AMERICAN CERAMIC SOCIETY

bulletin

emerging ceramics & glass technology

MAY 2024

Chalcogenide glasses:

Engineering in the infrared spectrum

Electric melting | Glass passivation of semiconductors | Augmented reality glasses

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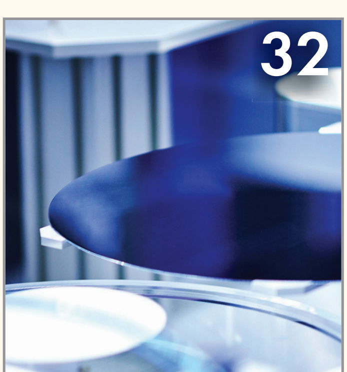
feature articles



Cover image

A chalcogenide glass billet, resting on the stand in the bottom left, is opaque under visible light but is transparent when viewed in the infrared, as shown on the screen in the top right.
Credit: J. David Musgraves

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As seen on *Ceramic Tech Today*...

Credit: International Institute of Tropical Agriculture, Flickr (CC BY-NC 2.0)

Ensuring future food supply: A review of silver-based nanoparticles to combat plant diseases

Agriculture and livestock management has relied largely on anti-microbial drugs to combat plant diseases, but this overreliance contributes to the growing problem of antimicrobial resistance. Silver-based nanoparticles could serve as another way to protect plants from pathogens, as discussed in a recent review paper.

Read more at www.ceramics.org/plant-protection

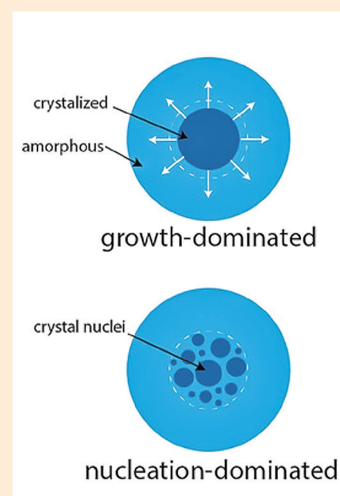
Also see our ACerS journals...

Spatial and temporal control of glassy-crystalline domains in optical phase change materials
By C. Y. Lee, C. Lian, H. Sun, et al.
Journal of the American Ceramic Society

Glass formulation and composition optimization with property models: A review
By X. Lu, J. D. Vienna, and J. Du
Journal of the American Ceramic Society

Impact of impurities on the thermal properties of a $Li_2S{-}SiS_2{-}LiPO_3$ glass
By J. Wheaton and S. W. Martin
International Journal of Applied Glass Science

Thermally matched chalcogenide glasses with high refractive index contrast for infrared graded-index lenses
By Q. Chen, A. Yang, C. Ma, et al.
International Journal of Applied Glass Science



Credit: Lee et al., *Journal of the American Ceramic Society*

Journal of the American Ceramic Society | International Journal of Applied Ceramic Technology | International Journal of Applied Glass Science | International Journal of Ceramic Engineering & Science

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ACSBA7, Vol. 103, No. 4, pp. 1–40. All feature articles are covered in Current Contents.

news & trends

Solar solutions shine at CES 2024

The year 2022 was an inflection point for solar energy, with rooftop installations growing rapidly in both the commercial and residential sectors. However, current solar panel design limits the options for integrating this technology into buildings. Several examples of novel solar solutions that would allow for better integration of solar technology into buildings were on display at the consumer technology trade show CES in January 2024.

Transparent solar technology wins 'Best of Innovation'

Silicon solar panels traditionally come in two formats: polycrystalline (blue) cells, which are less efficient but more affordable; or monocrystalline (black) cells, which are more efficient but less affordable. These cells capture energy mostly from the visible light spectrum (400–700 nm).

In contrast to these opaque cells, transparent solar technologies made from various materials capture energy mostly from the ultraviolet (100–400 nm) and infrared (760+ nm) wavelengths. This absorption spectrum makes transparent solar cells much less efficient than traditional ones. But their transparency opens new opportunities for integrating solar cells into the built environment, for example, as windows, screens, and even smartphone displays.

At CES 2024, the Best of Innovation award went to a transparent solar technology called SQPV glass, which is currently only available in Japan. This technology is based on initial research and patents from Japanese company International Frontier Technology Laboratory Inc., and the company's subsidiary inQs Co. Ltd. developed it into a commercial product.

Japan-based solar technology company inQs used a stained-glass window display to demonstrate their transparent solar technology at CES 2024.

Credit: TBW Advisors LLC, YouTube

The SQPV glass consists of strategically arranged nanomaterials sandwiched between two conductive glass sheets. Light is captured from both glass surfaces while maintaining a visible light transmittance of 75%.

In a *CNET* article on the invention, inQs chief international officer Rike Wootten notes that the glass is made of "very, very easy to find materials" and can be "easily and safely disposed of," in contrast to conventional solar panels.

news & trends

Panasonic demonstrates printing of semitransparent perovskite cells

Japan-based Panasonic Group also showcased (semi)transparent solar technology at CES 2024 in the form of inkjet-printed perovskite coatings.

As explained in a *CNET* article, Panasonic's goal is to directly deposit the perovskite coatings onto windows, walls, and facades, thus turning these surfaces into solar-energy generators. Panasonic can vary the coating's transparency depending on a customer's preference for efficiency or see-through ability.

Panasonic expects it will take several more years until deployment of this technology. However, the company reports that its coatings can already achieve 18.1% conversion efficiency.

Ambient Photonics showcases wide array of solar-integrated household products

In its booth at CES 2024, California-based Ambient Photonics demonstrated the potential to replace batteries with solar cells in a wide array of small household devices.

Solar-powered calculators, originally introduced in the late 1970s, are a prime example of how solar cells can be used to power small household devices.

The new Ambient Photonics solar cells, which are specifically designed for low-light environments, deliver about three times the energy than the cells found in old calculators. The cells come in several sizes, ranging from slightly larger than a thumbnail to about the size of a dollar bill.

Though not yet commercially available, the cells may be sold later in 2024 thanks to partnerships with Primax, to develop an ambient solar mouse, and Google, to create a "new consumer product." ■

Rising costs necessitate recalibration of offshore wind power projects

The future of wind power is big, both figuratively and literally. In addition to growing investments in the wind sector, wind turbines grew physically larger since the early 2000s, allowing them to capture more wind and produce more electricity.

In the past year, however, the wind sector experienced some setbacks compared to other renewable energy technologies. According to BloombergNEF's 2H 2023 Renewable Energy Investment Tracker report, onshore wind investment declined for four straight quarters due to grid constraints, permitting challenges,

The South Fork Wind project along Montauk Point in Long Island, New York, opened in March 2024. Pictured is one of the wind turbines under construction in November 2023.

Credit: New York State Energy Research and Development Authority

and faltering policy support. While offshore wind investment fared better, posting a strong 47% increase relative to the first half of 2022, the translation of this investment into tangible products is not such a rosy picture, as detailed in a *CNBC* article in November 2023.

As the *CNBC* article explains, specialist wind energy firms often find themselves outbid for seabed licenses by traditional

Corporate Partner news

AGC and AIST collaborate to achieve cost reduction in green hydrogen production

AGC Inc. and AIST Group began a collaborative research project in April 2024 aimed at understanding the characteristics of proton exchange membrane water electrolysis technology in high-pressure environments. Hydrogen produced in high-pressure environments has lower moisture content, which can lead to a reduction in investment costs. https://www.agc.com/en/news/index.html

Almatis celebrates 20 years of innovation and excellence

Almatis, a global leader in the production of high-performance specialty alumina products, celebrated its 20th anniversary on March 1, 2024. Founded more than a century ago, Almatis officially became an independent company on that date in 2004. https://www.almatis.com/news-event/news

Corning celebrates the impact—and continued promise—of its environmental technologies

Corning Incorporated recently celebrated the 50th anniversary of its Environmental Technologies business. Spurred by the U.S. Clean Air Act of 1970, Corning researchers developed the world's first ceramic substrates that set the standard for catalytic converters worldwide and launched the global emissions control industry. https://www.corning.com/worldwide/en/about-us/news-events.html

STC Material Solutions purchased by IDEX

STC Material Solutions entered into an agreement to be acquired by IDEX Corporation, a diversified global manufacturer. STC Material Solutions specializes in the design and manufacturing of technical ceramics and hermetic sealing products for the most extreme, mission-critical applications. https://ceramics.net/about-us/latest-news ■

oil and gas players. If they do win a contract, electricity prices are often too low to justify the manufacturing costs, "leaving companies looking to their governments in Europe and the U.S. to deliver greater subsidies and restore balance to the market."

This situation puts projects at risk of being abandoned if governments do not offer the support that wind energy firms believe is necessary for project completion. Such a situation is already playing out with several projects along the East Coast of the United States, as detailed by *The New York Times*.

The most egregious example occurred on Oct. 31, 2023, when Danish energy developer Ørsted backed out of two projects off the southern coast of New Jersey, citing "macroeconomic factors" such as inflation and rising interest rates. The news generated a lot of anger because the state had already approved a tax break to let the company keep as much as $1 million in tax credits that otherwise would have been returned to electricity ratepayers.

The trend toward so many wind energy firms attempting to renegotiate their contracts for established projects is due to several economic factors, as explained by Jacob Pedersen, senior analyst at Sydbank, in the *CNBC* article.

"We know a huge part of the problem is related to the projects that were won back in 2019/20 and at low prices. Since then, inflation and interests have gone up, it's become much more expensive to realize these projects, and that has left an order book of deficits, and that order book is now being smaller and smaller as time goes by," he says.

Pedersen argues that there is a "huge need for recalibration" on the cost of the planned energy transition, but there are indications that governments are taking action. For example, several offshore wind projects launched in the last year were awarded on "much, much better terms," according to Pedersen, which should allow companies to generate a profit in the future.

Some older projects are still proceeding as planned, however, despite the setbacks described earlier. For example, in November 2023, Ørsted confirmed it would proceed with construction of the South Fork Wind project, an array of 12 offshore wind turbines along Montauk Point in Long Island, N.Y. In March 2024, Ørsted announced that all 12 turbines had been installed and the wind farm was officially open. ■

Brian Sjogren
Guest columnist

Why glass is the key in the future of augmented reality

Figure 1. SCHOTT's high-index glass SCHOTT RealView® wafer.

Before the days of light-as-your-eye-glasses augmented reality (AR) devices, Harvard University produced "The Sword of Damocles" in 1968.[1] It was a heavy headset with multiple cables and mechanical arms meant to overlay simple wire-frame images onto the user's view.

Today's expectations for AR devices are far different—slim frames holding lenses that produce images as a new layer of reality. Obtaining the desired image quality, mechanical robustness, and optical performance within a compact footprint will require the development of novel materials and products. It is thus unsurprising that the market for AR devices is projected to grow to about $90 billion in the next two years.[2]

What goes into AR systems

Glass wafers with a high refractive index are vital in the optical system. Unlike a computer screen, where the image projects through the glass in one direction, AR devices project the image through the length of the glass. Homogeneity of the refractive index allows for tighter control of the total internal reflection so the user sees the best possible image quality with the designed field of view.

There are three main architectures used for AR systems. Diffractive waveguide architectures are processed using either surface relief gratings structures or reactive ion etch gratings structures built into or on top of the high-index glass. Holographic waveguide architectures use principles similar to Bragg gratings that reflect specific light wavelengths and transmit others. Reflective architectures use waveguides that direct the image to the eye through multiple partial reflectors.

Manufacturing waveguides is a complex process that includes coating, stacking, slicing, polishing, and shaping the glass. At the same time, AR device manufacturers demand strict tolerances across hundreds of layered glass parts with unique geometries. Automation and process refinements must progress for costs to decline.

The price for AR consumer devices remains high, just like the early days of cell phones that cost thousands of dollars. As the market expands and technology advances, manufacturing the components of these devices will become cheaper, and the devices will include more features.

Glass for the future of AR

SCHOTT's rich history in advanced optics gave the company an understanding of where the AR market could go, as well as the ability to evolve its high-index optical glass products into the next breakthrough for AR devices. SCHOTT created the Strategic Business Field Augmented Reality in 2016 and has worked on high-index glass wafers, SCHOTT RealView® (Fig. 1),[3] ever since.

In 2019, SCHOTT partnered with Lumus, a developer of reflective waveguide technology, to enable cost-effective, mass-scale manufacturing of waveguides for near-to-eye AR devices. The companies recently extended the partnership to include new architectures for even better performance and flexibility in the design of AR glass.[4]

The Lumus devices use a novel Z-lens architecture that is compact and lightweight yet has a high power efficiency and a field of view ranging between 15–70°. As AR applications evolve, both specialized Z-lens-style smart glasses and more expansive, immersive devices will coexist depending on use case needs, but they require very different optical properties. The market is going all-in on both technologies.

SCHOTT's partnership with Lumus goes beyond supplying glass wafers to produce waveguides. SCHOTT's vertically integrated production chain leverages more than a century of expertise across coating applications, precision polishing, bonding, contouring, and final assembly to help fabricate the Lumus waveguides.

AR has come a long way from the bulky contraption that was The Sword of Damocles. While technical challenges remain, steady progress in advanced optics and core components pave the way for more affordable and sleek AR devices.

About the author

Brian Sjogren is business development manager for augmented reality at SCHOTT North America (Duryea, Pa.). Contact Sjogren at brian.sjogren@us.schott.com.

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[1]"History of virtual reality," Virtual Reality Society. Accessed 5 March 2024. https://www.vrs.org.uk/virtual-reality/history.html

[2]"Augmented reality (AR) market by device type (head-mounted display, head-up display), offering (hardware, software), application (consumer, commercial, healthcare), technology, and geography—global forecast," MarketsandMarkets, published August 2021. https://www.marketsandmarkets.com/Market-Reports/augmented-reality-market-82758548.html

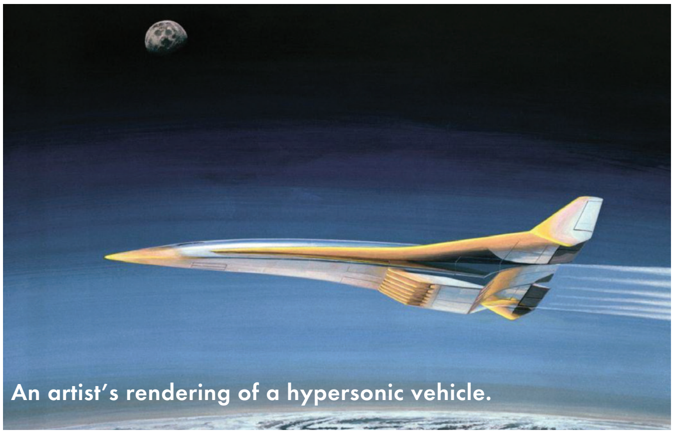
[3]"SCHOTT RealView®," SCHOTT AG. Accessed 5 March 2024. https://www.schott.com/en-gb/products/schott-realview-P1000268

[4]"Lumus and SCHOTT strengthen manufacturing partnership to meet the growing global market demand for optical AR glasses," SCHOTT AG, published 30 Jan. 2024. https://www.schott.com/en-gb/news-and-media/media-releases/2024/lumus-and-schott-strengthen-manufacturing-partnership ■

SOCIETY DIVISION SECTION CHAPTER NEWS

ACerS and USACA partner on hypersonic materials training program

On Jan. 8, 2024, the Department of Defense Cornerstone Consortium under the DOD Industrial Base Analysis and Sustainment program and the National Imperative for Industrial Skills initiative awarded The American Ceramic Society a contract to develop a sustainable, targeted, workforce training program on the science and engineering of materials for hypersonic applications.



