AMERICAN CERAMIC SOCIETY
bulletin
emerging ceramics & glass technology

APRIL 2022

Progress and future prospects of negative capacitance electronics:
A materials perspective

New issue inside:

Structured glass for semiconductors | Next-generation memory | AGG celebrates IYOG

contents

April 2022 • Vol. 101 No.3

feature articles

Progress and future prospects of negative capacitance electronics: A materials perspective

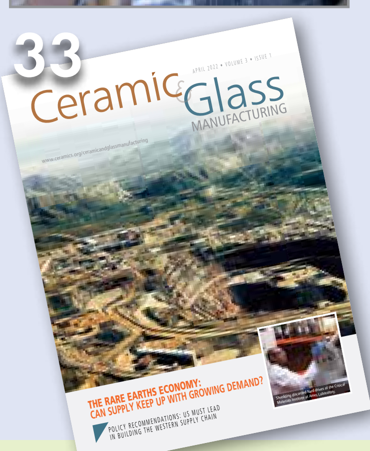
As miniaturization reaches its limits to improve the efficiency of transistors, researchers are exploring the possibility of using ferroelectric materials to boost performance through negative capacitance behavior. Includes an introduction by coauthor Michael Hoffmann.

by Michael Hoffmann, Stefan Slesazeck, and Thomas Mikolajickk

Structured glass: A new frontier for semiconductors

Ultrafine structured glass offers a game-changing element to semiconductor packaging. SCHOTT recently introduced FLEXINITY® connect, their ultrafine structured glass solution.

by Tobias Gotschke



Volume 3, Issue 1 — Ceramic & Glass Manufacturing

The rare earths economy: Can supply keep up with growing demand?

Also inside:

- *Industry news*
- *Policy recommendations: US must lead in building the Western supply chain*

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Editor's note:

Attentive readers may notice that this *Bulletin* is more slender than usual. A normal *Bulletin* and C&GM combined issue would run 64 pages, but an acute, global shortage of the paper we use forced us to reduce the number of pages printed. After careful consideration, we opted to print less content rather than publish a magazine with content split between print and online. The paper shortage is expected to continue through spring 2022. For more information on the shortage, visit our website at www.ceramics.org or contact customer service at customerservice@ceramics.org.

Correction:

The March 2022 issue of the *Bulletin* featured the incorrect logo for our new Corporate Partner Carborundum Universal Ltd. Included here are the correct logos.

murugappa | CUMI
CARBORUNDUM UNIVERSAL LIMITED

news & trends

US electric vehicle charging infrastructure poised for major expansion

On Nov. 15, 2021, President Biden signed the Infrastructure Investment and Jobs Act into law. Among its many initiatives, this bipartisan law established the National Electric Vehicle Infrastructure (NEVI) Formula Program, which aims "to provide funding to States to strategically deploy electric vehicle (EV) charging infrastructure and to establish an interconnected network to facilitate data collection, access, and reliability," according to a Department of Transportation fact sheet.

On Feb. 10, 2022, the U.S. Departments of Transportation and Energy announced they will begin making available the nearly $5 billion included in the infrastructure law for the NEVI Formula Program. The funding, which will be distributed over the next five years, will be used to create a network of EV charging stations along designated Alternative Fuel Corridors, which are a national network for alternative fueling and electric vehicle charging infrastructure along national highway system corridors.

"Americans need to know that they can purchase an electric vehicle and find convenient charging stations when they are using Interstates and other major highways," says Deputy Federal Highway Administrator Stephanie Pollack in a Department of Transportation press release. "The new EV formula program will provide states with the resources they need to provide their residents with reliable access to an EV charging station as they travel."

Credit: Tommy Krombacher, Unsplash

To access the NEVI funds, each state is required to submit an EV Infrastructure Deployment Plan to the new Joint Office of Energy and Transportation that describes how the state intends to use its share of the funds consistent with Federal Highway Administration guidance.

The Department of Transportation also released a new, free resource to help rural communities take full advantage of the funds at https://www.transportation.gov/rural/ev/toolkit.

An *Insider* article on the announcement elaborates some more details of the plan, including that a state can apply for funding to place charging stations in other public places such as transit stations, schools, and parking lots once its corridors are "fully built out." A corridor will be considered built out once it has a series of charging stations no more than 50 miles apart along Interstate highways, with each station featuring at least four DC fast charging plugs capable of pro-

American Ceramic Society Bulletin covers news and activities of the Society and its members, includes items of interest to the ceramics community, and provides the most current information concerning all aspects of ceramic technology, including R&D, manufacturing, engineering, and marketing. The American Ceramic Society is not responsible for the accuracy of information in the editorial, articles, and advertising sections of this publication. Readers should independently evaluate the accuracy of any statement in the editorial, articles, and advertising sections of this publication. *American Ceramic Society Bulletin* (ISSN No. 0002-7812). ©2022. Printed in the United States of America. *ACerS Bulletin* is published monthly, except for February, July, and November, as a "dual-media" magazine in print and electronic formats (www.ceramics.org). Editorial and Subscription Offices: 550 Polaris Parkway, Suite 510, Westerville, OH 43082-7045. Subscription included with The American Ceramic Society membership. Nonmember print subscription rates, including online access: United States and Canada, 1 year $135; international, 1 year $150.* Rates include shipping charges. International Remail Service is standard outside of the United States and Canada. *International nonmembers also may elect to receive an electronic-only, email delivery subscription for $100. Single issues, January–October/November: member $6 per issue; nonmember $15 per issue. December issue (*ceramicSOURCE*): member $20, nonmember $40. Postage/handling for single issues: United States and Canada, $3 per item; United States and Canada Expedited (UPS 2nd day air), $8 per item; International Standard, $6 per item.

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viding 150 kilowatts of energy each.

Market analysts note that this funding is only a small first step toward reaching the Biden Administration's goal of 500,000 public EV chargers by 2030 (the U.S. currently has just over 100,000).

As a *Grist* article explains, "According to the International Council on Clean Transportation, it costs between $30,000 and $140,000 to install a single DC fast charger. That means that the cash allocated could pay for between 36,000 and 166,000 fast chargers across the country—although it could be much more if states and private companies contribute their own funds, too."

However, U.S. Secretary of Transportation Pete Buttigieg is confident that EV charging will be increasingly cost-effective even without government support. "The fuel savings of electric compared to gas or diesel continue to bear out," he says in the *Grist* article. "We just haven't yet seen the market mature." ■

Vessel shortage could hamper offshore wind expansion

When faced with the energy crisis of the 1970s, key United States government personnel and agencies projected that the sun's "huge and virtually inexhaustible potential supply of energy" would likely serve as a mainstay of the energy industry in the future. Fifty years later, it is instead wind energy that has come to play a significant role, accounting for about 8% of U.S. electricity generation in 2020 in contrast to solar power's approximately 2%.

Investment in wind energy is not the only aspect of the industry that's increasing—the size of wind turbines is as well. Since the early 2000s, wind turbines have grown significantly in terms of both physical measurements and energy generation capacity.

For example, as noted on the Department of Energy's Office of Energy Efficiency & Renewable Energy website, the hub height for utility-scale land-based wind turbines increased from an average 98 feet to 295 feet in the last


Credit: BangorArt, Flickr (CC BY-NC-ND 2.0)

MPI Adventure, a wind turbine installation vessel, anchored off Luke's Point, Bangor, Belfast Lough, Northern Ireland.

30 years, while the turbine's rotor diameter (width of the circle swept by the rotating blades) increased from an average 89 feet to 410 feet during that same timespan. Likewise, maximum power rating, or capacity, increased from an average 0.2 MW to 3 MW.

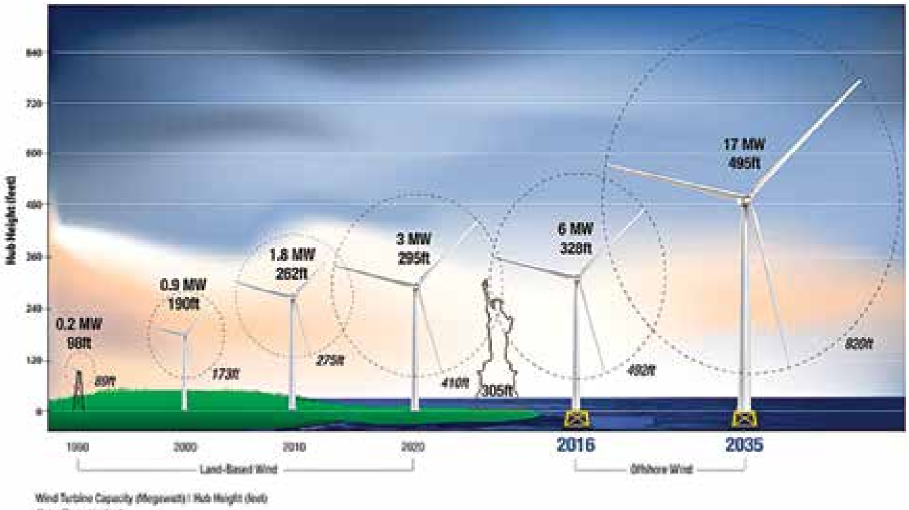
Offshore wind turbines are projected to grow even more than their land-based counterparts—from 328 feet in 2016 to up to 495 feet in 2035, with a rotor diameter of 820 feet and power rating of 17 MW.

While these increasingly large turbines excel at generating more energy, they also result in more waste upon decommissioning. Finding ways to recycle or reuse this waste is frequently discussed, yet there is another issue for super-sized turbines that does not receive as much attention—the issue of transportation.

Ships are used to transport the components of a wind turbine to the offshore location, where it is then assembled. Current state-of-the-art installation vessels can transport up to four 8-MW-class wind turbines at a single time. While these capabilities are sufficient for transporting wind turbines today, the move toward larger wind turbines will soon surpass the limits of current vessels.

"Turbines larger than 8 MW accounted for just 3% of global installations between 2010 and 2021, but that percentage is forecast to surge to 53% by 2030," explains a new report by independent energy research and business intelligence company Rystad Energy.

In the report, Rystad Energy looks at how the installation of super-sized offshore wind farms could face bottlenecks



Credit: Office of Energy Efficiency & Renewable Energy

in the coming years if operators do not invest in new vessels capable of transporting the massive turbines.

The report notes that only a handful of vessels currently exist that can install 10 MW+ turbines; none can install 14 MW+ turbines. However, the high cost of manufacturing a new installation vessel—$300–$500 million for one that can handle 14 MW+ wind turbines—makes it difficult for developers to finance the necessary ships, as they would need several offshore wind builds in sequence to get a return on their investment.

Contrast these costs with the rising demand for offshore wind installations and "There simply is not enough time to ramp up domestic capacity prior to an initial wave of offshore wind facilities being constructed," says Heather Zichal, CEO of American Clean Power Association, in written Congressional testimony presented last year to the U.S. House Committee on Foreign Affairs Subcommittee on Europe, Energy, the Environment and Cyber.

Taken together, Rystad Energy proposes that these factors may culminate in a slowdown in offshore wind installations in the coming years.

While the report describes the work by some companies to expand their carrying capacity through either new builds or upgrades of existing vessels, researchers are also exploring alternative ways to transport super-sized wind turbines that do not require massive ships.

For example, in 2017, researchers led by the University of Delaware investigated the possibility of assembling a wind turbine in port mounted on caissons, then lashing the entire structure to the side of a vessel or barge and hauling it to location. While this approach would allow for the use of smaller, lower-cost vessels, no ports currently exist that allow for this kind of onshore assembly.

Read the Rystad Energy report at https://www.rystadenergy.com/newsevents/news/press-releases. ■

international year of glass

Each month, we will be highlighting articles from different areas of glass science in the online blog *Ceramic Tech Today*.

The American Glass Guild unites artists and scholars of stained glass

By Kathy Jordan

Nothing could have prepared us for the lockdowns, social distancing, and other challenges that the COVID-19 pandemic brought.

Despite these challenges, International Commission on Glass president Alicia Durán and her team persevered to gain unprecedented support for the International Year of Glass 2022, which the United Nations officially declared in May 2021.

The American Glass Guild (AGG) is one of the many glass entities who joined the global chorus to endorse IYOG. AGG is a voluntary organization comprised of craftspeople, artisans, artists, and scholars with great experience in their fields. AGG members give freely of their time, resources, and array of talents to help promote the crafts and arts that have given them so much individually and, quite often, have become their livelihood.

AGG offers access to accumulated technical, best practice, and historical knowledge that is unattainable anywhere else. Since 2006, the Guild's all-volunteer Board and Committee members have organized and presented educational conferences, seminars, and lectures to the glass community and to the public. We welcome and share the ideas and discoveries of novices with as much encouragement as we do for the most well-known artists and scholars. We open our conferences and literature to present and future architects, owners, and stewards of stained, leaded, and decorative glass so that they can make informed decisions when judging proposed materials and techniques.

The pandemic-driven rise of the virtual world allowed AGG to become a greater global educational organization. We expanded our offering of online forums, blogs, workshops, and educational programs to help increase knowledge of the stained and decorative glass industry throughout the world. New processes and techniques borrowed from other art fields have opened the range of artistic capabilities employed in modern and contemporary stained glass design and fabrication.

In recognition of the International Year of Glass, AGG will hold its 16th annual conference at the Corning Museum of Glass in Corning, New York, from July 14–17 (Thursday through Sunday), with workshops on July 13 and 14. We are hosting national and international speakers who will explore the old and new applications of glass, the use of light in glass design, provide case studies, and push the limits of creativity while honoring the tradition of stained glass and the innovation of new techniques and technology.

With an epic location, AGG 2022 is shaping up to be an event for the books. The Corning Museum of Glass is the world's largest space dedicated to the display of contemporary art and design in glass. This interactive, educational, hands-on, and family friendly museum is also home to the largest collection of art glass in the world, from the work of early Mesopotamians to the beautiful stained glass windows of Louis Comfort Tiffany and Narcissus Quagliata.

For more information on AGG and the upcoming summer conference, please visit www.americanglassguild.org.

About the author

Kathy Jordan is president of the American Glass Guild. Contact Jordan at president@americanglassguild.org.

Credit: American Glass Guild

AGG president Kathy Jordan paints a stained glass window.

SOCIETY DIVISION SECTION CHAPTER NEWS

Welcome new ACerS Corporate Partners

ACerS is pleased to welcome its newest Corporate Partners

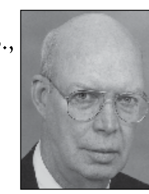
Horiba Scientific

INNEX Innovative Industries

XJet

To learn about the benefits of ACerS Corporate Partnership, contact Kevin Thompson, membership director, at (614) 794-5894 or kthompson@ceramics.org. ■

Remembering Dale Niesz, ACerS president 1987–88



Niesz

Dale Niesz, a native son of Ohio and a ceramic engineer to the core, died Feb. 25, 2022. Born in Canton, Ohio, in 1939, he earned B.S., M.S., and Ph.D. ceramic engineering degrees from The Ohio State University. Besides pursuing a rigorous academic discipline, Niesz played offensive end on the OSU football team 1957–1960 under coach Woody Hayes. He was a devoted Buckeye fan his entire life.

On graduation, Niesz joined the Battelle Memorial Institute in Columbus, Ohio, as a research engineer and eventually became manager of materials engineering. In 1987, he joined the faculty at Rutgers, The State University of New Jersey, where he stayed until he retired in 2004. While at Rutgers, he served as director of the Center for Ceramic Research, and in 1994 he became chair of the Department of Ceramic and Materials Engineering. One of his early important achievements was experimentally demonstrating the Weibull specimen size effect on the measured strength of ceramics.

He was a strong leader in the ceramic engineering community, serving as ACerS president 1987–88, and he was a charter member and president of the International Ceramic Federation. His many accolades include ACerS Distinguished Life Member, ACerS Fellow, OSU College of Engineering Distinguished Life Member, and elected member of the International Academy of Ceramics.

After retirement, he returned to central Ohio, where the Society staff enjoyed his occasional drop-in visits at Society headquarters in Westerville, Ohio. Niesz is survived by his wife, Janice, two daughters and their families. A more extensive obituary is posted online at https://ceramics.org/in-memoriam. ■

Eastern Tennessee Section makes plans for technical and social events

Members of the recently formed Eastern Tennessee Section gathered and discussed plans for a quarterly technical meeting, a quarterly social event, and outreach to the local universities. Stay tuned for more news about the Section's first technical event, which will take place in April 2022. ■

Northern Ohio Section seeks new leadership

The future is bright for the materials community in Ohio! ACerS Sections provide a local source of ceramic and glass industry education, information, and interaction. The Northern Ohio section is looking for new leadership and volunteers to guide a local, tight-knit group of ceramic and glass industry professionals in northern Ohio, which covers the broad region including Cleveland, Akron, and Canton. Contact Karen McCurdy at kmccurdy@ceramics.org to learn more about getting involved and positioning this Section for an exciting future. ■

www.ceramics.org/ceramictechtoday

Credit: Southern California Section

The Southern California Section hosted its inaugural event on Feb. 12, 2022, at the HRL Laboratories in Malibu, California. Ceramics and glass professionals in Southern California enjoyed networking, a lab tour, and planning of future events.

Names in the news

Members—Would you like to be included in the Bulletin's Names in the News? Please send a current head shot along with the link to the article to mmartin@ceramics.org. The deadline is the 30th of each month.


