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Glass Science in the United States: Current Status and Future Directions

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We review the current state of academic research in glass science in the United States. Our analysis is based on an evaluation of the number of journal articles published across the major segments of glass research. While the great majority of commercial opportunity is in silicate glasses and glass ceramics, together these represent less than one-quarter of publication activity. Academic research activity in glass ceramics is essentially nonexistent in the United States, while the attention given to metallic and chalcogenide glasses is disproportionately larger than the current industrial value for such glasses. We identify areas of glass research that are presently less explored, yet highly promising in terms of both industrial application and training students for future careers in industry.

Introduction

Researchers from universities and industry have contributed to the advancement of society by applying the scientific method to better understand glass. One of the earliest examples in the United States occurred during the 1870s, when thousands of people died annually from railroad accidents, many of which were caused by poorly functioning railroad signals. One significant safety improvement was the invention of glass lens covers for railroad lanterns, which placed focusing rings on the inside rather than the outside of the lens cover. The internal focusing rings made the lens cover more resistant to fouling from dirt and ice. The proper size and placement of the internal rings was crucial to enable the lens to properly direct light. The inventor, Charles Houghton of Corning Glass Works, worked with two Cornell University researchers, George Moler and William Anthony, to understand the basic principles of optics that were necessary for the invention.[1]

Otto Schott was one of the first researchers to apply the scientific method to the study of glass and subsequently disseminate his findings through publication. In 1879, Schott published “Studies on the Toughening of Glass,” in which he presented the results of experiments he conducted to identify how various processes, temperatures, cooling methods, and glass compositions related to the toughness of the resultant glass.[2] Schott and Carl Zeiss would eventually build upon this work and develop toughened borosilicate glasses for thermometerware and laboratory tubing.

Much has changed since Schott’s publication. Scientists are still trying to answer questions related to the

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toughening of glass, but today glass is being used in applications that Schott, Houghton, Moler, and Anthony could not have imagined. We begin this article by providing a brief overview of the general nature of glass research at US universities in recent years. In the spirit of the Grand Engineering Challenges recently proposed by the National Academy of Engineering, we devote the remainder of this work to describing potential research topics that the authors believe are especially important for enabling future advances in glass science and engineering. These topics were selected for the dual purpose of advancing the fundamental science of glass and providing practical value to the US glass industry. Moreover, we believe that research in these topical areas would prepare students well for a future career in industrial glass research, product and/or process development, or manufacturing. We therefore publish this article for the purpose of stimulating conversation in the glass research community among those in academia, funding agencies, industry, and other stakeholders regarding the future direction of glass science in the United States.

Current Status of Glass Science in the United States

Academic glass research in the United States has several funding sources at the state and federal levels of government, including the New York State Energy Research and Development Authority, the US Department of Energy, the National Institute of Standards and Technology, the National Institute of Health, and the National Science Foundation (NSF). For example, the NSF provided roughly $25 million in funding for glass research in the 2007–2012 time frame, with over 25 different universities receiving some level of funding to support research in glass. Corporations, including Corning Incorporated, also provide targeted funding for academic glass research either directly or through consortia such as the Glass Manufacturing Industry Council.

In this section, we review the current status of glass research in the United States by analyzing the distribution of publications in the most relevant journals for glass science. We find that silicate glasses and glass ceramics, which are by far the most important materials for the US glass industry, account for less than one-quarter of the publication activity. For the purposes of this study, glass ceramics are defined as glasses subjected to controlled crystallization to form materials with at least one glassy phase and one crystalline phase.

Methodology

The literature data were analyzed for articles published between January 1, 2007 and May 31, 2013. We searched for all articles using the keyword "glass" in the title or abstract of the document. This initially resulted in over 6000 publications for the time period under study. As we wished to classify each publication individually, the number of articles needed to be further restricted. We therefore decided to limit the articles to those in which the first author was affiliated with a US-based university. In other words, all publications originating outside the United States or from nonacademic institutions within the United States were eliminated. We further restricted our search to specific journals that are known as key sources for publishing glass science articles from US-based authors. These journals are the following: *Journal of Non-Crystalline Solids, Physical Review B, Physical Review Letters, Journal of the American Ceramic Society, Journal of Chemical Physics,* and *International Journal of Applied Glass Science*. This resulted in roughly 1400 search results, which were manually sorted to determine the primary family of glass under study and the type of research being conducted. Of the 1400 articles initially found, 925 were found to be focused on glass science. The remaining 475 articles that were eliminated made use of the keyword "glass" somewhere in their title or abstract but did not actually focus on glass science.

