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Welcome to the Glass Age

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Glass is one of the world's most transformative materials. Featuring tremendous versatility and distinctive technical capabilities, glass has been responsible for numerous cultural and scientific advancements from windows to optical fiber. Today, the pace of glass innovation is accelerating, thanks to scientists' deep understanding of glass physics and chemistry, combined with modern analytic and control technologies. We believe that the world has entered the Glass Age. We have an unprecedented opportunity to harness the unique capabilities of glass to solve some of our world's most urgent challenges, such as more effective healthcare, cleaner energy and water, and more efficient communication. Realizing the potential of the Glass Age will require collaboration, resources, and support, but it is an opportunity we cannot afford to waste.

Keywords: *nanotech; collaboration; modeling; formulation; fabrication*

Introduction

Throughout history, we have defined epochs by the materials and movements that have transformed civilization. There was the Stone Age, the Bronze Age, and the Iron Age, which gave mankind new tools and methods for expression. More recently, we have defined eras by social, cultural, and technological transitions that not only convey new capabilities, but also capture our aspirations, e.g., the Space Age and the Information Age. In this communication, we present the case for why we are now living in the Glass Age. We begin by describing the unique technical capabilities of glass that make it such a remarkable material. We discuss the transformative impact glass has made on the world in which we live. We then describe some of the most exciting developments in glass science and the opportunities that lie ahead, and conclude by discussing why it is so vital to support research and development in this field and what's at stake for our future.

Remarkable Technical Capabilities

Since denotations of eras by material have thus far been confined to technology prehistory, we must first address the question: Is it anachronistic to define an era by a material? We argue an emphatic no, because, despite the shift to a digital world and the growing fascination with virtual reality, materials remain the building blocks of our society and culture. As technology writer Tim Bajarin notes, "the materials sciences are the lifeblood of all of tech creations."[1] Second, glass is no ordinary material. It is an incredibly versatile platform that scientists and engineers can exploit in nearly limitless ways to unleash remarkable technical

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capabilities. Although the readers of this journal include experts on many of these attributes, there is merit in considering them collectively.

First, glass is one of the world's most enduring engineering materials. Silica glasses get their stability from a continuous network of silicon–oxygen bonds, which remain intact from the time the component sand is mined through the life cycle of the material, which is why glass objects last for centuries. Next, glass is virtually impermeable, which makes it useful for a broad range of applications including hermetic containers, long-lasting displays, advanced substrates for integrated circuits, and new architectural components. An oxygen molecule would take approximately five trillion years to pass through one millimeter of silica glass.[2] Glass also features unprecedented transparency, which makes it uniquely effective for optical and RF transmission. The glass used for optical fiber is more than 30 times as transparent as the purest water. Engineered glass also features tremendous thermal and mechanical stability. High-purity fused silica can withstand processing temperatures of more than 1000°C without compromising its integrity. Additionally, glass is predominantly elastic at room temperature, able to return to its original shape after most stress events. Finally, despite its reputation for being fragile, glass can be engineered to be incredibly strong and damage resistant. Scientists estimate glass's theoretical strength at greater than 15 GPa.

One of the Most Transformative Materials of All Time

Next, we must consider the impact that glass has had on the world. Indeed, glass is arguably one of the most transformative materials of all time. As popular science author Steven Johnson writes, "A world without glass would strike at the foundation of modern progress."[3]

