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Two Centuries of Glass Research: Historical Trends, Current Status, and Grand Challenges for the Future

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The field of glass science and technology has a remarkable history spanning about two centuries of research. In this article, we analyze the number of research papers and patents related to glassy and amorphous materials in the published literature. The publication rate has increased roughly exponentially since 1945. Within the most recent decade, China has become the clear dominant player in the global glass research community, while the publication rate has declined in many of the historically most prolific countries. Oxide glasses, metallic glasses, amorphous carbon, and amorphous silicon have drawn the most research attention overall and are still given the greatest focus today. Publication data are also analyzed in terms of the properties under study, author keywords, affiliation, and primary characterization techniques. We find that the level of published (fundamental) glass research from industrial laboratories has dropped significantly, despite the opportunities for new breakthroughs to solve some of the most challenging problems facing the world today. But, surprisingly, the number of patents issued worldwide has surpassed the number of published scientific articles, indicating a very high level of activity in technological research.

Introduction

The history of glassmaking dates back more than 5000 years, making glass one of the most important and impactful materials throughout recorded human history. Indeed, glassy materials have proven to be one of the key enablers of modern human civilization. Throughout most of history, the understanding of glass was strictly empirical, based on trial-and-error experimentation. The first modern scientific research on glass was published starting in the eighteenth century by Lomonosov,[1] who performed the first systematic studies of glass composition–property relationships. This early research in glass also includes the 1827 work by Griffiths on the dissolution of glass in water[2] and several

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papers by the great Michael Faraday, who published some of the earliest studies on glass technology.[3,4] Other pillars of glass science and technology in the late 1800s and early 1900s were Otto Schott, William E.S. Turner, F. W. Preston, and George W. Morey.

Our understanding of glassy materials has grown immensely in the nearly two centuries that have followed this groundbreaking work. Advances in glass science and technology have served as essential ingredients for modern day society, including architecture, transportation, medicine, energy, science exploration, and the communication and display of information. Given the amazing amount of progress in the understanding and application of glassy materials, especially in recent decades, it is perhaps helpful to take a step back to analyze the current state of glass science and the historical trends that have led us to where we are today. Such exercise may also prove helpful in considering what might come next for glassy materials and their opportunities for future impact on global society.

In a previous article published in this journal,[5] we reviewed the current status of academic glass research in the United States, considering all glass-related articles published in six of the top glass science journals during the time frame of 2007 to 2013. In the current article, we broaden this analysis to consider *all* of the published literature in glass science and technology, dating back nearly two centuries. Our goal is to provide a global view of the historical trends and current status of glass research, as well as our thoughts on opportunities for glass science and technology in the future. We hope this article will help contribute to a global discussion on future directions for glass, building on the immense framework of understanding and literature published by our forerunners in the field.

Methodology

In this study, we consider the publications cataloged in the "Physical Sciences" library of the SCOPUS bibliographic database from Elsevier, which comprises 7200 journal titles. We specifically search for articles with the words "glass," "glasses," "vitreous," "amorphous," or "non-crystalline" in the title of the article. To focus on papers pertinent to glass science and technology, we exclude all papers with "spin," "substrate," or "electrode" in either the title or abstract, and we restrict our search to the following subject areas: materials science, engineering, chemistry, physics, earth sciences, and multidisciplinary fields. While we do not evaluate the quality of glass publications in this article, and the question of quality itself is a subjective and potentially controversial matter, the quantity of publications—regardless of impact—is an effective and objective proxy for the level of activity in the research of glass.

Although our primary interest is in glass, we also include the keyword "amorphous", since the terms "glassy" and "amorphous" are sometimes used interchangeably in the literature. Here, we remind the reader that glasses and amorphous solids are thermodynamically distinct classes of noncrystalline solids, with glasses having a short-range order similar to that found in the corresponding molten state, and amorphous solids having a short-range order distinct from that of the liquid. Also, a glass exhibits a continuous relaxation to the liquid state upon heating, whereas an amorphous solid does not. For more information on the differences between glasses and amorphous solids, we refer the reader to Gupta.[6]

Our search strategy described above was chosen to minimize the number of nonglass articles, that is, those articles that make use of glass but where the primary focus is not on the scientific or technological aspects of glass itself. With this chosen search strategy, we obviously miss many real glass-related articles. However, this approach ensures that we have a much cleaner dataset to work with and still have more than enough data to obtain decent statistics.

The total number of glass-related publications registered at SCOPUS is about 650,000 considering any of the keywords ("glass," "amorphous," etc.) in the article title, keyword list, or abstract, and accounting for all types of documents, including letters, conference proceedings, errata, and technical notes. When we restrict the keywords to the *title* of the publication only, the number of documents is reduced to approximately 230,000. For a cleaner dataset, we further restrict our search to journal articles only. Using this most restrictive strategy, our search resulted in a total of about 120,000 glass-related articles from the SCOPUS database, including all families of glasses (oxide, metallic, organic, polymeric, and so on). A similar search performed in the Web of Science (Thomson Reuters Scientific) yielded a comparable number, viz., about 176,000 papers. The articles obtained through this search strategy were sorted according to a variety of fields, including publication date, journal title, country of origin, affiliation, and type of glass study.

We also performed a parallel search of the patent literature using the Derwent Innovations Index (Thomson Reuters Scientific). This search covered patents granted between 1963 and 2013 using the same keywords as in the SCOPUS search in the patent titles. This search resulted in about 370,000 patents issued worldwide. The patents obtained were sorted according to date issued and grantee.

Results

From 1837 to 1913, the number of glass-related journal articles published satisfying the abovementioned criteria fluctuated from around one to five articles per year. Within the ensuing 100 years (1913–2013), the number of publications per year increased by more than three orders of magnitude. Figure 1 shows a comparison of the number of glass-related publications with article counts for five other types of materials. Here, we consider both search strategies: including any of the specified keywords in the article title, abstract, or keyword list (Fig. 1a) or keywords appearing in the article title only (Fig. 1b). From the mid-1940s to the early 1970s, there was a significant increase in the publication rate for all five of the materials classes listed. The growth rate then slowed in the 1970s, but the actual numbers continued to increase, reaching about 5500 glass-related papers per year (considering keywords in the article *titles* only). It is interesting to note that "glasses" and "inorganic glasses" (meaning inorganic, nonmetallic glasses—including both oxides and chalcogenides) were about the same until the early 1970s, just after metallic glasses were discovered (in the 1960s) and jointly with organic and polymer glasses became as popular as traditional inorganic glasses. The material class exhibiting the highest growth rate is "composites," which also includes a number of types of "glass matrix" and "glass fiber" composites. Among the various types of material systems under consideration, the only exception to the observed exponential growth pattern is "refractories," which nearly saturated in the 1970s and has thenceforth been fluctuating at around 250 articles per year.