An artist's rendering of a hypersonic vehicle.

Credit: NASA

The program will focus on ultrahigh-temperature ceramic materials, ceramic matrix composites, and, where used in combination with advanced ceramics, carbon/carbon composites, refractory metals, and cermets. Subject matter experts will develop full-day tutorial sessions for delivery in environments compliant with International Traffic in Arms Regulations, as well as half-day tutorial sessions for delivery over an online distance learning platform.

"ACerS has a long tradition of supporting the ceramic and glass industry with continuing education. This program will allow the Society to extend its valuable skills training to those working in the hypersonics industry," says Mark Mecklenborg, ACerS executive director.

The American Ceramic Society, a 501(c)(3) professional organization, will partner with the United States Advanced Ceramics Association (USACA), a 501(c)(6) trade association, on the effort.

"This ACerS–USACA partnership fills a critical knowledge gap for engineers, designers, technicians, and allied personnel working with these materials," says Ken Wetzel, USACA executive director.

The first course under this program took place at the Composites, Materials & Systems Conference in St. Augustine, Fla., on Jan. 21, 2024. Purdue University professor and ACerS Fellow Rodney Trice taught the one-day short course. A second one-day, in-person course will take place at the NSMMS/CRASTE conference on June 28, 2024, in Madison, Wisc. Two half-day virtual courses on ceramic-based materials for extreme environment applications are in development.

Questions about the program can be directed to Amanda Engen, ACerS director of communications and workforce development, at aengen@ceramics.org. ■

Call for 2024–2026 EPDC co-chair

The Education and Professional Development Council (EPDC) is the central location for exchanging ideas between education and professional development organizations within ACerS. The EPDC co-chairs serve as a resource for organizing events throughout ACerS, including the development of new initiatives. The EPDC co-chairs operate on a two-year term, with staggered elections.

ACerS members who have interest or experience with education or professional development initiatives are encouraged to apply. To review the position details and apply, visit ceramics.org/epdc. The deadline to complete the nomination form is **Wednesday, May 8, 2024**. Contact Yolanda Natividad at ynatividad@ceramics.org with any questions. ■

FOR MORE INFORMATION:

ceramics.org

Dayton/Cincinnati/Northern Kentucky Section hosts lecture on superconductors at the University of Cincinnati

On Feb. 16, 2024, the Department of Mechanical and Materials Engineering at the University of Cincinnati hosted Michael Sumption, professor of materials science and engineering at The Ohio State University, who gave a lecture on recent developments in the field of superconductors.

Sumption explained how superconductors have potential in sustainable energy applications, such as to create magnetic fields for tokamaks and high-energy accelerators. He shed light on current advancements in Type II superconductors, including both A15 compounds and high-temperature superconductors. His main focus, however, was on engineering nanoscale precipitates in internally oxidized Nb_3Sn superconductors to optimize the material's flux pinning centers. ■

Michael Sumption, right, with University of Cincinnati professor Donglu Shi and graduate students after the seminar.

Michael Sumption's seminar on Feb. 16, 2024, focused on recent advances in high-temperature superconductors.

ACerS International United Arab Emirates Chapter welcomes featured speaker

The ACerS International United Arab Emirates Chapter organized its inaugural event, a talk on "Additive manufacturing and 3D printing of ceramic structures," on Feb. 26, 2024. Rashid K. Abu Al-Rub of Khalifa University presented the talk, which was attended by more than 50 guests from around the world. The Chapter plans to host similar events in the future to discuss scientific research and discoveries, share ideas, and initiate international and industrial collaborations and engagements. ■

more SOCIETY DIVISION SECTION CHAPTER NEWS

WEBINARS TO WATCH

Check out these recent additions to the ACerS Webinar Archives:

HOW TO WRITE A GRANT-WINNING PROPOSAL

Original air date: March 6, 2024

Hosted by: Energy Materials and Systems Division

Featured speakers: Levent Karacasulu, Odai Al Balasmeh, and Varun Kumar Reja

LEARNING FROM BONE TO ENGINEER TOMORROW'S MORE SUSTAINABLE BIOCEMENTED MATERIALS

Original air date: March 7, 2024

Hosted by: Cements Division

Featured speaker: Chelsea Heveran

ACerS members can view these webinars and other past recordings by visiting the ACerS Webinar Archives at www.ceramics.org/webinararchives.

MEMBER HIGHLIGHTS

Volunteer Spotlight: Christina Bisulca

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

ACerS is pleased to announce **Christina Bisulca** has been selected for Volunteer Spotlight, a program that recognizes a member who demonstrates outstanding service to The American Ceramic Society through volunteerism.

Bisulca is the Andrew W. Mellon conservation scientist at the Detroit Institute of Arts (DIA). She has a Ph.D. in materials science through the heritage conservation science program at the University of Arizona and an M.S. in objects conservation through the Winterthur Program in American Material Culture offered by the University of Delaware and Winterthur Museum, Garden, and Library.

Bisulca works with conservators and curators at DIA to conduct scientific investigations of collections for a deeper understanding of their history, manufacture, and condition. She is chair of the Art, Archaeology & Conservation Science Division.

We extend our deep appreciation to Bisulca for her service to our Society! ■

ACerStudent Engagement: Nathan McIlwaine

Nathan McIlwaine is a Ph.D. candidate at The Pennsylvania State University and serves as a member of the ACerS President's Council of Student Advisors (PCSA). McIlwaine has attended a variety of ACerS conferences and events, and has volunteered with the Ceramic and Glass Industry (CGIF) for outreach events.

"My student involvement in ACerS has been invaluable for my professional development and networking skills. The mentorship I experienced through various ACerS activities helped me build my ideal career trajectory, and I found the ACerS educational outreach volunteering opportunities to be fulfilling ways to help inspire the next generation of materials scientists and further my passion for the field."

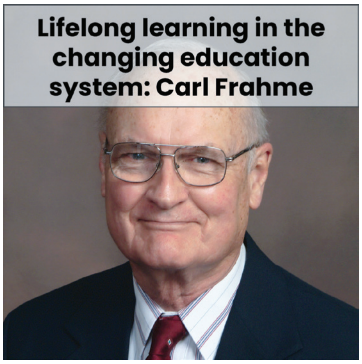
You can take advantage of these opportunities as well by becoming a student member of ACerS. Visit https://ceramics.org/members/membership-types to learn more. ■

FOR MORE INFORMATION:

ceramics.org/members

Ceramic Tech Chat: Carl Frahme

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 third Wednesday of each month

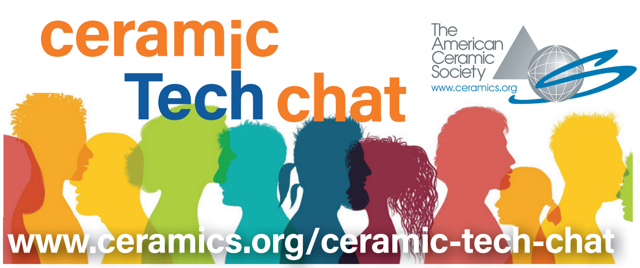


In the March 2024 episode of Ceramic Tech Chat, **Carl Frahme**, longtime consultant and educator, shares how he first became involved as an instructor for ACerS educational courses, describes how these courses evolved over time, and explains why he finds being a science educator so fulfilling.

Check out a preview from his episode.

"I've had a long career. Anybody can look at me and say, 'Well, he's not young.' But I've had to reinvent myself many, many times. When I went through undergraduate and graduate school, the tools we had were a slide rule and paper and pencil. We didn't have calculators, we didn't have computers. ... So, I've had to learn computer technology and all kinds of new areas of technology that didn't exist. If you don't keep up, as an instructor or as somebody in the industry, you're dead in the water. You can't allow that to happen. So, we all have to keep on learning."

Listen to Frahme's whole interview—and all our other Ceramic Tech Chat episodes—at https://ceramictechchat.ceramics.org/974767. ■



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.

Raj N. Singh, FACerS, Regents Professor at Oklahoma State University, was elected as a member of the National Academy of Engineering. Induction will take place at the NAE Annual Meeting in September 2024. ■

more MEMBER HIGHLIGHTS

The outsized research impact of ACerS members and journal authors

In October 2023, the latest version of a regularly updated and publicly available database of top-cited scientists was published (DOI: 10.17632/btchxktzyw.6). Analysis of the rankings revealed that the ceramic and glass community has a substantial impact on scholarly literature given its size relative to much larger fields, such as biomedicine and physics.

ACerS Fellows, such as Yuri Gogotsi, and Distinguished Life Members, such as the late luminaries Anthony Evans and Larry Hench, are highly ranked among all the researchers on the career impact list. When considering only "materials" researchers, 17 of the top 25 career high-impact researchers are contributors to ACerS journals, many of them frequent contributors.

When considering only recent years for impact, ACerS journal authors are once more among the most highly ranked. In rankings based solely upon metrics for the year 2022, 17 of the top 25 most impactful materials researchers published in ACerS journals.

In an email, Michel Barsoum, FACerS, Distinguished Professor in the Department of Materials Science and Engineering at Drexel University, noted that "for a small society that is great impact." Barsoum, who has authored 50 papers in ACerS publications, is ranked third among materials researchers and 124 among all researchers in all disciplines based on 2022 impact. ■

AWARDS AND DEADLINES

FOR MORE INFORMATION:

ceramics.org/members/awards

Nomination deadlines for Division awards: May 15, May 30, July 1, or July 31 , 2024

Contact: **Vicki Evans** | **vevans@ceramics.org**

Division	Award	Deadline	Contacts	Description
GOMD	Alfred R. Cooper Scholars	May 15	Steve Martin swmartin@iastate.edu	Recognizes undergraduate students who demonstrated excellence in research, engineering, and/or study in glass science or technology.
ED	Edward C. Henry Award	May 30	Aiping Chen apchen@lanl.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.
ED	Lewis C. Hoffman Scholarship	May 30	Aiping Chen apchen@lanl.gov	Recognizes academic interest and excellence among undergraduate students in ceramics/materials science and engineering.
ECD	Bridge Building Award	July 1	Jie Zhang jiezhang@imr.ac.cn	Recognizes individuals outside of the United States who have made outstanding contributions to engineering ceramics.

Division awards (continued)

Division	Award	Deadline	Contact	Description
ECD	Global Young Investigator	July 1	Amjad Almansour amjad.s.almansour@nasa.gov	Recognizes the outstanding young ceramic engineer or or scientist whose achievements have been significant to the profession and to the general welfare of the global community. Nominations are open to candidates from industry, academia, or government-funded laboratories around the world.
ECD	James I. Mueller Lecture	July 1	Young-Wook Kim ywkim@uos.ac.kr	Recognizes the enormous contributions of James I. Mueller to the Engineering Ceramics Division and to the field of engineering ceramics. This award aims to recognize the accomplishments of individuals who have made similar contributions.
ECD	Jubilee Global Diversity Award	July 1	Michael Halbig michael.c.halbig@nasa.gov	Recognizes exceptional early- to mid-career professionals who are women and/or underrepresented minorities (i.e., based on race, ethnicity, nationality, and/or geographic location) in the area of ceramic science and engineering.
EMSD	Outstanding Student Researcher	July 31	Charmayne Lonergan clonergan@mst.edu	Recognizes exemplary student research related to the mission of ACerS Energy Materials and Systems Division. ■

Nomination deadline for Society awards: August 1, 2024

Contact: **Erica Zimmerman** | **ezimmerman@ceramics.org**

Society award	Description
Samuel Geijsbeek PACRIM International Award	Recognizes individuals who are members of the Pacific Rim Conference (PACRIM) societies for their contributions to ceramic and glass technology that have resulted in significant industrial and/or academic impact, international advocacy, and visibility of the field. Industrial candidates will be evaluated based on the technology's development and commercialization, its current usefulness and importance, its uniqueness, and its economic significance. ■

CERAMICANDGLASSINDUSTRY FOUNDATION

Student engagement at ICACC 2024: IGNITE MSE and shot glass competition

(All photos credit: ACerS)

The Ceramic and Glass Industry Foundation oversees student engagement within ACerS, from professional networking and outreach events to award competitions and leadership opportunities. The CGIF helped organize several events at the 48th International Conference and Expo on Advanced Ceramics and Composites (ICACC 2024) designed specifically to enhance the conference experience for students.

IGNITE MSE PROFESSIONAL DEVELOPMENT SYMPOSIUM

The second International Gathering and Networking of Individuals To Explore Materials Science and Engineering (IGNITE MSE) took place before and during ICACC 2024 from Jan. 28–Feb. 2, 2024.

A symposium featured three speakers who talked about the importance of soft skills to elevating one's career and shared their career journeys. The speakers included Marissa Reigel of Saint-Gobain NorPro, Bryan Harder of NASA Glenn Space Research Center, and Andrea Vozar of GE Aerospace Research.

In addition to the symposium, IGNITE MSE included networking activities, a luncheon featuring professionals from Saint-Gobain and Boeing, and a bonus tour of the Kennedy Space Center.

Twenty-one students from seven different countries participated in the IGNITE MSE activities and enjoyed networking throughout ICACC 2024. To learn more about upcoming IGNITE MSE events at ACerS conferences, visit https://foundation.ceramics.org/ignite-mse.

Bryan Harder of NASA Glenn Space Research Center gives his talk titled "My career at NASA: From coatings to combustion."

PCSA SHOT GLASS COMPETITION

The President's Council of Student Advisors (PCSA) organized the annual shot glass competition at ICACC 2024. In this competition, participants must build a protective device using pipe cleaners or straws to prevent a shot glass provided by SCHOTT North America Inc. from breaking; the shot glass that stays intact when dropped from the tallest height wins.

Marwan Ben Miled (left) and Manon Faral (right), winners of the ICACC 2024 shot glass competition.

Marwan Ben Miled from the University of Limoges, France, and Manon Faral from the University of Montreal, Canada, took home first place in the ICACC 2024 shot glass competition.

Support students through innovative programming such as IGNITE MSE and the PCSA by visiting ceramics.org/donate. ■

IGNITE MSE participants at ICACC 2024.

Medical device coatings: Materials and markets

By BCC Publishing Staff

The global market for medical device coatings was valued at $5.8 billion in 2022 and is expected to grow at a compound annual growth rate (CAGR) of 10.9% to reach $9.7 billion by 2027.

Coatings are used to improve the biocompatibility of medical devices with the human body, reduce the risk of infection, prevent blood clotting, and improve the device's durability and longevity. Types of medical device coatings, which are used in various applications (Table 1), include

- **Antimicrobial**: Contains compounds that can kill or inhibit the growth of microorganisms, thus reducing the risk of infections caused by bacteria, viruses, and fungi.
- **Hydrophilic**: Designed to reduce the surface tension of water, thus improving the flow of liquids over various surfaces and helping prevent the build-up of biofilm and bacterial adhesion.
- **Drug-eluting**: Designed to release a specific drug or medication over time, thus providing controlled and sustained treatment at the affected site.
- **Antithrombogenic**: Used to deliver drugs or other agents that inhibit the formation of blood clots, thus reducing the formation of blood clots and preventing the potential complications associated with them.