The development of spectacles in the 13th century allowed monks to copy and study religious texts, and helped popularize reading following the invention of the printing press. The development of crown glass in the 14th century allowed people to incorporate windows into their homes to let in light, while keeping out cold, wind, and rain. Hans Lipperhey's invention of the telescope in the early 17th century expanded our understanding of the structure and wonderment of the universe in which we live. Antoni van Leeuwenhoek's development of the microscope enabled the discovery of the cell, bacteria, and viruses, leading to life-saving developments such as vaccines and antibiotics. Glass mirrors led to the formal use of linear perspective during the Renaissance, encouraging artists such as Rembrandt to paint self-portraits. The development of tempered glass by Austrian chemist Rudolf Seiden in the early 1900s led to safer military gear and automotive windshields. Glass's numerous applications in architecture transformed urban planning, inspiring famed architect Le Corbusier to declare, "Glass is the most miraculous means of restoring the law of the sun."[4] Glass lenses and picture tubes created major shifts in popular culture by enabling photography, motion pictures, and television. And the invention of low loss optical fiber by Peter Schultz, Robert Maurer, and Donald Keck in 1970 created the backbone of the Internet and ushered in a communications revolution.

The Glass Age

In light of glass's long history and profound impact on the world already, why do we believe we are living in the Glass Age today? The first reason is the ubiquity of glass and its central role in our day-to-day lives. We interact with glass screens on our computers and smart phones, take pictures through glass lenses, transmit and receive information via glass fibers, protect materials in glass covers and containers, and incorporate decorative and functional glass elements into our homes.

The second reason is the accelerating pace of glass innovation. In the past 10 years alone, glass scientists have unleashed capabilities that we could not have imagined a short time ago. Our own company, Corning Incorporated, has a 165-year history of glass innovations, yet some of its most recent innovations have happened in relatively quick succession. In the past decade, Corning scientists have developed chemically strengthened glass 1 mm thick that can withstand the impact of a baseball traveling at more than 100 km/h, thin strands of optical fiber that can wind around a pencil without losing signal quality, flexible glass that is slimmer than a dollar bill, and antimicrobial glass that suppresses the growth of mold, mildew, fungi, and bacteria. Researchers at the University of Cambridge, Aalborg University, and Wuhan University of Technology have created hybrid glasses from metallic–organic frameworks.[5] Researchers at Sheffield University's

Department of Materials Science and Engineering are developing vitrification techniques for converting hazardous nuclear waste into inert materials to increase the safety and practicality of nuclear energy.[6] Scientists at Mo-Sci Corporation have developed bioactive glasses that heal flesh wounds by stimulating the body's natural defenses.[7] And researchers have made great strides in understanding glass transition and relaxation, which Nobel Prize winning physicist Philip Anderson famously declared "The deepest and most interesting unsolved problem in solid state theory."[8]

But ultimately, the answer to the question lies in the transition from magic to science. For centuries, laymen and scientists alike marveled at the fourth century Lycurgis Cup and its "magical" ability to appear jade-green from some perspectives and blood-red from others, without understanding that the effect was caused by the presence of tiny silver and gold particles. When monks used early spectacles as reading aids, they did not understand the principle of refraction. When Murano glassmaker Angelo Barovier created extraordinarily clear crystal in the 15th century by melting only the whitest river stones with the purified residues from the ashes of halophilic plants, he did not know how silica interacted with sodium and manganese. Today, we understand how different formulation and fabrication techniques combine to determine the atomic state and structure of a glass, which in turn control the mechanical, thermal, and optical properties. This understanding has prompted scientists John Mauro, Adam Ellison, and David Pye to describe glass as "the quintessential nanotech material."[9] Our understanding of glass physics and chemistry also allows us to move away from time-consuming trial-and-error experimentation to sophisticated modeling techniques to predict both manufacturing-related attributes (e.g., viscosity, liquidus temperature, and refractory compatibility) and end-use properties (e.g., elastic moduli, compressive stress, and damage resistance).[10] This not only dramatically accelerates the design of new industrial glasses, but also allows us to distribute results on a broader scale because the processes become repeatable. This is why the pace of glass innovation has increased so dramatically in recent years, and why we believe some of our greatest innovations still lie ahead. The true excitement of the Glass Age derives from combining the rich palette of the Periodic Table with modern analytic and control technologies to unleash new capabilities for a broad range of industries.

