intrinsically in vitro in such a short period of time, and display normal human cerebral cortex development broadly, if not perfectly. They do not grow beyond a 4-mm-diameter size, apparently because the lack of a blood supply limits access to nutrients. They lack many brain parts and cell types. And it is not yet clear how close the electrical potentials in organoids are to brain potentials, nor whether organoid neurons connect with the regions seen in an actual brain. Ethicists need not worry just yet, and may never need to worry, about the philosophical implications of "consciousness in a dish." Indeed, perhaps the more interesting philosophical implication of these organoids is the extent to which these seemingly bland and undifferentiated (albeit totipotent) ES cells can self-assemble into such a complex emergent structure.

As tissue engineering further improves the structure and reproducibility of these organoids, they will likely find their strongest application in the modeling of diseases (*7*). Combining new stem cell technologies with genome-editing tools, such as TALEN and CRISPR-Cas9 (*8*), will allow genetic modeling of many neurological and neuropsychiatric disorders. This may allow rapid screening of disease phenotypes, pathogenic mechanisms, and drug effects. Functional studies of human-specific genetic changes using human cerebral organoids may also be possible, providing insight into similar genes that act differently in humans and other mammals throughout evolution. Human pluripotent ES cells and cerebral organoids promise to advance our understanding of neuroscience and stem cell biology … and quickly.

Reference and Notes

1. J. H. Lui, D. V. Hansen, A. R. Kriegstein, *Cell* **146**, 18 (2011).
2. M. A. Lancaster *et al.*, *Nature* **501**, 373 (2013).
3. Y. Sasai, *Nature* **493**, 318 (2013).
4. J. A. Siegenthaler *et al.*, *Cell* **139**, 597 (2009).
5. S. B. Lizarraga *et al.*, *Development* **137**, 1907 (2010).
6. J. A. Barrera *et al.*, *Dev. Cell* **18**, 913 (2010).
7. Y. Sasai, *Cell Stem Cell* **12**, 520 (2013).
8. T. Gaj, C. A. Gersbach, C. F. Barbas 3rd, *Trends Biotechnol.* **31**, 397 (2013).

Acknowledgments: We thank M. A. Lancaster for discussion on the experimental details; W. F. Hu, M. B. Woodworth, and D. Jayaraman for critical reading; and the Walsh lab for general discussion.

10.1126/science.1245812

MATERIALS SCIENCE

Structure and Motion of a 2D Glass

The structure and dynamics of a two-dimensional silica film provide fundamental insights into amorphous materials.

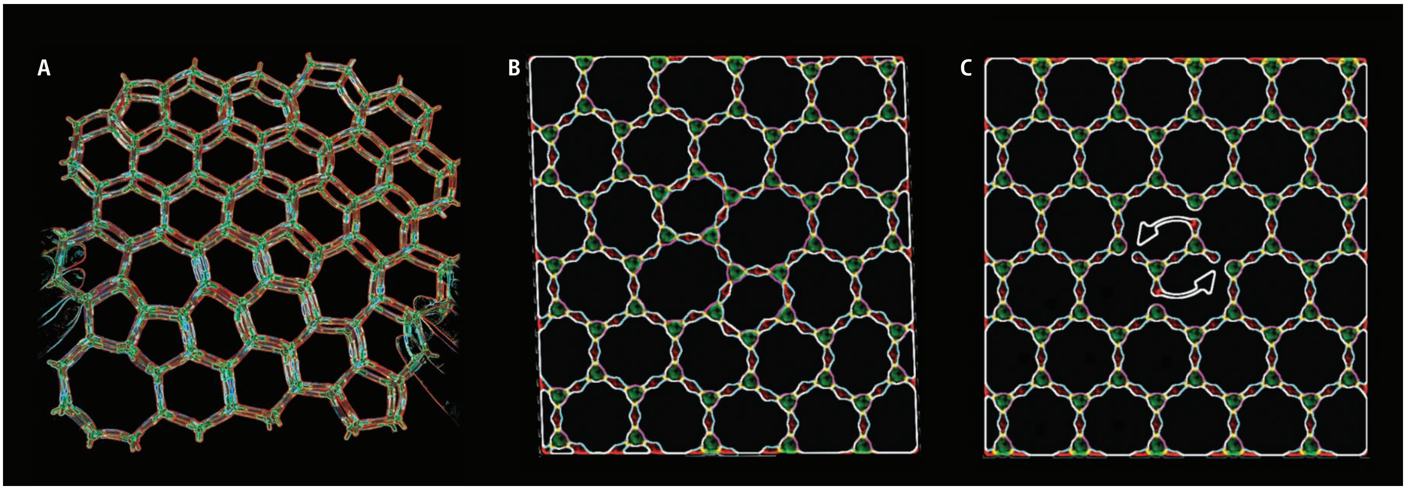
Markus Heyde

Fritz Haber Institute of the Max Planck Society, Faradayweg 4-6, 14195 Berlin, Germany. E-mail: heyde@fhi-berlin.mpg.de