Various types of materials are used for medical device coatings, but the polymers segment dominated the market with 43.6% in 2021, followed by metals and ceramics with 27.6% and 18.7%, respectively. Ceramics commonly used as medical device coatings include

- **Alumina**: Exhibits excellent corrosion resistance, good biocompatibility, high strength, and high wear resistance. Aluminas are prized for their protective capabilities.
- **Hydroxyapatite**: Helps with osseointegration, i.e., improves the bond between the implant and the surrounding bone. It also promotes bone growth.

Bioactive glasses are also used as medical device coatings. Patented bioactive glasses, marketed as Bioglass 45S5 and Ceravital, have been observed to promote bone ingrowth within one hour following implantation.

North America dominates the global medical device coatings market with a market share of 35.9% in 2021. The growing geriatric population, rise in hospital-acquired infections, and increase in healthcare expenditures are major factors contributing to the growth and development of medical device coatings in this region.

About the author

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BCC Publishing Staff, "Medical device coatings: Global markets," BCC Research Report HLC049F, March 2023. https://bit.ly/BCC-March-2023-coatings

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Table 1. Global market for medical device coatings, by application, through 2027 ($ millions)

Applications	2021	2022	2027	CAGR % (2022–2027)
General surgery	1,742.6	1,917.0	3,353.6	11.8
Cardiovascular devices	1,182.0	1,302.2	2,326.2	12.3
Orthopedics	874.2	954.9	1,636.9	11.4
Radiology	437.1	471.7	760.6	10.0
Dentistry	376.7	403.8	628.6	9.3
Neurology	286.2	301.2	428.3	7.3
Gynecology	228.7	237.9	318.2	6.0
Others	178.1	183.8	235.5	5.1
Total	5,305.6	5,772.5	9,687.9	10.9

Glass-coated DNA scaffolds receive power-up through inorganic infiltration

In a novel development, researchers used DNA nanotechnology to create high-strength, lightweight glass nanolattices functionalized with metal and metal oxide particles.

DNA nanotechnology is a materials design paradigm that uses DNA's unique chemical and structural properties to create programmable nanostructures for applications both within and outside of biological contexts.

Of the various assembly techniques used in this field, DNA origami is a frontrunner. This technique uses numerous short "staple" strands of DNA to direct the folding of a long "scaffold" strand. The resulting scaffold has fixed dimensions and allows for the attachment of molecules at prescribed positions.

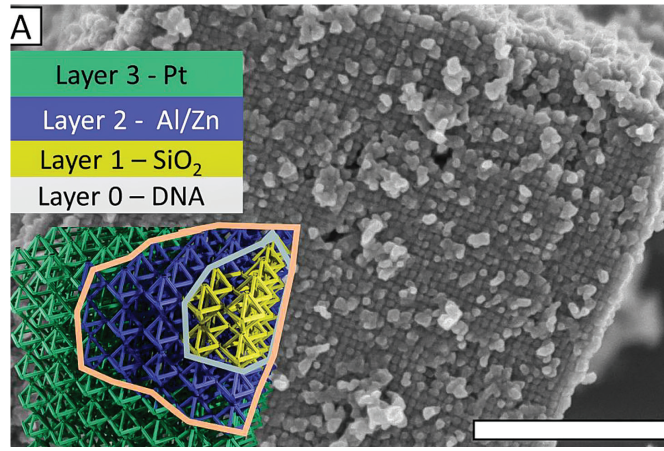
In July 2023, researchers at Columbia University, the University of Connecticut, and Brookhaven National Laboratory published an open-access paper that revealed a novel use for DNA origami scaffolds—as a framework for creating high-strength, lightweight glass nanolattices.

They noted that this nanolattice could serve as a stable platform for next-generation catalysts, battery cathodes, and other applications. However, for its potential to be fully exploited, they would need a way to incorporate other functionally active materials into the nanolattice.

To achieve this goal, several authors from the original study teamed up with researchers in the Soft and Bio Nanomaterials Group and the Electronic Nanomaterials Group at Brookhaven's Center for Functional Nanomaterials. Through their combined expertise, the researchers successfully incorporated metal and metal oxide particles into the silica nanolattice, as described in a new open-access paper.

Their success relied on liquid-phase and vapor-phase infiltration, two emerging methods for converting polymer templates into functional organic–inorganic hybrids. The latter technique was pioneered by researchers in the Electronic Nanomaterials Group, who helped explore its potential to be used with the glass-based scaffold.

The researchers used the liquid-phase and vapor-phase infiltration methods both alone and together. They determined that combining these methods allowed for the creation of more complex structures.



Using liquid-phase and vapor-phase infiltration, researchers created glass-coated DNA origami scaffolds functionalized with metal and metal oxide particles. The superimposed graphics on this structure, which was imaged using a scanning electron microscope, reveal the layers of silica, alumina-doped zinc oxide, and platinum on top of the DNA origami scaffold. Scale bar: 1 µm.

Structural and spectroscopic analyses of the infiltrated nanolattices revealed a diverse set of nanostructures with varying electrical and optical properties. The underlying DNA origami scaffold remained preserved under the inorganic nanostructures.

In a Brookhaven press release, lead author Aaron Michelson, postdoctoral researcher at the Center for Functional Nanomaterials who began this research as a Columbia University graduate student, says it was surprising how many different material compositions of nanostructures they achieved using an identical process protocol.

"Typically for research like this, you need to spend a considerable amount of time with just one class of materials trying to get it to work, day in and day out. Whereas here, nearly everything we tried worked quickly, and at some point, we just had

Research News

Backyard insect inspires invisibility devices and other next-generation technology

Researchers led by The Pennsylvania State University precisely replicated the complex geometry of particles, called brochosomes, that leafhoppers secrete and coat themselves in. These particles absorb both visible and ultraviolet light, and designing synthetic brochosomes could allow for the development of bioinspired optical materials with applications ranging from invisible cloaking devices to more efficient solar energy harvesting. For more information, visit https://www.psu.edu/news. ■

Theory linking ignition with flame provides roadmap to better combustion engines

Tohoku University researchers theoretically linked ignition and deflagration in a combustion system, unlocking new configurations for stable, efficient combustion engines. Previously, researchers believed a steady-state solution exists only when the inlet velocity matches the velocity of either the deflagration wave or detonation wave. The Tohoku researchers posit that an infinite number of solutions exist if autoignitive conditions are considered. For more information, visit https://www.tohoku.ac.jp/en/press/index.html. ■

to stop producing structures because we wanted to write about it," he says.

The structures described in the paper include various combinations of zinc, aluminum, copper, molybdenum, tungsten, indium, tin, and platinum, as well as composites such as aluminum-doped zinc oxide, indium tin oxide, and platinum/aluminum-doped zinc oxide.

With the potential of this new approach confirmed, the researchers plan to use the method in more complex research. They also plan to offer visiting scientists at the Center for Functional Nanomaterials access to the technique.

The open-access paper, published in *Science Advances*, is "Three-dimensional nanoscale metal, metal oxide, and semiconductor frameworks through DNA-programmable assembly and templating" (DOI: 10.1126/sciadv.adl0604). ■

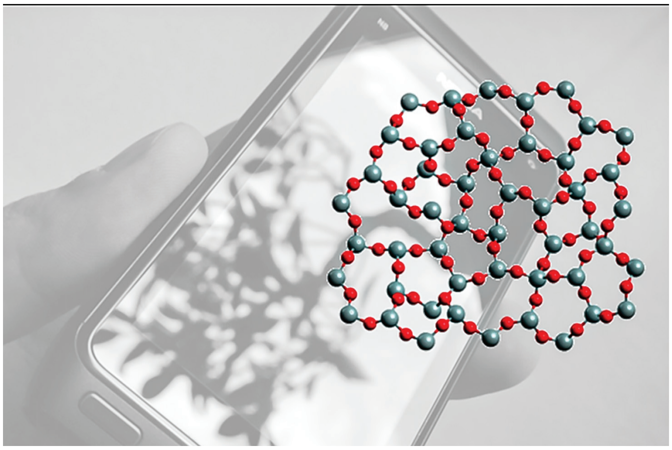
Toward better glass design: Neutron scattering data reveal correlation between medium-range order and fragility

Researchers led by Corning Incorporated proposed a new way to predict the fragility of aluminosilicate glasses based on their structure.

Fragility describes how rapidly the particles in a supercooled liquid stop moving in a collective manner as the material is cooled toward the glass transition. In other words, it describes the point at which a supercooled liquid can reversibly transform between a rubbery or viscous state and a rigid, glassy state.

Materials with a high fragility will transition quickly into a glass, whereas materials with a low fragility take longer to transform. Knowing a material's fragility allows manufacturers to optimize the melting and forming processes during glass fabrication.

Fragility is defined based on the temperature dependence of the supercooled liquid's viscosity, and as such it is measured by both viscometry/dilatometry and calorimetry techniques. However, these measurement techniques, in addition to being labor-intensive and time consuming, are often plagued by a high level of systematic error.



Credit: Oak Ridge National Laboratory

Thanks to neutron scattering data collected and analyzed at Oak Ridge National Laboratory, researchers have a new way to predict the fragility of aluminosilicate glasses based on their structure.

Rather than viscosity, identifying structural parameters that correlate with fragility could enable a straightforward method for predicting this property without cumbersome experiments.

Currently, there are two approaches to interpret fragility based on structure: the temperature-dependent constraint theory advanced by Gupta and Mauro and the coarse-grained

Researchers prove fundamental limits of electromagnetic energy absorption

Duke University researchers determined the theoretical fundamental limit for how much electromagnetic energy a transparent material with a given thickness can absorb. Their theory is validated with transfer matrix calculations of homogeneous materials and full-wave numerical simulations of electromagnetic metamaterials. The finding will help engineers optimize devices designed to block certain frequencies of radiation while allowing others to pass through. For more information, visit https://pratt.duke.edu/news. ■

model by Sidebottom. These approaches are based on the linkages between a glass's network-forming cationic species (A) and oxygen atoms. However, while the former theory considers A–O–A linkages on the short-range level (constraints per atom), the latter theory considers the longer-range order (coordination number). Regardless, both approaches can be used to derive universal interpretations of fragility for a wide range of glass-forming liquids.

The new approach proposed by the Corning-led researchers considers A–O–A linkages on an even longer length scale, i.e., the medium-range atomic ring structure. It is designed solely for use with the industrially relevant aluminosilicate glass system rather than being a universal descriptor like the other two approaches.

To develop this method, the Corning researchers worked with colleagues at Oak Ridge National Laboratory, the University of California, Los Angeles and the University of Oxford to run experiments on NOMAD, a neutron diffractometer beamline at Oak Ridge's Spallation Neutron Source. The data gathered from these experiments were then analyzed using a new neutron scattering data analysis tool, RingFSDP, developed by Corning and Oak Ridge scientists.

Their analysis revealed that small atomic ring structures are more unstable and deform more easily than large atomic ring structures. As such, glasses with a higher proportion of small rings will have higher fragility, whereas glasses with a higher proportion of large rings will have lower fragility.

In an Oak Ridge press release, senior author Douglas Allan, Corporate Research Fellow at Corning, says that this finding as well as others that connect underlying structural features to a glass's fragility "will have a significant impact on glass design and production."

The open-access paper, published in *Nature Communications*, is "Revealing the relationship between liquid fragility and medium-range order in silicate glasses" (DOI: 10.1038/s41467-022-35711-6). ■

Free digital resource dives into the history of Roman-period glassblowing

Rome's significant influence on the craft of glassblowing warrants its close study even today. And thanks to a new freely available digital resource offered through the Corning Museum of Glass, anyone can learn about this history from the comfort of their home.

"The Techniques of Roman-Period Glassblowing" is the third digital publication by artist and scholar William Gudenrath. Gudenrath is recognized internationally as one of the foremost authorities on glassmaking techniques of the ancient world through the 18th century.

Credit: Corning Museum of Glass, YouTube

Artist and scholar William Gudenrath demonstrates how the iconic Roman-period bird vessels were created.

His first two electronic resources, released in 2016 and 2019, focused on the techniques of Renaissance Venetian and Venetian-style glassworking, respectively. These publications earned him the moniker of "glass detective" by the Associated Press.

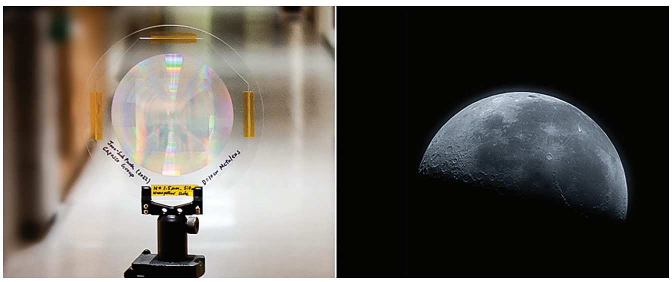
The new digital publication on Roman glassblowing highlights the Roman-period innovations that laid the groundwork for modern glassworking. Gudenrath identified many of these innovations through reverse-engineering early glassblowing practices.

The Roman glassworking publication contains nearly twice as many long- and short-format videos as the previous publications on Venetian glassworking, with 53 in total. A visual index of objects provides direct links to most of the videos, though a few additional videos appear in the first chapter as well.

The publication is organized into seven chapters, starting with the history of glassblowing and then diving deeply into the creation of different types of glass objects, such as long-necked and short-necked vessels and compound objects (processes involving two conjoined bubbles). The objects are organized to reflect increasing complexity and difficulty, and as such "the publication can be used as a tutorial for an aspiring student of historical glassblowing," Gudenrath writes in the introduction.

Access the full free publication and explore the decades of observation and experience it contains by visiting https://romanglassblowing.cmog.org. ■

Tiny tubes and far away stars—large metalens images the night sky



Credit: Capasso Lab, Harvard SEAS

(Left) The 10-centimeter-diameter glass metalens. (Right) Image of the moon taken by the metalens from the roof of the Science Center in Cambridge.

Researchers at the Harvard John A. Paulson School of Engineering and Applied Sciences developed a method for creating 100-millimeter-diameter metalenses, which makes applications in astronomy and free-space optical communications possible.

Metalenes are precisely engineered and extremely thin lenses that can focus light without causing image distortions. The Harvard researchers previously used deep-ultraviolet projection lithography to create metalenses up to 10 mm in diameter, which would be useful for applications in virtual and augmented reality. But they now discovered how to stitch together multiple exposures of the photolithography process, allowing them to create a much larger metalens while retaining the small-scale precision.

The resulting all-glass metalens contained 18 billion nanostructures and was 10 times larger than previous attempts, demonstrating the feasibility of large-scale manufacturing. The researchers also used it to produce detailed images of the sun, the moon, and a faint nebula using only the lens, a color filter, and a camera sensor. The images were detailed enough to see major sun spots on the sun's surface, matching NASA's observation on the same day.

To further explore the metalens' application in astronomy, the researchers subjected the structure to extreme temperatures and temperature changes. The metalens showed no significant changes after 10 cycles between –195.8°C (liquid nitrogen bath) to 200°C (hot plate). It also showed no significant damage after a vibration stress test, making it a promising choice for launching into space.

The researchers suggest that higher resolution manufacturing techniques, such as deep-ultraviolet immersion lithography, could be used to produce even smaller nanostructures on the metalens.

The paper, published in *ACS Nano*, is "All-glass 100 mm diameter visible metalens for imaging the cosmos" (DOI: 10.1021/acsnano.3c09462). ■

Nanoscale goldbeating: Ancient Egyptian technique adapted for fabricating 2D thin films

Researchers from the University of South Florida, the University of Illinois at Urbana-Champaign, and Clemson University developed a top-down, solid-state method based on the age-old Egyptian craft of goldbeating for creating 2D thin films.