For comparison, Fig. 2 shows the number of patents granted by decade, as determined through the Derwent Innovation Index. The number of granted patents concerning glasses and amorphous materials has been growing steadily since the 1940s and reached a higher number/year than those of published scientific articles. About 370,000 glass-related patents have been granted worldwide in the last 50 years, including 98,000 new patents in the past 4 years. Surprisingly, this is more than number of glass-related publications in the SCOPUS database (>200,000) over the same 50 years. One must be aware, however, that it is a common industrial practice to register several related patent applications in different countries on the same invention. Therefore, the number of patents is always greater than the actual number of unique inventions being disclosed.

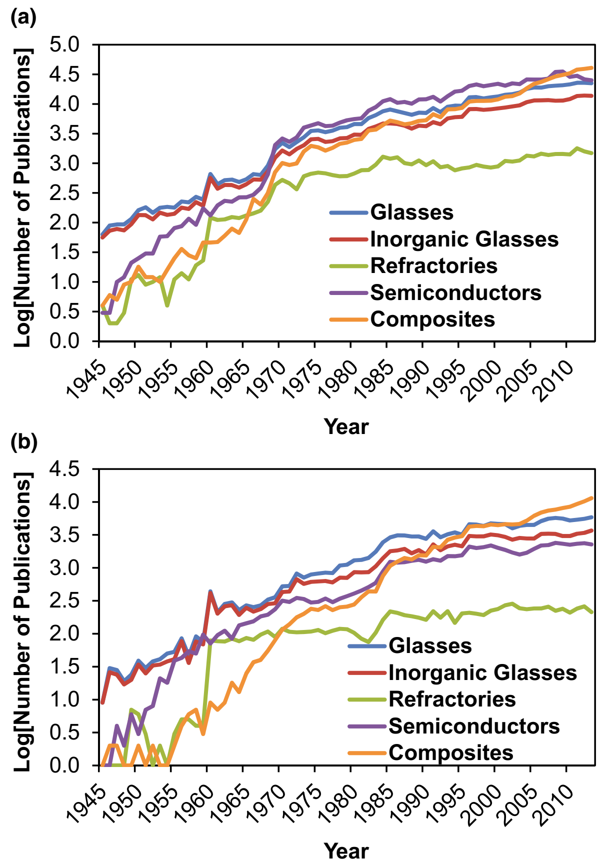

Fig. 1. Number of publications per year in the SCOPUS database by material type: (a) including all types of publications (letters, notes, conference proceedings, etc.), all areas of knowledge, and the main keywords "glass," "glasses," "amorphous," "vitreous," or "non-crystalline" in the article title, abstract, or keyword list; and (b) using a restricted search with the main keywords only in the article title, and selecting only articles published in hard science journals.

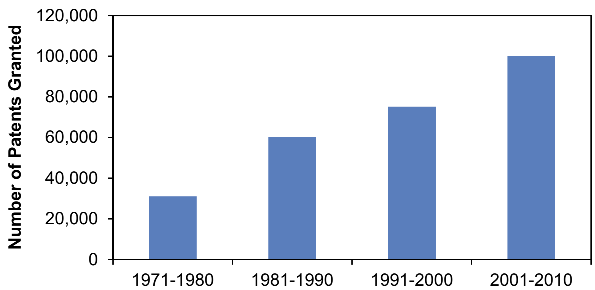

Fig. 2. Number of patents granted worldwide by decade. Here, we consider any of the keywords "glass," "glasses," "amorphous," "vitreous," or "non-crystalline" in the title of the patent. Between 1963 and 2013, a total of about 370,000 glass-related patents have been issued worldwide.

Most Prolific Institutions

Figure 3 plots the total number of glass-related papers from 1850 to 2013 by affiliation. The most prolific institution is Tohoku University in Japan, where the group led by Prof. Akihisa Inoue has published about 2500 articles related to metallic glasses. Other Japanese universities, including Kyoto University, Osaka University, the Tokyo Institute of Technology, and the University of Tokyo are also in the top ten. The Russian Academy of Sciences (which includes several different laboratories throughout the Russian Federation) is second in this list. Several European and Chinese universities also appear among the most prolific institutions overall.

Interestingly, in the United States, the most productive institution overall (Bell Labs) is an industrial research laboratory rather than a university. Corning Incorporated is also high on the list; IBM Thomas J. Watson Research Center and Philips Research also appear further down on the ranking. These are the only four company laboratories listed among the world's top 160 most prolific institutions in glass science. Other top institutions in the United States include several universities (Massachusetts Institute of Technology, the Pennsylvania State University, and Stanford University) and a U.S. government research laboratory (Argonne National Laboratory).

In Figure 4, we show a similar ranking by institution, but considering only the most recent 4 years (2010–2013). Tohoku University is still in the lead, followed again by the Russian Academy of Sciences. However, a number of Chinese universities have over-

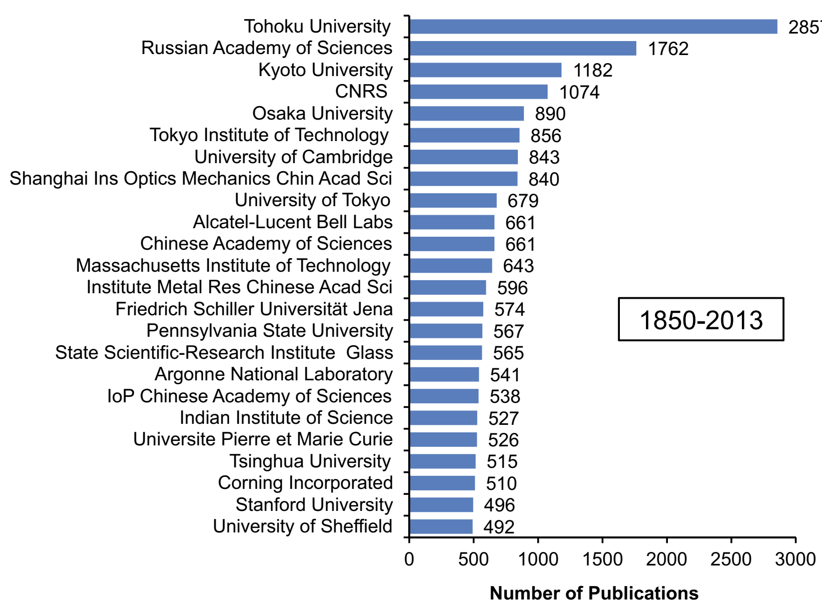

Fig. 3. Total number of publications in glass science (1850–2013), sorted by affiliation. Tohoku University of Japan leads this ranking, a direct result of the extremely prolific research work on metallic glasses of the group lead by Prof. Akihisa Inoue. Overall, there is a mix of Japanese, Russian, European, Chinese, Indian, and American institutions. It is relevant to stress the presence of Bell Labs and Corning Incorporated as the only two company laboratories within the 25 most prolific institutions in this ranking.