Conclusion and a Call to Action

We believe that we have an unprecedented opportunity to harness the power of glass to solve some of our world's most urgent challenges. As we strive to meet the needs of an aging population, glass plays a vital role in health and medicine by enabling new tools for biomedical discovery and therapeutic delivery. As we strive to make our environment greener, glass offers solutions, such as electrochromic windows, to make our homes more energy efficient, solar technologies to provide cleaner energy, and new tools for water purification. As we continue to improve the way we interact with the world and each other, glass can enable quantum communications with unlimited bandwidth and exceptional security. And as we dissolve the boundaries between the physical and virtual world, glass can enable new display technologies such as holographic applications. This issue of *IJAGS* illustrates some of the most cutting-edge glass research that is helping to enhance healthcare, explore planetary and geological phenomena, and augment reality.

But we will not realize the promise of the Glass Age without collaboration, resources, and support. We need to educate organizations and influencers about the unique capabilities, tremendous versatility, and significance of glass to our world. We must build bridges in the global glass community and create strong collaborations between corporations, universities, and professional associations. We need a healthy supply of funding from government agencies and the private sector, and we need to make sure that the distribution of funding and research is weighted toward the fields that arc most relevant to future industrial applications in orr1er to ensure both the greatest benefits to society and career opportunities for graduating glass scientists and engineers. We need to invest in the science of glass processing as well as glass composition because that is how we turn innovative compositions into useful objects. We should also encourage scientists to conduct exploratory research and self-directed projects, which have led to some of the greatest breakthroughs in glass science, such as Frank Hyde's development of vitreous silica, the foundation for numerous innovations from telescope mirrors to optical fiber.

Earlier, we noted the evolution of glass from magic to science. We now have the opportunity to turn science back into magic by unleashing capabilities that make our world cleaner, our lives healthier, our experiences richer, and our knowledge more expansive. Let us not waste it.

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References

1. T. Bajarin, "Why Glass Is Critical to the Future of Tech," *Recode.net* (2015). http://www.recode.net/2015/12/14/11621456/why-glass-is-critical-to-the-future-of-tech (accessed July 16, 2016).
2. Estimation based on F. J. Norton, "Permeation of Gaseous Oxygen Through Vitreous Silica," *Nature* 191, 701 (1961).
3. S. Johnson, *How We Got to Now: Six Innovations that Made the Modern World*, 1st edition, 41, Riverhead Books, New York, 2014.
4. R. Lattimore (trans.), "Glass: The Fundamental Material of Modern Architecture by LeCorbusier," *West 86th*, 19 [2] (2012). http://www.west86th.bgc.bard.edu/translated-text/glass-modern-architecture.html (accessed July 17, 2016).
5. T. D. Bennet *et al.*, "Hybrid Glasses from Strong and Fragile Metal-Organic Framework Liquids," *Nat. Commun.*, 6 DOI: 10.1038/ncomms9079.
6. P. A. Binham, N. C. Hyatt, and R. J. Hand, "Vitrification of UK Intermediate Level Radioactive Wastes Arising from Site Decommissioning: Property Modelling and Selection of Candidate Host Glass Compositions," *Glass Technol. Eur. J. Glass Sci. Technol. Part A*, 53 [3] 83–100 (2012).
7. P. Wray, "Cotton Candy that Heals? Borate Glass Nanofibers Look Promising," *Am. Ceram. Soc. Bull.*, 90 [4] 25–30 (2011).
8. P. W. Anderson, "Through the Glass Lightly" (lett.), *Science*, 267 [5204] 1615–1616 (1995).
9. J. C. Mauro, A. J. Ellison, and L. D. Pye, "Glass: The Nanotechnology Connection," *Int. J. Appl. Glass Sci.*, 4 64–75 (2013).
10. J. C. Mauro, A. Tandia, K. D. Vargheese, Y. Z. Mauro, and M. M. Smedskjaer, "Accelerating the Design of Functional Glasses Through Modeling," *Chem. Mater.*, 28 [12] 4267–4277 (2016).