Results

Figure 1 plots the number of papers published from January 1, 2007 through May 31, 2013 in each of the six main journals under study. Please note that the *International Journal of Applied Glass Science* is a relatively new journal, first appearing in the year 2010. In Figs. 2 and 3, we plot the breakdown of journal publications by the type of glass under study. Roughly 21% of the articles were primarily concerned with silicate glasses, with the next largest portion (17%) devoted to model glasses (i.e., theoretical glasses not based on any real chemistry). Publications on model glasses were particularly prevalent in the physics literature. Metallic glasses accounted for 13% of publications in the journals considered. This number is probably an

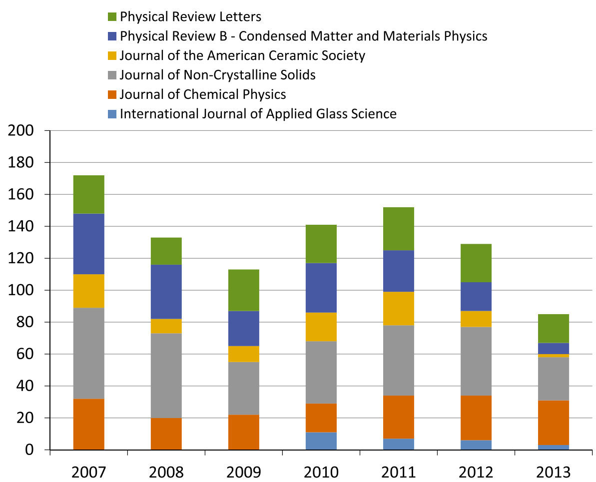

Fig. 1. Number of glass science-related articles published by year in each of the six major journals for glass-related papers. Here, we consider only those articles where the first author is affiliated with a university in the United States. The International Journal of Applied Glass Science began publication in 2010. Please note that the data for 2013 extends only through the end of May that year.

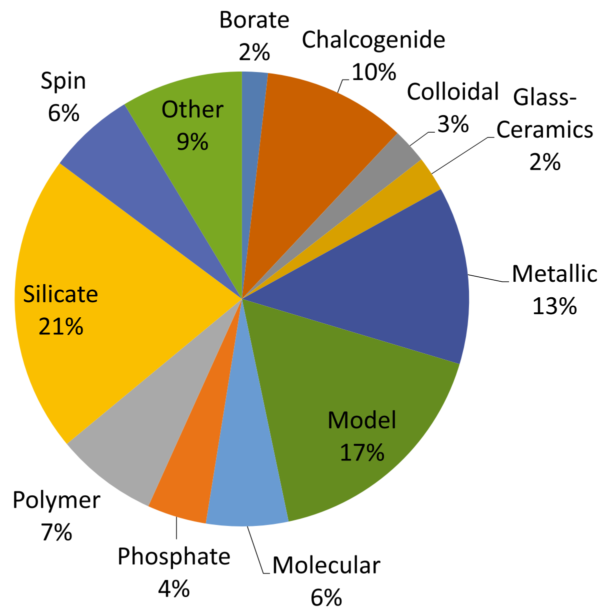

Fig. 2. Breakdown of glass science-related journal publications by the primary type of glass under study. Here, "model" glasses refer to purely theoretical glasses without any associated chemistry (e.g., hard disks or binary Lennard-Jones systems). This category does not include modeling studies of real-world glass-forming systems. For example, a molecular dynamics study of silicate glasses would be classified here as focusing on "Silicate" rather than "Model" glasses.

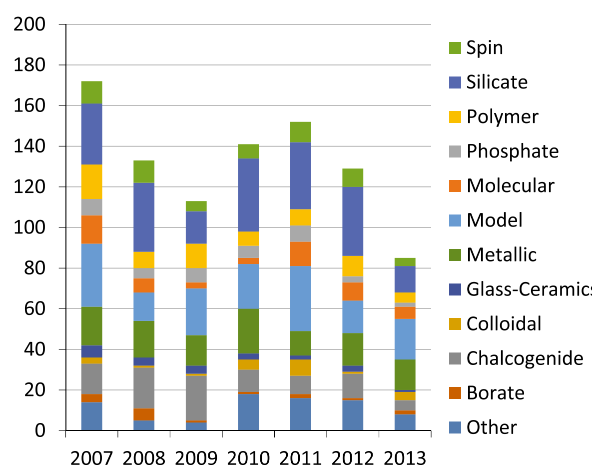

Fig. 3. Number of publications by year and primary glass family under study. The interest level in each type of glass has been fairly consistent over the time period of this study.

underestimate because we did not include journals such as *Intermetallics* that focus solely on metallic systems. Studies of chalcogenide glasses made up 10% of the total journal publications. Glass ceramics only accounted for 2% of all publications.