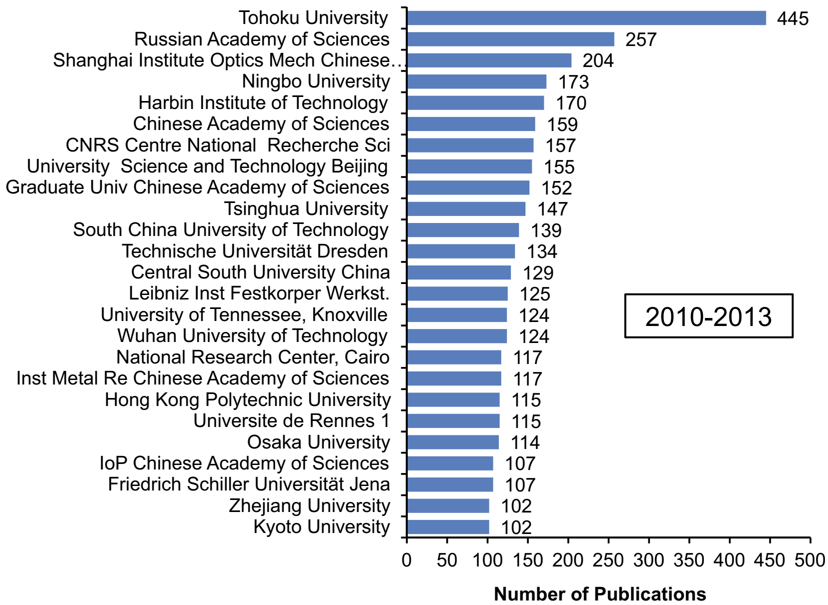

Fig. 4. Number of publications by affiliation in recent years (2010–2013). Tohoku University of Japan still leads the ranking. However, there has been a significant change in the mix of the most prolific institutions. There is now a clear dominance of Chinese institutions, followed by Japanese, then a few German and French, plus one Egyptian and one American university. It is worth mentioning that Corning Incorporated (#55 most prolific institution) is the single industrial company that appears in the ranking of the 160 most prolific institutions in this time period.

taken many of the European and American institutions from the previous figure. There is no longer any industrial research laboratory near the top of list. Except for Corning Incorporated (the #55 most prolific institution in 2010–2013), there is no industrial laboratory among the top 160 most prolific organizations.

Next, we consider the top institutions in terms of the number of glass-related patents granted. Figure 5 shows the cumulative number of patents granted to the twenty most prolific industrial companies in the past 4 years (2010–2013). Japanese companies lead the overall ranking by a large margin. Asahi Glass and Nippon Electric Glass are first and second, respectively. Corning Incorporated (U.S., #3), Saint-Gobain (France, #6), and Schott (Germany, #8) are the only non-Asian companies among the top twenty. It is interesting to note that six universities and (surprisingly) a dozen individual inventors (all Asian) also appear among the top 100.

Most Prolific Countries

We now turn our attention to the breakdown of glass-related publications by country. As depicted in Fig. 6, the United States has the greatest cumulative number of publications overall, followed by Japan and China. Russia and three European countries (Germany, France, and the United Kingdom) follow. Outside of Europe, India and South Korea also have very strong rankings.

However, the more recent trends paint a different picture, as depicted in Fig. 7(a). Here, we plot the number of glass-related publications for the top ten most prolific countries in 1850–2013 as a function of year. The output from Chinese institutions has grown precipitously in recent years, surpassing that of every other country. India and South Korea have also grown rapidly, while the rate of growth in research activity has slowed down or even become negative in all other eight countries in this list, starting in the mid-nineties. The precipitous rise of Chinese research has coincided with a distinct slowing of the growth rate in the United States. While this slowdown in the United States is troubling, the situation is dramatically worse in several of the other top countries, including Japan, Germany, and Russia, all of which actually produced *fewer* research publications in 2001–2010 compared to 1991–2000.

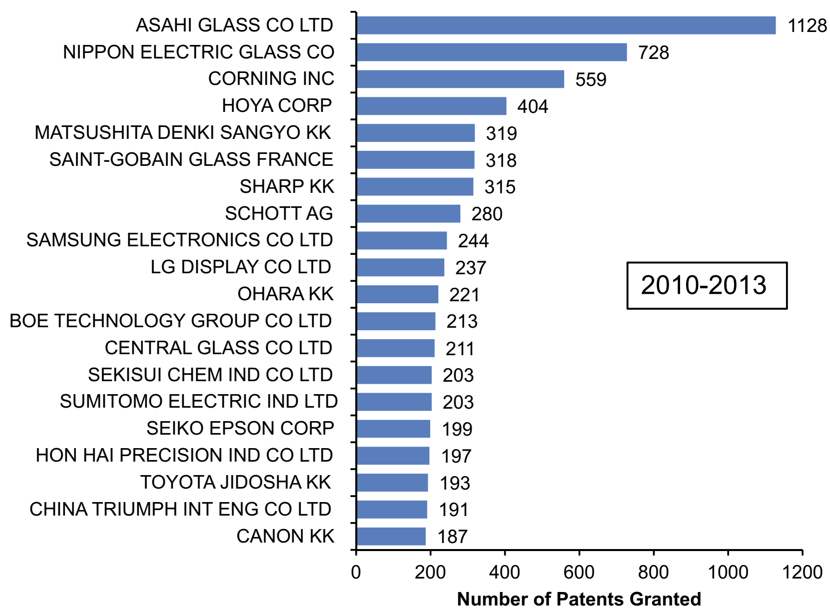

Fig. 5. Number of glass-related patents granted in 2010–2013, sorted by institution. Japanese companies lead the overall ranking by a large margin. Asahi Glass and Nippon Electric Glass are first and second, respectively. Corning Incorporated (U.S., #3), Saint-Gobain Glass (France, #6), and Schott AG (Germany, #8) are the only non-Asian companies among the top twenty.