Berndt

Chris Berndt, FACerS, distinguished professor at Swinburne University of Technology, Victoria, Australia, received the 2021 Victoria Prize for Science and Innovation in the Physical Sciences by the Victorian Government. The prize comes with an AUD$50,000 stipend. ■

more SOCIETY DIVISION SECTION CHAPTER NEWS

Italy Chapter organizes two workshops

The ACerS Italy Chapter is organizing two workshops for May and June.

The May workshop, "The thousand lives of glass," takes place in Venice, Italy, on May 20, 2022. This workshop (in Italian) is free and available to researchers, industries, and students interested in glass science and technology. The workshop aims to bring innovative ideas on the use of glass out of laboratories and transfer them to anyone interested in developing what glass has to offer. Visit https://ceramics.org/wp-content/uploads/2022/02/Le-mille-vite-del-vetro.pdf for more details.

The June workshop is an Italian–French bilateral workshop on ceramic matrix composites in Montecatini, Italy, on June 25, 2022. For more information, please visit the ACerS Italy Chapter webpage at https://ceramics.org/members/member-communities/international-chapters/italy-chapter-2. ■

Spain Chapter sponsors Additive Manufacturing Symposium at the SECV Conference in May 2022

The SECV Conference is scheduled for May 3–6, 2022. Visit https://secv.es/congreso-secv-2022/programa for details. ■

Thailand Chapter: Call for abstracts for ACXAS2022

The Asian Conference on X-ray absorption spectroscopy (ACXAS-2022) invites the submission of work related to the recent advances and development in XAS characterization in all disciplines ranging from materials science to earth sciences and biology. For more information, visit the conference website at https://acxas2022.com. ■

Cements Division: 12th Advances in Cement-Based Materials call for abstracts

Cement is the key ingredient in concrete—the most-used building material in the world—so every advance in understanding how it behaves presents an opportunity to reduce greenhouse gases, advance construction engineering, and improve quality of life around the world. Organized by ACerS Cements Division, the 12th Advances in Cement-Based Materials will take place July 11–13, 2022, at the University of California, Irvine. The deadline for abstract submission is **April 15, 2022**. Additional meeting information may be found at http://bit.ly/cements2022. ■

EMSD introduces new logo

The Energy Materials and Systems Division received seven thoughtful and creative entries to its recent logo creation contest. The winning logo was designed by Anushka Pandey of the National Institute of Technology, Rourkela, India. Ms. Pandey will receive a $500 prize and two years of complimentary ACerS membership with EMSD affiliation. Congratulations! ■

EMSD
Energy Materials and Systems Division

Volunteer spotlight

ACerS Volunteer Spotlight profiles a member who demonstrates outstanding service to the Society.

Gorzkowski

Edward P. Gorzkowski, III, is branch head of the Multifunctional Materials Branch at the U.S. Naval Research Laboratory in Washington, D.C. He received his B.S. and Ph.D. degrees in materials science and engineering from Lehigh University.

Gorzkowski has authored more than 90 peer-reviewed articles and proceedings, delivered more than 30 invited talks (including plenaries at international conferences), and served as a guest editor for a special issue of the journal *IEEE Ultrasonics, Ferroelectrics, and Frequency Control*. He holds eight patents.

Gorzkowski is active in ACerS as vice-chair of the Electronics Division. He belongs to the Basic Science and Energy Materials and Systems Divisions. He was a founding member and co-chair of the Washington D.C., Maryland, and Northern Virginia Section. He co-organized the Electronic Materials and Applications conference in 2022 and 2023, and organized symposia sessions at EMA, MS&T, and PacRim conferences, both present and past.

Gorzkowski has served on the ACerS Books Subcommittee and is a former chair of the Young Professionals Network. He received the 2015 Du-Co Young Professionals Award, a 2018 Best Paper award from *The Journal of the American Ceramic Society*, and the 2020 Richard M. Fulrath Award.

We extend our deep appreciation to Gorzkowski for his service to our Society!

IN MEMORIAM

Dale Niesz

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

Ceramic Tech Chat: Welcome to IYOG 2022

Hosted by ACerS Bulletin editors, Ceramic Tech Chat talks with ACerS members to learn about their unique and personal stories of how they found their way to careers in ceramics. New episodes publish the second Wednesday of each month

In the February episode of Ceramic Tech Chat, University of Central Florida professor Kathleen Richardson and The Ohio State University professor Manoj Choudhary discuss the importance of glass in our lives, give the history of the United Nations International Year of Glass 2022, and preview some of the events taking place to celebrate this International Year.

Listen to their whole interview—and all of our other Ceramic Tech Chat episodes—at http://ceramictechchat.ceramics.org/974767.

Two members elected to National Academy of Engineering

Congratulations to our members recently honored with election to the NAE!

John Mauro, FACerS, professor in the Department of Materials Science and Engineering at The Pennsylvania State University and *JACerS* editor.

Julie Schoenung, FACerS, department chair and professor in materials science and engineering at the University of California, Irvine.

Meet the Strategic Planning for Emerging Opportunities Committee

The SPEO Committee comprises the leaders of ACerS principal committees and Society member groups, such as the President's Council of Student Advisors, the Young Professionals Network, and technical interest groups. The committee is responsible for identifying emerging opportunities that the Society should consider as part of its strategic planning process. ACerS Board of Directors develops ACerS long- and short-term strategy, which, in turn, is implemented through the Society's committees and member groups. Thus, SPEO serves an important role, complementary to the Board, in setting and achieving the Society's strategic direction.


Mathur

Sanjay Mathur 2021–22
Chair & president-elect
University of Cologne, Germany


Bordia

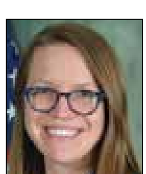
Raj Bordia 2021–22
President-elect nominee
Clemson University


Poerschke

David Poerschke 2018–22
Publications Committee chair
University of Minnesota


Trice

Rodney Trice 2018–22
Meetings Committee chair
Purdue University


Rueschhoff

Lisa Rueschhoff 2020–22
Member Services Committee chair
Air Force Research Laboratory


Blair

Victoria Blair 2020–23
Member at-large
U.S. Army Research Laboratory


Fukushima

Manabu Fukushima 2019–22
Member at-large
National Institute of Advanced Industrial Science and Technology, Japan


Randall

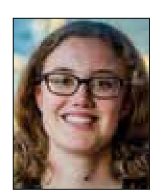
Clive Randall 2021–24
Member at-large
Pennsylvania State University


Gong

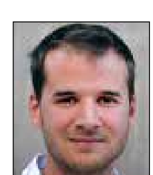
Yuxuan Gong 2020–22
Young Professionals Network co-chair
JELD WEN, Inc.


Hampton

Ashley Hampton 2021–23
Young Professionals Network co-chair
Allied Mineral Products, LLC.


Brandt

Olivia Brandt 2021–22
President's Council of Student Advisors chair
Purdue University


Bauchy

Mathieu Bauchy
SPEO standing guest, Technical Interest Group leader
Focus: Computational design of ceramics and glasses
UCLA


Singh

Gurpreet Singh
SPEO standing guest, Technical Interest Group leader
Focus: Products arising from polymer-derived ceramics
Kansas State University

AWARDS AND DEADLINES

ceramics.org/members/awards

Award deadlines for May and beyond

Several prestigious Division award deadlines are in May. Full details are online at www.ceramics.org/awards.

The Energy Materials and Systems Division seeks nominations for its award, due in July. Full details are online at www.ceramics.org/awards.

Contact: Erica Zimmerman | Member engagement manager
ezimmerman@ceramics.org | 614.794.5821

Division	Award	Nomination Deadline	Contacts	Description
GOMD	Alfred R. Cooper	May 15	Steve Martin swmartin@iastate.edu	Recognizes undergraduate students who demonstrated excellence in research, engineering and/or study in glass science or technology.
EDiv	Edward C Henry	May 30	Elizabeth Paisley eapaisl@sandia.gov	Recognizes an outstanding paper reporting original work in *The Journal of the American Ceramic Society* or the *Bulletin* during the previous calendar year on a subject related to electronic ceramics.
EDiv	Lewis C. Hoffman Scholarship	May 30	Elizabeth Paisley eapaisl@sandia.gov	Recognizes academic interest and excellence among undergraduate students in the area of ceramics/materials science and engineering.
EMSD	Outstanding Student Researcher	July 31	Yang Bai Ayang.bai@oulu.fi	Recognizes exemplary student research related to the mission of ACerS' Energy Materials and Systems Division.

STUDENTS AND OUTREACH

NEW—Glorious Glass Demo competition

In honor of the United Nations International Year of Glass 2022, the Glass & Optical Materials Division is holding a glass demonstration competition to showcase the beautiful complexity of glass science and glass art. The top three awardees will each receive a cash prize, plaque, conference registration, and recognition at the GOMD Annual Meeting 2022 in Baltimore, Md.

The Glorious Glass Demo competition involves creating a three-to-five minute video showing the general public something interesting and fun about glass science and/or glass art. While the idea for the demonstration must center around glass science or glass art, in what way this objective is accomplished is up to you! In addition to the video, you will be asked to submit a one-page report explaining the science behind your demonstration to professionals in the field of glass science and glass art.

Visit https://ceramics.org/glorious-glass-demo for more information and to enter the competition. The deadline is **April 18, 2022.** ■

Graduate students—Opportunities to explore and grow

- Penn State, ACerS, and the University of Kiel invite applications to their NSF-funded PACK fellowship exchange experience at the University of Kiel, Germany. http://packfellowship.org.
- Join ACerS Global Graduate Researcher Network, and put yourself on the path toward post-graduate success https://ceramics.org/ggrn. ■

CERAMICAND**GLASS**INDUSTRY FOUNDATION

CGIF hosts successful Virtual Winter Workshop for students and young professionals

The 7th Annual Winter Workshop was held virtually this year on Feb. 17–18, 2022, and welcomed participants from North America, Europe, Africa, and Asia.

Winter Workshop is an event for materials science and engineering students and young professionals to learn from industry professionals and network with others in ceramic and glass engineering fields.

Each year, the workshop provides a combination of technical presentations, professional development sessions, and networking opportunities. This year's online event concluded with an interactive interviewing and resume writing workshop.

We want to send out a heartfelt thank you to the presenters, participants, and committee members who helped make Winter Workshop a huge success! ■

Next-generation memory: Global markets to 2026

By BCC Publishing Staff

The global next-generation memory market was valued at $4.5 billion in 2020 and is estimated to grow at a compound annual growth rate (CAGR) of 22.5% to reach $14.8 billion in 2026.

The nonvolatile memory segment holds the largest market share and is expected to grow at a CAGR of 22.7% to reach $9.6 billion by 2026. The nonvolatile memory segment includes

- **Magneto-resistive random access memory (MRAM)** uses magnetic charges instead of electric charges to store data. The two types of MRAM are toggle MRAM, which uses a transistor and a magnetic tunnel junction cell to provide simple high-density memory, and spin-transfer torque MRAM, which offers a significant reduction in switching power compared to toggle MRAM.
- **Ferroelectric random access memory (FRAM)** uses ferroelectric film to store data. FRAMs are broadly classified into two types: the first works by detecting a change in the amount of charge stored in a ferroelectric capacitor; the second works by detecting a change in the resistance of a semiconductor due to spontaneous polarization of ferroelectric material.
- **Resistive random access memory (RRAM)** is based on the reversible formation and disruption of a conductive filament in a resistive layer that provides low- and high-resistance states. The physical mechanism by which RRAM devices operate can be divided into two categories: oxide resistive random access memory (OxRRAM) and conductive-bridging random access memory (CBRAM).
- **3D Xpoint** is a resistance-based technology that consists of a simple, stackable, transistor less design in which memory cells meet at the intersection of word lines and bit lines, allowing the cells to be addressed individually. Intel and Micron jointly developed this technology and have not disclosed the internal read/write voltages.
- **Nano random access memory**, which is designed and owned by Nantero, blends tiny carbon nanotubes with conventional semiconductors.

Table 1. Global markets for next-generation memory, by application, through 2026 ($ millions)

Application	2020	2021	2022	2024	2026	CAGR % (2021–2026)
Enterprise storage	1,274.7	1,530.1	1,850.3	2,765.6	4,259.3	22.7
Consumer electronics	1,079.9	1,300.7	1,577.6	2,371.5	3,671.5	23.1
Industrial	712.8	855.2	1,033.3	1,542.1	2,371.4	22.6
Automotive and transportation	424.1	508	612.8	911.5	1,397.1	22.4
Telecommunications	308.9	369.1	444.2	657.6	1,003.1	22.1
Military and aerospace	218.7	260.5	312.6	459.9	697.4	21.8
Healthcare	167.1	198.7	238	348.8	526.8	21.5
Others	296.9	349.3	415.2	599.9	892.9	20.06
Total	4,481.8	5,371.5	6,483.9	9,656.8	14,819.5	22.5

The volatile memory segment is anticipated to grow at a CAGR of 22.2% to reach $5.2 billion by 2026. The need for high bandwidth, low power consumption, and highly scalable memories is increasing the demand for volatile memories such as high-bandwidth memory and hybrid memory cube.

- **High-bandwidth memory (HBM)**, which was jointly developed by AMD and Hynix, is a 3D architecture-based solution to the memory bandwidth problem. HBM technology uses vertically stacked memory chips connected by microscopic cables called through-silicon vias and silicon interposer technology to interconnect stacked dynamic RAM dies.
- **Hybrid memory cube (HMC)** is a high-performance RAM interface for through-silicon vias-based dynamic RAM memories. Co-developed by Samsung Electronics and Micron Technology, HMC consists of a 3D configuration composed of stacked dynamic RAM layers and a single logical control layer to handle all read-write traffic.

The wafer sizes for next-generation memory technologies are segmented into 200 mm, 300 mm, and 450 mm. Currently, 300 mm in diameter is the largest wafer size in full production. A larger wafer diameter allows more amortization of fixed costs, resulting in a lower cost per chip.

North America is estimated to account for the highest share of the global next-generation memory market throughout the forecast period, growing at a CAGR of 22.7% to reach $5.9 million by 2026. However, the Asia-Pacific region is expected to be the fastest-growing regional market with a CAGR of 23.1%, with China accounting for most of the demand.

About the author

BCC Publishing Staff provides comprehensive analyses of global market sizing, forecasting, and industry intelligence, covering markets where advances in science and technology are improving the quality, standard, and sustainability of businesses, economies, and lives. Contact the staff at Helia.Jalili@bccresearch.com.

Resource

BCC Publishing Staff, "Next-generation memory: Global markets to 2026" BCC Research Report SMC130A, December 2021. www.bccresearch.com.

Probing the ocean's origins—ultrahigh-pressure magnesium hydrosilicates may have served as reservoirs of early water

Credit: Timothy M Roberts, Flickr (CC BY-SA 2.0)

Where did all the water on Earth come from? A new paper posits that magnesium hydrosilicates served as reservoirs of water in early Earth.

In a recent paper, researchers from several universities in China and the Skolkovo Institute of Science and Technology in Russia advance a new hypothesis about the origins of primordial water.

Currently, there are two prevailing and opposing views on where Earth's water came from.

1. That water is primordial, i.e., water was released from inside Earth during formation.

2. That water was "donated" later by water-rich aerolites (stony meteorites consisting of silicate minerals).

Scientists have traditionally favored the second explanation—that water was brought to Earth from somewhere else. However, several recent studies have increased the amount of evidence supporting the argument that Earth contained the necessary building blocks to form water on its own, too.

The deuterium/hydrogen (D=H) ratio is one statistic that scientists have highlighted to support the first viewpoint. Earth's deep mantle has a low D=H ratio quite close to that of enstatite chondrite meteorites, which are the fundamental building blocks of the young Earth. This similarity suggests that water within Earth's interior may have come directly from the protosolar nebula.

"However, this hypothesis raises several questions. Compared with other planetary materials such as iron and silicates, water has a much lower condensation temperature and therefore would have been released to space at the high surface temperature of the newborn Earth and then by the Moon-forming impact. To avoid complete loss, water must have been stored inside the Earth in the planet's neonatal accretion period," the researchers write.

In their paper, they advance the hypothesis that water was contained in hydrous minerals. Hydrous minerals are minerals that contain water in their structure. When certain conditions are met, such as the mineral is transported to an area with lower pressure, the minerals disassociate and release the water contained inside.

There is a sizable amount of research on the role hydrous minerals play in the water storage and transportation mechanisms within Earth's mantle. Magnesium hydrosilicates specifically have received a lot of attention due to oxygen, magnesium, and silicon being the most abundant elements in Earth's mantle.

However, research on magnesium hydrosilicates to date has focused on polymorphs that currently exist in Earth's mantle—an environment that is far different from the mantle during Earth's formative years.

For the new study, the researchers wanted to consider polymorphs that could have withstood the high temperatures and pressures of the core–mantle separation process. During that time in Earth's history, Earth had a fairly even distribution of elements throughout, rather than the metallic core we know today. In other words, the elements that make up magnesium hydrosilicate would have been available deep within Earth millions of years ago.

To identify possible magnesium hydrosilicate polymorphs, the researchers used a variable-composition evolutionary structure prediction algorithm and ab initio molecular dynamics simulations to model the ternary system $MgO–SiO_2–H_2O$.