They synthesized colloidal solutions of zero-dimensional nanospheres and one-dimensional nanorods and then drop-casted and assembled the solutions in (sub)monolayers onto polished silicon substrates. Subjecting the solutions to solid-state, uniaxial compression transformed the nanospheres and nanorods into 2D leaf-like morphologies.

The exact morphology of the final sample depended on the material's original shape, size, particle arrangement, and interparticle separation. Materials with larger interparticle separations required almost twice the applied compressive stress to achieve the same morphology as materials with smaller interparticle separations.

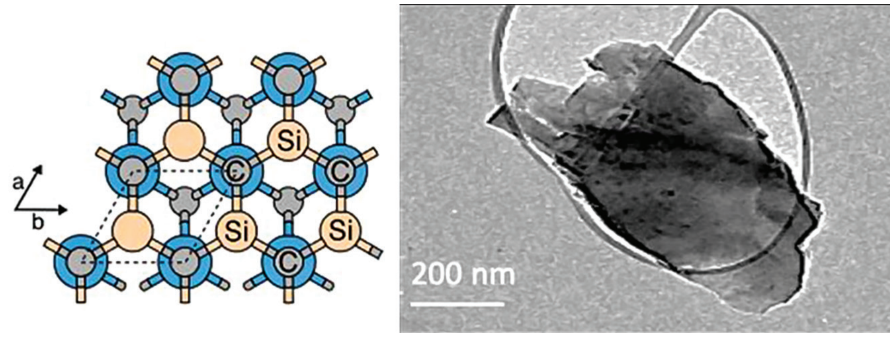
The open-access paper, published in *PNAS Nexus*, is "Nanoscale goldbeating: Solid-state transformation of 0D and 1D gold nanoparticles to anisotropic 2D morphologies" (DOI: 10.1093/pnasnexus/pgad267). ■

Monolayer silicon carbide achieved with both top-down and bottom-up synthesis methods

Synthesizing 2D silicon carbide is challenging due in part to the different chemical bonding preferences between silicon and carbon. Carbon naturally forms in flat, layered structures when bonding with itself (*sp*^{2} hybridization), while silicon prefers to bond in buckled or corrugated shapes (*sp*^{3} hybridization).

First-principles calculations predict that *sp*2 bonded (planar) silicon carbide is not only possible but should be the most energetically favorable configuration for this material in two dimensions. However, most experimental attempts to date on synthesizing 2D silicon carbide did not achieve the idealized honeycomb structure. That is because multilayer nanosheets—even just a bilayer—resemble the bulk silicon carbide structure, which consists of *sp*^{3} bonding. Only a true monolayer of silicon carbide can form the stable planar structure.

Two recent papers successfully achieved monolayer silicon carbide, and they did so through two completely different approaches.



(Left) Schematic depicting the honeycomb structure of monolayer silicon carbide. (Right) Transmission electron microscopy image of monolayer silicon carbide.

Top-down synthesis of monolayer silicon carbide

In July 2021, researchers at the University of New Mexico published an open-access paper describing a top-down method for synthesizing monolayer silicon carbide.

The trick with using a top-down approach is that bulk silicon carbide features *sp*^{3} bonding. As such, there needs to be a phase transformation from *sp*^{3} to *sp*^{2} bonding to isolate a monolayer of silicon carbide.

To achieve this transformation, the researchers exfoliated hexagonal bulk silicon carbide in isopropyl alcohol or N-methyl-2-pyrrolidone using bath sonication for 24 hours. They then centrifuged the dispersion at an average rate of 1,000 rpm for about 5 minutes.

Drops of the silicon carbide dispersion were placed on different substrates, such as a holey carbon grid or silicon substrate, and dried at ambient conditions prior to characterization with electron microscopy and Raman spectroscopy, for example.

Characterization of the drops confirmed that the monolayer silicon carbide had a stable planar structure. Additional analysis of the material's optical properties showed that the nanosheets had strong emission in the visible range.

"These results indicate that 2D SiC may be used for blue-green luminescent devices, e.g., light emitting diodes, as well as integrated micro/nano electronic circuits, such as LED integrated computer chips and biolabeling and biosensing," the researchers conclude.

The open-access paper, published in *Nanomaterials*, is "The creation of true two-dimensional silicon carbide" (DOI: 10.3390/nano11071799).

Bottom-up synthesis of monolayer silicon carbide

In February 2023, researchers from Lund University, Chalmers University of Technology, and Linköping University in Sweden published an open-access paper describing a bottom-up method for synthesizing monolayer silicon carbide.

Their process began with a 360-μm-thick silicon carbide wafer, on which they sputtered a less-than-3-nm-thick film of either tantalum carbide or niobium carbide. The covered wafer was then annealed at 1,700°C for 10 minutes.

During the annealing process, the silicon and carbon atoms from the wafer migrated to the surface of the carbide system and rearranged to form a stable, planar monolayer of silicon carbide. This structure, which was confirmed via spectral measurements, remained stable at temperatures up to 1,200°C under vacuum conditions.

Currently, the monolayer silicon carbide cannot be removed from the underlying bulk material because it interacts strongly with the metal carbide layer that it sits on. The researchers note that future experiments will likely investigate ways to decouple the monolayer silicon carbide from the substrate.

The open-access paper, published in *Physical Review Letters*, is "Bottom-up growth of monolayer honeycomb SiC" (DOI: 10.1103/PhysRevLett.130.076203). ■

Reducing aggregate toxicity: Graphene oxide may aid in treatment of Alzheimer's disease

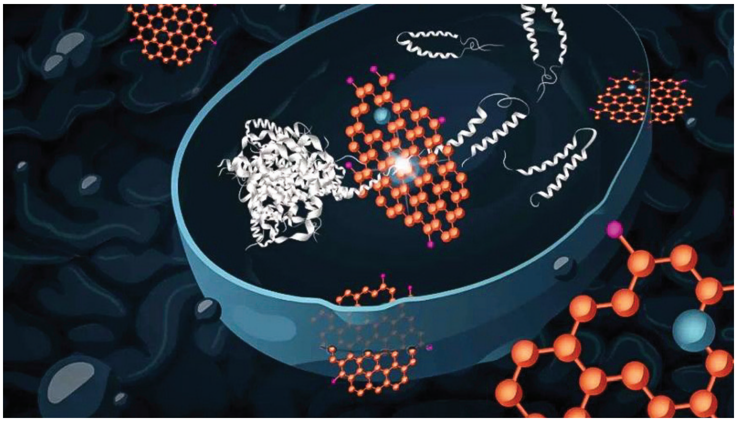
Researchers from Chalmers University of Technology in Sweden and the Technical University of Denmark used yeast as a model system to explore graphene oxide's potential to help treat Alzheimer's disease by preventing the buildup of harmful amyloid-β aggregates.

They cultivated yeast containing amyloid-β cells to early exponential phase and then mixed it with graphene oxide (GO) nanoflakes, with an average size of 90 nm. Scanning electron microscopy showed the cell surface was covered with GO flakes, but the cells retained their morphological integrity, indicating that the interaction with GO nanoflakes was not harmful. Transmission electron microscopy confirmed internalization of the GO nanoflakes by the amyloid-β cells.

Further analysis revealed that treatment with GO nanoflakes can diminish amyloid-β toxicity. The researchers propose that two independent pathways are behind this success, with the latter being driven by a presently unknown mechanism.

1. Direct mitigation: the internalized GO suppresses amyloid-β aggregation.
2. Indirect mitigation (mechanism presently unknown): the internalized GO boosts cellular machinery for coping with protein misfolding and oxidative stress.

To investigate the potential of GO to treat other causes of dementia, the researchers used another yeast model to explore GO's ability to suppress HTT103QP aggregation, a hallmark of Huntington's disease. Analysis of the model revealed that GO could help treat this disease as well.



Credit: Katharina Merl, Chalmers University of Technology

Graphene oxide (orange) can effectively enter yeast cells and reduce the toxicity of harmful amyloid-β aggregates (light grey) by preventing amyloid-β accumulation and by increasing the cell's ability to handle misfolded proteins and oxidative stress.

"The findings offer insights for rationally designing GO nanoflakes-based therapies for attenuating cytotoxicity of [amyloid-β], and potentially of other misfolded proteins involved in neurodegenerative pathology," the researchers conclude.

The open-access paper, published in *Advanced Functional Materials*, is "Graphene oxide attenuates toxicity of amyloid-β aggregates in yeast by promoting disassembly and boosting cellular stress response" (DOI: 10.1002/adfm.202304053). ■

First-in-human clinical trial suggests minimal health risks of inhaling graphene oxide

As the possibilities attainable with nanoscience start to materialize in more and more industrial sectors, concerns about the health risks of working with nanomaterials are becoming a big topic of discussion. In light of this concern, researchers led by the Universities of Edinburgh and Manchester in the United Kingdom conducted the first-in-human clinical trial on inhaled graphene oxide nanosheets.

Graphene oxide has gained a lot of attention recently in biomedical settings due to its hydrophilicity and reasonable colloidal stability plus compatibility with blood cells. However, the toxicological data available for graphene oxide is limited and inconsistent due to the many different sources of this material and its variability in dimensions and chemical properties.

In the new study, the researchers synthesized highly purified graphene oxide nanosheets using a modified Hummers' method, i.e., a chemical process that involves adding potassium permanganate to a solution of graphite, sodium nitrate, and sulfuric acid. They sized the nanosheets based on samples from previous pre-clinical studies on rodents that demonstrated no acute or longitudinal adverse effects.

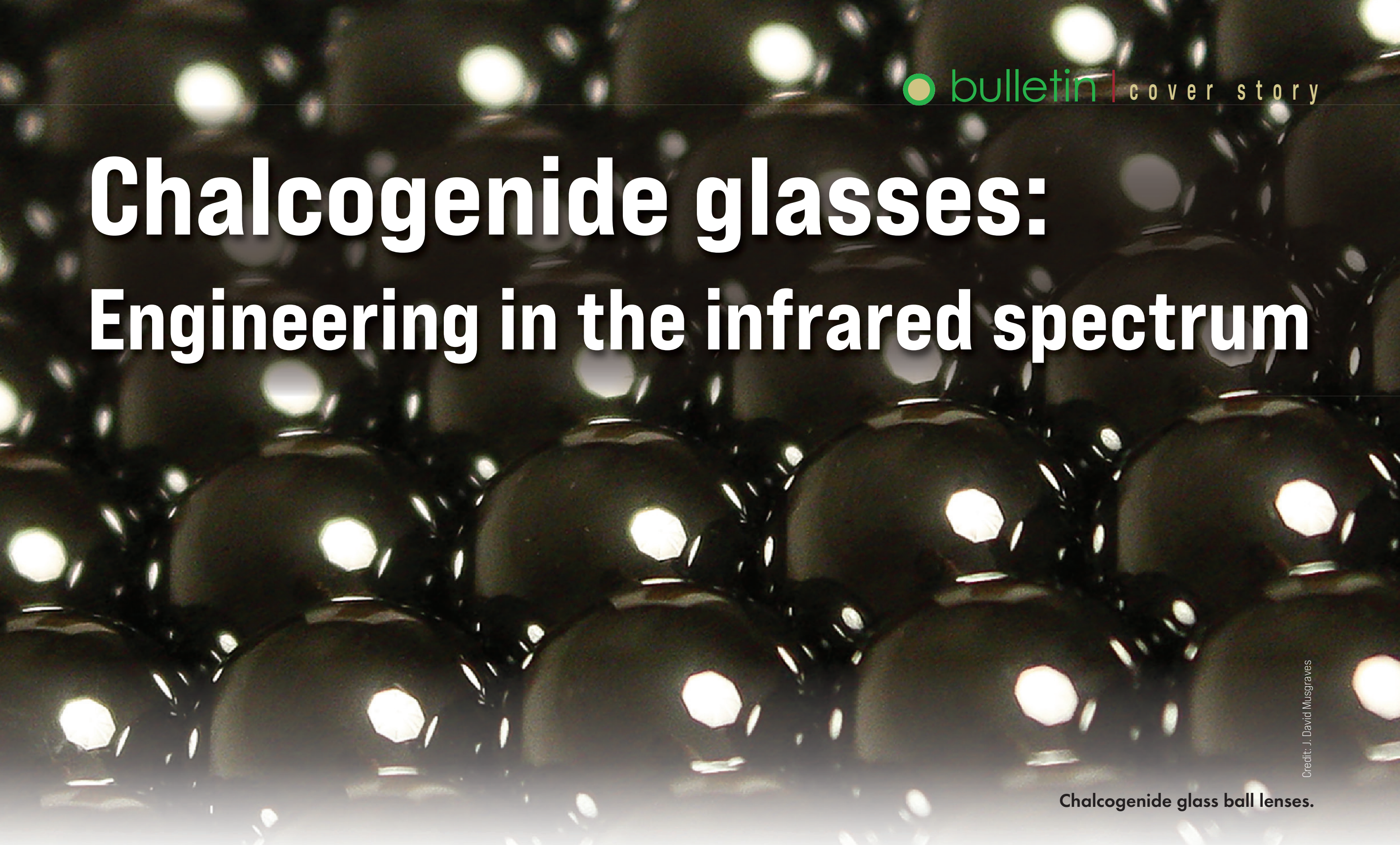
Fourteen volunteers inhaled either the graphene oxide or filtered air for two hours under carefully controlled conditions, and they did so at three separate times spaced two weeks apart. The researchers measured heart rate, blood pressure, and lung function and took blood from each volunteer before and after each exposure. Vital signs were monitored up to four hours after exposure ended.

The data showed no acute changes in respiratory or cardiovascular function, nor systemic inflammation, in any of the volunteers. There was a slight suggestion that graphene oxide may influence the way the blood clots, but the researchers stress that this effect was very small.

The researchers acknowledge that higher concentrations or longer durations of graphene oxide exposure may result in physiological effects. But for comparison, their previous studies on diesel exhaust exposure using similar concentrations were accompanied by cardiovascular dysfunction in that same amount of time.

The open-access paper, published in *Nature Nanotechnology*, is "First-in-human controlled inhalation of thin graphene oxide nanosheets to study acute cardiorespiratory responses" (DOI: 10.1038/s41565-023-01572-3). ■

Chalcogenide glasses: Engineering in the infrared spectrum



Credit: J. David Musgraves

Chalcogenide glass ball lenses.

By J. David Musgraves

The advances in chalcogenide glasses in the past six decades are only the beginning of a much larger future.

The fundamentally useful thing about glass is its optical transparency. There are certainly stronger building materials and other equally inert container materials, but the fact we can see through glass makes it very special.

The glass that we experience every day in windows, bottles, and screens for electronic devices is typically different types of silicate glass. Silicate glasses transmit more than 90% of the light that humans can see, i.e., in the wavelength range of 400–800 nm.

However, visible light is only a small slice of the electromagnetic spectrum. The same glass that transmits light with wavelengths from 400–800 nm does not fare nearly as well if we want to view light with wavelengths from 4,000–8,000 nm. As such, other types of glass are needed for these applications.

Devices that transmit light in the infrared region of the electromagnetic spectrum are all around us in the modern world, from contactless thermometers to the lasers used to repair our vision. These applications, discussed in more detail later, require windows, lenses, and fiber optics that can transmit wavelengths anywhere between about 1 and 15 microns (1,000–15,000 nm).