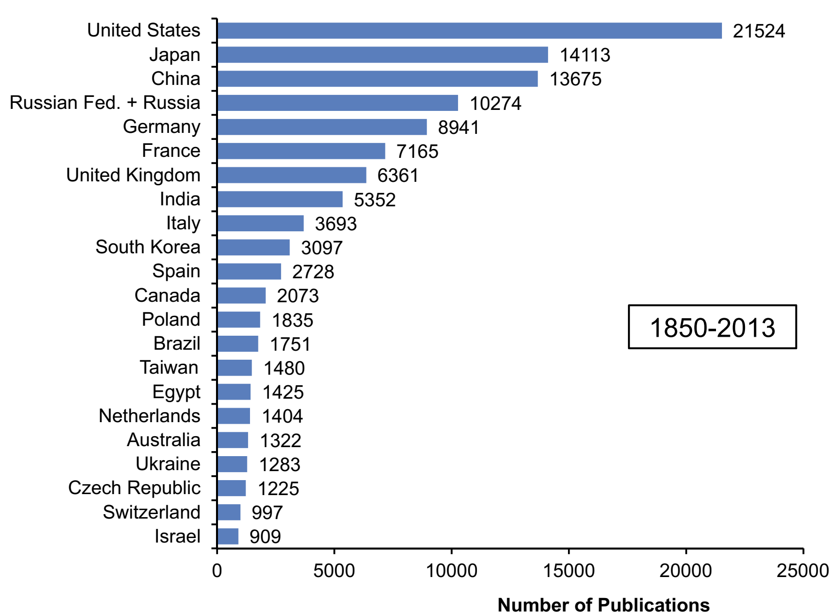

Fig. 6. Most prolific countries in the history of glass research (1850–2013). The United States is the leader overall, followed by Japan and China.

Figure 7(b) shows the number of glass-related publications for the second half of the top twenty most prolific countries in 1850–2013. They all showed steady growth in the past 50 years, except for Spain and the Netherlands, with stagnant research activity in the past 20 years, and Brazil, which has shown a signif-

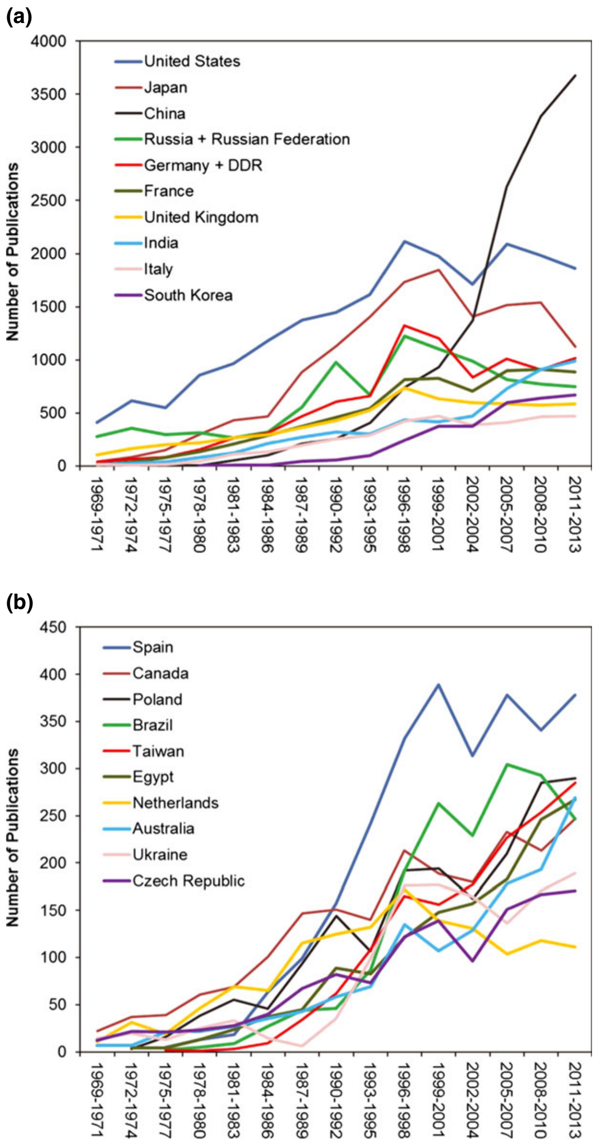

Fig. 7. (a) Number of glass-related publications for the top ten most prolific countries in 1850–2013. The output from Chinese institutions has grown precipitously in recent years, surpassing that of every other country. India and South Korea have also grown rapidly, while the rate of growth in research activity has slowed down or even become negative in all eight other countries in this list, starting in the mid-1990s. (b) Number of glass-related publications for the second half of the top twenty most prolific countries in 1850–2013. They all showed steady growth in the past 50 years, except for Spain and the Netherlands, which had stagnant research activity in the past 20 years, and Brazil, which has shown a significant growth rate from the early 1990s until about 2005, but has since shown declined research activity.

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In Figure 8, we compare the distribution of recent glass-related publications from China versus that of the United States. While the number of publications from China has surged beyond that of the United States, the types of material systems under study are not too dissimilar. There is somewhat more emphasis on metallic glasses in China and on polymeric glasses in the United States. The percentage of articles on silicate glasses is similar for both countries.

Beyond China, other countries showing notable increases in research activity include India and South Korea. Figure 9 shows the ranking of countries for the most recent 4 years (2010–2013), indicating that India has now surpassed both France and Russia. Other countries showing recent high rates of research productivity include Poland, Taiwan, and Egypt.

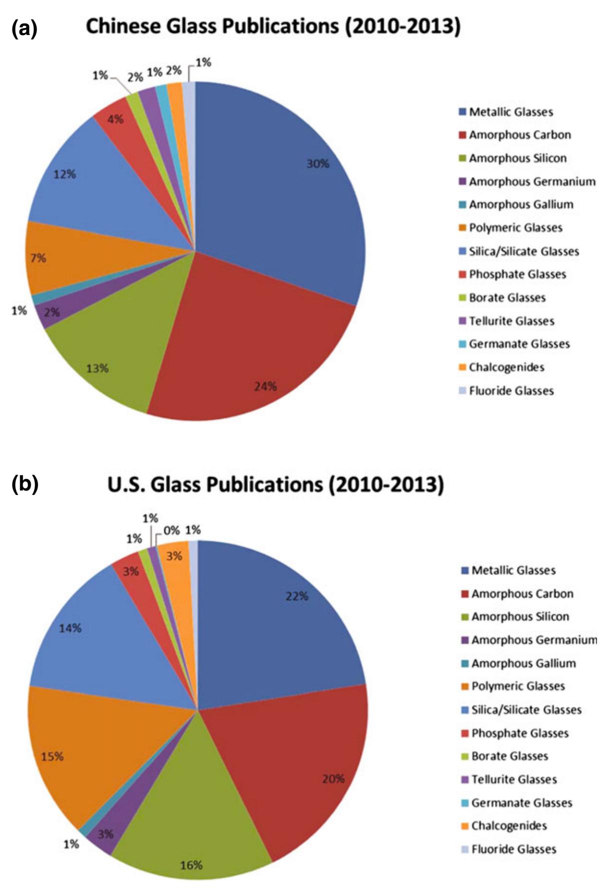

Fig. 8. Distribution of recent publications in (a) China and (b) the United States by glass type.