In Figs. 4 and 5, we plot the breakdown of journal publications by the type of investigation. Structural studies of glass account for the greatest percentage of publications (22%), followed by thermodynamic properties (14%), relaxation studies (11%), and mechanical properties (9%). Investigations focusing on modeling and simulation techniques accounted for 7% of total publications. Glass melting accounted for only 2% of publications. Other largely overlooked areas include electrical (2%), chemical (2%), and acoustic (1%) properties, as well as surfaces (2%) and new applications of glass (0%).

In Fig. 6, we show an overlay of the publication data with percentage of NSF funding over the same time period. In our analysis of NSF data, we used the primary search keyword "glass" in the title of the award. Funding for conferences, workshops, seminars, and travel grants was not considered. Also, the abstract of each award was read to verify that the funding was indeed being directed toward research in glass science. There is a clear correlation between the two sets of data in Fig. 6, indicating that the funding directions are indeed reflected in the ultimate breakdown of publications. A notable exception is the "model" glass category, which received only 2% of NSF funding but

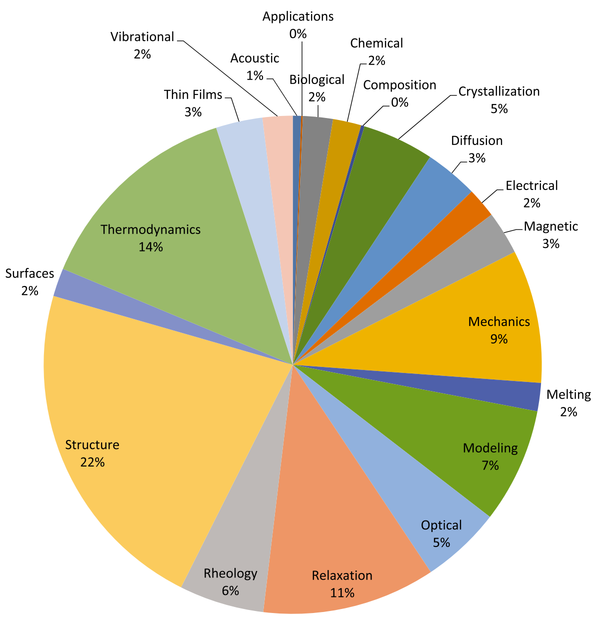

Fig. 4. Breakdown of glass science-related publications by the type of study being conducted. Here, "modeling" refers to modeling studies that are not focused on any particular set of properties.

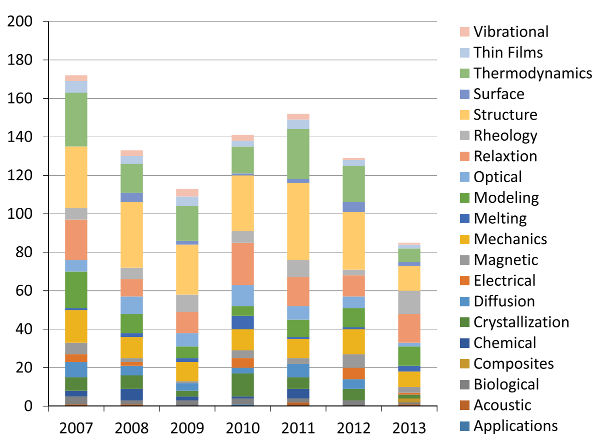

Fig. 5. Number of publications by year and type of study. As in Fig. 3, the breakdown of publications is fairly consistent year-to-year during the time period of this study.

accounted for 17% of publication activity. We attribute this discrepancy to the fact that studies of purely model systems require significantly less funding. Please note that here we have focused on NSF grants somewhat arbitrarily, that is, based primarily on ease of access to the funding data. However, we expect that the correlation between funding and publication levels will continue to hold if other sources of funding are also considered. Also, this analysis merely shows a correlation between funding ("input") and publications ("output") and does not address the issue of why the funding is a certain way, that is, by analyzing the number of proposals submitted versus the percentage of those proposals granted in each area.

Implications

When considering the current and likely future industrial and commercial relevance of these various glass families, the distribution of research indicates an underweighting of silicate glasses and glass-ceramics. This is a concern for the US glass industry because the research areas pursued by US universities largely define the expertise, skills, and experience that will reside at those universities and with their graduates in the future. If research in the field of glass science is not sufficiently focused on topics of technical relevance for future industrial applications, it will become increasingly difficult to meet the challenges faced by the US glass industry and less likely that future researchers in this field will have the required skills and expertise needed to enable the US glass industry to compete globally.

