in the future. With collaborators at the National Renewable Energy Laboratories and the National Institute of Standards and Technology, I have a reputable network of mentors to assist me in understanding behavior and stability of these novel materials.

To facilitate progress, we use computational predictions to find suitable compositions. These predictions are then followed up with combinatorial research methodologies that allow for high-throughput thin film growth and characterization. Combining these techniques forms a rapid and constantly evolving learning loop. Our group's prior experience with piezoelectric $Al_{1-x}Sc_xN$ will provide the necessary groundwork for me to reach a more complete understanding of the ferroelectric phase.[4] This material is at the forefront of innovation and technology and will act as a catalyst for additional discoveries in the ferroelectric nitride family.

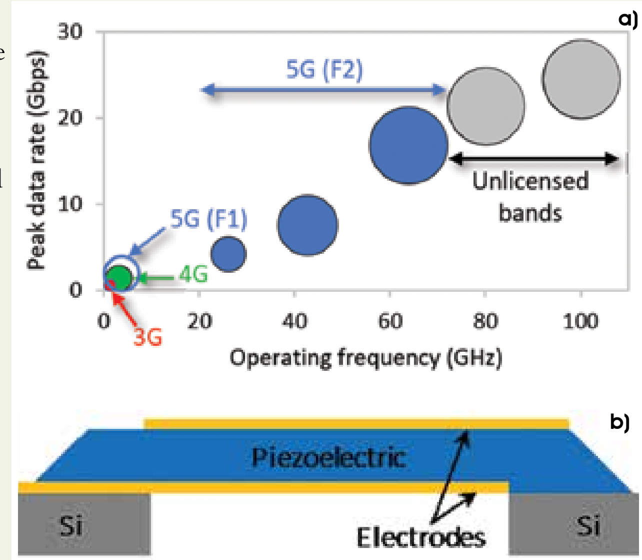

Figure 1. (a) Comparison of telecommunication bands by generation (adapted with permission from N. Orloff, NIST), (b) Cross section schematic of an FBAR device.

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Danny Drury is a first-year Ph.D. student in the materials science program at Colorado School of Mines. Outside of his school responsibilities, Danny enjoys ultimate frisbee, working on his motorcycle, and exploring the beautiful scenery Colorado offers with his fiancé and puppy. ■


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