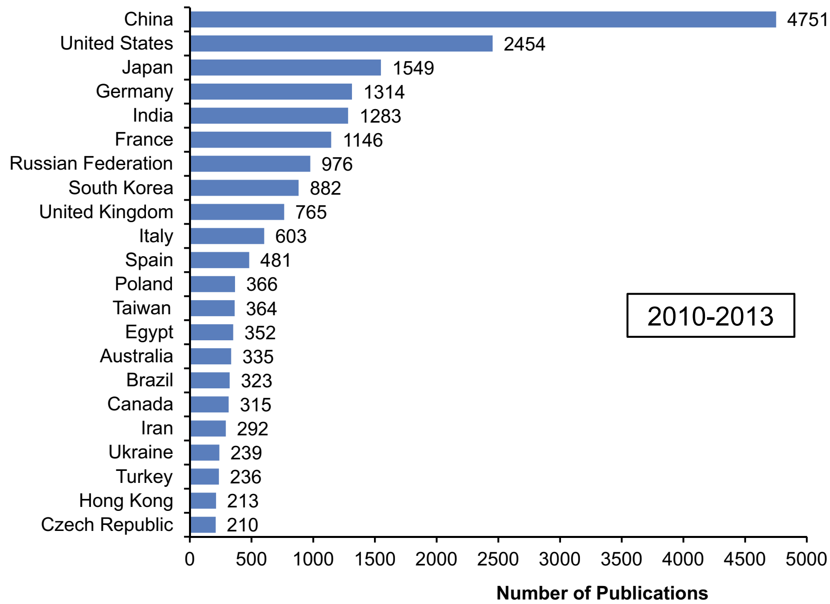

Fig. 9. Number of glass-related publications by country in the most recent 4 years. The dominance of China is clear, nearly doubling the output of the next most prolific country (the United States).

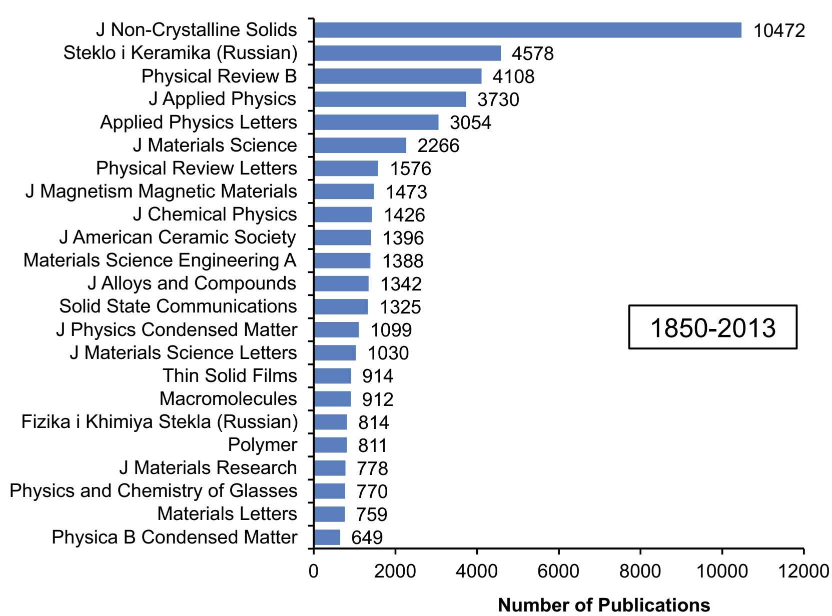

Fig. 10. Cumulative number of glass-related publications by journal from 1850 to 2013. Journal of Non-Crystalline Solids leads this journal ranking by a large margin. It is interesting to note that several physics (more than chemistry) journals and materials science journals follow in the ranking. Two polymer journals also appear. Among the specialized journals, only three journals: Steklo I Keramika (Russian), Fizika I Khimiya Stekla (Russian), and Journal of the American Ceramic Society appear among the top 30.

Most Prominent Journals

Within the glass science community, *Journal of Non-Crystalline Solids* (JNCS) is clearly the single most significant journal, publishing more than double the number of glass-related articles as the next most popular journal, as shown in Fig. 10. The historical dominance of this journal is maintained even today. As depicted in Fig. 11, in recent years, JNCS still publishes more than double the number of glass-related papers compared to the next most popular journal.

Beyond JNCS, physics journals including *Physical Review B*, *Applied Physics Letters*, and *Journal of Chemical Physics* are excellent sources of glass-related research. Overall physics journals are more popular than chemistry journals for glass research, although the *Journal of Physical Chemistry B* appears on our list of highest ranked journals for recent years (Fig. 8). Materials science journals such as *Acta Materialia* are also well represented in this ranking. Another noteworthy trend is an increase in the number of relevant specialized journals in recent years compared to prior history.

Material Systems

In Figure 12, we plot the total number of papers published in the period 1850–2013 by the type of material system under study. In this case, the above-listed glass types were searched in the article title, keyword list, and abstract. Metallic glasses, oxide glasses, amorphous carbon, and amorphous silicon have received the most attention overall. (Amorphous silicon and carbon, we note, are not actually glasses at all, i.e., they do not undergo a glass transition.) Among oxide glasses, silicates have received the most attention (not surprisingly), followed by phosphates. With regard to the several application types of glassy materials (last 7 columns), glass composites are the most popular, followed by bio-glasses, semiconductor glasses, and glass-ceramics, which are all nearly tied for second place.