Future Directions for Glass Science

In the previous section, we provided a snapshot of the current state of glass research in US academia. We would like to use the remainder of this paper to provide suggestions for research topics that, in our view, are currently underrepresented in the academic research community. Here, we introduce the research topics as a series of open questions, grouped into twelve different subject areas in glass science. The proposed topics have been chosen to meet the following criteria:

1. The research topics both advance the fundamental science of glass and are also of practical interest to the US glass industry.
2. These topics are not currently given sufficient attention by the global glass research community, or these topics are underrepresented by research groups in the United States compared with the rest of the world.
3. Students who conduct research projects in these areas will be well prepared for a future career in industrial glass research, product and/or process development, or manufacturing.

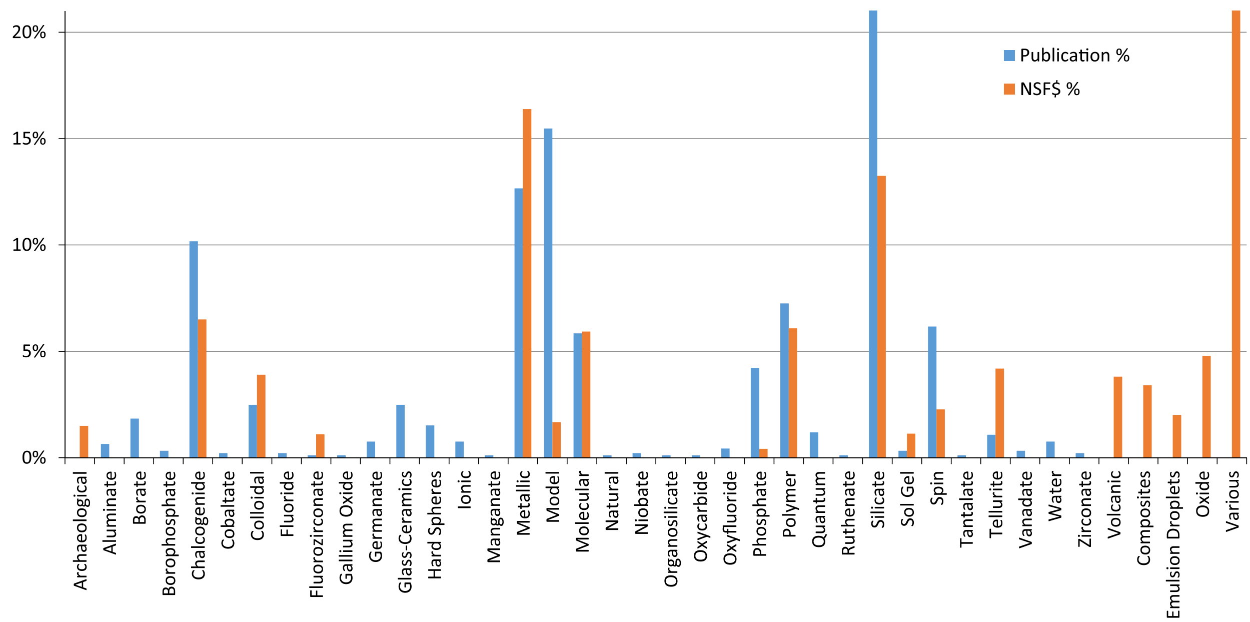

Fig. 6. Overlay of the percentage of NSF funding and the percentage of journal publications by primary glass family under study, both over a time frame from January 1, 2007 to May 31, 2013. There is a clear correlation between the direction of funding (input) and the number of publications (output). However, model systems have a disproportionately high percentage of publications, probably since they do not require significant funding. For the NSF funding, "various" indicates that multiple types of glasses were covered by the grant rather than focusing on a single glass family and "oxide" refers to multiple types of oxide glasses being covered under the same grant.

Thus, we hope that these topics could be used to fulfill both of the primary purposes of academic research, viz., to advance the fundamental science and to provide a solid education for students, preparing them for entry into the workforce.

In each section below, relevant citations are provided for the various topics under consideration. Of course, it is not possible to include a completely exhaustive list of references. Here, we primarily cite newer articles that address key aspects related to the specific research topics or questions listed below. However, in each case, the references do not provide a complete solution to the problem, but rather give suitable background information on the problem or point to new approaches or results that could provide a suitable starting point for future research. Topics that we consider to be either "fully solved" or already given sufficient attention in the literature are not listed here. For a more complete outline of research topics, we refer the interested reader to the comprehensive monograph edited by Bange and Weissenberger-Eibl.[3]