Creating a glass that maximizes transparency in these long wavelengths requires different starting materials and approaches to melting and forming the glass than is used in silicate glasses. Fortunately, chalcogenide glasses stand ready to fulfill this role.

Chalcogenide glass compositions

The compositional families of glasses studied by materials scientists divide into two broad categories: oxide and nonoxide glasses.[1] The silicate glasses that surround us in everyday life fall into the first category. These glasses are usually soda-lime silicate glasses, meaning they are formed from a backbone of silicon dioxide (SiO_2) with the addition of the oxides of sodium, calcium, magnesium, and aluminum.

Chalcogenide glasses, in contrast, are one of only several types of nonoxide glasses, a category which also includes halide and metallic glasses. They are named for, and formed of, three of the chalcogen elements in Group 16 on the periodic table: sulfur, selenium, and tellurium (Figure 1). These three elements can be made into amorphous solids without the addition of any other elements, though only in very small pieces or thin films.

Oxygen is also in the chalcogen group, but it cannot form a glass by itself. Polonium and livermorium, the final two chalcogen elements, are rare and acutely hazardous. Polonium is produced as the byproduct of nuclear reactors, while livermorium is produced in a beam line and has a half-life of about 60 seconds. So far, no one has attempted to synthesis these elements in a glassy form.

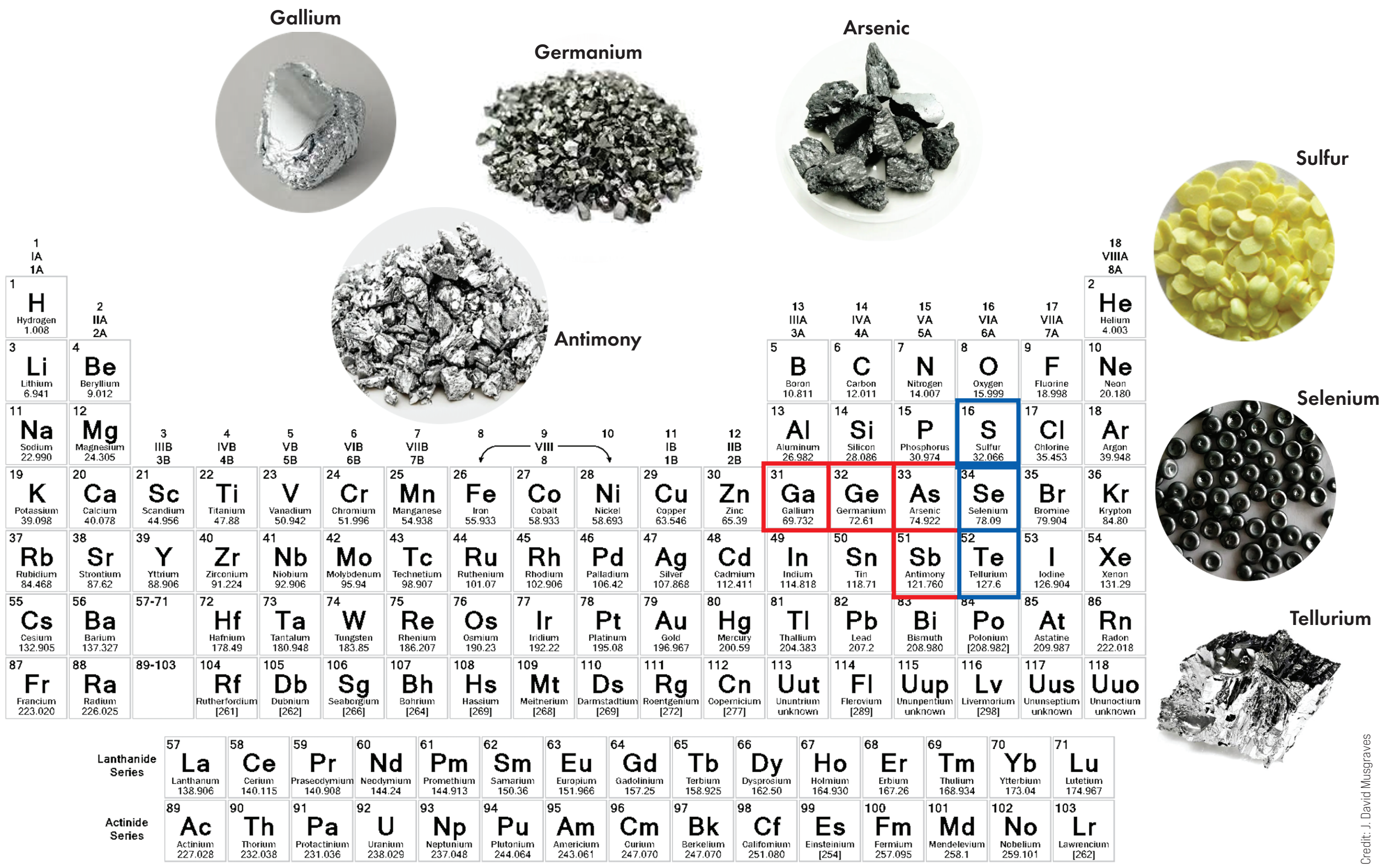


Figure 1. The chalcogen elements used to create chalcogenide glasses (blue outline) and main additives used in these glasses (red outline).

While films and small pieces of elemental sulfur, selenium, and tellurium can be quenched into a glassy form, in commercial applications, they are always modified with some combination of germanium, arsenic, gallium, and/or antimony to improve the thermal and optical properties of the resulting glass. For specialized applications, chalcogenide glasses can also be doped with several different elements, including the rare earths, which make them useful for active infrared optical systems.

The GeAsS and GeAsSe glass families both exhibit a wide glass-forming region, as seen in Figure 2. The glass-forming boundaries of the two glass families is shown in the ternary diagram, with the forming window extending from the line to the 100% chalcogen (sulfur or selenium) in the lower left corner. It is interesting to note that very heavy germanium concentrations can be vitrified in the selenium-based glasses, and that especially in the sulfur-based glass family, small melts of extremely chalcogen-deficient glasses are still achievable.

The changes in transmission window, refractive index, and glass transition temperature of chalcogenides compared to commercial silicate glasses can best be understood by comparing the atomic level structures of the two glass types. The silicate glass structure, shown in Figure 3a, is dominated by the backbone of Si–O bonds in the shape of SiO_4 tetrahedra connected at the corner oxygens. This bond arrangement gives these glasses an inherently 3D interconnected network structure.

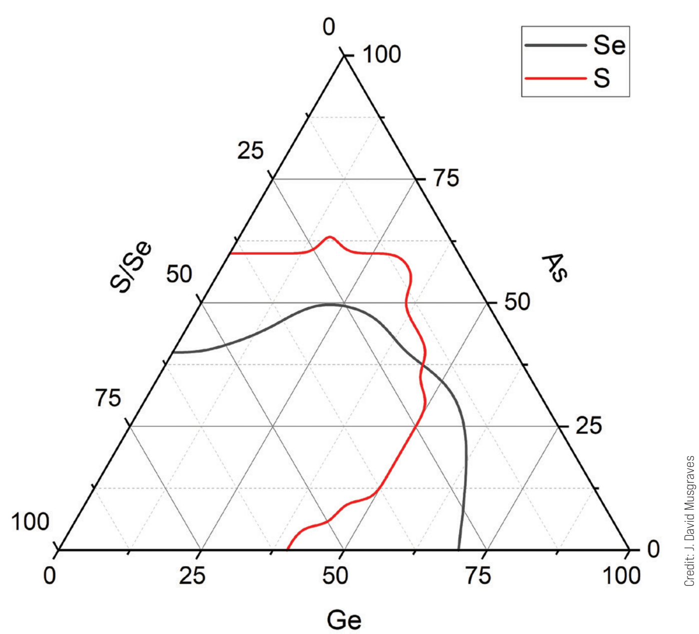


Figure 2. Glass-forming regions of the Ge–As–(S/Se) families.

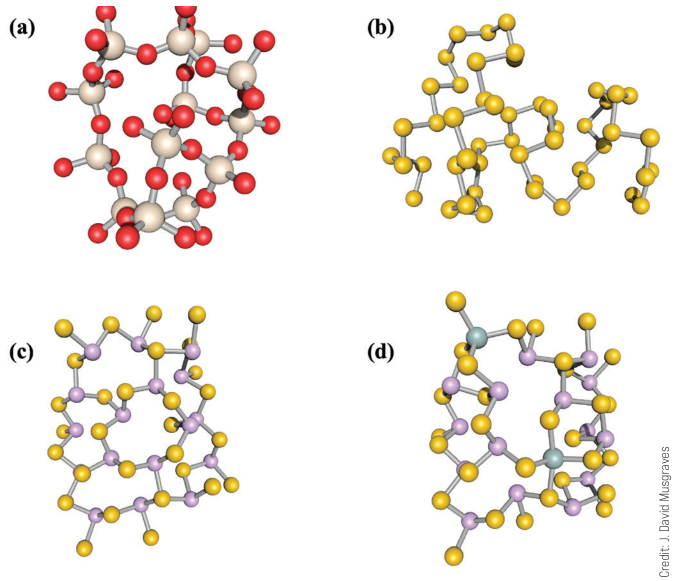


Figure 3. Network structures of glassy (a) silica, (b) selenium, (c) $As_{40}Se_{60}$, and (d) $Ge_{10}As_{30}Se_{60}$.

Compare this structure to the very basic selenium glass in Figure 3b, which is inherently a one-dimensional chain due to selenium's 2-fold coordination. When arsenic is added to selenium, as in the workhorse commercial chalcogenide composition $As_{40}Se_{60}$ (Figure 3c), for example, the 3-fold coordination of arsenic creates inherently 2D sheet-like structures. The 4-fold coordination of germanium is used to crosslink the chalcogenide network as in Figure 3d. Antimony is 3-coordinated, like arsenic, and can be used in commercial spaces where avoiding arsenic contamination is critically important.

The inherently 3D crosslinked structure of silica means it takes more thermal energy to break the network apart; this fact is reflected in the much lower glass transition and melting temperatures of chalcogenide glasses compared to silicates. Amorphous selenium has a glass transition temperature near room temperature and is completely molten by 221°C. The Si–O bond strength also contributes strongly to the elevated glass transition temperature of silicates compared to chalcogenide glasses.

Manufacturing chalcogenide glasses

One of the most difficult engineering constraints on the manufacturing of chalcogenide glasses is that they cannot contain oxygen. Any oxygen in the glass causes it to begin absorbing infrared light, just like silicate glasses do. It is the presence of the heavy glass-forming elements and lack of oxygen that give chalcogenide glasses their infrared transparency.

Synthesis of chalcogenide glasses begins with securing elemental sulfur, selenium, tellurium, germanium, arsenic, and antimony of high purity (>99.999%). These raw materials must be stored and shipped under inert atmospheres. Once received, the elements are weighed into a container, typically fused silica, inside a glove box environment. The container is then transferred from the glove box to a vacuum chamber using a specialized vacuum fitting that keeps the fused silica container sealed to the atmosphere.

Once under vacuum, the silica container is sealed with a torch to form an ampoule containing only the raw elements under vacuum. The ampoule is then placed into a furnace and slowly raised to the melting temperature. (See the next section on "Properties of chalcogenide glasses" for more information regarding the thermal properties of chalcogenides.)

Fabricating chalcogenide glasses that are free of bubbles and striae (internal ripples in the density of the glass) requires additional steps. The melt is typically rocked inside the furnace at the melt temperature for roughly 12 hours to ensure complete dissolution of the elements and melt homogeneity. Following this period, the ampoule is slowly quenched down from the melt temperature over a period up to six hours. Such slow annealing has several benefits:

1. Removes bubbles from the viscous melt.
2. Gives the slowly stiffening melt sufficient time in a viscoelastic state to remove the stress that causes striae in the subsequent glass.
3. Prevents cracking of the glass billet from thermal shock as it comes to room temperature.

This process, shown in Figure 4, is much more akin to what would be called pot melting in the oxide glasses. It is difficult to imagine ever scaling chalcogenide glass production sizes to anything comparable to today's window glass manufacturing scale.

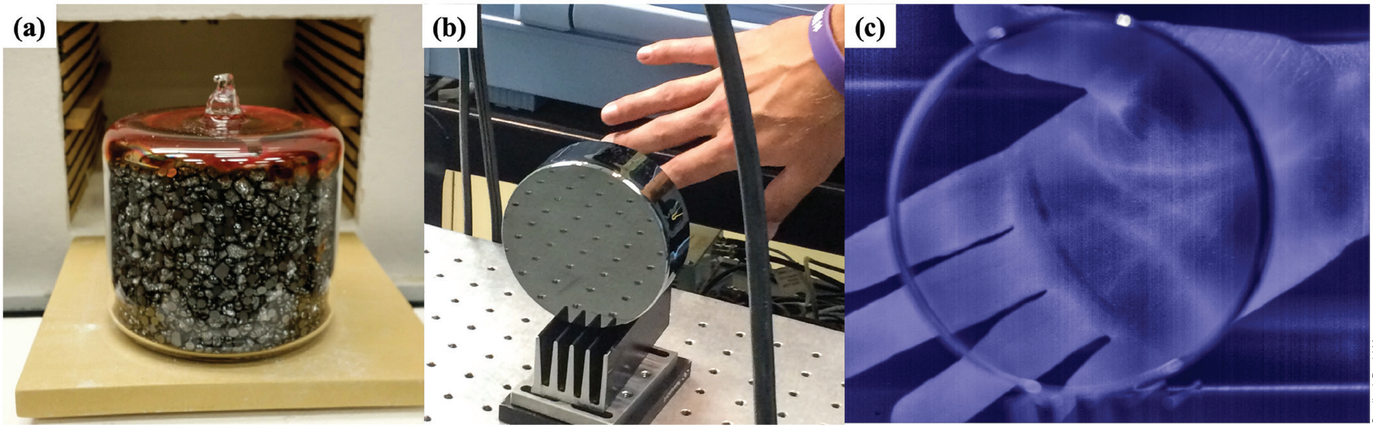


Figure 4. (a) Unreacted batched elements. (b) Polished billet from the melt. (c) Infrared image through the billet.

Properties of chalcogenide glasses

Optical properties

Infrared transmission window

The infrared region of the electromagnetic spectrum is typically divided into four ranges: the near-infrared (NIR) is 0.75–1.4 µm, the short-wavelength infrared (SWIR) band is 1.4–3 µm, the mid-wavelength infrared (MWIR) is 3–8 µm, and the long-wavelength infrared (LWIR) is 8–15 µm.

Different applications operate in different segments of the infrared region. The NIR is used in a wide variety of biomedical imaging applications, the SWIR is home to almost all of the world's telecommunication signals, the MWIR is where many important molecular detection fingerprints lie, and the LWIR is useful for thermal imaging of people and houses. Depending on the application requirements, a chalcogenide glass for a lens or fiber may need to operate at a single wavelength or across several of the infrared bands.

Pure fused silica transmits the furthest into the infrared of all the oxide glasses, but it experiences a cutoff at about 2.3 µm. This cutoff makes it the perfect material for long-haul telecommunications fiber optics, which operate at 1.55 µm, but makes it ineligible for any of the MWIR and LWIR applications.

Sulfide glasses have the valuable property of being transparent in a small part of the visible band in addition to the NIR, SWIR, and MWIR bands. The small addition of visible transparency (the $As_{40}S_{60}$ glasses are a deep ruby color to the eye) means that complex optical systems that use a visible guide laser can be aligned in the visible but will be guaranteed to work in the MWIR.