In Figure 13, we see that the same four types of glasses have retained their dominance in the most recent 4 years. Among the oxide glasses, silicates continue to lead over other types. For the various application types (last 7 columns), glass composites, bio-glasses, and glass-ceramics are now the top three. For more details, we refer the interested reader to several

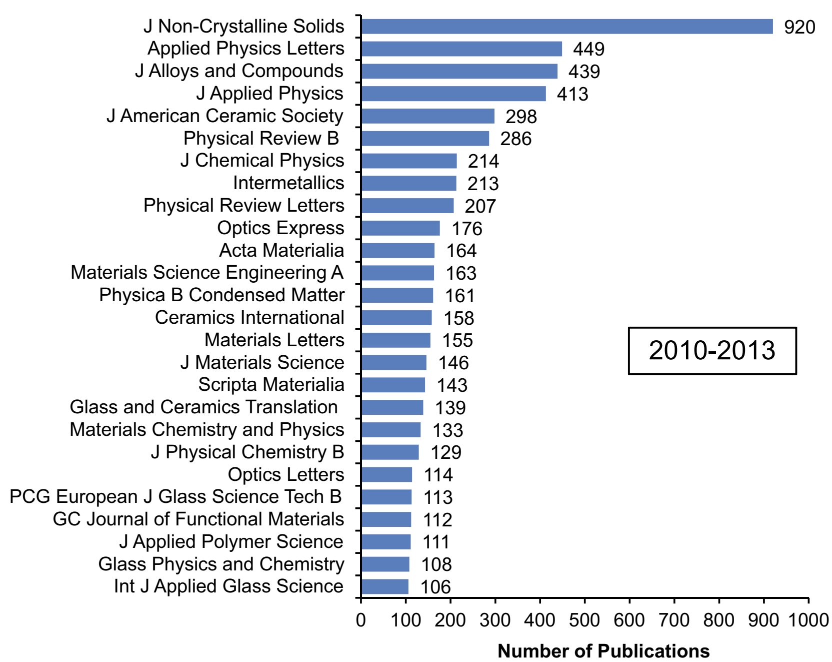

Fig. 11. Number of glass-related publications by journal in recent years (2010–2013). Journal of Non-Crystalline Solids continues to lead the journal ranking. Physics (more than chemistry) and materials science journals follow in the sequence. More specialized journals now appear among the top 30: Journal of the American Ceramic Society, Ceramics International, Glass and Ceramics (Steklo I Keramika in Russian), Physics and Chemistry of Glasses—European J. Glass Science & Technology B, Glass Physics and Chemistry (Fizika I Khimiya Stekla in Russian), and the new International Journal of Applied Glass Science in this order.

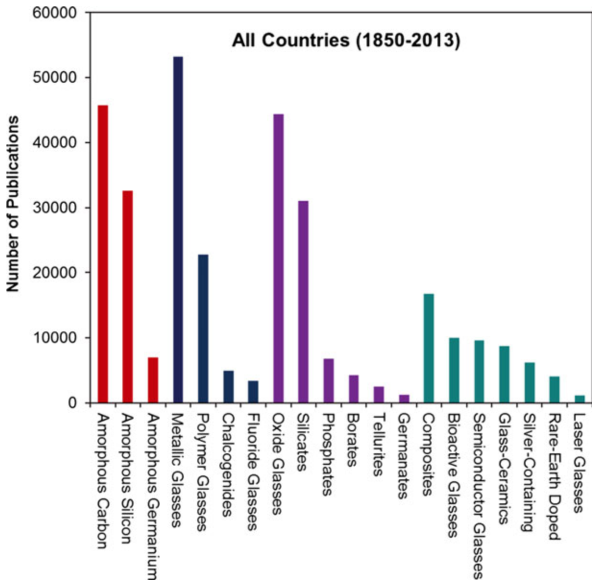

Fig. 12. Total number of publications in the period 1850–2013 registered in the SCOPUS database for various types of glasses and amorphous solids. In this case, to widen our search, the keywords were searched in the article title, keyword list, and abstract. Research activity in metallic glasses, amorphous carbon, and oxide glasses dominate. Research in amorphous silicon is also very significant. Among the oxide glasses, silicates dwarf that of every other type of oxide system, as expected. With regard to several types of application-oriented glasses (last 7 columns), glass composites is the top, whereas bio-glasses, semiconductor glasses, and glass-ceramics are about even in second.

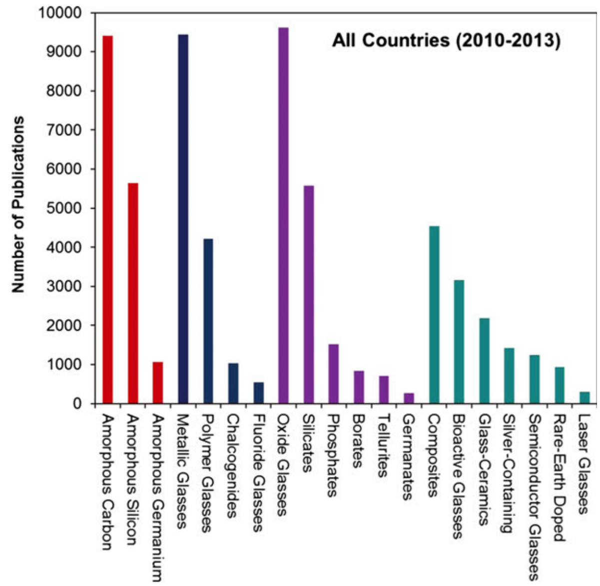

Fig. 13. Number of publications in 2010–2013 for various types of glasses and amorphous solids. As in the previous figure, the keywords were searched in the article title, keyword list, and abstract. The research activity in metallic glasses, amorphous carbon, and oxide glasses still dominates. Research in amorphous silicon continues to be significant. Silicates continue to lead over the other types of oxide glasses. Glass composites, bio-glasses, and glass-ceramics are the top three most studied types of application-oriented glasses (last 7 columns).

recent review articles related to the current status and future directions of glass-ceramic research.[7–9]

Research Areas

In Figures 14 and 15, we consider the most frequently studied types of glass properties, both historically and in recent years. Optical and mechanical properties have received the most attention overall, with mechanical properties becoming the most popular in recent years. Thermal and rheological properties have also received considerable attention from researchers, both historically and today.

In Figures 16 and 17, we plot the most frequently selected keywords chosen by authors when submitting their manuscripts. Crystallization dominates due to the strong activity in the metallic glass community. This is even clearer if one sums the number of papers having the keywords "glass forming ability" + "nucleation" + "crystal growth." The next most popular set of keywords include those related to "glass transition" and other dynamic and thermodynamic properties.

Finally, in Figs 18 and 19, we consider the popularity of various characterization techniques, both historically and in recent years. The preferred characterizations techniques have been and still are X-ray methods, thermal analysis, electron microscopy, several types of optical spectroscopies, and some types of computer simulations methods such as molecular dynamics.

Grand Challenges for the Future

While the field of glass science is growing healthily in a global sense, many of the countries with traditionally strong glass research programs have clearly fallen behind fast-growing newcomers, particularly China.