Glass Structure-Property Relationships

To be suitable for a particular application, a glass must meet stringent requirements for all of the properties of interest, which include attributes of the glass "as used" such as resistance to brittle failure and those properties that are important for its manufacture such as melt viscosity at a given temperature. Property optimization involves a careful balancing of the chemical composition of the glass to achieve these desired attributes.[4] All of the macroscopic properties of a glass are, of course, a direct result of its underlying structure.[5] It is therefore highly beneficial to take advantage of fundamental understanding of glass structure–property relationships when designing a new glass composition. However, this can be a challenging endeavor for many industrial glass composition families, which typically combine multiple network forming oxides (SiO_2, Al_2O_3, B_2O_3, P_2O_5, etc.) with a mixture of network modifiers (Li_2O, Na_2O, K_2O, MgO, CaO, SrO, BaO, etc.). The structural role of each network former and modifier depends on both the chemical composition of the glass and its thermal history.[6–12] It is therefore critical to conduct fundamental research to develop a detailed understanding of the composition and thermal history dependence of glass structure and its relationship to macroscopic properties. Ultimately this will lead to the development of quantitatively predictive models for these relationships, in line with the objectives laid out by the White House's recent Materials Genome Initiative. Recently, significant progress has been made in developing predictive models for structure-property relationships based on topological constraint theory.[13–16] However, use of this approach to enable quantitative design of new glass compositions is still in its infancy, and hence, there are still tremendous opportunities to develop new or enhanced modeling approaches. Specific questions that should be addressed include:

1. Can a universal model be developed to predict bonding preferences in oxide glasses with different combinations of network formers and modifiers? Recently, a general statistical mechanical approach for predicting such bonding preferences was introduced.[17] However, significant work is still required to determine the bond energy parameters for specific glass chemistries and apply this approach to real glass-forming system. Also, further work is required to couple this approach with topological constraint models for the prediction of glass properties. Finally, any new model development must be accompanied by thorough experimental validation, in terms of both the microscopic glass structure and the macroscopic properties of the glass.
2. Can these models be extended to mixed anion glasses such as oxyhalide or oxynitride glasses[18]? What unique properties can be achieved with mixed anion glasses that cannot be obtained through purely oxide compositions?
3. What are the structural origins of the mixed alkali and mixed alkaline earth effects in oxide glasses,[19–21] and how can these effects be leveraged in the design of new glass compositions?
4. What are the optimum potential energy functions describing interatomic bonding in oxide glasses[22,23]? How can these potentials be derived, and what do they tell us about the hierarchy of bond constraints in the glass network?
5. How can atomistic scale simulations predict glass structure accounting for realistic thermal histories? While standard molecular dynamics are limited by time steps on the order of 10^{-15} s, new simulation techniques based on kinetic Monte Carlo or energy landscape analysis offer the opportunity to extend the time scale by many orders of magnitude.[24,25]
6. What new experimental characterization techniques could reveal more information about the intermediate range structure of glass?

Predictive Modeling of Liquidus Temperature and Viscosity

The two most important properties for industrial glass production are the liquidus temperature [26,27] and the viscosity curve [28] of the glass-forming melt. As the melt is cooled from high temperature, the liquidus temperature represents the first opportunity for the liquid to crystallize. Obviously, crystallization means that the liquid has failed to become a homogeneous glass and can also lead to significant problems in glass manufacturing.[4] More important than the liquidus temperature itself is the *liquidus viscosity*, that is, the viscosity of the glass-forming liquid at its liquidus temperature. A low liquidus viscosity means that the molten glass is very fluid at its liquidus temperature, thus making it easier to crystallize. A high liquidus viscosity indicates the opposite, that is, there is a large kinetic barrier to crystallization. When designing any new commercial glass composition, it is therefore desirable to maximize the liquidus viscosity to ensure high-quality glass formation without crystallization. The compositional dependence of liquidus temperature and, hence, liquidus viscosity, is one of the most poorly understood properties relevant to the manufacture of glass by any method.[29,30] Specific problems include:

1. What governs the thermodynamics and kinetics of nucleation and crystal growth[31–36] in multicomponent oxide systems of industrial interest?
2. How can the physics of nucleation and crystal growth be controlled through design of the glass chemistry?
3. Can the liquidus temperature of multi-component systems be accurately predicted from a non-empirical (i.e., physically derived) model?
4. Can the differences between bulk and surface nucleation and crystallization be predicted from glass chemistry?
5. What is the role of melt viscosity in nucleation and crystal growth? Can models for the composition dependence of viscosity[37] be employed to gain insight into crystallization kinetics?

6. What is the connection between crystallization and the topology of the underlying glass network[38]? Are there common physics with other properties that can be exploited to build understanding or enable a more quantitatively predictive model?