The selenides are the most widely used chalcogenide glasses. Except for the $As_{40}S_{60}$ glass, all currently available commercial chalcogenides are selenide glasses. The selenides transmit all the way from the SWIR through the LWIR.

Certain specialized applications may require operation in the far-infrared (15–1,000 µm). In that case, the telluride family of chalcogenide glass is the only candidate material class.

High refractive index

As can be seen indirectly in Figure 5, the chalcogenide glasses have much higher refractive indexes than the oxide glasses. The baseline transmission of the chalcogenides is much lower than silica because more of the light is lost due to the Fresnel reflection at the high index surfaces.

At a wavelength of 4 µm, $As_{40}S_{60}$ has a refractive index of 2.417, and the baseline transmission is only 70%. Meanwhile, $As_{40}Se_{60}$ has a refractive index of 2.795 and a baseline transmission of about 60%. The tellurides can lose up to 50% of the incident light due to surface reflection. This transmission loss highlights the need for good antireflective coatings on chalcogenide optics, which can be challenging if the application demands a very wide wavelength range.

However, the high refractive index of the chalcogenides lets infrared lens manufacturers achieve designs that are not possible in silica systems. The high refractive index permits much more bending of the light rays at the glass surface (due to Snell's Law), which allows production of much smaller lenses and the ability to achieve a very high numerical aperture.

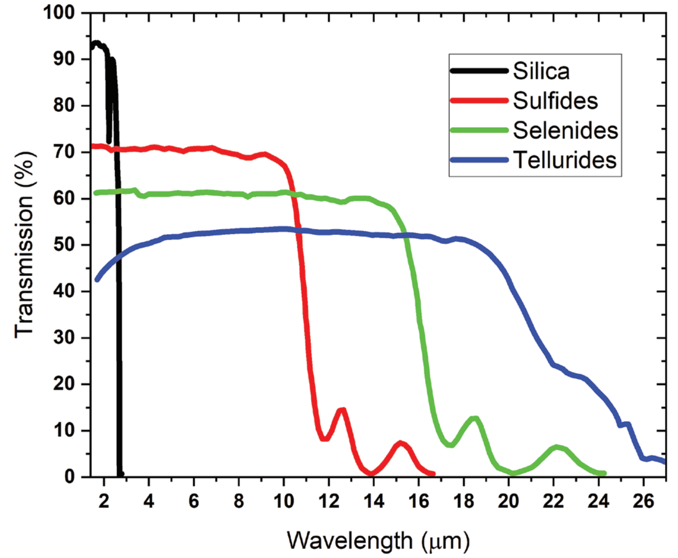


Figure 5. Infrared transmission of several families of glass.

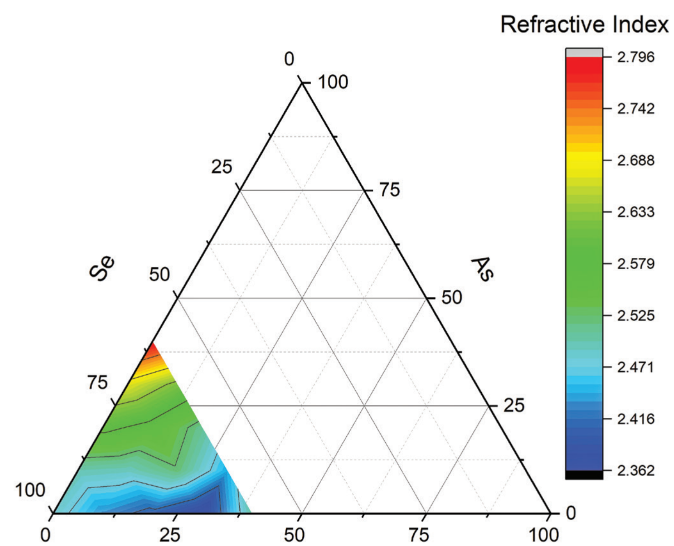


Figure 6. Variation of refractive index at 4 µm for some GeAsSe glasses.

Another benefit of the chalcogenide glasses is that their refractive indexes can be tuned to a required value (within a range) by simply altering the ratio of the constituent elements, as shown in Figure 6. In the photonic and fiber optic applications discussed in the next section, a change of 0.01 in the refractive index is enough to provide waveguiding behavior, so the ability to tune the refractive index all the way from 2.362 to 2.796 is a powerful tool for the optical designer. The refractive index of a variety of compositions at a variety of wavelengths can be found in References 2–4.

High n_2 and rare earth solubility

In addition to the high refractive index, chalcogenides also exhibit both a high nonlinear refractive index (n_2) and high rare earth solubility, both of which make these glasses excellent materials for active optical elements. The high n_2 of chalcogenide glasses, about 1,000x that of silica, is used in applications such as all-optical switching, optical limiting and modulation, and infrared supercontinuum generation.[5] The incorporation of rare earth elements mean chalcogenide glasses can be made into infrared lasers, especially when drawn into fiber form. More details on these applications are included in the next section.

Thermal properties

The exact definition of "glass" has varied over the years, but a simplistic definition is that glasses are solids at room temperature but with the atomic structure of a liquid; the material converts to a liquid directly upon heating without undergoing a first-order phase change, such as melting.[6] Instead, glasses have a glass transition temperature (T_g), which represents the transition point between a glassy solid and a supercooled liquid as the material is heated. Increasing from this temperature range, which can be detected using a calorimeter, causes the glass to soften to a water-like fluid according to its viscosity curve.

Low T_g

Soda-lime glass has a glass transition temperature of anywhere from 520 to 600°C; fused silica, the pure SiO_2 backbone of the soda-lime silicates (shown in Figure 3a) has a T_g around 1,200°C. In contrast, the T_g of commercial chalcogenide glasses ranges from 185–368°C, with 185°C being the T_g of the most common commercial composition, $As_{40}Se_{60}$.

For hot forming applications, such as precision glass molding of lenses or drawing of fiber optics, the lower T_g can be very beneficial from the perspective of cost savings: the energy required to hot form chalcogenides is somewhere between a half and a third that of silicate glasses.

On the other hand, the low T_g of chalcogenides can eliminate their consideration in some very high-temperature applications where the only viable option may be crystalline silicon, depending on the required wavelength range. Crystalline germanium also transmits well in the infrared, but its optical properties change dramatically at high temperatures, often eliminating it from consideration for a different reason than the chalcogenides.

Steep viscosity curve

Once the temperature of any glass is raised higher than its T_g, its viscosity decreases monotonically with temperature until reaching that of water. The viscosity of a solid is 10^{12} Pa•s and the viscosity of water is 10^{-3} Pa•s, meaning a change of 18 orders of magnitude between a glass's T_g and what could be called its "melting point." The temperature window between these two points is critical during any hot forming operations.

Chalcogenides exhibit a relatively abrupt change in viscosity near their T_g, which provides a narrower temperature range within which the glass must be processed. This steep change from a brittle state to a malleable one allows for more precise control in molding and fiber drawing processes. The viscosity of chalcogenide glasses drops rapidly over a small temperature range, reducing the risk of crystallization and allowing for the formation of complex shapes with smoother surfaces and finer details.

In contrast, silicate glasses require a broader temperature range to achieve a workable viscosity, which can often lead to a more energy-intensive process due to the need for higher temperatures to maintain the material in a plastic state suitable for forming. This broader temperature range for silicate glasses can lead to increased structural relaxation and potential for devitrification, which can adversely affect the optical quality of the final product.

The temperature window between the T_g and the point at which the glass behaves like a liquid is referred to as the "working point." The narrow working point of chalcogenides is particularly beneficial in precision glass molding operations, where it enables rapid thermal cycling and increased production rates. For fiber drawing, the advantage of chalcogenide glasses lies in their ability to be drawn at lower temperatures with high precision, leading to uniform fiber diameters and exceptional optical properties.

Table 1 lists the commercially available chalcogenide glasses along with their density, coefficient of thermal expansion, and some thermal and optical properties.

Chalcogenides in application

Molded infrared optics (thermal imaging)

The largest commercial application (by volume of glass) for chalcogenide glasses is in thermal imaging systems in the form of molded lenses. The thermal properties of chalcogenide glasses discussed above make them perfect candidate materials for precision glass molding (PGM).

PGM is a replicative process, where a glass preform is heated above its T_g, pressed into the lens shape between two precision mold surfaces, and then cooled back to room temperature.[7] This lens-making process can be quite cost effective because the precision mold surfaces can be made large enough in diameter to have multiple lens cavities, thus allowing for the molding of 2–10 lenses per heating/cooling cycle. PGM is also capable of easily and repeatably molding aspheric surfaces, which cannot be obtained by standard grinding and polishing operations; instead, it requires diamond turning, which is a very serialized and time-consuming process.

Chalcogenide glasses, with their unique optical properties, have found a significant niche in the production of optical components for spectroscopic applications. These glasses are particularly suitable for fabricating diffraction gratings and prisms, which are essential in spectroscopy for dispersing light into its component wavelengths. The process, akin to PGM, involves imprinting the delicate structures necessary for spectral analysis onto the glass, leveraging its softening point characteristics for precise moldability.[8] This manufacturing technique is highly efficient because it allows for the production of multiple optical components with intricate patterns in a single cycle, significantly reducing the cost and time associated with traditional methods.

The high refractive index and broad transmission spectrum of chalcogenide glasses enhance the performance of spectroscopic instruments, enabling the accurate detection and

Table 1. Commercially available chalcogenide glasses and their properties.

*Vendors: 1) CDGM Glass Company Ltd. (Central Islip, N.Y.), 2) LightPath Technologies (Orlando, Fla.), 3) Rochester Precision Optics (West Henrietta, N.Y.), 4) Schott AG (Mainz, Germany), 5) Umicore SA (Brussels, Belgium), and 6) Vitron Spezialwerkstoffe GmbH (Jena, Germany).

Composition	Density (g/cm^3)	CTE (ppm/°C)	T_g (°C)	Refractive index at 5 µm	Thermal change at 5 µm (ppm/°C)	Vendors*
$As_{40}S_{60}$	3.20	22.5	197	2.4129	−3.2	1, 3, 4
$As_{40}Se_{60}$	4.63	21.4	185	2.7909	33.4	1–6
$Ge_{10}As_{40}Se_{60}$	4.47	20.0	225	2.6192	21.15	1, 3, 4, 6
$Ge_{33}As_{12}Se_{55}$	4.41	12.5	368	2.1404	67.7	1, 3, 4, 6
$Ge_{28}Sb_{12}Se_{60}$	4.66	14.0	285	2.6183	62.0	1–4, 6
$Ge_{30}As_{13}Se_{32}Te_{25}$	4.84	13.4	275	2.7993	103.8	1, 3, 4, 6

analysis of chemical, biological, and environmental samples across a wide range of industries. These applications take full advantage of the glasses' properties to provide high-resolution spectral data, which is crucial for analytical techniques such as gas chromatography and mass spectrometry.

The adaptability of chalcogenide glasses to these demanding applications further solidifies their role as a material of choice in the advancement of thermal imaging devices.

Photonics

Chalcogenide glasses are extremely interesting materials in the developing photonics ecosystem. One chalcogenide photonic application is already widely deployed: rewritable memory. The composition $Ge_{22.2}Sb_{22.2}Te_{55.6}$, referred to as GST or GST225, is initially deposited on the rewritable disk substrate via sputtering and deposits in a glassy form. During operation of the rewritable memory disk, lasers are then used to write and rewrite bits of memory into this chalcogenide layer.[9]

During the write phase, a laser is used to warm the glassy area until it is just able to crystallize. The crystalline form of GST has a much higher refractive index than the glassy form, so during the read step, the high index will be read as 1 as opposed to 0 for the glassy form. During the rewrite step, the crystalline bits are flash melted by a second laser and quenched back into the glassy state.

Academic researchers have harnessed all the optical properties of chalcogenide glasses to form a wide array of waveguides, resonators, modulators, and more. Because of their large refractive index, chalcogenides can reduce the diameter of optical ring resonators in sensing systems, and some researchers have even selectively tuned the refractive index post-deposition by taking advantage of the photosensitivity of the glass. Chalcogenide glasses have been fabricated into photonic ring resonators with a Q-factor of 10 million.[10]

Specifically for ring resonators, which are commonly used in photonics for applications such as filtering, modulating, and sensing, the Q-factor measures the resonator's ability to confine light for extended periods, thereby enhancing light–matter interactions within the resonator. The higher the Q-factor, the lower the energy loss and the longer the photon lifetime within the resonator, which corresponds to a narrower resonance linewidth. High-Q ring resonators are sought for their ability to enhance light-matter interactions, making them invaluable in applications that require high sensitivity or selectivity, such as narrowband filters, optical sensors, and nonlinear optical devices.[11]

Chalcogenide glasses are rapidly emerging as a pivotal material in on-chip photonic applications due to their remarkable optical properties. Their mid-infrared transparency makes them ideal for the fabrication of on-chip photonic circuits, which are essential for next-generation environmental sensing and health diagnostics. These materials are being integrated into on-chip lasers that rely on their ability to be doped with rare earth elements, offering a spectrum of laser wavelengths tailored for specific chemical detection and analysis. The high nonlinearity of chalcogenide glasses also makes them suitable for on-chip nonlinear optical devices, which are critical for frequency conversion and the generation of entangled photon pairs in quantum circuits.

Moreover, the thermal stability and moldability of chalcogenide glasses facilitate the creation of complex photonic structures on-chip, including high-quality microresonators and integrated optical isolators. Such components are key in controlling light propagation and interaction in photonic integrated circuits, paving the way for advancements in optical computing and signal processing.

The versatility and high performance of chalcogenide glasses in these applications highlight their transformative potential in the realm of on-chip photonics.

Fibers

Optical fibers made from chalcogenide glasses are commercially available through several sources. The main use of these fibers is the transmission of infrared laser light, acting just like their silicate glass counterparts but operating in the SWIR to LWIR range. CO_2 lasers, which can be used for everything from eye surgery to antimissile countermeasures, operate principally at 10.6 µm, and delivery of this laser power to a manipulable point (e.g., an optical scalpel) requires transmission through a fiber delivery mechanism.[12,13]

Unlike their silicate fiber optic counterparts, which are drawn from a single doped preform rod, chalcogenide glass fibers are often drawn using the double crucible method.[14] As implied by the name, this technique relies on a nested pair of crucibles containing the glass of the core and cladding separately. During the draw process, the core fiber is drawn out through the nozzle of the cladding glass, which encases the emerging core as it solidifies.

In addition to pure laser power delivery, many applications use the broad infrared transparency window to perform spectroscopy because many important chemicals have characteristic infrared-absorption features. Many drugs, explosives, and contaminants can be identified through these "molecular fingerprints," which makes infrared spectroscopy useful in everything from water monitoring to pharmaceutical quality control to TSA security inspections.

Challenges and perspectives

There has been an explosion in technologies and applications for chalcogenide glasses since the first commercial chalcogenide glass was developed at Texas Instruments in 1962. Although their original TI1173 glass composition still lives on under a variety of trade names, the number of commercial compositions has increased to six (Table 1), with another 10 under final development.

Academic researchers continue to explore even more varieties of chalcogenide glass compositions, optimizing their materials on a laboratory scale to achieve perfect combinations of refractive index, thermal expansion, and many other properties necessary in the development of tomorrow's technologies.