The modeling revealed two thermodynamically stable polymorphs that could have withstood the core–mantle separation process—α-$Mg_2SiO_5H_2$ and β-$Mg_2SiO_5H_2$ with base centered monoclinic lattices. These magnesium hydrosilicates are more than 11% water by weight and are stable at pressures of more than 2 million atmospheres.

The researchers explain that these magnesium hydrosilicates would have originally existed at the center of the forming Earth. However, as the core grew, they were displaced to shallower depths with lower pressures and disassociated into $MgSiO_3$, MgO, and water.

"The released water would be gradually transported to the surface of the Earth, to form its hydrosphere. As to the other products of dissociation of $Mg_2SiO_5H_2$, namely, $MgSiO_3$ and MgO, they are still in the lower mantle, playing the role of its main phases," the researchers write.

They conclude the paper by highlighting some of the numerous implications this hypothesis could have on other areas of research. For example, it could explain why Mars is so dry compared to Earth.

"Mars, for example, is too small to produce pressures necessary to stabilize magnesium hydrosilicate," Skoltech full professor Artem R. Oganov says in a Skoltech press release. "This explains why it is so dry and means that whatever water exists on Mars, it likely came from comets."

Nankai University professor Xiao Dong adds the hypothesis could also improve our understanding of planets outside our solar system.

"To be habitable, an exoplanet has to have a stable climate, which requires both continents and oceans. So there has to be water, but not too much," he says in the press release. "There was an estimate that for an Earth-like planet of any size to be habitable, it should have no more than 0.2% water by weight. Our results imply that for large Earth-like planets, called 'super-Earths,' the story is likely different: In such planets, pressures stabilizing the magnesium hydrosilicate must exist even outside the core, locking up large amounts of water indefinitely. As a result, super-Earths can have a much greater water content and still support the existence of exposed continents."

Finally, Oganov notes that the hypothesis could have implications for a planet's magnetosphere. "At temperatures of more than 2,000 degrees Celsius, magnesium hydrosilicate will conduct electricity, with hydrogen protons serving as charge carriers. This means that our hydrosilicate will contribute to the magnetic fields of super-Earths," he says in the press release.

In an email, Oganov says that if the new hypothesis is correct, then the water released by the magnesium hydrosilicates could have brought other components with it to Earth's surface, which would imply there are additional detectable geochemical signatures of the process.

"But it will require us to understand better the chemical behavior of the elements at ultrahigh pressures. We are exploring this," he says.

The paper, published in *Physical Review Letters*, is "Ultrahigh-pressure magnesium hydrosilicates as reservoirs of water in early Earth" (DOI: 10.1103/PhysRevLett.128.035703). ■

New analysis model determines reliability and sensitivity of cold-bent curtain wall glass


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

Example of a curved glass curtain wall at the Seattle-Tacoma International Airport.

Researchers from Northeastern University in the U.S. and Avic Xi'an Aircraft Industry Group Co., Ltd. in China looked to develop an analysis model to determine the reliability and sensitivity of cold-bent curtain wall glass.

Curtain walls are an increasingly popular design element that serve mainly an aesthetic rather than structural purpose. These non-load-bearing frames consist of a thin aluminum frame that can be filled with various materials, and glass is one of the most popular choices.

Curtain wall glass is often manufactured using cold bending, which involves attaching planar glass sheets to the curved aluminum frame so that it deforms within an allowable range of stress to achieve a curved effect. After glass is cold bent, residual stress remains in it even after installation. If this stress is greater than the strength of the glass, the curtain wall will eventually break.

"Therefore, studying the stress state of glass cold bending has become the basis for the application of curtain wall cold bending methods," the researchers write in their recent paper.

They explain that it is "impossible" to account for all the factors involved during the glass cold-bending process, such as volatility of material properties and geometric parameters, and these uncertainties lead to many random variables that increase the complexity of simulations. So, researchers have proposed a variety of models to reduce complexity.

Based on these previous results, the researchers developed their own method based on finite element analysis. They compared the predictions of their model to experimental results and also performed reliability and sensitivity analyses using Monte Carlo and adaptive Kriging-Monte Carlo simulations.

Based on comparison of the simulated and experimental results of the stress and displacement of each measuring point of the curtain wall glass, the researchers concluded that their finite element method "is realistic and can be used to formulate the limit state function for the cold-bending reliability and sensitivity analysis of curtain wall glass."

In addition, the adaptive Kriging-Monte Carlo simulations demonstrated high computational efficiency and fast convergence speed and met the accuracy requirements for reliability analysis. "Therefore, [Kriging-Monte Carlo simulation] is especially suitable for the reliability and sensitivity analysis of cold-bent curtain wall glass," they write.

The paper, published in *Journal of Building Engineering*, is "Reliability and sensitivity analysis of cold-bent curtain wall glass" (DOI: 10.1016/j.jobe.2022.104116). ■

New flash sintering process advances method toward commercialization

Syed I. A. Jalali and Rishi Raj at the University of Colorado Boulder invented a new flash sintering process that could advance the method toward commercialization.

The traditional flash sintering process requires that electrodes be attached to the green body to control the current flowing through the sample. However, the attachment of electrodes to the sample can complicate the flow of uniform current density throughout the entire workpiece, which complicates the achievement of a uniform microstructure.

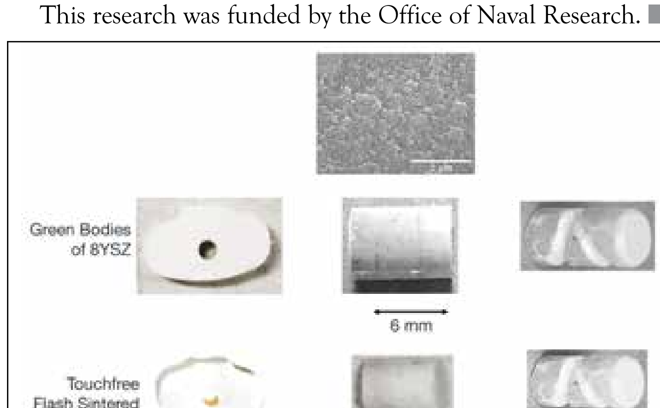
Jalali and Raj's new process involves flash sintering a free-floating green body of an arbitrary shape without touching the workpiece with current-carrying electrodes. The feat is achieved by directing the plasma, which is generated within the reactor, into the specimen.

The sample sinters in the normal way, that is, with a bright glow of electroluminescence. The sintering is uniform throughout the specimen, and a density of more than 99% can be achieved in 8% mol. yttria stabilized zirconia. The microstructure is very uniform with a grain size of approximately 200 nm.

In addition to touch-free flash sintering overcoming the challenge of achieving a uniform microstructure, the plasma aspect of this invention further injects new scientific questions into the atomistic mechanism of the flash phenomenon, which could have far-reaching consequences.

Jalali and Raj are interested in pursuing commercial developments of the touch-free flash sintering process through joint ventures. Email Raj with inquires at rishi.raj@colorado.edu.

This research was funded by the Office of Naval Research. ■



Credit: Jalali and Raj

ceramics in biomedicine

New glass and clay-based samples demonstrate broad virus inactivation

In a recent open-access paper, researchers from several universities and institutions in Spain investigated the potential of nanoparticle-embedded clay and glass as viral disinfectants.

Disinfectants based on inorganic materials have gained much attention recently due to setbacks with organic-based disinfectants, which have low resistance to heat, high decomposability, and short lifespans.

In an email, ACerS Fellow and CINN-University of Oviedo professor José S. Moya explains that he and other researchers associated with the Nanomaterials & Nanotechnology Research Center (CINN), which is a joint initiative of three institutions, have spent the last 10 years studying inorganic materials with strong bactericidal activity. When the COVID-19 pandemic began, the National Spanish Council for Scientific Research requested that they investigate if these inorganic materials also had virucidal activity.

Moya says they chose to investigate both nanoparticle-embedded clay and glass in this study so they could compare results from a material with known virucidal activity (a nanoparticle-embedded clay) and a material with unknown virucidal activity (a glass).

For the nanoparticle-embedded clay, the researchers chose kaolin embedded with silver or copper oxide nanoparticles. For the glass, they chose a biocompatible and antibacterial soda-lime glass with high CaO content. They tested the effectiveness of the two materials against both enveloped and nonenveloped viruses.

The researchers found that both the nanoparticle-embedded kaolin and soda-lime glass demonstrated strong antiviral properties against the two types of viruses. Specifically, the materials led to a more than 99.9% reduction of viral infectivity after one hour in contact with the viruses.

The researchers suggest that the mechanisms behind the reduced viral infectivity are related to the properties of the materials. In the case of the nanoparticle-embedded clay, kaolin adsorbs the virus on its surface and dispenses the nanoparticles only as need to inactivate viruses rather than releasing the nanoparticles into the environment.

In the case of the soda-lime glass, the glass appears to induce virus aggregation. However, some details of the glass virucide mechanism remain unknown. For example, Moya says they do not yet know if the release of ions in the glass causes membrane depolarization, such as that observed in the case of bacteria, or if a synergistic effect is produced by release of calcium and boron ions.

"At the present moment we are in contact with the group of virologists led by Prof. E. Nistal to carry out a more complete study that allows us to know in more detail the mechanism of action of the G3 glass and the possible synergistic effect of calcium and boron," Moya says.

The open-access paper, published in *Materials Today Bio*, is "Broad virus inactivation using inorganic micro/nano-particulate materials" (DOI: 10.1016/j.mtbio.2021.100191). ■

Revealing the surface structural cause of scratch formation on soda-lime-silica glass

Researchers from the University of Bayreuth in Germany looked to identify the surface structural cause of scratch formation on soda–lime–silica glass surfaces.

Scratch resistance of the surface of container glasses is one of the key challenges for the glass industry, as scratches in the glass surface can lead to crack formation. Soda–lime–silica glass is of particular interest because this type of glass is widely used in the container industry.

In recent years, the effect of indenter geometry and applied normal load on the plastic deformation, microcracking, and chipping of glass has gained attention in numerous studies. However, "To the best of our knowledge, there is no information available on the surface structural behavior of the silicate network in terms of an elaborate analysis of network connectivity, which is responsible for triggering the formation of a visible scratch," the researchers write.

University of Bayreuth researchers explored how structure plays a role in scratch formation on a type of glass widely used in the container industry.

To understand the role surface structure plays in scratch formation, the researchers created samples of both untreated and heat-treated soda–lime–silica glass. Based on spectroscopy and microscopy analyses performed before and after scratch tests, they determined that the heat-treated glass was more sensitive to visible formation of scratches than the untreated glass. They suggest this vulnerability is due to the subsurface structure of heat-treated glass.

Up to a depth of about 5 nm, the heat-treated glass contains relatively lower concentrations of "mechanically weakening elements," i.e., nonbridging oxygens and SiOH/H_2O species, and a high concentration of bridging oxygens, which "indicated a strong and rigid network." In contrast, the untreated glass has higher concentrations of nonbridging oxygens and SiOH/H_2O species at that same depth, which "is accountable for its lower hardness."

Critically, the reverse is true in the 5–100 nm region—the heat-treated glass is mechanically weaker in this "intermediate zone" due to a higher O_{Total}/Si ratio. However, in the bulk region of the glasses (1–5 µm, or 1,000–5,000 nm), the heat-treated glass is again stronger due to a lower variation of the bond angle in its network at this depth.

Simply put,

- Untreated glass: **weak** (up to 5 nm)—**strong** (5 to 100 nm)—**weak** (1 to 5 µm)
- Heat-treated glass: **strong** (up to 5 nm)—**weak** (5 to 100 nm)—**strong** (1 to 5 µm)

The mechanically weaker "intermediate zone" of the heat-treated glass is what the researchers identify as a key factor in visible scratch formation.

"This depth is critical to propagation of cracks from a surface flaw during a scratching event because the size of the cavities in the vicinity of crack tips is reported to be in the same range on the order of nanometers," they write.

So, "A weaker structural network in this region … is expected to contribute to easy propagation of a surface-initiated crack to the depth of the stronger bulk network," they explain. "Any surface injuries will be subsequently accompanied by higher scratch depths, wear volume, and material pile up."

The researchers are working on a new study that extends the X-ray photoelectron spectroscopy measurements for several hours—accompanied by argon etching with low-energy gas cluster ion beam—to ensure that the glass network is not affected despite prolonged exposure.

"This may give rise to the possibility to probe further into the depth of the glass network to complementarily correlate the distribution of Qn species obtained by Raman investigations in the bulk structure of the solid specimens," they add.

The open-access paper, published in *Scientific Reports*, is "Revealing the surface structural cause of scratch formation on soda-lime-silica glass" (DOI: 10.1038/s41598-022-06649-y). ■

Consequences of methodology—influence of indenter tip radius on failure mechanisms in borided steel

In a recent study, researchers from the National Polytechnic Institute of Mexico and Tecnológico de Monterrey investigate the effect that one seemingly minor methodological change can have on experiments—the radius of the indenter tip used in scratch testing.

Scratch testing is a common method used to test the adhesion strength of thin films and hard coatings. The test involves applying a progressively increasing indenting load over the coated sample, which moves at constant speed until a failure mechanism is identified along the scratch groove. The load at which a well-defined failure mechanism is observed is called the critical load.

Researchers have evaluated the effect of indenter tip radius on the critical loads of various coating and substrate combinations. However, despite the variety of these studies, "there is no information focusing on adhesion strength analysis of a coating/substrate system developed by a thermochemical diffusion process such as nitriding, cementing or more precisely, boriding," the researchers write.

So, they investigated the effect that indenter tip radius has on critical loads of borided materials, specifically double phase boride layers (FeB/Fe_2B) on AISI H13 steel, which is a tool steel grade standardized for hot working.

The researchers used a diamond Rockwell-C indenter tip for the scratch adhesion tests. Initial loads of 1, 2.5, 5, and 10 N and final loads of 10, 25, 50, and 100 N were selected for indenter tip radiuses of 20, 50, 100, and 200 µm, respectively.

Scanning electron microscopy analysis revealed that the predominant failure mechanisms in borided steels were lateral cracking, chipping, and gross chipping. While an indenter tip radius of 20 µm developed more severe damage on the borided surface, the more severe substrate plastic deformation occurred with an indenter tip radius of 200 µm. Thus, overall, "the smaller indenter tip radius generated more severe damage," the researchers write.

The paper, published in *Materials Letters*, is "Scratch test in boride layers: influence of indenter tip radius on failure mechanisms" (DOI: 10.1016/j.matlet.2022.131918). ■

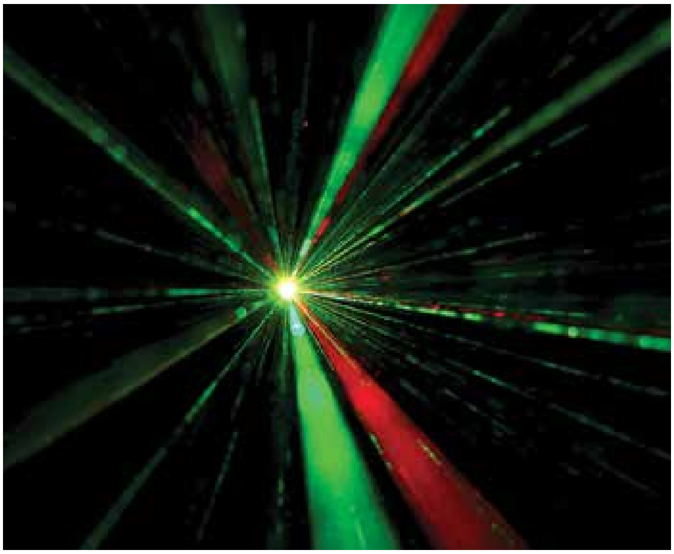
Standard sintering aids and dispersants can degrade lasing performance of transparent ceramics

In a set of recent studies, a team of researchers from Nanyang Technological University in Singapore and Jiangsu Normal University in China investigated how different factors in the fabrication process of transparent ceramics affected the final material's lasing performance.

In the first article, published in 2019, the researchers explored the effects of a common sintering aid. Dopants such as ThO_2, ZrO_2, and HfO_2 are widely used to help control the formation of pores and secondary phases in transparent ceramics during fabrication. When these dopants are added, some of the cations in the ceramics are replaced by tetravalent cations in the dopants. This replacement generates cation vacancies, leading to slower exaggerated grain growth and easier elimination of residual pores. However, because of the charge imbalance between the ceramic's cations and the doped tetravalent cations, the concentration of point defects is increased in doped transparent ceramics—which puts the ceramic at risk of a detrimental phenomenon called photodarkening.

Photodarkening refers to when a transparent material becomes nontransparent under electrical or irradiation excitation due to electrons or holes becoming trapped in point defects or complex defect clusters. These areas in the structure then become known as color centers, or areas that absorb additional light, and can negatively affect a material's performance as a laser gain medium.

The photodarkening effect has been reported in some aliovalent ion-doped transparent materials, such as Si^{4+}-doped YAG, Y^{3+}-doped ZrO_2, and B^{3+}-doped SiO_2. However, "to the best of our knowledge," no studies have investigated the photodarkening phenomenon in terms of laser ceramics, the researchers write.



Researchers in Singapore and China investigated how different factors in the fabrication process of transparent ceramics affected the final material's lasing performance.

They explored the photodarkening effect in laser ceramics using highly transparent $Yb:Y_2O_3$ ceramics doped with and without ZrO_2. After irradiation by a 940-nm laser diode, they observed the photodarkening phenomenon in ZrO_2-doped $Yb:Y_2O_3$ ceramics but not in those without ZrO_2.