Fundamentals of Glass Relaxation

As an inherently nonequilibrium material, glass is continually relaxing toward its equilibrium liquid state.[39–41] This spontaneous relaxation is accelerated when glass is subjected to heat treatment cycles, such as during the fabrication of panels for liquid crystal displays.[4] The relaxation behavior of glass therefore has enormously important implications for the manufacturing of high-resolution displays for mobile devices, televisions, etc. Relaxation effects also play a vital role in the chemical strengthening of glass, because stress relaxation can lead to a compromise in the strength of ion-exchanged glass.[42] In addition to their technological importance, glass transition and relaxation phenomena are at the cutting edge of condensed matter physics.[43–46] Hence, problems related to glass relaxation offer the opportunity to obtain solutions that both advance fundamental physical understanding and are directly applicable to practical problems of industrial concern. Some of the key questions that need to be addressed include:

1. What are the structural origins of primary and secondary relaxation modes in oxide glasses[47]?
2. What is the relationship between primary and secondary relaxation phenomena, and how can these be controlled through glass chemistry?
3. How can the nonequilibrium thermodynamics of a glass be accurately described going beyond the conventional representation of fictive temperature[48–51]?
4. What are the fundamental mechanisms of stress relaxation vs. structural relaxation in oxide glasses[52]?
5. Can stress relaxation and structural relaxation be quantitatively predicted as a function of glass composition and thermal history, e.g., using energy landscape theory[53–55]?
6. What is the relationship between enthalpy relaxation and volume relaxation[56–59]? Can enthalpy relaxation experiments be used to predict volume compaction?
7. What experimental techniques can be used to measure the spectrum of relaxation times[60] in silicate glasses with high glass transition temperatures?
8. What is the chemical and structural origin of the room temperature relaxation effect that is observed in some silicate glasses[61]?
9. Does a "reversibility window" where relaxation effects are minimized exist in multi-component silicate glasses[62–64]?

Glass Brittleness and Breakage

The advent of new ultra-thin chemically strengthened glass such as Corning® Gorilla® Glass (Corning Incorporated, Corning, NY) has opened the door to completely new applications for glass as a protective cover material.[65–68] Despite the recent surge of technology in this field, there is still much opportunity for new breakthroughs in the fundamental understanding of chemically strengthened glass and in the development of new types of glassy materials with enhanced mechanical properties. Of particular interest would be to discover how to make glasses with increased fracture toughness to avoid brittle failure. Specific questions include:

1. Is it possible to develop silicate glasses with high fracture toughness (i.e., low brittleness)? Research in the metallic glass community has revealed a brittle-to-ductile transition at high values of Poisson's ratio.[69–72] Is such a transition also possible in transparent oxide glasses[73]?
2. Can crack initiation and propagation events be understood at the nanoscopic level through experiments and modeling[74–77]? Can these insights be used to develop new ultra-strong and ultra-tough glasses?
3. How can the fragmentation pattern be controlled in ultra-thin strengthened glass[78,79]?
4. Is it possible to design an oxide glass or a glass/polymer composite that withstands attack from water, thereby suppressing slow crack growth or static fatigue[80]?
5. What insights can be gained through molecular dynamics simulations regarding the chemical strengthening of glass[81,82]?
6. How can glass achieve a greater fraction of its theoretical strength? This question has been the focus of the Usable Glass Strength Coalition,[83] which has served as an excellent example of collaboration among researchers and technology stakeholders in academia, industry, and the government.

In addition to these questions, we should emphasize that there is currently a dearth of research in the area of fractography of glass.[84] This is a field that is only growing in scientific and technological importance, and yet, to the best of our knowledge, there is currently no academic program in the United States devoted to glass fractography-related education and research. This is an area with abundant career opportunities but without a supply of qualified graduates to fill the needs of glass industry.

Chemical Durability of Glass

The chemical durability of glass is of great concern for such diverse application areas as nuclear waste storage, laboratory glassware, and glasses for long-term outdoor use, including photovoltaic, automotive, and architectural applications.[85–88] Current understanding is based primarily on empirical data. Hence, there is an urgent need to develop a solid fundamental understanding of the chemical durability of glass to address the following questions:

1. What is the compositional dependence of glass durability in various acids, bases, and water?
2. Can this composition dependence of glass be quantitatively predicted through (preferably non-empirical) modeling?
3. How can solutions be optimally designed to give uniform isochemical etches of a given glass composition?
4. How can chemical treatments be used to alter the physical properties of glass[89]? For example, how can etching be used to strengthen glass or to induce glass relaxation?
5. What new understanding can be gained through atomistic simulations of glass corrosion[90]?