Future research and development of chalcogenide glasses face many challenges. In the realm of infrared lenses, crystalline germanium continues to be the gold standard material, though chalcogenides are appearing on more and more customer drawings. Crystalline germanium is a much tougher material than chalcogenide glasses, which tend to be both brittle and comparatively soft, so many U.S. Department of Defense or space customers still require germanium. There is not a clear materials science path to increasing the toughness of glasses to that of germanium, but many optical coating companies have developed diamond-like-carbon coatings that make the scratch resistance of the glasses similar to germanium.

In terms of commercial adoption, there are always fears about the arsenic content of the common chalcogenide glasses. The European Registration Evaluation Authorization of Chemicals (REACH) Regulation went into effect in 2015, effectively banning the use of arsenic in the glass industry in the bloc. Increasingly, chalcogenide glass manufacturers are being asked to supply glass containing antimony rather than arsenic while maintaining the same thermal and optical performance.

In the booming photonics industry, chalcogenide glasses face the challenge of gaining acceptance into a large fabrication environment. In such tightly environmentally controlled spaces, fears of cross contamination from arsenic and selenium make it a slow process to adopt the glasses. In smaller companies and in academic research laboratories, there is less of a barrier to entry, and chalcogenide photonic devices are already being widely commercialized.

As glass manufacturers begin to offer more and more chalcogenide glass compositions, infrared optical designers and engineers will have a much bigger toolbox with which to work. The advances in chalcogenide glass since that first TI1173 have been amazing, but they are only the beginning of a much larger future.

About the author

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Empowering sustainability:

The US glass industry charged to break barriers for a greener future

By Scott Cooper and Kerry Ward

A federally funded program led by the Glass Manufacturing Industry Council brings together key players to advance electric melting technology in the U.S. glass industry.

The glass industry, like many others, is under increasing pressure to reduce its carbon footprint and transition toward more sustainable manufacturing practices. One promising avenue for achieving this reduction is through the adoption of electric melting technology.

Electric melting offers potential reductions in carbon emissions of up to 90% compared to traditional fuel-fired furnaces, making it an attractive option for environmentally conscious glass manufacturers. However, despite its promise, widespread adoption of electric melting faces several challenges that must be addressed to unlock its full potential.

Electric melting has been known for decades and is already used in certain glass industry segments. Electric furnaces are particularly well-suited for the production of specialty glasses and smaller-scale operations (Figure 1). These furnaces reduce gaseous emissions, including NO_x and SO_x, and can use renewable electricity sources, making them an appealing option for manufacturers looking to reduce their environmental impact.

In recent years, advancements in electric melting technology made higher volume production possible, driving interest in its broader application across the glass industry. However, despite these advancements, the widespread adoption of electric melting in high-volume industry segments, such as container and flat glass manufacturing, is limited due to several technical and economic challenges. For example, efficiently producing dark-colored glasses in a reduced oxidation state is difficult because of intense foam during melting onset. A similar effect was noted in nuclear waste glasses, which are melted in cold-top, all-electric furnaces. Similarly, achieving high quality and maintaining furnace longevity are ongoing challenges that must be addressed to make electric melting a viable option for large-scale glass production.

(a)

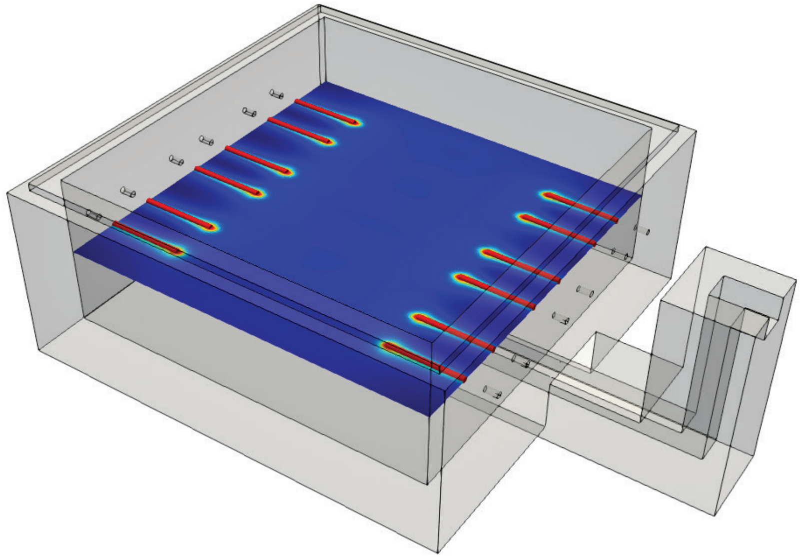
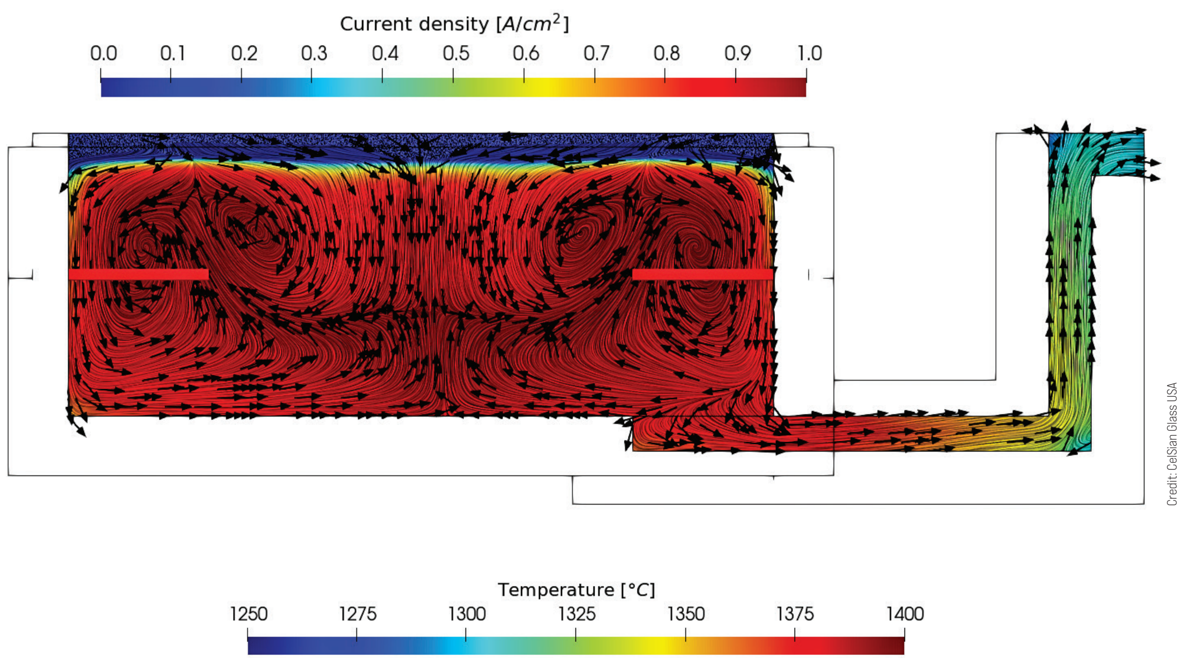


Figure 1. Electrification of the glass melting process offers a path to decarbonization for the glass manufacturing industry. (a) An all-electric glass furnace passes current through the pool of molten glass through electrodes. The melter is about 5 m long x 5 m wide x 2 m deep and produces roughly 50 tons/day. (b) Computational fluid dynamic models allow manufacturers to quickly assess performance criteria, such as temperatures and glass flow.

(b)



To address these challenges and accelerate decarbonization in the glass industry, the Glass Manufacturing Industry Council (GMIC) proposed a research program to study innovative ways to overcome these barriers and advance electric melting technology. In January 2024, GMIC's project was one of 48 selected by the U.S. Department of Energy to advance decarbonization in the industrial sector.

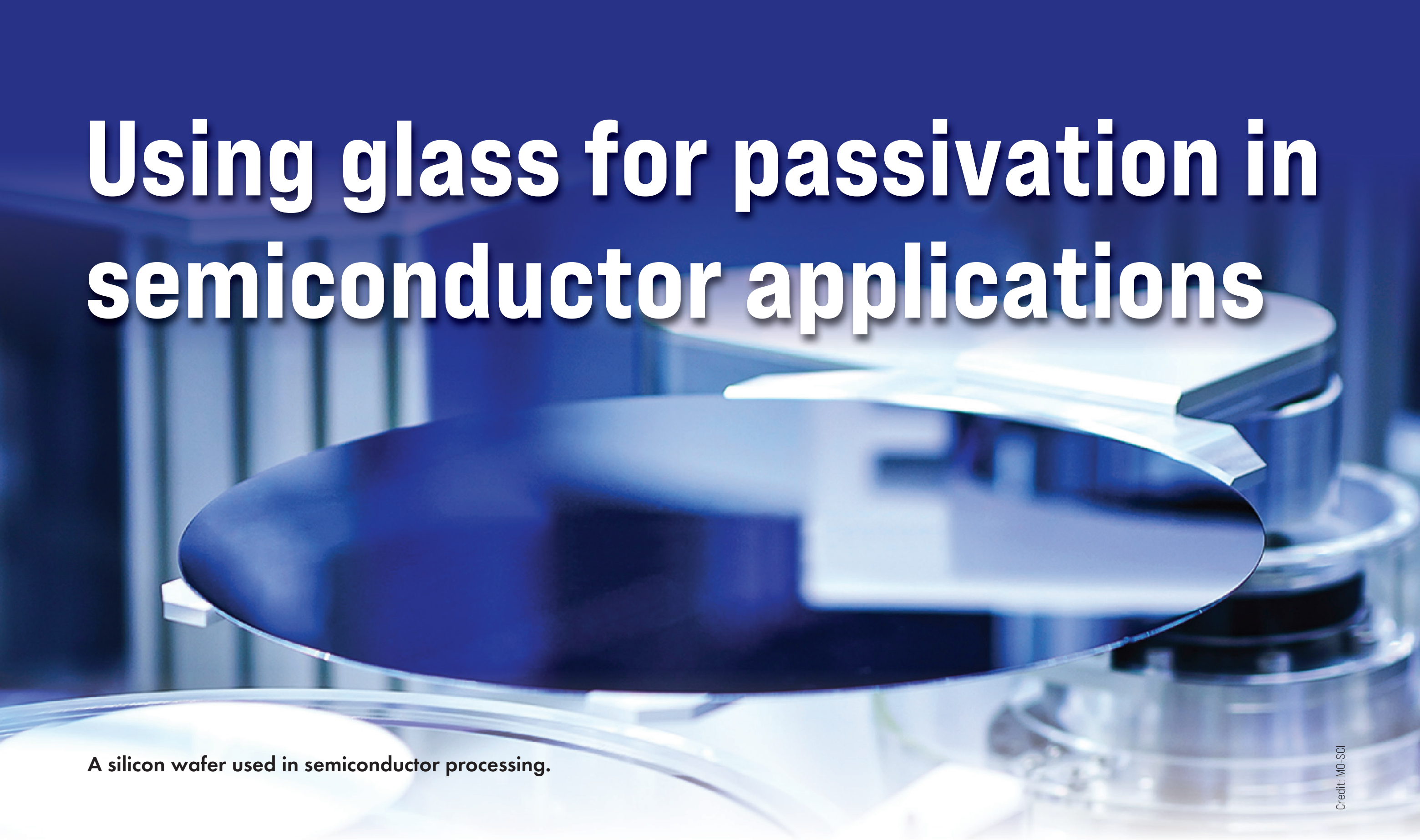
The program calls for $3 million in federal funding over three years for research. The project team consists of GMIC, CelSian Glass USA, TECO, RoMan Manufacturing, and Pacific Northwest National Lab (PNNL). The partnership with PNNL will create a unique opportunity for industry to exchange with the national lab, where decades of research into nuclear waste vitrification have advanced the state of electric glass melting technology. CelSian Glass USA will conduct lab testing and offer modeling capability at its new location in Toledo, Ohio. TECO will conduct furnace modeling and advise on design considerations. RoMan Manufacturing brings expertise in electrical power systems for the glass industry.

GMIC will convene an industrial steering committee of manufacturers to guide the project team, with results presented annually at the Glass Problems Conference, which this year will take place Sept. 16–19, 2024, in Toledo, Ohio. GMIC will also collaborate with the Ceramic and Glass Industry Foundation to create and distribute educational kits about glass technology, how glass products save energy, and ways to connect with local employment opportunities. These kits will be targeted at disadvantaged communities near glass processing plants. The project is anticipated to start in mid-2024.

About the authors

Scott Cooper is technical director of CelSian Glass USA and will be the principal investigator for this project. Kerry Ward is executive director of the Glass Manufacturing Industry Council and will be the project's program manager. Contact Cooper and Ward at scott.cooper@celsianglass.com and kward@gmic.org. ■

Using glass for passivation in semiconductor applications



A silicon wafer used in semiconductor processing.

Credit: MO-SCI

By Cheol-Woon Kim

With its unique properties and versatility, glass is a compelling choice in semiconductor manufacturing to prevent degradation and ensure long-term reliability of components.

In the fast-paced world of semiconductor manufacturing, where precision and reliability are paramount, choosing a suitable passivation material is critical to ensuring the optimal performance of electronic devices.

Among the library of viable materials, glass has gained significant attention for its unique properties and versatility. This article looks at how glass is used for passivation and what properties make it highly suitable for the job.

Understanding passivation in semiconductors

Before unpacking the specifics of glass as a material for passivation, it is essential to understand the concept of passivation in semiconductor manufacturing. Passivation involves depositing a protective material onto the surface of metals or metal alloys to enhance their resistance to environmental factors.

The layering material can be organic or inorganic and should exhibit excellent electrical insulation and strong substrate adhesion, as well as block the ingress of chemical species. In the case of semiconductors, passivation is crucial to preventing degradation and ensuring long-term reliability.[1,2]

Why glass is used for passivation

Glass has emerged as a compelling choice for passivation due to its unique combination of properties. For example, glass can be formulated in numerous ways, with common types including lead aluminosilicate, zinc borosilicate, lead zinc borate, and bismuth zinc borate. This compositional diversity allows manufacturers to produce glass capable of meeting low- and high-voltage electrical specifications; matching the coefficient of thermal expansion of semiconductor materials; and meeting the low-temperature processing requirements.[3,4]

Glass is chemically durable and thus can provide an inert barrier against external elements, such as moisture and contaminants, which might otherwise compromise the semiconductor's performance. Moreover, the high transparency of some glasses, such as borosilicate glass, makes them ideal for applications with critical optical properties, such as photovoltaics. This transparency enables efficient energy transmission and absorption, contributing to the overall performance of semiconductor devices and solar cells.[5,6]

How semiconductors are passivated

Glass is deposited onto semiconductors in a variety of ways. Choosing methods for passivation depends on factors

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such as the semiconductor device's specific requirements, the passivation layer's desired properties, and the overall manufacturing process. Methods for achieving glass passivation in semiconductor manufacturing include[7]

- Chemical vapor deposition, including plasma-enhanced deposition;
- Physical vapor deposition, including E-beam deposition;
- Sputter coating; and
- Atomic layer deposition.

In manufacturing, the process of glass passivation is frequently followed by chemical procedures, such as the etching of contact windows or the electrolytic deposition of contacts. These procedures may pose a threat to the integrity of the glass.