The absence of the photodarkening effect in the non-doped $Yb:Y_2O_3$ ceramics was reflected in lasing performance—the ZrYbY ceramic laser had a slope efficiency of about 9%, while the non-doped YbY ceramic laser had a slope efficiency of 17%.

The results led the researchers to wonder if any other processing parameters could lead to photodarkening. In a follow-up paper published in December 2021, they explored whether the dispersant used in the powder synthesis process could induce photodarkening as well.

Powders for laser ceramics are commonly synthesized using coprecipitation, which involves dissolving the starting materials in a common solvent and then adding a precipitating agent to form a solid. $(NH_4)_2SO_4$ is often used as a dispersant in the process, and while the addition of sulfate ions does improve the final powder morphology, it is difficult to completely remove the ions from the ceramic. Thus, "The residual sulfate ions could cause photodarkening and laser efficiency degradation," the researchers write.

To test the possible effect of $(NH_4)_2SO_4$ on lasing performance, the researchers synthesized nanocrystalline $Yb:Lu_2O_3$ ceramic powders using either $(NH_4)_2SO_4$ as a dispersant or an organic dispersant called poly(acrylic acid) (PAA). Like the previous study, they used a 940-nm laser diode to irradiate the samples.

Analysis of the samples revealed "clear experimental evidence" of photodarkening in the $Yb:Lu_2O_3$ ceramics fabricated using $(NH_4)_2SO_4$ as a dispersant. Again, this finding was reflected in the lasing performance—while the highest slope efficiency achieved by a $(NH_4)_2SO_4$-dispersed sample was 7.2%, one of the PAA-dispersed samples achieved a slope efficiency of 21.2%, despite having a lower optical quality than the $(NH_4)_2SO_4$-dispersed sample.

"Given that $(NH_4)_2SO_4$ is widely used as a dispersant in the chemical coprecipitation process to obtain nanocrystalline ceramic powders with low agglomeration, and the synthesized powders are popularly used to produce laser ceramics, we believe the result reported here could be useful for the laser ceramics community," the researchers conclude.

The 2019 paper, published in *Journal of the European Ceramic Society*, is "Pump laser induced photodarkening in ZrO_2-doped $Yb:Y_2O_3$ laser ceramics" (DOI: 10.1016/j.jeurceramsoc.2018.10.003).

The 2021 paper, published in *Optical Materials*, is "Efficiency degradation of laser ceramics caused by inappropriate dispersants and sintering aids" (DOI: 10.1016/j.optmat.2021.111789). ■

Unexpected starfish skeleton structure may help develop strong, lightweight ceramics

Credit: Klaus Stiefel, Flickr (CC BY-NC 2.0)

Example of a *Protoreaster nodosus*, the starfish which inspired the design of strong, lightweight ceramics by Virginia Tech researchers.

A new study led by researchers at Virginia Polytechnic Institute and State University found that the skeleton of a certain starfish offers valuable insights into designing strong, porous calcium carbonate.

Calcium carbonate is an abundant, naturally occurring mineral that serves numerous purposes in various industries. However, its brittle nature makes its use in structural applications difficult.

Fortunately, studies have demonstrated that leveraging the advantages of size effects and hierarchical design strategies allows for the design of mechanically efficient ceramics and glass. Many marine creatures offer insights into such design strategies, as they have parts made from strong, porous calcium carbonate.

In the new study, the Virginia Tech researchers looked at the skeleton of a group of knobby starfish called *Protoreaster nodosus*. They found it achieved its strength through a unique structure unlike those seen in the previously studied marine creatures.

Compared to the other marine creatures, the crystalline calcium carbonate in this knobby starfish forms in a lattice architecture with very regular arrangements of branches. In fact, the skeletal organization of this starfish exhibited the highest structural regularity ever reported from this group of invertebrates.

Looking closer, the researchers saw that the millimeter-size calcareous elements making up the lattice, called ossicles, exhibit a porous lattice-like structure themselves. Specifically, the ossicles' microlattice exhibits a marked resemblance to a standard diamond–triply periodic minimal surface (TPMS) structure when viewed at normal to low-index planes.

"Although the existence of periodic minimal surfaces in echinoderm skeletal elements has been broadly accepted in the literature, to the best of our knowledge, the present study represents the first quantitative confirmation of a mineralized biological diamond-TPMS structure in nature," the researchers write.

On the atomic scale, crystallographic mapping from electron backscatter diffraction data confirmed that the ossicles' microlattice is essentially a single crystal structure because of the alignment of its atoms.

The researchers explain how this unique dual-scale lattice offers multiple strategies to achieve high stiffness, strength, and damage tolerance, including crystallographic coalignment, lattice geometric gradients, and suppression of cleavage fracture through microlattice dislocations.

The paper, published in *Science*, is "A damage-tolerant, dual-scale, single-crystalline microlattice in the knobby starfish, *Protoreaster nodosus*" (DOI: 10.1126/science.abj9472). ■

Ferroelectrics for energy-efficient electronics

By Michael Hoffmann

It has always fascinated me how fast computers have improved over the past decades. It is still hard to grasp that a modern smartphone has more processing power than all computers existing in the 1960s combined—while running on a tiny battery.

How was this dramatic improvement of energy efficiency possible? And how much further can we push it? These questions were the ones that motivated me to pursue semiconductor device research.

The answer to the first question is the miniaturization of transistors, which are the basic building blocks of every integrated circuit. By making transistors smaller and smaller, they also became faster, cheaper, and less energy hungry all at the same time. Without this continued miniaturization, things like smartphones, the internet, or self-driving cars would not exist today.

If we could prolong this trend, entirely new applications might become feasible, for example, fully autonomous sensor systems, which consume so little power that they can extract all of it from the environment without the need for a battery. On the other hand, the demand for more computing power will keep growing strongly in the coming decades. Therefore, we must keep the power consumption of our electronics in check, such that they can help combat climate change rather than exacerbate it.

Of course, there are physical limits to transistor miniaturization as we approach atomic dimensions. So, research on new materials for semiconductor devices is vital to further improve energy efficiency.

One example is the so-called gate insulator in a transistor, which enables the control of the electric current flowing through the device by the application of a voltage. For a long time, a thin silicon dioxide (SiO_2) film was used for this purpose. However, through miniaturization, this critical layer has become only a handful of atoms thick, which means that we cannot make it any thinner. How can new materials help to overcome this issue?

My current research focuses on a particularly elegant solution to this problem: One can replace the gate insulator with a ferroelectric, which is a material with a switchable electric polarization. Ferroelectrics were first discovered more than a hundred years ago and now are used in many applications today, for example, as ceramics in ultrasonic transducers and infrared sensors or as thin films in nonvolatile memory devices. Surprisingly, if we integrate a very thin ferroelectric layer into a transistor, it can amplify the applied voltage, which means that less power will be dissipated. Such a device is called a negative capacitance transistor, which in principle can overcome the current limits to miniaturization.

However, most ferroelectric materials cannot be used to build negative capacitance transistors because they must be compatible with the manufacturing processes of state-of-the-art semiconductor devices. For example, the thin ferroelectric layer (less than ~5 nm) must be deposited conformally on a 3D substrate, which is only possible with a process called atomic layer deposition. Furthermore, the ferroelectric must endure processing temperatures as high as 500°C, without degrading its properties. Lastly, the ferroelectric material should be compatible with silicon technology and have good insulating properties. Therefore, well-understood materials like perovskite ferroelectrics cannot be used.

So far, only the relatively new class of hafnium oxide and zirconium oxide-based ferroelectrics of fluorite structure fulfill all these requirements. Indeed, both hafnium oxide and zirconium oxide (although not ferroelectric) are already used in most advanced integrated circuits. Since the first report on fluorite-structure ferroelectrics in 2011, researchers have made a lot of progress in understanding their unique properties and application potential. It has been well established that for ferroelectricity in these materials to occur, they must be stabilized in a special orthorhombic crystal phase. However, there are still a lot of open questions, especially regarding the application in ultrathin films for negative capacitance transistors.

In a recent report in *MRS Bulletin*, Prof. Salahuddin from the University of California, Berkeley, and I reviewed the recent status of the research on negative capacitance transistors with a focus on these fluorite-structure ferroelectrics. At the time, we concluded that while first experimental results were promising, the microscopic origin of the negative capacitance effect in these new ferroelectrics was not well understood. Furthermore, the observed improvement in transistor behavior was not as good as theory had predicted.

Since then, there have been some significant advances in both our theoretical understanding and experimental progress on negative capacitance devices. On the one hand, it was shown that negative capacitance is an intrinsic property of fluorite-structure ferroelectrics, which means that in principle, large voltage amplification could be achievable.[1] While the ferroelectric films in that study were 10-nm thick, it remains to be seen if the same is true for even thinner films, which are needed for future negative capacitance transistors.

Furthermore, it was recently reported that negative capacitance does not only occur in ferroelectrics but also in materials which undergo a phase transition, such as antiferroelectrics.[2] This finding suggests that there might be many more materials that could be used for negative capacitance devices. In terms of demonstrating improved negative capacitance transistor behavior, there has also been significant progress. Cheema et al. recently reported negative capacitance in a fluorite-structure film as thin as 2 nm, which is ideal for transistor applications.[3] Interestingly, it was found that these 2-nm fluorite-structure films consisted of a mixture of ferroelectric and antiferroelectric phases, which seems to be related to the negative capacitance effect.

These recent results are very promising for potential real-world applications, but there are still some open questions that require further investigation. For example, it is still unclear how the microstructure of a fluorite-structure ferroelectric film affects its negative capacitance behavior. Is a mixture of ferroelectric and antiferroelectric phases needed or coincidental? How can we optimize these ultrathin fluorite-structure films to obtain the maximum voltage amplification effect? What are the practical and fundamental limits to such negative capacitance devices? To answer these questions, we will need more insights from both structural characterization as well as basic theory.

Beyond these fundamental questions and further optimizations of device performance, we also need to shift our attention to the topics of manufacturability, variability, and reliability of negative capacitance transistors. In the end, we want to fabricate billions of devices at scale, typically on silicon wafers with 300-mm diameter. Because hafnium oxide and zirconium oxide-based materials are already used in semiconductor manufacturing, there seem to be no general roadblocks in terms of integration of their ferroelectric counterparts. However, because these films are polycrystalline, device-to-device variability might arise as a concern in very small transistors. In terms of reliability, first investigations are encouraging, as these new ferroelectric films seem to be at least as reliable as state-of-the-art gate insulators.[3]

In summary, the new class of fluorite-structure ferroelectric films shows promise for next-generation transistors with negative capacitance, which can be much more energy efficient than conventional devices. While some basic and practical questions still need to be addressed, the demonstration of first proof-of-concept devices is encouraging. Therefore, and due to the excellent compatibility of fluorite-structure ferroelectrics with advanced semiconductor manufacturing, it looks like ferroelectric gate insulators are here to stay.

Learn more about negative capacitance electronics in the following pages, which contain an excerpt from an open-access paper that I coauthored in 2021.

About the author

Michael Hoffmann was a researcher in NaMLab gGmbH at TU Dresden and is now a postdoctoral scholar at the University of California, Berkeley. Contact Hoffmann at michael.hoffmann190@gmail.com.

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Progress and future prospects of negative capacitance electronics: A materials perspective

By Michael Hoffmann, Stefan Slesazeck, and Thomas Mikolajick

The energy efficiency of computation has seen a remarkable trend of exponential improvement over the past 70 years.[1]

Since the 1960s, this advancement was largely driven by the miniaturization of metal–oxide–semiconductor field-effect transistors (MOSFETs) whose lateral dimensions have reached below 100 nm in the year 2003, marking the beginning of the nanoelectronics era. Since then, further improvements have been enabled by materials innovations (e.g., strain engineering and gate oxides with high relative permittivity ε_r) and the adoption of new device concepts (FinFET and fully depleted silicon on insulator technology). However, in recent years, the energy efficiency improvements in nanoelectronics have begun to slow down as we are approaching practical as well as fundamental physical limits.

In Fig. 1, two historic trends emphasize how close we are to some of these limits, as indicated by the scaling of the supply voltage V_{dd} and the equivalent gate oxide thickness (EOT) of MOSFETs over the past 50 years. Since originally SiO_2 was used as the gate oxide, the EOT is defined as the SiO_2 thickness that would be needed to achieve the same capacitance as a gate oxide with higher ε_r and thickness d. Thus, with a relative SiO_2 permittivity of 3.9, the EOT can be calculated as EOT = $3.9/\varepsilon_r d$. While lowering V_{dd} is the most effective way to improve the energy efficiency of integrated circuits, a reduction in the EOT is needed to increase the electrostatic coupling of the gate to the semiconductor channel in highly scaled devices. With a lower EOT, less voltage is needed to switch the device between "on" and "off" since the voltage drop across the gate oxide is reduced.

For many decades, SiO_2 was used as the gate dielectric material in silicon-based MOSFETs due to the high quality of the Si/SiO_2 interface and its ease of fabrication. During this time, the EOT in Fig. 1 corresponds to the physical SiO_2 thickness. Below a physical oxide thickness of roughly 3 nm, quantum-mechanical tunneling of electrons through the gate dielectric became so large that it started to significantly contribute to the overall power dissipation. Therefore, at the turn of the century, nitrided SiO_2 (SiON) gate dielectrics were applied to increase ε_r to around 5 and reduce the EOT below 2 nm. However, soon after its introduction, SiON had to be replaced by dielectrics with even higher ε_r to continue further EOT scaling.

The result was the adoption of the so-called high-k metal gate (HKMG) technology (k is often used synonymous with ε_r) based on amorphous HfO_2 dielectrics with $\varepsilon_r \approx 17$ in 2007, enabling an EOT scaling down to 0.8 nm in recent products. Nevertheless, due to the inherent presence of a thin SiO_2 interface layer between the high-k dielectric and the silicon channel, EOT scaling below 0.5 nm is practically impossible without strongly degrading device performance and reliability. However, even if one could reduce the EOT to zero, there is a more fundamental limit, which prevents a further reduction of

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V_{dd}, which is needed to further improve the energy efficiency of integrated circuits.

In any logic MOSFET, a large-enough ratio between the drain current I_d in the on-state and in the off-state must be ensured to achieve acceptable performance (high I_{on}) and static power consumption (low I_{off}) at the same time; see Fig. 2. As it turns out, due to the Boltzmann distribution of electron energies in the source, there is a fundamental lower limit of 60 mV/dec at room temperature for how much gate voltage V_g is needed to change the drain current I_d by a factor of 10. Due to this "Boltzmann limit," the supply voltage cannot be reduced below roughly 0.5 V in conventional MOSFETs, which is not far from 0.7 V used in current technologies; see Fig. 1. The inverse of the subthreshold slope S can be written as[2]

$$S^{-1} = 2.3\frac{k_BT}{q}\frac{\partial V_g}{\partial \Psi_s} = 2.3\frac{k_BT}{q}\left(1+\frac{C_s}{C_{ins}}\right), \quad (1)$$

where k_B is the Boltzmann constant, T is the temperature, q is the elementary charge, Ψ_s is the surface potential, and C_s and C_{ins} are the semiconductor and gate insulator capacitance, respectively [see Fig. 2(a)].

One potential solution to overcome the Boltzmann limit is the use of band-to-band tunneling devices. However, such devices typically have a low I_{ON} and will not be discussed here. Normally, in Eq. (1), both C_s and C_{ins} are positive quantities, and thus, the capacitive voltage divider $dVg/\Psi_s = (1 + C_s/C_{ins})$ will always be larger than 1. In 2008, it was first proposed by Salahuddin and Datta that if $C_{ins} < 0$ in a MOSFET [see Eq. (1)], one could overcome the Boltzmann limit, which would enable a further reduction of V_{dd} and, thus, MOSFET power dissipation; see Fig. 2(b).[3] In this case, the negative capacitance (NC) would lead to an internal amplification of the surface potential Ψ_s with respect to the applied gate voltage V_g, i.e., $d\Psi_s/dV_g > 1$. Therefore, in a such a negative capacitance field-effect transistor (NCFET), one could overcome both the impending EOT and the Boltzmann limits to further improve the energy efficiency of electronics.