Acoustic Properties of Glass

Acoustic properties are among the least studied of all the physical properties of glass. This is a topic that is completely omitted in most standard glass science textbooks[91] and a subject that has been given only limited attention in the scientific literature,[92] most notably with the excellent work of Vacher and coworkers.[93–96] Hence, there are many fundamental and applied research topics open for study, the results of which could be utilized in the design of new glass compositions acoustically sensitive applications. The acoustic properties of glass are becoming more technologically important as glass becomes a candidate material for use in new electronic devices and in many automotive and architectural applications. Potential areas of research include the following:

1. Can acoustic damping be predicted as a function of glass composition and sound frequency?
2. What is the dependence of acoustic damping on the thermal history of a glass?
3. How does glass homogeneity influence the acoustic damping spectrum?
4. Can glasses be designed to control acoustic wave propagation, i.e., directionality, lensing, reflection/refraction, etc.?
5. What is the relationship between the acoustic properties and thermal conductivity of glass?
6. What is the role of acoustic properties in glass relaxation? Can one property be predicted from the other?

Thermal Conductivity of Glass

Thermal conductivity is another property of glass that has been largely neglected by the research community, aside from some classic work in the physics literature.[97–101] However, there are potentially many exciting applications for new glass compositions that could achieve exceptionally high or low values of thermal conductivity. Some relevant questions include the following:

1. What is the dependence of thermal conductivity on glass composition, temperature, thermal history, and homogeneity?
2. What are some approaches to significantly increase or decrease the thermal conductivity of a glass?
3. Is it possible to design composite systems to achieve high thermal conductivity, such as metal- or carbon-filled porous glasses[102]?
4. How can glass structure be designed to emulate the conductive properties of crystalline alumina or beryllium oxide?
5. Can glasses be designed with exceptionally low values of thermal conductivity, for example, glasses filled with nanoporosity or foam-like glasses[103]?

Optical Properties of Glass

From windows and light bulbs to optical communication fiber and ultra-precision transistor substrates for modern liquid crystal displays, the favorable optical properties of glass have played an essential role in many of the most revolutionary technological breakthroughs for glassy materials. However, in a recent review article by Ballato and Dragic, the authors lamented that "from a materials perspective, modern optical fibers are boring."[104] Although we disagree with this assessment, this raises the important question of what new advances in optical properties could drive the next breakthroughs in glasses for optical and photonic applications.

1. What is the impact of glass composition on Brillouin scattering and how can this scattering be minimized[104]?
2. Is it possible to design a clear glass with zero stress-optic coefficient without the use of toxic elements[105,106]?
3. What new glasses could be designed for radiation detection and for use in high-energy particle physics[107]?
4. Can photonic crystal and photonic bandgap fibers be designed to achieve attenuation lower than that of standard silica fibers[108]? What other advantages can be realized through design of multimaterial fibers[109]?
5. Which glass compositions can achieve high optical nonlinearity while maintaining low loss[110]?

Glass Surfaces

While most focus in the glass research community is on bulk properties, a glass interacts with the environment via its exposed surface. Glass surfaces present unique challenges and opportunities for characterization and understanding, because the physical chemistry of the bulk glass is not necessarily transferable to its surface.[111–114] Engineering of glass surfaces could very well provide the next wave of breakthroughs in glass technology. For example:

1. Is it possible to design oxide glass surfaces that are intrinsically hydrophobic?
2. Is it possible to design such surfaces to be both hydrophobic and oleophobic (i.e., antifingerprint)?
3. How can a glass surface be hardened to provide greater resistance to mechanical damage[115]?
4. Can the surface of a glass be tailored to provide higher chemical durability or greater resistance to attack by water[113]?
5. Can a glass surface be designed to have antiglare or antireflective properties?
6. What novel functional or catalytic groups can be designed into glass surfaces?
7. For any type of coating on glass, can the surface of the glass itself be engineered to achieve the desired properties such that no coating is needed?

Glass Formation under High Pressure Conditions

Nearly all industrial glass production is performed under ambient pressure. However, it is well known that crystalline materials of the same composition can exist in variety of different polymorphs depending on temperature and pressure. These various crystalline polymorphs are characterized by different symmetries and short- and long-range ordering, leading to unique values of thermodynamic and mechanical properties. First-order phase transitions between such polymorphs can occur by changing the temperature and/or pressure conditions of the system. More recently, an analogous phenomenon known as polyamorphism has been discovered within the phase space of noncrystalline materials.[116,117] For example, water has been shown to exist in two distinct noncrystalline phases: the standard low-density amorphous (LDA) phase formed by hyperquenching liquid water into the glassy state under ambient pressure, and a high-density amorphous (HDA) phase formed by pressurizing ice at low temperatures.[118–120] As with standard crystalline polymorphism, the LDA and HDA forms of water display distinct short-range ordering. As both are noncrystalline, there is no long-range ordering in either phase. Polyamorphism has also been observed in a number of other compositions, including organic and metallic glasses.[121,122] Numerical simulations also indicate that silica may exist in distinct glassy phases[123,124]; however, this has not yet been confirmed experimentally. Research opportunities in this area include:

1. What novel glass structures and properties can be obtained from high-pressure/high-temperature treatments[125]?
2. Which silicate systems could exhibit polyamorphism at high pressure/temperature?
3. Is it possible to design a composite glass with mixed LDA and HDA phases of the same glass composition?
4. Could such LDA/HDA composites be used to enable "transformation toughened" glasses analogous to partially stabilized zirconia ceramics[126]? For example, when a crack propagates through such an LDA/HDA composite, is it possible to induce a spontaneous HDA→LDA polyamophic phase conversion to close the crack?