Silicon oxide (silica) glass plays a key role in many modern technologies, from semiconductor devices and optical fibers to supporting materials in heterogeneous catalysis and novel durable glasses. Yet little is known about the atomic structure of amorphous materials. Recent studies of two-layer glass structures have started to shed light on the structure of amorphous silica (*1*, *2*). On page 224 of this issue, Huang *et al.* provide direct evidence for dynamic rearrangements of such two-dimensional (2D) silica films under a probing electron beam (*3*).

Diffraction methods are widely used to determine the structures of crystals and their surfaces. However, diffraction is of limited value for analyzing amorphous materials, which have no long-range order and periodicity. Zallen once wrote that "the atomic structure of an amorphous solid is one of its key mysteries, and structural information must be won with great effort" (*4*).

Transmission electron microscopy (TEM) and scanning tunneling microscopy (STM) methods have the potential to overcome these difficulties. In TEM, increased resolution as a result of aberration correction has brought a renaissance to the field (*5*). Scanning probe microscopes are now also capable of true atomic resolution. Molecular motions or even chemical reactions can be followed with both techniques (*6*–*8*). It has been proposed that noncrystalline materials can also be characterized with these methods (*9*, *10*), but this has not yet been realized.



Follow the motion. Silica consists of silicon and bridging oxygen atoms. In the 2D structure, crystalline silica has only six-membered rings. Zachariasen proposed more than 80 years ago that amorphous silica forms a network of rings of different sizes (*12*); recent studies of 2D silica bilayers have verified this model (**A**) (*1*, *2*). Huang *et al.* now provide experimental evidence for a transformation from amorphous (**B**) to crystalline structures (**C**) in such bilayers.

CREDIT: FIGURE PANELS B AND C FROM (1)

Published by AAAS

It is only as a result of the 2D flatness and defined structure of a recently developed class of materials that the characterization of amorphous solids at the atomic scale has become possible. Freund initiated the synthesis of thin films of silica and other oxides (*11*). The sample system that offers the clearest insights into amorphous systems is the bilayer silica film. The atomic structure of these bilayers can be tuned between crystalline and vitreous phases. Studies of such films have finally verified the atomic glass network, also known as random network theory, postulated by Zachariasen (*12*) more than 80 years ago. The film structure resembles the original 2D drawings in all of its atomic details (see the figure, panel A).

Recent studies with STM (*1*), followed by TEM (*2*), have revealed the atomic structure of amorphous silica bilayer films. The characterization of real-space data allows for a clear assignment of atomic sites. The position of oxygen and silicon atoms can be determined, and the ring structures, and their distribution and local neighborhood can be directly visualized. Chemical sensitivity imaging with STM and atomic force microscopy has allowed direct assignment of all atomic species on the surface (*13*). Furthermore, the structural transition from a crystalline to an amorphous domain has been investigated by STM imaging of an interface region (*14*).

Huang *et al*. now report the observation of structural rearrangements in an amorphous silica bilayer film. The authors used a probing electron beam to deliberately cause these rearrangements. Remarkable images and videos show the movements of structural building blocks at the atomic scale. The opening and closing of ring structures and the subsequent rearrangements can be directly observed. The results open new ground for modeling the atomic structure and dynamics in glasses. By providing the opportunity to study vitreous materials at the atomic level, this unique model system is likely to have great impact on the general understanding of dynamic processes in amorphous bulk materials.

Future work might allow a direct assessment of atomic structures at the transition temperatures, where the liquid solidifies to either the crystalline or the amorphous state. Doping, adsorption, growth, and chemical reactivity studies of 2D glasses are another focus of ongoing experiments. Band structure measurements or other material properties of 2D silica films might reveal unexpected features similar to those of graphene. Finally, 2D silica films can be grown on various substrates. Such films may find applications as new gate materials in the semiconductor industry.