The chemical resistance of different passivation glasses varies significantly and serves as a crucial factor in determining the suitable glass type and the accompanying etching process.[8]

Comparing glass to other materials

While various materials can be used for passivation, glass stands out for its exceptional stability over temperature, humidity, and time. Literature searches reveal a lack of head-to-head comparisons with other common passivation materials; however, general comparisons can be drawn.[6]

Amorphous silicon films used in solar cells present numerous advantages. These advantages include a lower deposition temperature, in contrast to the temperatures commonly employed in cell manufacturing. However, it is essential to note that amorphous silicon films exhibit sensitivity to subsequent high-temperature processes, which are frequently necessary in industrial manufacturing technology.[9]

Similarly, AlO_x passivation films can be applied at relatively low temperatures, but they can be limited by slow deposition speeds when using specific application methods. This slowdown can generate problems for high-throughput techniques, such as solar cell production.[9]

Polyimide, a common passivation material lauded for its strength and thermal stability, is also susceptible to moisture absorption. This characteristic can impact the strength and dielectric properties of the protective coating, risking the integrity of the semiconductor.[10]

Applications of glass passivation

Passivation glasses demonstrate outstanding performance in wafer passivation and encapsulation processes, providing advantages to a diverse range of semiconductor devices,[8] including thyristors, power transistors, diodes, rectifiers, and varistors.

Glass also has applications in solar cell passivation. In a recent study, researchers developed a method for enhancing borosilicate glass passivation using high temperatures before lowering the temperature to accommodate the metallization process. In doing so, they notably improved the solar cell's efficiency.[11]

In another study, phosphosilicate glass was found to significantly enhance the practical lifetime of minority carriers and improve the overall performance of solar cells, particularly in structures involving nanocrystalline silicon and crystalline silicon.[12]

MO-SCI's expertise in glass thin films

Fueled by the increasing prevalence of smart devices and advancements in the automotive and aerospace sectors, the semiconductor passivation glass market is anticipated to grow consistently in the next few years.[3]

The expertise of MO-SCI, LLC (Rolla, Mo.) lies in leveraging the unique properties of glass to create tailored solutions, ensuring the reliability and performance of many applications, including glass seals and glass coatings. For more information, contact MO-SCI at https://mo-sci.com/contact-us.

About the author

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Jonathon Foreman
ACerS journals managing editor

Processing approaches to sustainable glass and ceramic production

Engineering sustainability into the manufacture of ceramic and glass products requires accounting for many factors. A new Topical Collection, "Sustainability in glass and ceramic production," presents ACerS journal articles that highlight the processing approaches to improve sustainability.

The articles in this collection fall generally into five categories:

- Glass melting and batching analysis
- Surface engineering
- High-temperature ceramic processing
- Overcoming membrane bottlenecks
- Additional fabrication techniques

Regarding the first category, traditional glass manufacturing involves the melting and reaction of constituent materials in large quantities. The glass industry has invested heavily in modeling and measurement techniques to understand the fundamental and macroscopic mechanisms involved in this process.

The first two papers of this collection focus on developing models that account for raw material feed rates and compositions. The third paper explores the effects of the arrangement of electrodes used to improve the energy efficiency of gas-powered melters (Figure 1).

The output of the models in these papers are in good agreement with measured results. Such findings allow researchers to explore the effects of processing conditions with computers, a methodology that is both faster and less expensive than directly working with melters even on a pilot scale.

Sustainability in the glass industry applies not only to the manufacture of glass. One must consider fabrication of products from glassy materials. For example, surface modification for decoration or functionality must add value, retain the integrity of the base glass, and be cost effective.

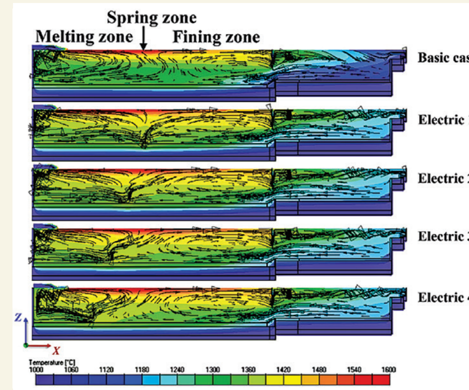
In the second category of this collection, the article "Powder-fed directed energy deposition of soda lime silica glass on glass substrates" provides insights into the processing conditions and costs for additive and subtractive surface modifications using mechanical and optical (laser) methods.

Regarding the third category, manufacture of high-temperature ceramics for transportation and energy generation has seen dramatic growth in recent years. Creating these high-temperature ceramics often requires processing at high temperatures, which is expensive and can be challenging to produce consistent parts.

Among the areas being explored to improve the sustainability of high-temperature ceramic processing are new materials, new production methods, and new in-situ and in-operando measurement techniques. The authors of the open-access article "Future insights on high-temperature ceramics and composites for extreme envronments" report on the Inaugural Orton Workshop, where participants from academia, government, and industry gathered to evaluate the state-of-the-art in this field with the intent of accelerating research and development efforts on all fronts.

Regarding the fourth category, ceramic membranes for environmental and energy applications are typically fabricated via costly and time-consuming, repetitive, coating–sintering processes to form a multilayered structure. The articles in this category provide overviews of current and emerging membrane materials and explore manufacturing and performance improvements along with expanded applications.

The final section of the collection contains articles spanning a wide range of fabrication and modeling techniques, including photopolymerization for preparation of complex-shaped green bodies, design of injection moldable ceramic-like material, and spark plasma sintering of transparent ceramics.



Credit: Han et al., *Journal of the American Ceramic Society*

Figure 1. Glass flow streamlines showing base case (no boost) and effects of boost electrode position changing from a central location (Electric 1) toward the materials inlet (Electric 4). The authors conclude that the best glass quality is obtained in Electric 4.

The Topical Collection "Sustainability in glass and ceramic production" can be found on the ACerS Publication Central hub at https://ceramics.onlinelibrary.wiley.com. Click on the "Collections" menu and select "Topical Collections" from the drop down. You will see this collection along with others created over the past few years. You can also directly access this collection using the link https://ceramics.org/sustainability-collections.

Further reading: Glass problem solutions in Ceramic Transactions

The Ceramic Transactions book series contains talks from the Glass Problems Conference. At this annual conference, organized by the Glass Manufacturing Industry Council, researchers focus on practical problems encountered in industrial settings and their approaches to resolving them.

View and purchase books in the Ceramic Transactions series by visiting https://ceramics.onlinelibrary.wiley.com/series/2120. ACerS members can receive a 35% discount on physical copies by using the code CERAM at checkout. ■

UPCOMING DATES

CROWNE PLAZA KNOXVILLE DOWNTOWN UNIVERSITY, KNOXVILLE, TENN.

The 12th American Conference on Neutron Scattering (ACNS 2024) will provide essential information on the breadth and depth of current neutron-related research worldwide. Hosted by the Neutron Scattering Society of America, the conference will feature a combination of invited and contributed talks, poster sessions, and tutorials.

HOTEL BONAVENTURE, MONTREAL, QC, CANADA

The theme for the 10th International Congress on Ceramics will be "Enabling a better world through ceramic and glass materials."

DAVID L. LAWRENCE CONVENTION CENTER, PITTSBURGH, PA.

The Materials Science & Technology (MS&T) 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.

HILTON DAYTONA BEACH RESORT AND OCEAN CENTER, DAYTONA BEACH, FLA.

The 49th International Conference & Exposition on Advanced Ceramics & Composites (ICACC 2025) will provide a platform for state-of-the-art presentations and information exchange on cutting-edge ceramic and composite technologies.

calendar

Calendar of events

May 2024

9–11 ➡ 8th International Symposium on Advanced Ceramics and Technology for Sustainable Engineering Applications (ACTSEA 2024) – GIS Taipei Tech Convention Center, Taiwan; https://www.actsea-symposium.com

19 ★ Nucleation, Growth and Crystallization in Glasses: Fundamentals and Applications 2024 – Golden Nugget Las Vegas Hotel & Casino, Las Vegas, Nev.; https://ceramics.org/event/nucleation-growth-and-crystallization-in-glasses-fundamentals-and-applications-2024

19–23 2024 Glass & Optical Materials Division Annual Meeting – Golden Nugget Las Vegas Hotel & Casino, Las Vegas, Nev.; https://ceramics.org/gomd2024

June 2024

16–19 ➡ 5th International Symposium on New Frontier of Advanced Silicon-Based Ceramics and Composites (ISASC-2024) – Seogwipo KAL Hotel, Jeju Island, Republic of Korea; https://www.isasc2024.org

17–19 ACerS 2024 Structural Clay Products Division & Southwest Section Meeting in conjunction with the National Brick Research Center Meeting – Sheraton Oklahoma City Downtown Hotel, Oklahoma City, Okla.; https://ceramics.org/clay2024

19–21 14th Advances in Cement-Based Materials – Missouri University of Science and Technology, Rolla, Mo.; https://ceramics.org/cements2024

23–27 ➡ American Conference on Neutron Scattering (ACNS 2024) – Crowne Plaza Knoxville Downtown University, Knoxville, Tenn.; https://ceramics.org/acns2024

July 2024

14–18 International Congress on Ceramics – Hotel Bonaventure, Montreal, Canada; https://ceramics.org/ICC10

15–19 ➡ 15th International Conference on the Structure of Non-Crystalline Materials, 15th European Glass Society Conference, and the SGT Annual Conference – Churchill College, Cambridge, U.K.; https://sgt.org/mpage/ESG15NCM15

August 2024

4–9 Gordon Research Conference – Mount Holyoke College, South Hadley, Mass.; https://ceramics.org/event/gordon-research-conference

18–22 ➡ 14th International Conference on Ceramic Materials and Components for Energy and Environmental Systems – Budapest Congress Center, Budapest, Hungary; https://akcongress.com/cmcee14

19–23 ➡ Materials Challenges in Alternative Renewable Energy (MCARE) 2024 – The Lotte Hotel Jeju, Jeju Island, Republic of Korea; https://www.mcare2024.org/index.php

25–28 ICG Annual Meeting 2024 – Songdo Convensia, Incheon, Republic of Korea; https://ceramics.org/event/icg-annual-meeting-2024

October 2024

6–9 ACerS 126th Annual Meeting with Materials Science and Technology 2024 – David L. Lawrence Convention Center, Pittsburgh, Pa.; https://ceramics.org/mst24

January 2025

26–31 International Conference and Expo on Advanced Ceramics and Composites (ICACC 2025) – Hilton Daytona Beach Oceanfront Resort, Daytona, Fla.; https://ceramics.org/icacc2025

February 2025

25–28 EMA 2025: Basic Science and Electronics Division Meeting – Hilton City Center, Denver, Colo.; https://ceramics.org/event/ema-2025-basic-science-and-electronic-materials-meeting

May 2025

4–9 16th Pacific Rim Conference on Ceramic and Glass Technology and the Glass & Optical Materials Division Meeting – Hyatt Regency Vancouver, Vancouver, Canada; https://ceramics.org/pacrim16

August 2026

31–Sept. 1 ➡ The International Conference on Sintering – Aachen, Germany; https://www.sintering2026.org/en

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.

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

Julianne Chen
Guest columnist

A carbon-neutral future with Penn State's pride, LionGlass

A quick glance into the average person's life would demonstrate the ubiquitous presence of glass. From electronic device screens to windows in cars and buildings, there is no escaping the beautiful yet somewhat mysterious material we know as glass.

However, glass production worldwide is the cause of about 86 million metric tons of carbon dioxide emissions every year.[1] This excess atmospheric CO_2 is a major driver of climate change, leading to droughts, melting ice caps, rising sea levels, and harm to local ecosystems due to volatile climates.[2]

The most common glass composition used is soda-lime silicate glass, batched mainly from sodium carbonate (soda ash), calcium carbonate (limestone), and quartz sand (hence the name soda-lime). The main sources of carbon emissions from soda-lime glass production are 1) the high temperatures required to melt the raw materials (1,400–1,500°C) and 2) the carbon dioxide emissions from the carbonates as they decompose into oxides.

John Mauro's group at The Pennsylvania State University recently developed a new glass family that could one day replace soda-lime silicate glasses with fewer emissions: LionGlass™.

LionGlass is the trade name for Penn State's patent-pending zinc aluminosilicophosphates (ZASP) family of glasses. LionGlass has a melting temperature of around 1,100°C, so manufacturing LionGlass requires about 30% less energy to power the furnace, which results in fewer furnace-based carbon emissions. Plus, these glasses completely remove the need for carbonate batch materials, so the overall reduction in carbon emissions is 50–60%.

Since LionGlass was first reported in the "Deciphering" column of the May 2023 *Bulletin*,[3] various characteristics of LionGlass, including crack resistance and chemical durability, have been tested and compared to soda-lime silicate glass. The results from these tests allowed Mauro's group to optimize many iterations of the composition for different applications.

In the original composition, nicknamed LG1, the Vickers hardness instrument only went up to 1 kgf, and the 50% initiation threshold—i.e., the force at which a sample will crack at the corners of an indent 50% of the time—had not been reached. This result indicates that LG1 had a crack resistance greater than soda-lime glass (0.12 kgf) by at least 10 times. The increased crack resistance means LionGlass can easily go through light weighting, i.e., make strong glass products that pass performance criteria with less mass.

Further research led to the development of the composition KLG1, which has a chemical durability on par with that of soda-lime silicate glass. A modified KLG1 composition, nicknamed KLG2, is being created through lowering the liquidus temperature below 950°C. Additionally, through attenuated total reflectance-Fourier transform infrared spectroscopy, we are hoping to understand how modifier ions are being leached, either through ion exchange or diffusion of water molecules.

Figure 1. Glass blown flower created from LionGlass™ by Nicholas Clark, the post-graduate scholar leading research efforts on LionGlass.

Credit: Nicholas Clark

Other avenues outside of traditional industrial glass applications are also being explored for LionGlass. For example, Penn State's Glass Studio is attempting glass blowing with LionGlass. The new iterations of LionGlass are more durable and resistant to devitrification, i.e., where the surface of the glass crystallizes, so LionGlass can be continuously reheated for glass art. Previous trials of creating simple designs, such as flowers (Figure 1), were successful, so LionGlass could one day be incorporated into the artistic world as well as the industrial!

Global warming is a constant looming threat to humanity's survival, and manufacturing processes must be changed to save the environment. LionGlass could one day replace all soda-lime glasses in circulation and innovate the commodity glass industry for a carbon-neutral future.

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Julianne Chen is an undergraduate student at The Pennsylvania State University, studying materials science and engineering. After graduating in spring 2025, she plans to pursue a Ph.D. in solid-state batteries and semiconductors. In her free time, Julianne enjoys playing guitar and perfecting pastry recipes as a professional pastry chef. ■

CACT Center for Advanced Ceramic Technology

2024 Summer Industrial Short Courses at AU

Scientific and technological advances shape the face of industry today. Engineers, technologists, and managers need to keep up with the swift changes in the field, meaning they must be lifelong learners. Each summer, Alfred CACT seeks to increase individuals' expertise in the field of ceramics and glass through its industrial short course offerings. CACT can work with you to develop custom content that can be conducted either on campus or at your site, or join us at one of the following programs, currently accepting registrations.

Fracture Analysis & Failure Prevention of Glass and Ceramics
When: June 10 – 14, 2024
Instructors: Dr. James Varner, Professor of Ceramic Engineering Emeritus at Alfred University and Dr. Jeffrey Swab, Senior Research Scientist with the Army Research Laboratory, Aberdeen Proving Ground.

Computational Methods for Glass & Ceramics
When: July 15 – 18, 2024
Instructors: Dr. Collin Wilkinson, Assistant Professor of Glass Science at Alfred University and Rebecca Welch, Visiting Scholar at Alfred University.

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