5. What is the impact of pressurization on the bulk and surface properties of various glass compositions[127,128]?
6. What novel properties can be achieved by quenching glass from high-temperature/high-pressure conditions?
7. Can pressurization equipment be designed to compress samples of large geometry under high pressure and temperature?

Heterogeneous and Structured Glasses

A recent issue of this journal was devoted to the topic of glass and nanotechnology, where a compelling case was made for glass and glass ceramics as the quintessential nanotech material.[66] Recent reviews of glass-ceramic science and technology paint a very optimistic picture of opportunities for this family of materials, in terms of both opportunities for new fundamental understanding and new technological applications.[129–131] Nano- and microstructured glasses and glass ceramics have also found exciting new applications as bioactive materials. The importance of glass microstructure for biological applications has been emphasized in several excellent review monographs that have been recently published.[132–138] Beyond bioglasses, there are still many interesting questions to address concerning heterogeneous and structured glasses:

1. What unique properties can be achieved through laminated glasses or glass/polymer laminates[139–142]?
2. What new properties can be obtained by tailoring the composition and microstructure of glass-ceramics[129–131]? In particular, transparent glass ceramics seem to be technologically underutilized.[143,144] The search for additional transparent glass-ceramic systems beyond β-quartz and spinel and the study of their optical properties when doped with transition metals or rare earth elements should be quite rewarding.
3. How can controlled inhomogeneities or phase separation be introduced into a glass in a controlled manner[145]?
4. What new opportunities can be found for glass/cermet composites[146]?

Glass Melting and Processing

There are many opportunities for advancements in glass melting and processing technology to improve manufacturing efficiency or enable more environmentally friendly glass formation.[147,148] From a purely scientific viewpoint, there are also many unanswered questions regarding the thermodynamics and kinetics of glass melting, fining, and homogenization.[149–155] Many of these questions are best addressed through an interdisciplinary approach, combining traditional glass science with physical chemistry, computational fluid dynamics, and the various engineering disciplines.[156–159] Some questions for consideration include the following:

1. What are the detailed chemical reactions involved with batch melting? What are the rate-limiting steps, and how can the melting process be optimized?
2. How can volatilization and condensation be controlled in glass melter design?
3. What are the fundamental reactions between a glass melt and different types of refractory materials? How can refractory dissolution be minimized?
4. What opportunities could be found for alternative melting and fining processing, such as ultrasonic, microwave, and plasma techniques? All of these technologies could locally heat the glass to high temperature and provide enhanced melting or fining, but the physics and chemistry need to be understood at a fundamental level.
5. What new glass-forming technologies could be developed to enable large-scale manufacturing of glass article with different geometries?

Summary and Conclusions

We have provided a snapshot of the current status of academic glass research in the US. Analysis of publication data indicates that less than one-quarter of students at US universities who are doing research in glass science are studying systems that would make them well prepared for a future career in the glass industry. In our experience at Corning Incorporated, students with expertise in glass families that are industrially relevant (particularly silicate glasses and glass ceramics) are more likely to be hired into a position in industry and also require less on the job technical training after being hired.

Please note that our intent is not to discourage research being performed on other types of glass systems, as there is always scientific value in pursuing this type of basic research. We publish this article for the purpose of stimulating conversation in the glass research community among researchers in academia, funding agencies, industry, and other stakeholders regarding the future direction of glass science in the United States and increasing the emphasis on glass research of industrial relevance.

There is currently a lack of research in glass-ceramics in the United States. Other areas such as glass fracture mechanics, crystallization behavior, and glass surfaces deserve to be given significantly more attention compared to the current level of research. Areas such as acoustic properties and thermal conductivity of glass are almost completely unexplored. The science and technology of glass melting and processing are also mostly overlooked. We hope that the list of potential research topics provided in this paper will serve as encouragement for researchers in academia to pursue these topics. This also opens the possibility of developing new collaborations with industrial research partners. We believe that a new focus on these research opportunities is in the best interests of all those involved, viz., the students and professors who are conducting university research activities, government funding agencies who have it as their mission to promote the welfare and prosperity of their country, and ultimately the glass industry and its contribution to US economic development.

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