References

1. L. Lichtenstein *et al*., *Angew. Chem. Int. Ed.* **51**, 404 (2012).
2. P. Y. Huang *et al*., *Nano Lett.* **12**, 1081 (2012).
3. P. Y. Huang *et al*., *Science* **342**, 224 (2013).
4. R. Zallen, *The Physics of Amorphous Solids* (Wiley, New York, 1983).
5. H. Rose, *Optik* **85**, 19 (1990).
6. E. Nakamura, *Angew. Chem. Int. Ed.* **52**, 236 (2013).
7. J. Wintterlin, S. Völkening, T. V. W. Janssens, T. Zambelli, G. Ertl, *Science* **278**, 1931 (1997).
8. D. G. de Oteyza *et al*., *Science* **340**, 1434 (2013).
9. R. Wiesendanger *et al*., *Surf. Sci.* **181**, 46 (1987).
10. W. Raberg, V. Lansmann, M. Jansen, K. Wandelt, *Angew. Chem. Int. Ed. Engl.* **36**, 2646 (1997).
11. T. Schroeder *et al*., *Surf. Rev. Lett.* **7**, 7 (2000).
12. W. H. Zachariasen, *J. Am. Chem. Soc.* **54**, 3841 (1932).
13. L. Lichtenstein, M. Heyde, H.-J. Freund, *J. Phys. Chem. C* **116**, 20426 (2012).
14. L. Lichtenstein, M. Heyde, H.-J. Freund, *Phys. Rev. Lett.* **109**, 106101 (2012).

10.1126/science.1245217

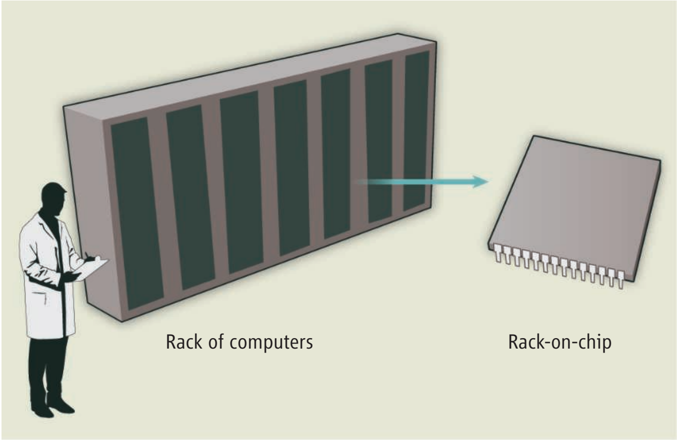
APPLIED PHYSICS

Directing Data Center Traffic

A data center design based on an integrated chip-scale approach will be required to deal with the increasing volumes of Internet traffic.

Yeshaiahu Fainman[1] and George Porter[2]

The widespread adoption of cloud computing has led to the construction of large-scale data centers hosting applications serving millions of users. Underpinning these data centers are tens to hundreds of thousands of servers that communicate internally with each other at high server-to-server bandwidths that are orders of magnitude greater than their connections to end users. Today's data centers consist of racks of 20 to 40 discrete servers, each configured with 8 to 16 CPU cores, hundreds of gigabytes of memory, and potentially tens of terabytes of storage. To meet cost and energy scaling requirements, a new data center design will be required in which a rack of multiple, discrete servers, including the top-of-rack network switch, is integrated into a single chip (see the figure). These integrated "rack-on-chips" will be networked, internally and externally, with both optical circuit switching (to support large flows of data), and electronic packet switching (to support high-priority data flows).



Shrinking data centers. Evolution of a data center design in which a rack of multiple, discrete servers, including the top-of-rack network switch, is integrated into a single chip.

Numerous technological advances must be made for this vision to be realized. First, the energy efficiency of the processor cores must be improved to facilitate efficient heat dissipation, and this problem is the focus of many researchers in the field. We will focus instead on supporting better intra- and interprocessor networking. Although industrial efforts are under way to densely integrate optical networks within multicore processors (*1*), we argue that integrating rack-level networking requires more aggressive technology advancements.

Historically, optical technologies have enabled a large number of advancements in networking and communications, leading to the existence of the Internet with long-distance data transmission

CREDIT: P. HUEY/SCIENCE

---

[1] Department of Electrical and Computer Engineering, University of California, San Diego, 9500 Gilman Drive, La Jolla, CA 92093, USA. [2] Department of Computer Science and Engineering, University of California, San Diego, 9500 Gilman Drive, La Jolla, CA 92093, USA. E-mail: fainman@eng.ucsd.edu; gmporter@cs.ucsd.edu

Published by AAAS