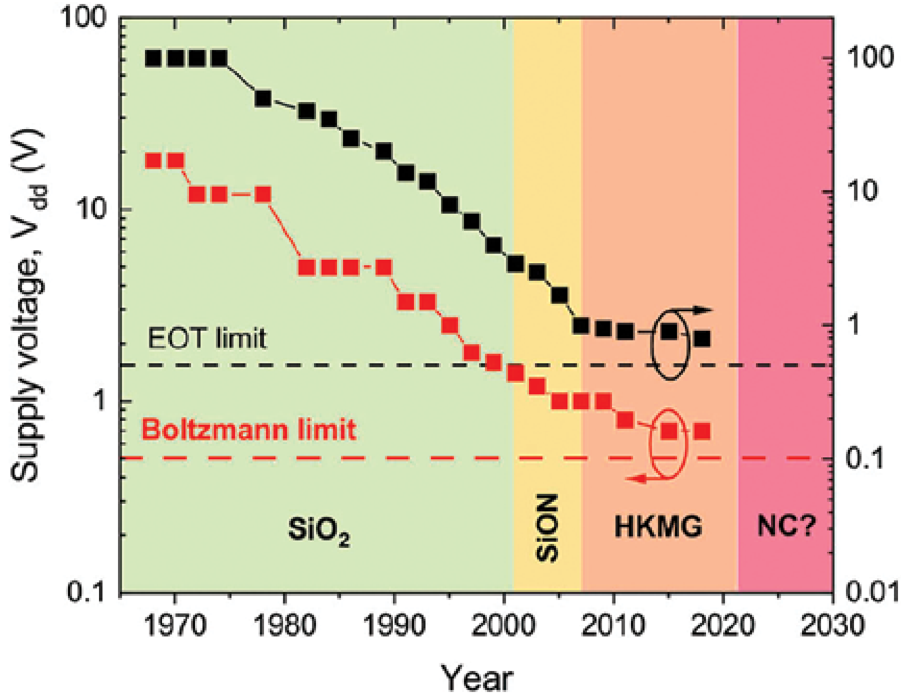

Figure 1. Historic trend of the supply voltage and equivalent oxide thickness (EOT) scaling in commercial metal–oxide–semiconductor field-effect transistor technologies. The black dashed line indicates the EOT limit given by the necessary SiO_2 interface between the silicon channel and the high-k material, and the red dashed lines indicates the minimum supply voltage due to the Boltzmann limit. HKMG: high-k metal gate. NC: negative capacitance.

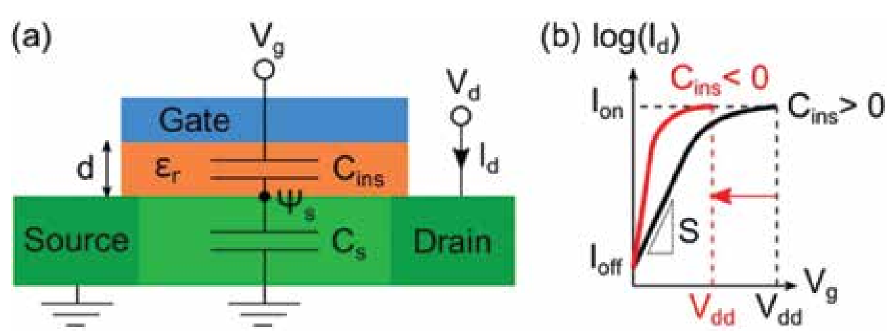

Figure 2. (a) Schematic MOSFET structure where, C_{ins}, d, and ε_r are the capacitance, thickness, and relative permittivity of the gate insulator, respectively. C_s is the semiconductor capacitance, Ψ_s is the surface potential, and V_g and V_d are the gate and drain voltage, respectively. (b) Schematic MOSFET transfer characteristics for a positive and negative insulator capacitance. V_{dd} is the supply voltage, and I_{on} and I_{off} are the drain currents in the "on" and "off" state, respectively. S is the subthreshold slope.

Ferroelectric negative capacitance

There is a special class of materials, called ferroelectrics, which possess a polarization even when no electric field is applied. This so-called spontaneous polarization P_S stems from a noncentrosymmetric crystal structure and can be reversed by the application of an electric field, which is larger than the coercive field. This normally leads to a polarization hysteresis, which makes ferroelectrics ideally suited for nonvolatile memory devices.

Since all ferroelectrics are also pyroelectric and piezoelectric, these materials are used, e.g., in ultrasonic transducers and infrared detectors. Furthermore, the permittivity of a ferroelectric depends on the applied electric field, making ferroelectrics useful for tunable capacitors in microwave electronics. As we will see, under certain conditions, the ferroelectric permittivity can even become negative. Above the Curie-temperature, the ferroelectric transitions into a paraelectric state in which the spontaneous polarization is zero.

Landauer first predicted in 1976 that the instability of the ferroelectric polariza-

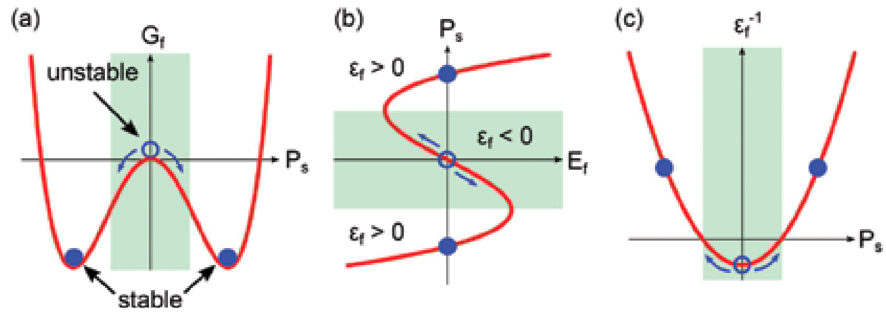

Figure 3. (a) Ferroelectric free energy-polarization (G_f–P_s) landscape at the zero electric field (E_f = 0). (b) Polarization-electric field dependence derived from (a). For low P_s, the relative permittivity ε_f is negative. (c) Inverse of ε_f as a function of polarization derived from (a) and (b). The state of negative permittivity is thermodynamically unstable.

tion can lead to a negative capacitance.[4] His reasoning was based on a simple thermodynamic Landau model (Figure 3).

While this simple energy landscape model neglects the important effects of domain nucleation and growth, it is still useful to illustrate many of the basic physics of ferroelectric NC.

From Fig. 3(a), it is immediately clear that the region of negative permittivity (i.e., NC) is thermodynamically unstable since it corresponds to a maximum of the free energy if we just consider the ferroelectric by itself. The question is: Can we access this NC region and if yes, how?

There are two different ways to tackle this problem: (1) If we switch the ferroelectric polarization from one stable state to the other one by applying an electric field, we should be able to measure a *transient* NC for a limited time during switching. (2) We integrate the ferroelectric into a larger structure such that the NC state becomes thermodynamically *stable* when the total free energy of the system is minimized.

However, the use of transient NC in applications has two major disadvantages: (1) Since most ferroelectrics switch via irreversible domain nucleation and growth mechanisms, transient NC is typically associated with a large polarization hysteresis, which is detrimental for applications in energy efficient electronics, as it leads to power dissipation and necessitates an increase in the applied voltage levels. (2) Due to the well-known voltage–time trade-off, switching a ferroelectric completely from one stable polarization state to the other can either be fast (requiring a high voltage) or happen at low voltage (taking a long time), but not both at once. Therefore, transient NC effects are too slow to be useful for high-speed digital electronics operating at low voltages and GHz frequencies. Both of these drawbacks are a direct consequence of the instability of the NC region. However, if we would be able to stabilize the intrinsic NC state, we could theoretically overcome both of these limitations.

Originally, Salahuddin and Datta suggested that the ferroelectric NC state around P_s = 0 could be stabilized by adding a positive capacitance in series to the ferroelectric capacitance.[3] In this case, the total capacitance of the system would be positive, and there would be no polarization hysteresis. It has since been shown that such a stabilization is unlikely when using a metal–ferroelectric–metal (MFM) capacitor in series to a metal–dielectric–metal capacitor due to the effects of leakage currents and domain formation, which destabilize the NC state. Therefore, the ferroelectric should be in direct contact to the positive capacitance layer, without a metal layer in between.

It is important to mention here that the present discussion has neglected the formation of ferroelectric domains, i.e., regions of different polarization orientation in the material, which form to reduce the depolarization energy of the system. However, as it turns out, a stabilized NC behavior without hysteresis can also emerge in multidomain ferroelectrics with dielectric layers. To distinguish both effects, we will use the terms *intrinsic* NC for a homogeneously (de)polarized ferroelectric and *extrinsic* NC for effects due to the presence of ferroelectric domains. In the simplest case, in a ferroelectric/dielectric structure, to reduce the depolarization energy, the ferroelectric would break into an equal number of up- and down-pointing domains divided by 180° domain walls. Then, if an external electric field is applied, domains pointing in the same direction as the external field will expand, while antiparallel domains will become narrower due to lateral domain wall motion. This leads to an average depolarization field, which is opposite to the external electric field, thus leading to a negative contribution to the permittivity of the ferroelectric layer. If the lateral motion of domain walls is reversible, this extrinsic NC effect can be stable and, thus, hysteresis-free.

Ferroelectrics for negative capacitance devices

Now that we have established the basic principles of ferroelectric NC, we will return to discuss its application in the future highly scaled energy efficient MOSFETs. Prospective ferroelectric materials for NC transistors need to fulfill a set of conditions to be useful for practical devices:

1. Robust ferroelectricity at 5-nm thickness and below
2. Compatibility with CMOS technology [complementary metal–oxide–semiconductor]
3. Thermal stability on silicon
4. Conformal deposition on 3D substrates
5. Large electronic bandgap and conduction band offset to silicon

A small ferroelectric thickness has two advantages: First, it helps to stabilize the NC state. Second, it enables a reduction of the distance between neighboring NCFETs in state-of-the-art FinFET technology. This will be even more critical for future nanowire or nanosheet device geometries. Furthermore, these materials must be integrated into a silicon CMOS process flow, where they have to withstand temperatures of around 500°C as well as hydrogen annealing. Also conformal and homogeneous deposition techniques for ultrathin ferroelectric films must be available for 300 mm wafer processing. A high electronic bandgap and conduction band offset to silicon are necessary to reduce gate leakage currents. Very few materials fulfill all these conditions. Additionally, they need to show NC.

The first experimental report of ferroelectric NC dates back to 2006, when Bratkovsky and Levanyuk calculated the electric field in thin layers of ferroelectric $BaTiO_3$ by considering the finite screening length in the metal electrodes.[5] They first observed the predicted negative slope in the $P–E_f$ graph; see Fig. 3(b). Later, various NC effects were observed in ferroelectric P(VDF–TrFE) as well as ferroelectric perovskites such as lead zirconate titanate. From the application perspective, none of these materials are easily integrated with current semiconductor fabrication technologies. While polymer ferroelectrics such as P(VDF–TrFE) are incompatible with the high temperature processing used, perovskite ferroelectrics have severe integration issues, especially in 3D structures such as FinFETs, and they degrade under hydrogen annealing. The relatively low bandgap of perovskite ferroelectrics is another drawback.

Hafnium oxide-based ferroelectrics

Fortunately, in 2011, it was reported that thin films of silicon doped HfO_2 exhibit ferroelectricity (recall that HfO_2 was the standard high-k gate dielectric in MOSFETs since 2007).[6] This surprising discovery has led to a strong interest in NC transistors.

Ferroelectricity in HfO_2 stems from the stabilization of a polar orthorhombic $Pca2_1$ phase in thin polycrystalline films with a relatively small grain size of around 5 nm–30 nm. This ferroelectric o-phase appears at the boundary between the well-known nonpolar tetragonal $P4_2/nmc$ t-phase and the monoclinic $P2_1/c$ m-phase. It is currently believed that the t-phase can transform into the o-phase by the application of an electric field, leading to antiferroelectric-like characteristics.

Many different dopants such as silicon, aluminum, yttrium, gadolinium, and lanthanum promote the stabilization of the o-phase in HfO_2. However, one of the most popular material systems is the solid solution of $Hf_{1-x}Zr_xO_2$ (HZO), which shows a broad window of ferroelectricity around 1:1 Hf:Zr ratio and a lower crystallization temperature (<500 °C) compared to most of the other dopants.

It was further shown that epitaxial HZO films exhibit ferroelectricity stemming from a rhombohedral R3m phase.[7] Recently, ferroelectricity was even observed in atomic layer deposited (ALD) $Hf_{0.8}Zr_{0.2}O_2$ films as thin as 1 nm.[8] All these characteristics combined with the established CMOS integration and mature ALD processes make HfO_2-based ferroelectrics most promising for future NC device applications. However, the basic understanding of NC in these films is still in its infancy.

The first direct measurement of transient NC in gadolinium doped ferroelectric HfO_2 was reported in 2016 by applying short voltage pulses to a series connection of an MFM capacitor and a resistor.[9] Subsequently, similar transient NC effects were confirmed in ferroelectric HZO capacitors.[10] The large hysteresis observed in these measurements was a direct consequence of using MFM capacitors, which can only show transient NC effects. Therefore, subsequent studies have focused on using stacked ferroelectric/dielectric capacitor structures to enable hysteresis-free operation and to potentially stabilize NC in HfO_2-based ferroelectrics.

Indeed, hysteresis-free NC was recently observed in stacked capacitors using ferroelectric $Hf_{0.5}Zr_{0.5}O_2$ and dielectric Al_2O_3 or Ta_2O_5 layers, allowing the first pulsed electric measurement of the "S"-shaped $P–E_f$ curve as well as the double-well energy landscape as predicted by Landau theory [see Figs. 3(a) and 3(b)].[11,12] However, it was found that the NC effect in these ferroelectric/dielectric structures only occurs at voltages higher than 5 V.[13] This was explained by the presence of a large density of negative charges (either trapped or fixed charges or a combination of both) at the ferroelectric/dielectric interface, which stabilizes the negative polarization state at V = 0. Such a large interface charge would be detrimental for low power NC transistors, where it can shift the NC region out of the desired operating voltage range. However, it was shown that NC in such ferroelectric/dielectric capacitors is promising for electrostatic supercapacitor applications.[14]

It is still unclear if these hysteresis-free NC effects in ferroelectric/dielectric capacitors are of intrinsic or extrinsic origin. However, first-principles calculations and piezo-response force microscopy results indicate that lateral domain wall motion (as expected for extrinsic NC) is very slow and energetically unfavorable in HfO_2-based ferroelectrics. Nevertheless, the polarization kinetics have been found to be in good agreement with nucleation-limited switching dynamics.

How the nucleation of domains in nanoscale grains of ferroelectric HfO_2 can be reconciled with the observed hysteresis-free NC needs further investigation. Additionally, the report of vanishing or even negative energy of 180° domain walls in ferroelectric HfO_2 is a reason for concern for NC devices since this would suggest that the stabilization of an intrinsic NC state at low voltage might be very challenging as even unit cell wide domains could form. More basic materials research on ferroelectric HfO_2 is necessary to better understand its fundamental limitations with respect to NC applications.

Realistic NC device considerations

While the general material properties of HfO_2-based ferroelectrics seem suited for application in highly scaled NC transistors, there are multiple issues arising in practical devices.

Figure 4 illustrates how a realistic gate stack of an NC transistor using an HfO_2-based ferroelectric might look like (this schematic compilation of imperfections is not exhaustive). The HfO_2-based layer consists of multiple grains with defect-rich grain boundaries between them. While most grains might be in the ferroelectric o-phase, some nonferroelectric grains in the m- or t-phase might still be present. Furthermore, the polar axis of the ferroelectric grains can be tilted and, thus, can have in-plane polarization contributions in addition to out-of-plane ones. Transmission electron microscopy indicates that even inside a single ferroelectric grain, there might be multiple domains separated by either 180° or 90° domain walls. The movement of such domain walls inside polycrystalline is not well understood so far.

At the metal/ferroelectric and ferroelectric/dielectric interfaces, thin layers of the t-phase might be present. In addition, it

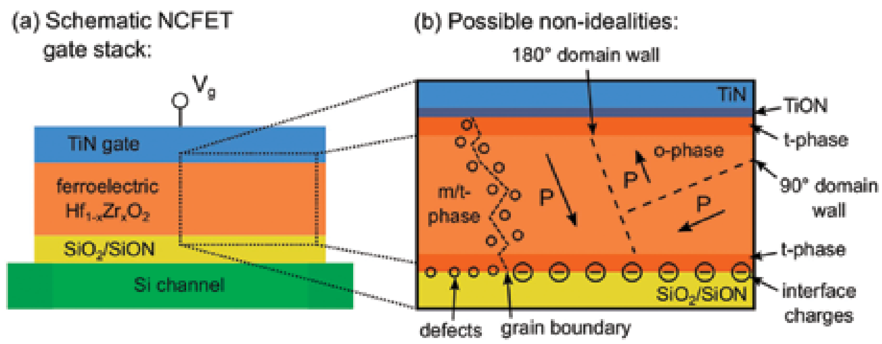

Figure 4. Schematic gate stack of a negative capacitance transistor using a HfO_2-based ferroelectric. (b) Magnification of the HfO_2-based layer highlighting some potential nonidealities, which are often present in such films and are critical for negative capacitance devices.

is typically found that between HfO_2 and TiN, a thin TiON layer forms during the annealing processes. From the ferroelectric interface to the SiO_2 or SiON layer underneath, fixed interface charges and trapped charges can be present, which partly screen the ferroelectric polarization. Overall, the trapping and de-trapping of charges at this interface must be minimized for NC applications as it will strongly affect the electrostatics inside the ferroelectric stack. Note that this is one of the most serious practical concerns since the ferroelectric polarization can lead to a significant electric field in the dielectric layer. Furthermore, charges can be trapped or de-trapped from defects at grain boundaries or even inside the bulk of the film (for clarity not shown in Fig. 4).

These potential complications could explain why simulations assuming a homogeneous ferroelectric layer with the out-of-plane polar axis, no defects, or charge trapping have so far failed to reproduce and predict experimental NC device characteristics. Such simplified simulations can even result in qualitatively wrong predictions, e.g., that an internal metal layer between the ferroelectric and SiO_2 improves device behavior, when, in reality, it destabilizes the NC state when domain formation and leakage are considered. Therefore, more elaborate device simulations are needed to capture the critical effects of ferroelectric domains and charge trapping, which will help to better guide the device design.