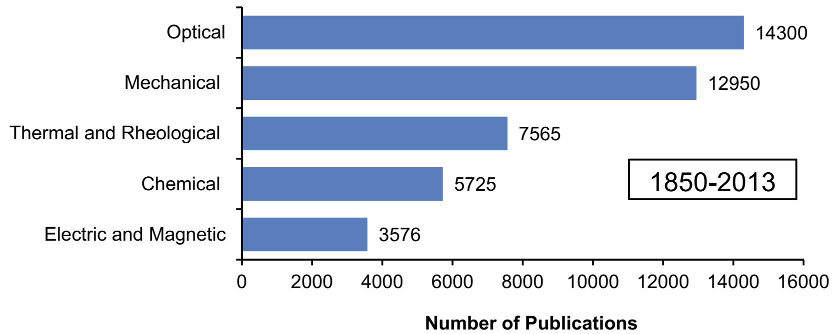

Fig. 14. Total number of glass-related publications by property type. Optical and mechanical properties have garnered the most attention overall.

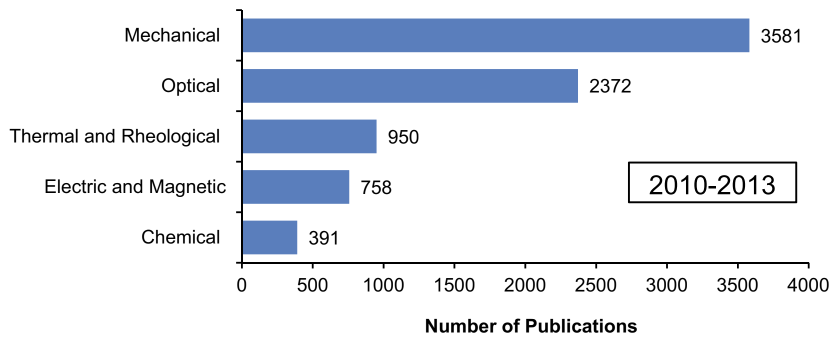

Fig. 15. Number of publications by property type in recent years (2010–2013).

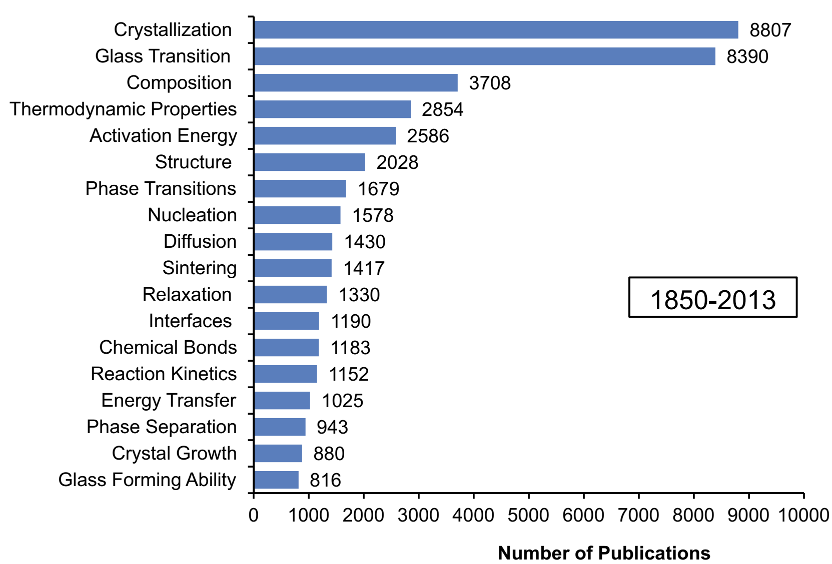

Fig. 16. Most frequent keywords chosen by authors when submitting their glass-related papers. Crystallization is the most popular topic, followed by glass transition.

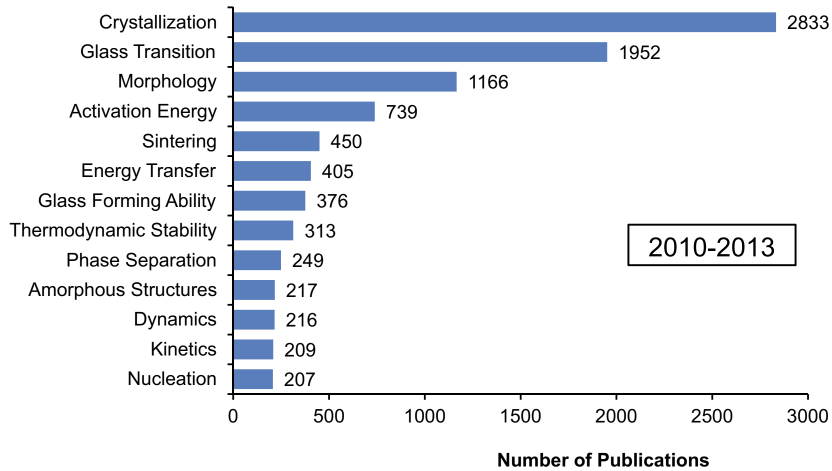

Fig. 17. Most popular keywords selected by authors in recent years (2010–2013). Again, crystallization is the most popular topic, followed by glass transition.

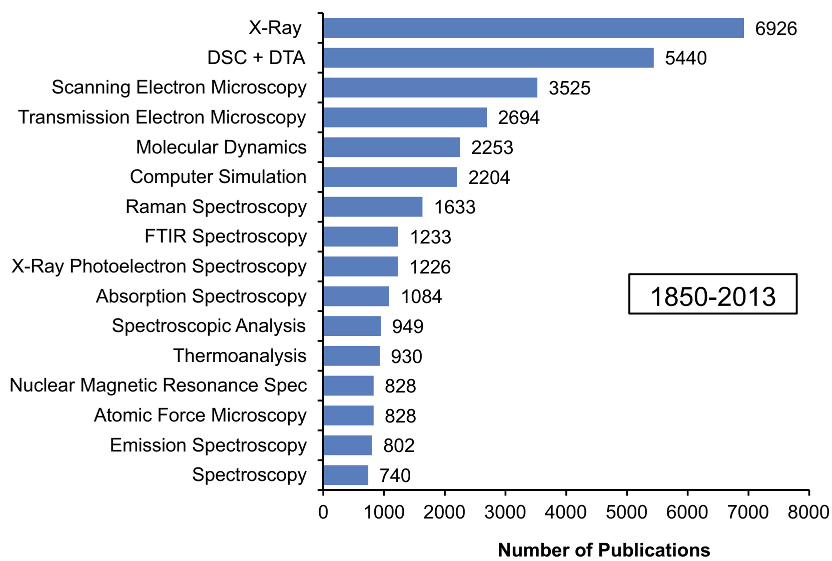

Fig. 18. Total number of glass-related publications organized by characterization technique.

This raises the question of how the downward trajectories in these countries can be reversed so that they can continue to succeed in a much more competitive global environment. The answer to this question has clear relevance for the long-term quality of life in the United States, Japan, and many European countries, where the rate of research has either dramatically slowed or has shown significant declines in recent times. Glass research and development have also not grown sufficiently in many developing countries, except perhaps India, Brazil, and Egypt, the only three among the top 20 most prolific countries in glass research.

Related to this issue is the unfortunate decline of industrial research in the fundamental sciences. Before the breakup of AT&T, the most creative and most prolific research laboratory in the world was an industrial laboratory (Bell Labs)[10] not affiliated with any university. Today, Corning Incorporated stands as the only

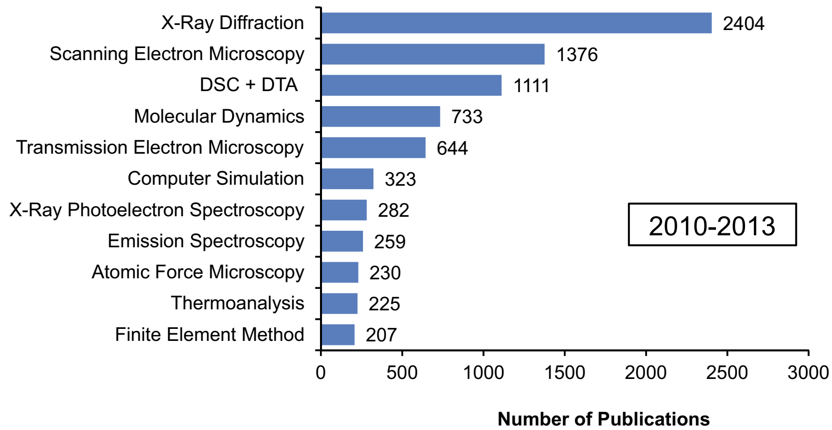

Fig. 19. Most popular characterization methods in recent years (2010–2013).

large company that routinely publishes fundamental research in the peer-reviewed glass and glass-ceramics literature. In the case of Corning, this comes from recognition that the long-term future of the company is dependent on having a healthy pipeline of fundamental and exploratory research activities.[11] This type of research is encouraged and promoted, as it is recognized that the most significant scientific and technological breakthroughs require a sufficient focus on fundamental understanding and scientific exploration. However, Corning is one of the few large companies in the materials sector that still demonstrates a consistent commitment to basic research. This positive corporate attitude toward basic research will need to spread to other companies before the state of industrial glass research as a whole can move beyond incremental development work to more longer-term fundamental research.[12] This is the only way that any hope of significant—and potentially revolutionary—breakthroughs can be achieved.

With the hope of stimulating a renewed interest in fundamental glass research, recently, we published a list of nearly 100 open questions grouped into twelve different areas of glass research.[5] Each of these questions addresses an area that we feel is not currently being given enough attention in the research community. The proposed research areas discussed in this prior work all have ample room for new and exciting breakthroughs in fundamental science. At the same time, many of them address problems of practical industrial concern. We will not repeat these suggestions here, as the interested reader can find the full list of topics in ref. 5.

In lieu of proposing more specific research topics, here, we would like to suggest several broader "grand challenge" problems for glass science and technology. We propose these challenges in a similar spirit as the Grand Engineering Challenges promulgated by the U.S. National Academy of Engineering. These grand challenges are formulated in terms of questions that address some of the most pressing issues facing our world today, as well as the potential role of glassy materials in solving these problems:

1. How can glass be used to combat global warming?[13]
2. How can glass help enable the next generation of renewable energy?[14,15]
3. How can glass help to store energy, for example, with new solid state batteries?[16]
4. How can glass be used to enable safe, affordable drinking water and a clean, pollution-free atmosphere?
5. How can glass be used to reduce energy consumption and eliminate waste?[17]
6. How can glass be used to fight disease and improve human health?[18–24]
7. What is the future role of glass in information and communication technology?[25]
8. Can ultra-strong, high-toughness glasses be developed to improve safety in architectural and other structural applications?[26]
9. How can strong, lightweight glass boost the future of transportation, for example, in electric cars?
10. Can we develop ultra-light, strong glass containers that reduce waste and energy consumption?

11. Can ultra-fast switching chalcogenide glasses be developed into nonvolatile memory media that could be the basis for glass computers?[27]
12. Can ultra-clean optical fibers reach the ultra-low loss absorption limit?
13. Can ultra-strong (>10 GPa), tough, low density, corrosion-, and abrasion-resistant glasses be developed and applied for a number of high-tech applications?
14. Can glass be used as efficient drug or nutrient delivery media for agriculture, animals, and humans?
15. Can glass be manufactured at large scale in a totally sustainable, environmentally friendly way?

This is by no means a complete list. We encourage the reader to think of other ways in which advances in glass science and technology can potentially contribute improvements to global health and prosperity. We also refer the reader to additional publications by Bange and Weissenberger-Eibl,[28] Rohrer,[29] Zanotto and Coutinho,[30] and Hench[31] discussing future opportunities for glass and ceramic materials.

Conclusions

Between 230,000 (keywords in the article title) and 650,000 (keywords in all fields) papers have been published in nearly two centuries of research in glass science and technology. The publication rate has increased roughly exponentially since 1945. While the United States is the most prolific country overall, in recent years, China has taken a commanding lead. Oxide glasses, amorphous carbon, amorphous silicon, and metallic glasses have received the most attention historically and are still the leading focus areas today, with an especially strong showing from Japanese researchers on metallic glasses. Crystallization and glass transition phenomena are the most popular topics of study. Recent years have been characterized by a decline in (scientific) industrial glass research, with Corning Incorporated as the sole industrial laboratory in the top 160 most prolific institutions in the past 4 years. It will require a great concerted effort to counteract this decline of scientific industrial research and also the recent weakening of fundamental research activities in the United States and other historically strong countries. On the other hand, the number of patents issued worldwide has surpassed the number of published scientific articles. This demonstrates the very high level of activity on (practical) technological research.

It is our hope that a renewed focus on glass and materials education, starting at a young age, will help encourage more students to pursue careers in science, technology, and engineering. We have also proposed a series of "grand challenge" questions regarding the use of new glassy materials for solving some of the world's most pressing issues. Answers to these questions are left as a research challenge to glass scientists and technologists, and as an exercise for the reader!

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