Progress on negative capacitance devices

While a large number of experimental results have been published in the last five years,[15,16] few reports contain all necessary features of an NC transistor, which are as follows:

1. Improved subthreshold swing or on-current compared to an appropriate reference device,
2. Hysteresis-free operation, and
3. Characteristics that are largely independent of measurement conditions (e.g., measurement speed and voltage sweep range).

In particular, the third point is critical since the transient NC effects can under some conditions (typically DC measurements) lead to extraordinary small subthreshold swings and an apparent lack of hysteresis. However, when the measurement speed or voltage range is changed even slightly, significant hysteresis emerges. Therefore, such experimental results should be treated with caution.

Furthermore, due to the previous discussion on transient NC, reports of connecting an MFM capacitor to the gate of a MOSFET cannot be considered promising for low power NC electronics due to the inherent instability of the NC state in such a structure and the voltage–time trade-off. Therefore, we will not review devices with the internal metal gate structure or any hysteresis in the transfer characteristics here.

One of the most prominent works claiming NC behavior in ferroelectric HZO without hysteresis in MoS_2 transistors was published in 2018.[17] However, hysteresis-free operation in these devices was only observed for DC measurements. Slightly increasing the measurement speed resulted in an emergence of hysteresis, which is not expected for stabilized NC in this frequency range. More consistent reports of hysteresis-free NC transistor behavior independent of the measurement speed were shown by Kwon et al. when using 1.8-nm thin HZO gate oxides.[18] While the subthreshold swings were always above the 60 mV/dec Boltzmann limit, they showed improved characteristics compared to reference devices using pure HfO_2 instead of HZO.

Theoretical works have suggested that instead of achieving sub-60 mV/dec subthreshold swings, NC might be more useful in reducing the "voltage loss" due to short channel effects. Indeed, recent experimental results indicate that short channel devices show more pronounced improvements from using HZO compared to reference devices using HfO_2. Some of the most promising results so far show a 10 times reduction in off-current or a two times increase in the on-current for short channel devices. While these results are encouraging, one has to keep in mind that they are reported compared to reference devices with HfO_2 gate dielectric. Therefore, they present no direct proof of stabilized NC in the HZO transistors but at least an encouraging indication.

Outlook

To move the field of NC research forward, the gap between the fundamental understanding of NC in HfO_2-based polycrystalline ferroelectrics and practical transistor engineering needs to be bridged. As long as no other material system fulfilling all requirements [for NC devices] is found, HfO_2-based ferroelectrics seem to be the only contender for NC transistors going forward. Some properties of HfO_2-based ferroelectrics are of special interest for NC device applications and should be focused on in the future.

First, fabricating ultrathin (<5 nm) HfO_2-based ferroelectric films predominantly in the orthorhombic phase is still one of the biggest challenges for NC devices. While recent results on such ultrathin films have shown ferroelectricity, spatial homogeneity of such layers is a prerequisite for nanoscale transistors and must be studied in more detail. The careful engineering of the ferroelectric interfaces and annealing conditions might be two of the most effective ways to improve their ferroelectricity. Furthermore, the role of charge trapping and leakage currents in such films might be critical for NC device operation. It would be interesting to investigate devices with thicker dielectric interface layers to minimize detrimental leakage effects and relax the constraints on the critical ferroelectric thickness for NC stabilization. While such an approach might not be suitable for ultralow power logic, it could turn out useful for improving higher voltage devices.

Second, future research on NC in HfO_2-based ferroelectrics should focus on the role of nanoscale ferroelectric domains and their interaction with the grain structure in polycrystalline films. To better understand the role of domain walls, characterization of epitaxial films and first-principles calculations might be most promising. Furthermore, advanced electron microscopy techniques might be able to resolve ferroelectric domain structures even in polycrystalline HfO_2-based thin films. These techniques could also shed light on the impact of grain sizes and orientations of the different layers in the gate stack on device performance. More accurate multidomain models would help to guide the device design. Further experiments on different ferroelectric/dielectric heterostructure capacitors could also give some new insights into the domain structure, which strongly depends on the electrostatic boundary conditions. In particular, the control of interfacial charges in such heterostructures will be critical for NC devices.

Finally, when considering the fabrication of NC transistors, more rigorous characterization methods should be used to provide convincing proofs of stabilized NC. If no subthreshold swing below the Boltzmann limit is observed, then electrical characteristics have to be compared to an appropriate reference device, which should have as few processing differences as possible, but must have a nonferroelectric gate oxide. If an improvement compared to such a reference is reported, then it is necessary to show characteristics for different voltage sweep ranges and measurement speeds to exclude other effects such as charge trapping or transient NC from ferroelectric switching. To further our understanding of an optimal NC device design, we need to move away from simplified single-domain models (implying intrinsic NC) toward more realistic multidomain models based on insights into the microscopic structure of HfO_2-based ferroelectric thin films.

About the authors

Stefan Slesazeck is a researcher in NaMLab gGmbH at the Dresden University of Technology (TU Dresden). Thomas Mikolajick is a researcher in the Institute of Semiconductors and Microsystems at TU Dresden. Michael Hoffmann was a researcher in NaMLab gGmbH at TU Dresden and is now a postdoctoral scholar at the University of California, Berkeley. Contact Hoffmann at michael.hoffmann190@gmail.com.

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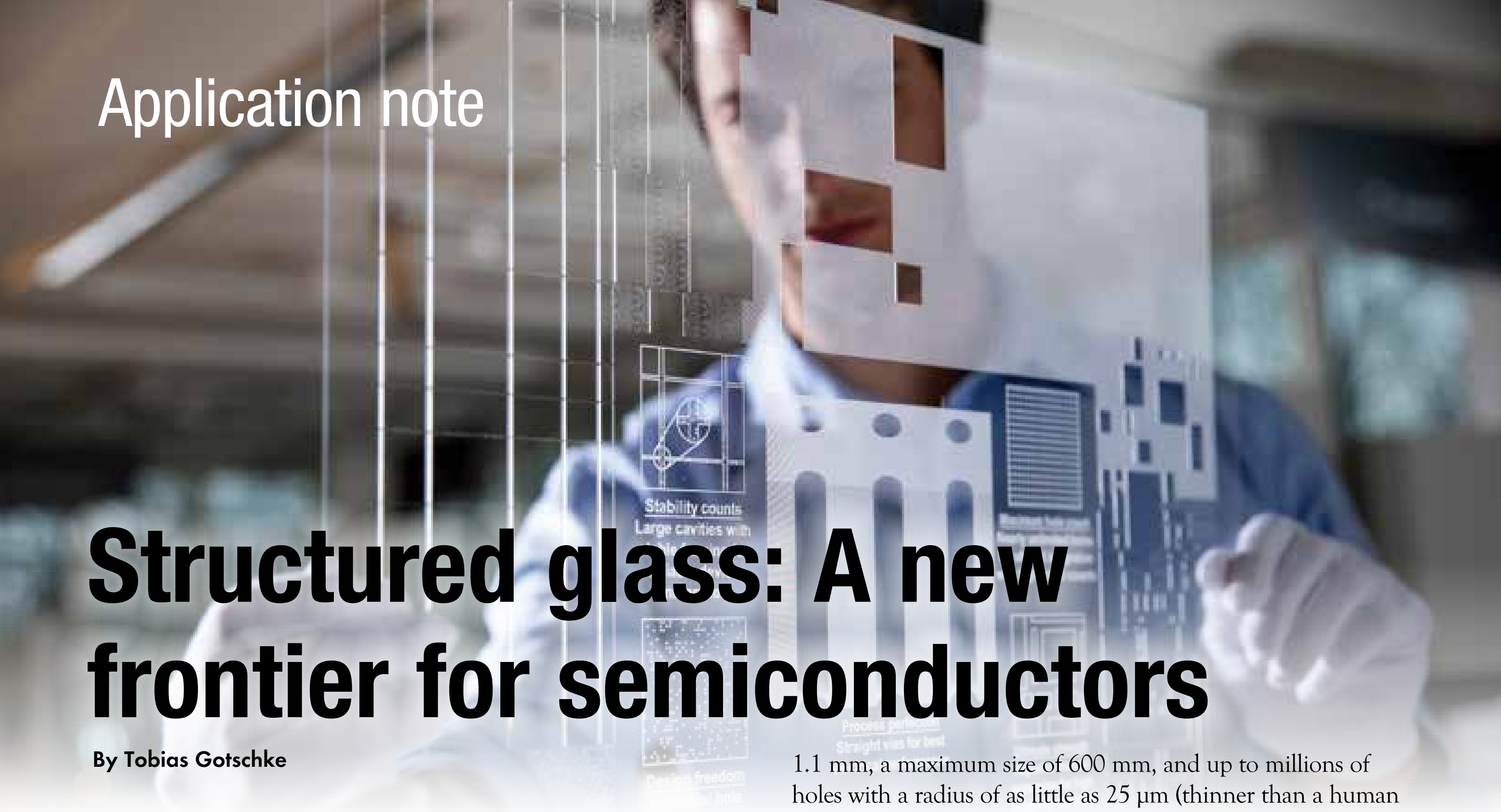
Application note



Structured glass: A new frontier for semiconductors

By Tobias Gotschke

Shortages in the semiconductor supply chain have influenced most electronics industries, holding back sales of everything from automobiles to gaming consoles. The shortage shone a light on the need for more efficient manufacturing of computer chips.

Ultrafine structured glass offers a game-changing element to semiconductor packaging. Structured glasses combine the smooth surfaces and mechanical stiffness of expensive single crystal silicon wafers with the large formats of copper clad laminate. Structured glass substrates also offer increased signal performance, high manufacturing precision, reduced signal latency, and cost efficiency compared to the printed circuit boards and silicon interposers traditionally used for advanced chip packaging solutions.

SCHOTT, an international technology group and inventor of specialty glasses, recently introduced FLEXINITY® connect, an ultrafine structured glass solution. FLEXINITY connect is the latest innovation in the advanced packaging industry and features versatility in format, which allows for a wide spectrum of applications. Tailored to handle the challenging demands of the advanced packaging industry, FLEXINITY connect offers the highest input/output counts and maximum end-product stability. It also combines the highest product performance with the lowest electrical loss and economic manufacturing costs.

"Replacing a printed circuit board with a glass core package requires a significant amount of adaptation in the supply chain and offers many benefits," says Tobias Gotschke, senior project manager of new ventures at SCHOTT. "The flexible positioning of through glass vias, or TGVs, allows for unmatched design freedom. Using SCHOTT's glass and structuring capability provides a faster ramp-up in manufacturing with higher yields."

FLEXINITY connect can be used in nearly any capacity because of the versatility of glass. With a thickness range from 0.1 mm to 1.1 mm, a maximum size of 600 mm, and up to millions of holes with a radius of as little as 25 µm (thinner than a human hair), the possibilities are endless—and can go beyond filling the void of the current semiconductor shortage.

Computing applications like datacenters and artificial intelligence can use FLEXINITY connect to increase efficiency and reduce thermal loads, resulting in higher computing power. Mobile and Internet of Things applications benefit from fast wireless communication, enabled by the integration of antenna in package for higher frequencies in the GHz regime and optimized materials for broad bandwidth in all climate zones.

Glass as a core component of semiconductor packages can also help the distressed automotive industry even more than traditional packaging solutions. The material properties of glass are sufficiently insensitive to humidity, the low thermal coefficients allow reliable operation of electronics over a wide range of temperatures, and specialty glasses with low dielectric constant and low dielectric loss allow efficient structures to be built at frequencies of 77 GHz and higher.

Another application for glass-based semiconductors is in-vitro medical diagnostics. The structured glass surface offers superior optical properties compared to engineering plastics, is a well-suited base material for functional and physical coatings needed in assay development, and it provides an excellent surface finish for all kinds of post processing.

With so many possibilities and applications, glass can do more than just alleviate the supply chain pressures that semiconductor manufacturers are feeling. It can unlock new opportunities to create electronic components for a wide range of uses and savings compared to traditional methods and materials.

About the author

Tobias Gotschke is senior project manager in the corporate division New Ventures at SCHOTT, responsible for driving business development for specialty glass in the advanced packaging industry. For more information, visit schott.com/flexinity. ■

UPCOMING DATES

HYATT REGENCY BALTIMORE, BALTIMORE, MD.

The 2022 GOMD meeting is special because the United Nations declared 2022 as the **International Year of Glass**. We will have a number of special events to commemorate this occasion as we meet together in person for the first time since 2019.

The 2022 technical program will feature four symposia: Fundamentals of the Glassy State; Glass and Interaction with its Environment—Fundamentals and Applications; Optical and Electronic Materials and Devices—Fundamentals and Applications; Glass Technology and Cross-cutting Topics.

UNIVERSITY OF CALIFORNIA, IRVINE, CALIF.

Cement is the key ingredient in concrete—the most-used building material in the world—so every advance in understanding how it behaves presents an opportunity to reduce greenhouse gases, advance construction engineering, and improve quality of life around the globe.

HILTON PANAMA, PANAMA CITY, PANAMA

The Pan American Ceramics Congress brings together a wide variety of experts from academia, industries, research institutes, and laboratories to discuss current state-of-the-art and various technical challenges in research, development, engineering, manufacturing, and application of ceramic and glass materials. The Congress will provide a collegial forum for information exchange on current status and emerging trends in various technologies in the American continent (South and Central America, Canada, and the United States).

DAVID L. LAWRENCE CONVENTION CENTER, PITTSBURGH, PA.

NEW this year—The Materials Science and Technology Partnership has engaged the commercial exhibition firm Event Partners to sell and manage the full exhibition at MS&T22. In addition, Event Partners will co-locate two commercial exhibitions run by the company within MS&T22: The Advanced Materials Show and the first-ever Nanotechnology Show.

The Materials Science & Technology technical meeting and exhibition series is a long-standing, recognized forum for fostering technical innovation at the intersection of materials science, engineering, and application. At MS&T, you can learn from those who are on the cutting edge of their disciplines, share your work with the leading minds in your field, and build the valuable cross-disciplinary collaborations unique to this conference series.

Calendar of events

May 2022

9–12 ACerS 2022 Structural Clay Products Division & Southwest Section Meeting in conjunction with the National Brick Research Center Meeting – Omni Charlotte Hotel, Charlotte, N.C.; https://ceramics.org/scpd2022

22–26 Glass & Optical Materials Division Annual Meeting (GOMD 2022) – Hyatt Regency Baltimore, Baltimore, Md.; https://ceramics.org/gomd2022

June 2022

13–15 12th Advances in Cement-Based Materials (Cements 2022) – University of California, Irvine; https://ceramics.org/cements2022

21–22 ceramitec 2022 – Munich, Germany; https://www.ceramitec.com/en/trade-fair/information/exhibition-sectors

28–30 2022 FIRE-ECerS Summer School: Eco-Design of Refractories – RWTH Aachen University, Germany; https://ecers.org/news/146/419/0622-FIRE-ECerS-SUMMER-SCHOOL/d,ceramic_details_conferences

July 2022

3–8 ➨ ICG Annual Meeting 2022 – Berlin, Germany; https://ceramics.org/event/icg-annual-meeting-2022

10–14 International Congress on Ceramics (ICC9) – Krakow, Poland; https://ceramics.org/event/international-congress-on-ceramics-icc9

24–28 Pan American Ceramics Congress and Ferroelectrics Meeting of Americas (PACC-FMAs 2022) – Hilton Panama, Panama City, Panama; https://ceramics.org/PACCFMAs

August 2022

28–Sept 1 ➨ 11th International Conference on High Temperature Ceramic Matrix Composites – Ramada Plaza Jeju Hotel, Jeju, Korea; https://www.ht-cmc11.org

29–31 ➨ 7th Ceramics Expo co-located with Thermal Technologies Expo – Huntington Convention Center, Cleveland, Ohio; https://ceramics.org/event/7th-ceramics-expo

September 2022

7–9 5th Energy Harvesting Society Meeting – Falls Church Marriott Fairview Park, Falls Church, Va.; https://ceramics.org/event/5th-energy-harvesting-society-meeting

October 2022

9–13 ACerS 124th Annual Meeting with Materials Science & Technology 2022 – David L. Lawrence Convention Center, Pittsburgh, Pa.; https://ceramics.org/MS&T22

November 2022

30–Dec 2 ASEAN Ceramics – Thailand; https://aseanceramics.com

January 2023

17–20 Electronic Materials and Applications 2023 (EMA 2023) – DoubleTree by Hilton Orlando at Sea World Conference Hotel, Orlando, Fla; https://ceramics.org/EMA23

22–27 47th International Conference and Expo on Advanced Ceramics and Composites (ICACC2023) – Hilton Daytona Beach Oceanfront Resort, Daytona, Fla; https://ceramics.org/ICACC23

27–31 The International Conference on Sintering 2023 (Sintering 2023) – Nagaragawa Convention Center, Gifu, Japan; https://www.sintering2021.org

July 2024

14–19 International Congress on Ceramics – Hotel Bonaventure, Montreal, Canada; www.ceramics.org

Dates in **RED** denote new event in this issue.

Entries in **BLUE** denote ACerS events.

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

denotes International Year of Glass event

denotes virtual meeting

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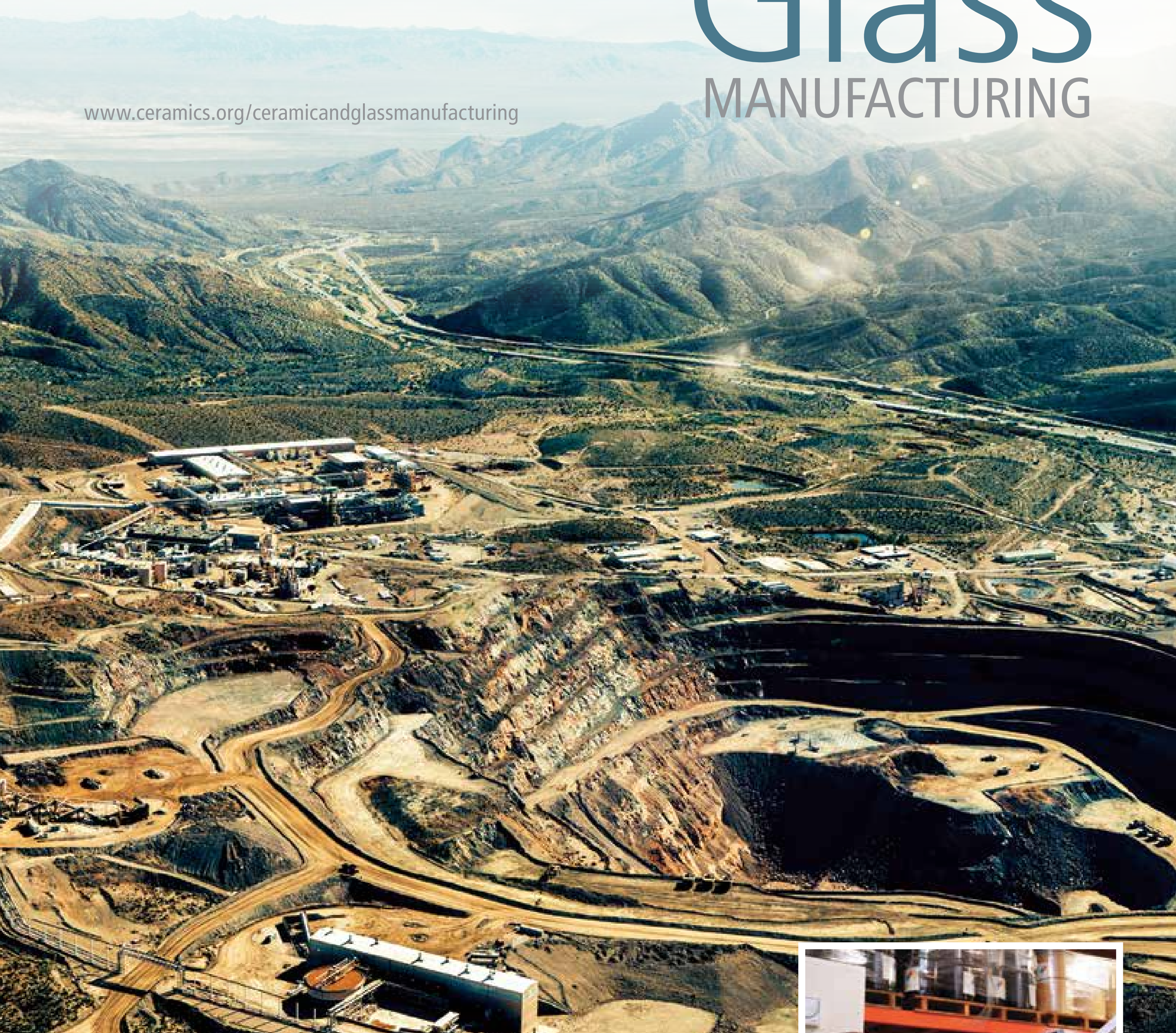

THE RARE EARTHS ECONOMY: CAN SUPPLY KEEP UP WITH GROWING DEMAND?

POLICY RECOMMENDATIONS: US MUST LEAD IN BUILDING THE WESTERN SUPPLY CHAIN

Shredding discarded hard drives at the Critical Materials Institute at Ames Laboratory.

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Executive Director & Publisher
Mark Mecklenborg

Editorial & Production
Eileen De Guire
Director of Technical Content and Communications
edeguire@ceramics.org

David Holthaus
Content Editor
dholthaus@ceramics.org

Lisa McDonald
Associate Managing Editor

Tess Speakman
Senior Graphic Designer

Kerry Burgdorfer
Graphic Designer

Michelle Martin
Production Editor

Editorial Advisory Board
Daniel Tipsord, TevTech LLC
James Hemrick, Reno Refractories Inc.
Keith DeCarlo, Blasch Precision Ceramics
Steve Houseman, Harrop Industries

Customer Service & Circulation
ph: 866-721-3322 **fx:** 240-396-5637
customerservice@ceramics.org

Advertising Sales
National Sales
Kevin Thompson, Industry Relations Director
kthompson@ceramics.org
ph: 614-794-5894

Europe
Richard Rozelaar
media@alaincharles.com
ph: 44-(0)-20-7834-7676 **fx:** 44-(0)-20-7973-0076

Editorial & Advertising Offices
The American Ceramic Society
550 Polaris Pkwy., Suite 510
Westerville, OH 43082

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INDUSTRY NEWS

Schott expects to complete its expansion in China by the end of 2022.

SCHOTT SETS PLANS FOR CONTINUED EXPANSION TO MEET HEALTHCARE NEED

Mainz, Germany-based Schott says it delivered glass vials for more than 5 billion doses of COVID-19 vaccine worldwide in 2021. Last year, the company tripled its capacity for presterilized, ready-to-use glass vials in the U.S. and expanded the capacity of prefillable glass syringes by 50% in Switzerland. This spring, a new production site for prefillable, polymer syringes will open in Germany. Schott also says it plans to triple its production capacity in China for glass vials and ampoules by the end of 2022.

HWI PLANS TO CONVERT CLOSED PLANT IN ALABAMA

HarbisonWalker International says it plans to invest approximately $25 million to convert its closed plant in Fairfield, Ala., into a manufacturing, service, and distribution hub for steel customers in the southern U.S. Construction will begin during the first quarter, and the 200,000-square-foot facility, called Alabama One, is expected to open before the end of 2022. The plant will produce magnesia-carbon brick refractories engineered for steel-making applications, such as steel ladles and low-emission electric arc furnaces. Initially, production will add 15,000 metric tons annually and eventually up to 30,000 metric tons.

HWI plans to hire 50 technicians and other staff for the facility.

Lithoz's second production facility will mean increased capacity and more efficient warehousing.

LITHOZ OPENS SECOND CERAMIC 3D PRINTING PRODUCTION SITE

Lithoz GmbH says it began production at a new ceramic 3D printing site in Vienna, Austria. The location is the second production site for Lithoz and its fourth location worldwide, after its headquarters in Vienna and bases in the United States and China. The company says a new central warehouse will mean quicker turnaround of orders, scalable production, and expanded storage capacity for raw materials. The facility includes a monitored production environment and a central quality assurance laboratory.

ASTM BEGINS PROJECTS TO ADVANCE ADDITIVE MANUFACTURING

ASTM International's Additive Manufacturing Center of Excellence is participating in three new America Makes projects aimed at advancing the adoption of additive manufacturing. The projects, totaling more than $1 million, address training, inspection, qualification approaches, and in-process monitoring. Formed in 2018, the ASTM Center is a partnership among ASTM International and organizations from industry, government, and academia. The Center supports standardization, develops training and certification programs, and provides market intelligence and advisory services.

ASTM International's headquarters in West Conshohocken, Pa.

CoorsTek's plant in Gumi, South Korea.

COORSTEK PLANT IN SOUTH KOREA EARNS CHEMICAL SAFETY AWARD

CoorsTek's plant in Gumi, South Korea, won an award from Korea's National Institute of Chemical Safety for its safety protocols and chemical accident prevention plan. The plant produces high-performance ceramics engineered for semiconductor processing applications, and a range of hazardous materials are used in the production process. The plant is subject to regular inspections to review safety procedures and chemical spill prevention plans. Plant manager BW Han says the Gumi team established a mobile-based wireless network to prevent the leakage of hazardous chemicals into nearby bodies of water.

American Rare Earth is focused on recycling products such as rare earth permanent magnets and lithium-ion batteries.

RARE EARTHS RECYCLING VENTURE GAINS INVESTMENT

HG Ventures, a venture capital firm and division of Indianapolis-based The Heritage Group, took an ownership stake in American Rare Earth LLC, a subsidiary of American Resources Corp., to scale up recycling of batteries, magnets, and e-waste to recover and supply rare earth metals to U.S. and global markets. American Rare Earths' first purification facility is expected to be operational in the first half of 2022. The Heritage Group is a fourth-generation, family-owned business managing a portfolio of companies specializing in heavy construction and materials, environmental services, and specialty chemicals.

ŞIŞECAM BUYS REFRACTORIES MANUFACTURER

Turkey-based glass producer Şişecam is acquiring the Italian company Refel, a leading refractory materials manufacturer. Şişecam says it wants to eliminate risks related to supply chain disruptions and secure its refractory supply so it can fully realize its new investments in glass manufacturing. Şişecam's products include flat glass, glassware, glass packaging, and glass fiber, as well as soda and chromium compounds. Şişecam operates 42 production plants in 14 countries.

Şişecam is one of the top glass-packaging producers in Europe.

HUBER ENGINEERED MATERIALS FINALIZES MAGNIFIN PURCHASE

Atlanta-based Huber Engineered Materials closed on its acquisition of RHI Magnesita's 50% ownership stake in a 50/50 joint venture, Magnifin Magnesiaprodukte GmbH & Co. KG. Magnifin products are sold globally by Martinswerk GmbH as part of Huber's fire-retardant additives business unit, which produces halogen-free fire retardants, smoke suppressants, and specialty aluminum oxides. Based in Breitenau, Austria, Magnifin has produced magnesium hydroxide products since 1990. Huber says the acquisition fits with its mission "to own and operate specialty chemical and mineral companies with market leading positions."

Magnifin's plant in Breitenau, Austria.

THE RARE EARTHS ECONOMY: CAN SUPPLY KEEP UP WITH GROWING DEMAND?

By David Holthaus

On Sept. 7, 2010, three Japan Coast Guard ships were patrolling the disputed waters around the Senkaku Islands in the East China Sea, responding to reports of increased fishing by Chinese and Taiwanese boats. The rich fisheries around the islands had long been claimed by Japan, China, and Taiwan, and an uneasy truce had evolved over the years.

On this day, however, faced with a spike in the number of Chinese trawlers, the Japan Coast Guard ordered the vessels to leave the area. Most complied, but one, the Minjinyu 5179, refused. And when the Coast Guard moved to board the recalcitrant trawler, the Chinese vessel collided with one of the Japanese ships. Minutes later, the trawler rammed a second Coast Guard ship.

The incident might have been just another minor drama in a long dispute over bountiful fishing waters. No shots were fired, and no one was injured. But Japan responded strongly, arresting the skipper under charges that carried a possible three-year sentence and detaining the other 14 crew members, according to the Asia Maritime Transparency Initiative.

Things escalated. Diplomats from both countries began firing missives back and forth, and their negotiations faltered. Previously arranged discussions on joint China–Japan economic initiatives were cancelled. Political, economic, and cultural exchanges that had been in the works were also scotched.

The rest of the world took note when China began enforcing an embargo on the export of rare earth metals to Japan. At the time, China accounted for nearly all the world's rare earths exports, and Japan had been importing a substantial portion of them for processing, manufacturing, and use in its auto industry.

It is unclear whether China choked off the supply of the metals to punish Japan, or whether it was reserving the materials to be used to fuel its own rapidly growing economy. In either case, China's move rattled the world's industrial economies, which were startled enough to begin to see the importance of developing their own rare earth supply chains.

But developing supply chains is a painstakingly slow process. And regarding rare earths, this industry faces an additional challenge—while rare earth elements are relatively abundant in the Earth's crust, it is not common to find these minerals in concentrations large enough to mine, according to the U.S. Geological Survey (USGS).

CHINA DOMINATES THE RARE EARTHS MARKET

Rare earth ores are found all over the world, but the largest concentrations occur in China, followed by the United States and Australia. But getting these materials out of the earth and processing them to be used in industry presents environmental challenges, beginning with mining. Processing the ore and extracting the metals also requires repeated use of acids and other chemicals, and the disposal of huge amounts of hazardous wastewater.

Rare earth oxides. Clockwise from top center: praseodymium, cerium, lanthanum, neodymium, samarium, and gadolinium. *Credit: Peggy Greb, USDA-ARS*

Rare earth elements are used in the manufacture of advanced ceramics and glass production. Their use in ceramics and glass accounts for 10% of the end distribution of rare earth elements in the U.S., according to the USGS.

The geology, environmental issues, and costs of overcoming these obstacles has meant that, to date, there is only one rare earth facility operating in North America.


In 2020, the Mountain Pass mine supplied more than 15% of the world's rare earths production. *Credit: MP Materials*

Las Vegas-based MP Materials operates the Mountain Pass mine near San Bernardino, Calif., 50 miles southwest of Las Vegas. It is an open-pit mine that began operating in the 1950s, and from the 1960s to the 1980s, it was the world's dominant source of rare earths oxides, according to the USGS. But rising demand, coupled with growing environmental concerns and costs, resulted in production there tailing off. By 1990, production in the U.S. was falling quickly, while production in China was accelerating.

Ownership of Mountain Pass changed hands a few times, but in 2015 the mine was idled. In 2017, it was acquired by MP Materials, a company that was formed by investment firms JHL Capital Group and QVT Financial. By the end of 2017, mining operations were restarted, and in 2018 the first sales of rare earths concentrates were made.

The operation has scaled up since then. In 2020, production volume of rare earths oxides increased 39% from the year before to 38,503 metric tons, according to its year-end financial report. That represented about 15% of primary global production and was an all-time high for U.S. production, says Matt Sloustcher, MP's senior vice president for communications and policy.

Driving that progress has been the soaring demand for the minerals and the magnets that are made with them, a demand largely driven by growth in the electric vehicle market.

RAPID GROWTH IS EXPECTED

Stepped-up domestic production is considered critical not only for national and economic security purposes, but simply to meet what is forecast to be exponential demand for rare earths materials.

Toronto-based Adamas Intelligence forecasts that total magnet rare earth oxide demand will grow at a rate of 9.7% annually through 2030. Because of an expected undersupply of neodymium, praseodymium, and dysprosium oxide, the company forecasts global shortages of neodymium–iron–boron alloy and powder to amount to 48,000 metric tons annually through 2030, "roughly the amount needed for some 25 to 30 million electric vehicle traction motors," the company says.

"A flood of investment is imminently needed to develop new sources of supply and downstream value chains to convert that supply into metals, alloys, magnets, and other materials used by high-tech industries globally," the company says in a September 2020 market report.

Rare earth elements, including neodymium and dysprosium, are used to make the powerful permanent magnets found in electric vehicles. Electric vehicle sales have grown rapidly over the last decade, and in 2020 alone, sales grew 67% worldwide over 2019, according to the World Resources Institute. President Biden has set a goal of making all vehicles sold in the U.S. zero-emission by 2030, and most would be electric-powered.

Green energy is also expanding the market for rare earths. Neodymium and dysprosium are used in wind turbine generators. In 2020, $24.6 billion was invested in new wind power projects, according to the U.S. Department of Energy. President Biden has set a goal of reaching 100% clean energy by 2035.

But China is still a critical link in the supply chain. The rare earth concentrate MP Materials produces currently is exported to a distributor, that sells that product to customers in China who refine the concentrate into separated rare earth products. The company is planning to restore the capacity to separate and process rare earths at the Mountain Pass facility sometime late this year, Sloustcher says.

And in December, MP Materials announced plans to build a 200,000-square-foot metal, alloy, and neodymium–iron–boron magnet manufacturing facility in Fort Worth, Texas. The company says the facility will have the capacity to produce 1,000 metric tons of magnets a year, with the potential to power about 500,000 electric vehicle motors annually.


A rendering of MP Materials' planned magnetics facility in Fort Worth, Texas. *Credit: MP Materials*

Those magnets will have a waiting customer in General Motors, which announced a preliminary agreement with MP Materials to source finished magnets to be used in more than a dozen of its electric vehicle models, with production ramping up in 2023.

"We are building a resilient and sustainable EV manufacturing value chain in North America," Shilpan Amin, GM's vice president for global purchasing and supply chain, says in a news release.

The companies also say they would collaborate "to seek policies that are supportive of the establishment of a secure, U.S. rare earth supply chain."


The Lynas Rare Earths mine in Western Australia. *Credit: Lynas Rare Earths*

US GOVERNMENT SUPPORTS, FUNDS NEW SOURCES

The effort has the support of the U.S. government, which, through executive orders and grants, has lent its weight to the effort.

President Trump issued two executive orders concerning rare earths in 2017 and 2020. With the 2020 order, he declared a national emergency to "reduce our vulnerability to adverse foreign government action, natural disaster, or other supply disruptions."

President Biden followed with an order in 2021 requiring new government assessments of supply chains across several sectors, including rare earths elements.

Government funding followed the orders. The Department of Defense in November 2020 awarded $9.6 million to MP Materials to support its plans to add processing and separation capabilities to its Mountain Pass facility.

In February 2021, the defense department awarded $30.4 million to Australia-based Lynas Rare Earth Ltd. The grant supports the company's wholly-owned subsidiary, Lynas USA LLC, which is developing a rare earths separation and processing facility in south Texas. The U.S. facility will process light rare earths from Lynas-owned facilities in Australia and Malaysia, the Department of Defense says.

Established in 1983, Lynas Rare Earths is the most significant producer of rare earths materials outside of China. It operates a mine in Western Australia and a large processing plant in Malaysia. It is constructing a $500 million processing facility in Western Australia that will supply the advanced processing plant in Malaysia and the planned facility in Texas, the company says.

Lynas is developing the Texas plant in partnership with San Antonio-based Blue Line Corp., a developer and manufacturer of specialty inorganic chemicals.

Texas is also the location of another promising development in the U.S. USA Rare Earths LLC owns the Round Top Heavy Rare Earth, Lithium and Critical Minerals Project in West Texas. The company says the Round Top mine should begin operating in 2023. It says the deposit there contains 16 of the 17 rare earths, as well as lithium and gallium. Company officials say the Round Top deposit has enough resources to last 100 years.

The company is also developing a pilot plant processing facility near Denver, Colo. Workers at the plant will separate ore into heavy rare earths such as dysprosium and terbium, as well as light rare earths such as neodymium and praseodymium. It will also be used to recover non-rare earth critical minerals such as lithium, uranium,

Ikenna Nlebedim shreds discarded hard drives at the Critical Materials Institute at Ames Laboratory. CMI has licensed the technology for extraction of rare earth metals and other useful elements from electronic waste. *Credit: Critical Materials Institute and the U.S. Department of Energy's Ames Laboratory* beryllium, and gallium, the company says. The plant has received its required permits and is in the process of being commissioned.

In April 2020, USA Rare Earth purchased equipment necessary for manufacturing neodymium–iron–boron magnets from Hitachi. The equipment came from a plant that Hitachi formerly owned and operated in North Carolina.

Officials say the equipment should provide most of what the company needs to establish rare earth magnet production and complete the company's domestic mine-to-magnet strategy. When completed, the company estimates, its plant will be able to produce 2,000 metric tons of magnets a year.

"We did not want the United States to lose this key equipment," CEO Pini Althaus said at the time. "So when it became clear that was an imminent possibility, we moved quickly to ensure that this essential part of the critical minerals supply chain remains in the U.S."

RESEARCH AND DEVELOPMENT EFFORTS HOLD PROMISE

Along with these greenfield projects, the domestic rare earths supply is also the focus of innovative research efforts. The Critical Materials Institute at the Ames Laboratory in Ames, Iowa, was launched in 2013, partly in response to the 2010 embargo by China.

CMI research focuses on rare earth materials, as well as battery materials (lithium, cobalt, manganese, graphite), indium and gallium. It is a public–private partnership that collaborates with private industry, as well as with universities and other national laboratories.

According to CMI director Tom Lograsso, the institute's research and development efforts are focused in three areas: diversifying sources of rare earths and critical materials; recycling and reuse; and developing substitutes.


Tom Lograsso

"There's a lot of places to locally source materials. That's the good news," Lograsso says. "Whether we can do it environmentally and economically are the challenges that remain. We can address the economics through technical innovations."

CMI has focused its research on the separation and processing links in the supply chain, Lograsso says. Such work evolved to China because of the lower cost of labor and the less-stringent environmental regulations there, he says.

Among CMI's projects is one to improve the efficiency of the separation processes. Doing so could cut the number of separation stages needed, and it would make the process environmentally safer by reducing the amount of acids and other hazardous chemicals used.

WORLD MINE PRODUCTION AND RESERVES

Rare earths are relatively abundant in the Earth's crust, but minable concentrations are less common than for most other mineral commodities. In North America, measured and indicated resources of rare earths were estimated to include 2.4 million tons in the United States and more than 15 million tons in Canada. This chart shows mine production and reserves in metric tons for 2020 and 2021.

	2020	2021	Reserves
United States	39,000	43,000	1,800,000
Australia	21,000	22,000	94,000,000
Brazil	600	500	21,000,000
Burma	31,000	26,000	NA
Burundi	300	100	NA
Canada	—	—	830,000
China	140,000	168,000	44,000,000
Greenland	—	—	1,500,000
India	2,900	2,900	6,900,000
Madagascar	2,800	3,200	NA
Russia	2,700	2,700	21,000,000
South Africa	—	—	790,000
Tanzania	—	—	890,000
Thailand	3,600	8,000	NA
Vietnam	700	400	22,000,000
Other countries	100	300	280,000
World total (rounded)	240,000	280,000	120,000,000

Source: U.S. Geological Survey, 2022

Researchers are also working to scale up the recycling of rare earths. The institute developed an acid-free, rare-earth magnet recycling process that recovers more than 99% purity rare-earth elements from recycled electronic waste, such as computer hard drives.

"This has gone to demonstration scale, to tens of thousands of kilograms" Lograsso says.

New domestic sources, expanded production from companies in allied countries, and continued technical innovations will all be needed as demand grows for the metals that will power the green economy. As the Adamas Intelligence report says, "The rapid demand growth of the 2020s will soon be dwarfed by the astronomical demand growth of the 2030s—and therein lies the real defining challenge and opportunity facing the global rare earth industry today."

Policy recommendations: US must lead in building the Western supply chain

This is an excerpt of an article that originally appeared in the June 22, 2021, edition of Orbis, the Foreign Policy Research Institute's quarterly journal of world affairs. Republished with permission.

By Ariel Cohen and James C. Grant

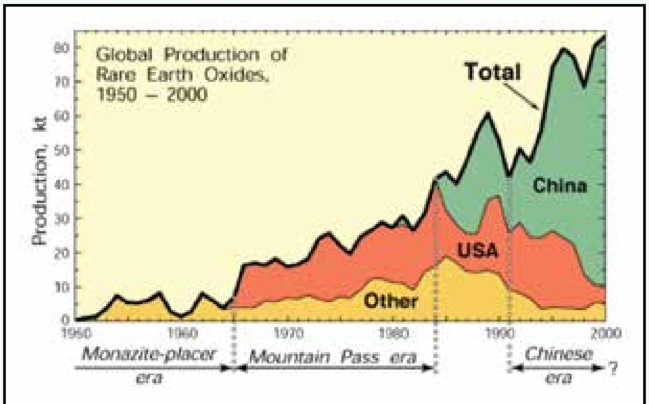
As it stands, Chinese domination of the critical mineral supply chains dwarves the U.S. by all conceivable metrics: China commands 85% of the rare earths elements (REE) export market, producing 62% of global raw mineral materials and importing $2 billion worth of critical minerals and REEs. In the event of an acute international crisis, China would likely use its leverage to further geostrategic aims by imposing critical mineral embargos. Considering the United States derives roughly 80% of its REEs from China, these would likely be catastrophic for the economy, including the high-tech, computers, electronics, electric mobility, aerospace, and military-industrial complex.

Given China's track record and threats in this space, the potential for future embargos is realistic. Like the Strategic Petroleum Reserve (SPR), the stockpiling of rare earths and critical minerals would provide sustainability in the face of international crisis. Supply delays during the COVID-19 pandemic exposed the U.S. lack of preparedness and supply chain bottlenecks, which is beginning to have short-term ramifications for U.S. semiconductors, appliances, autos, and other industries. Current semiconductor shortages in car and appliances factories are threatening to interrupt production and are leading to wait periods of up to six-month delivery times.

In the event of a critical minerals embargo, U.S. companies would be left stranded with limited REE stockpile capabilities. To counter the strategic vulnerabilities associated with reliance on Chinese critical mineral and REE supply chains, the United States must immediately establish a reserve of critical minerals like that of the SPR for oil imports. The capacity of such a reserve is open to discussion, but one-third to half of annual REE demand seems appropriate at the first stage, later expanding the reserve to a whole year of supply.

Developing domestic capacities to mine and refine critical minerals across the United States should be a priority for the U.S. government agencies, yet the private sector should be the primary driver behind REE exploration and production, like other mineral mining and processing. The sole Mountain Pass mine in California will not be sufficient for long-term aims of decoupling from Chinese critical mineral supply. Plans made by Lynas and Blue Line Corp. to build domestic REE refinement facilities in the United States should be the pioneering projects, leading to bigger and better ones throughout North America. The Biden administration should also reauthorize the Defense Production Act to speed up the planning, construction, and operation of these facilities, as expanding domestic mineral projects addresses a key strategic vulnerability.

U.S. corporations should be encouraged to expand rare earths extraction operations in Africa, Asia, and Latin America. The construction of mining infrastructure in African nations would be relatively inexpensive, given lower labor costs and less stringent environmental regulations. Africa's rich mineral reserves make it an ideal destination for supply chain diversification. However, the security challenges, from al-Shabaab to Boko Haram, will require U.S. and its allies to project power to protect the supply chain. Importantly, the African governments and audiences should be aware of U.S. efforts to address developmental needs of host countries, regions, and communities—in competition with China. Roads,



Credit: United States Geological Survey

schools, medical facilities, and environmental protection should be front and center for U.S. REE operations in Africa.

Finally, U.S. policymakers must set specific targets to decrease reliance on Chinese REEs and critical minerals. Targeting specific non-China reliance goals will increase intergovernmental and business sector cooperation and signal clear intent to international partners to build robust levels of Western REE self-reliance.

The United States and its allies should pursue policies that guarantee dependable access to these critical resources at affordable prices, like those in response to the 1970s Arab embargo-triggered energy crisis. President Richard Nixon launched Project Independence after the 1973 oil embargo, attempting to ensure that the U.S. would increase its capacity to refine and extract oil domestically while promoting a union of consumer countries to study the industry, and influence oil pricing. The International Energy Agency arose from such cooperative efforts of oil-consuming democracies.

Similarly, the U.S. must now explore critical mineral supply expansion while gathering allies into an REE "consumer club" to develop policies and build strategic cooperation and partnerships in the diversification of extraction and refinement facilities.

Critical minerals are the lifeblood of the 21st century, fueling high-tech manufacturing and renewable energy transition. These resources are the keystones of economic progress and industrial leadership in building 21st century defenses. The U.S. and her allies must diversify their critical mineral supply chains. Governments who underestimate their importance do so at their own risk.

ABOUT THE AUTHORS

Ariel Cohen, Ph.D., is nonresident senior research fellow at the Atlantic Council and director of the Energy, Growth and Security Program at the International Tax and Investment Center. He is the founding principal of International Market Analysis Ltd.

James C. Grant is research fellow and manager of programs at the International Tax and Investment Center and a junior fellow at the American Foreign Policy Council.

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deciphering the discipline

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.

Jake Evans
Guest columnist

Emerging materials for semiconductors: Oxides for stable solar fuel production

Semiconductors, or materials which can act as either conductors or insulators based on external stimuli, have demonstrated widespread application in energy, information, and sensing fields and thus form a remarkably influential class of materials.

Semiconductors have attracted particularly significant attention for solar energy applications due to the potential of this abundant, renewable energy source. However, solar panels can only provide electricity while the sun is shining, necessitating development of energy storage technology.

Batteries are one approach to solar energy storage. However, these systems are best suited for storage on shorter timescales, such as hours or days.[1] Another approach is to convert the energy captured into another form, such as heat or gravitational energy, but these methods do not generally exhibit high energy density.[2]

Nature offers a solution to the energy storage challenge. Plants directly convert sunlight into chemical energy, using chemical bonds as fuel tanks. By combining materials science and chemistry, scientists can mimic nature to store solar energy as chemical fuels.

Hydrogen is a clean-burning fuel with exceptional energy density and an abundant feedstock—water.[3] One way to make hydrogen is to decorate a semiconductor with a catalyst, immerse it in a corrosive bath (necessary for high efficiency), and illuminate it. Solar photons cause electrons to jump in energy within the material, allowing the electrons to travel to the catalyst, which decomposes water molecules into hydrogen and oxygen.[4]

A significant challenge of this approach is maintaining the stability of the semiconductor in the corrosive bath. This challenge has led to the development of "protection" layers, which ideally are transparent so the semiconductor can still absorb light, conductive so the catalyst can keep producing fuel, and—most importantly—stable to prevent corrosion.

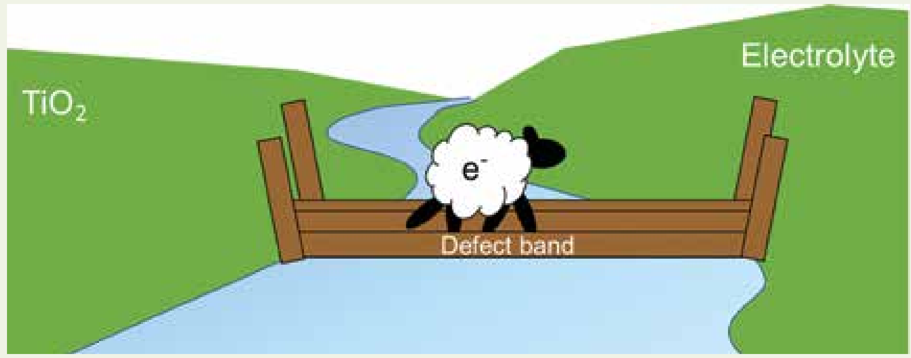

Figure 1. Illustrated analogy of the defect band in TiO_2 enabling electron conduction across the interface.

Titanium dioxide is as a material that can fulfill all three requirements.[5] A semiconductor itself, TiO_2 has a large band gap, meaning that it does not absorb the useful solar energy. It is exceptionally stable and is the reason that titanium metal is so resistant to corrosion. Plus, specialized techniques such as atomic-layer deposition (ALD) allow mere nanometers of TiO_2 to be added at a time, meaning the layer is effectively transparent.

The ALD technique can also produce defects in the TiO_2 structure, which allows electrons to be conducted through the normally insulating film to the catalyst to then produce a chemical fuel like hydrogen. To understand this process, imagine a large river cutting through a field with one side populated by sheep (Figure 1). The river represents the energy gap between the semiconductor and electrolyte and the sheep represent electrons. The river normally prevents any sheep from crossing, as it is too wide for them to jump across. Defects in the TiO_2 act like a bridge, though, allowing the sheep to cross.

Development of the TiO_2-based conversion system has led to devices that can produce chemical fuel from light for hundreds of hours, with even longer lifetimes possible.[6] Yet there is more work to be done! For example, in my group, we study TiO_2 protection layers for semiconductors and have found pinhole defects in deposited films. These defects, unlike the beneficial defects discussed earlier, provide footholds for corrosion to occur and cause the light-absorbing semiconductor to rapidly dissolve away. We are studying the origins and mechanisms of protection layer failure to develop mitigation strategies that can make solar fuel devices a viable technology and enable a greener future.

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Jake Evans is a Ph.D. candidate at the California Institute of Technology. His research focuses on semiconductor corrosion and mitigation strategies. Outside of lab work, Jake enjoys teaching science to local elementary school students and stargazing.

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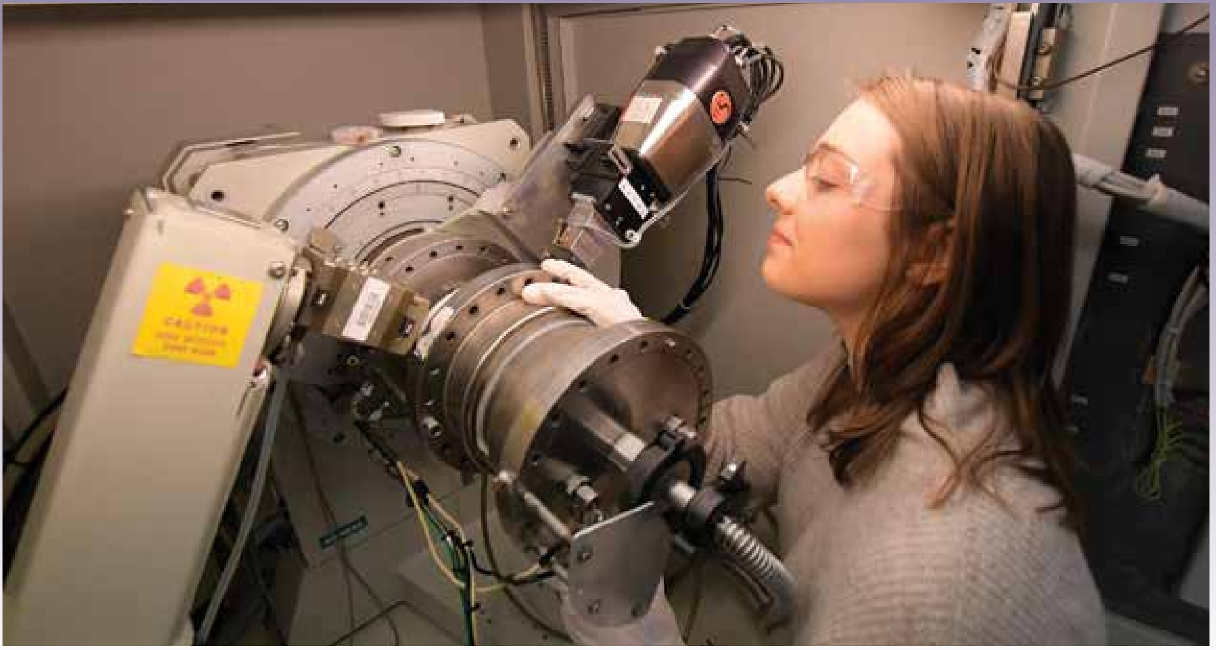

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