Science AAAS

Directing Data Center Traffic

Yeshaiahu Fainman and George Porter

Science **342**, 202 (2013);
DOI: 10.1126/science.1242906

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

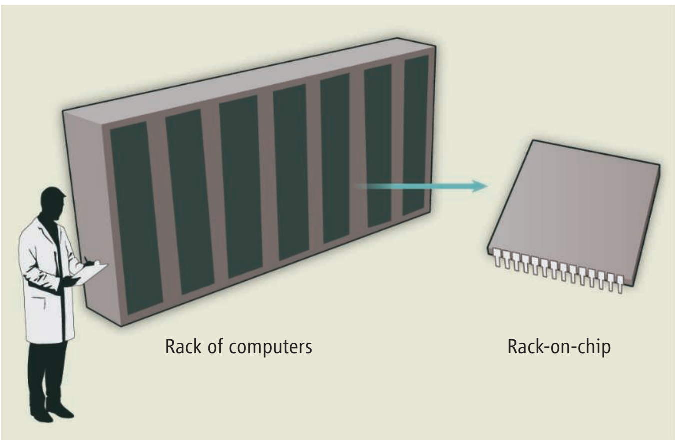
A data center design based on an integrated chip-scale approach will be required to deal with the increasing volumes of Internet traffic.

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).

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



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.

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

driven by power- and time-efficient regeneration. Recently, integrating circuit switching with packet switching has been examined with the goal to create hybrid networks within individual data centers (*2*, *3*), using optics to provide more efficient services for applications relying on large flows of data. The key insight is that by quickly reconfiguring optical paths, changes in traffic workloads can be supported. As we envision optical networking interconnecting tightly integrated rack-on-chip designs, providing both on- and off-chip connections, we need even faster optical reconfiguration and cost-effective integration to support the highly variable traffic flows between individual processors on the chip and among the chips. Next-generation data center designs built with rack-on-chip designs will need to support both circuit and packet switching.

Each processor in the rack-on-chip design must have a transceiver, consisting of a transmitter and receiver. Each processor core would be interconnected with the other cores through an optical circuit switch, which allows communication paths to be set up and reconfigured between the cores (similar to the top-of-rack switch in current data centers). The high bandwidth between processor cores will require using both spatial and spectral (wavelengths) degrees of freedom, with wavelength-division multiplexing. Pairing each processor core with a transceiver requires miniaturizing transceivers and integrating them with the rack-on-chip design. The transceiver should be low-power and highly efficient, meaning that excessive heat is not generated, and that only a small number of photons over relatively short distances should be necessary to represent a bit of information, transmitted with low loss, and detected with an efficient receiver.

Nanophotonic technologies may meet the requirements for miniaturizing transceivers and circuit switches, using metamaterials, resonant nanostructures, nanoscale lasers, modulators, and receivers and switches. For example, it is possible to use advanced lithography to write and assemble devices and circuits into subsystems that support the rack-on-chip design. Recent advances in silicon photonics using complementary metal-oxide semiconductor–compatible manufacturing processes (*4*) mean that chip-scale, highly integrated optoelectronic solutions can be realized at low cost while meeting the other needs of scalability, bandwidth, fault tolerance, and energy efficiency. However, the efficient generation of light on a silicon chip is still in its infancy, and may not be able to overcome the fundamental issues prohibiting efficient generation of light in indirect band-gap semiconductors. Alternative solutions similar to the delivery of electrical power from off-chip sources will bring the optical fields into the rack-on-chip. Or photons can be generated on the chip—for example, through heterogeneous integration of III-V compound semiconductor devices, such as nanolasers (*5*, *6*).

To achieve highly scalable optical circuit architectures that can support many processor cores, each switching element must be miniaturized, relying on high optical nonlinearities that are very difficult to achieve in natural materials. One approach could be to develop nonlinear metamaterials, which are deeply subwavelength composites, engineered on atomic scale and/or a scale of a few atomic layers, exhibiting a qualitatively different response to radiation than that predicted by the effective medium theories of classical physics (e.g., crystal symmetry breaking, exotic semimetal modulation materials, and composite metal-dielectric nonlinear materials). The high nonlinear coefficient of new nonlinear metamaterials together with small-volume localized modes will enable low energy-per-bit operation.

Once this optical networking technology is integrated with electronic processors as a rack-on-chip design, the number of such chips can then be scaled up to meet the needs of future data centers. This will enable delivering new kinds of applications, such as computational climate modeling and biological applications, big data applications harnessing huge data sets, and online applications delivered to hundreds of millions of users.

References and Notes

1. M. Asghari, A. Krishnamoorthy, *Nat. Photon.* **5**, 268–270 (2011).
2. N. Farrington *et al*., in *Proceedings of the ACM 2010 SIGCOMM Conference*, New Delhi, India, 30 August to 3 September 2010 (Association for Computing Machinery, New York, 2010), pp. 339–350.
3. G. Wang *et al*., in *Proceedings of the ACM 2010 SIGCOMM Conference*, New Delhi, India, 30 August to 3 September 2010 (Association for Computing Machinery, New York, 2010), pp. 327–338.
4. "Luxtera, Freescale collaborate on CMOS photonics fab," http://optics.org/article/39426, 9 June 2009.
5. M. P. Nezhad *et al*., *Nat. Photon.* **4**, 395–399 (2010).
6. M. Khajavikhan *et al*., *Nature* **482**, 204–207 (2012).

Acknowledgments: Supported by the Google Focused Research Award, the Defense Advanced Research Projects Agency, NSF, NSF Engineering Research Center for Integrated Access Networks, the Office of Naval Research, the Cymer Corporation, the U.S. Army Research Office, and the UCSD Center for Networked Systems.

10.1126/science.1242906

DEVELOPMENT

Getting Your Gut into Shape

Benjamin D. Simons[1,2,3]

Mechanical forces exerted between tissue layers in the intestine are all that is needed to make gut villi.

The specification and patterning of plant and animal tissues relies upon the spatial and temporal coordination of biochemical and physical processes at the molecular, cellular, and tissue scale (*1*, *2*). Yet, despite access to genetic manipulation techniques and in vivo live-imaging platforms, progress in understanding how these processes interact in development has proved challenging. Reliant on the interplay of gene regulatory and mechanical cues, the emergence of spatial organization in the gut epithelium provides a paradigm for morphogenic processes in vertebrates. On page 212 of this issue, Shyer *et al*. (*3*) combine in vitro analyses of tissue explants with the development of a biophysical modeling scheme to show that the seemingly complex process of intestinal villi specification can be explained simply through the action of mechanical constraints.

In vertebrates, the digestive tract arises from a primitive gut tube (*4*). As the gut matures, the foregut, midgut, and hindgut become morphologically distinct, before differentiating into specialized primary organs: The foregut (pharynx, esophagus, and stomach) is responsible for ingestion and the initiation of digestion, whereas the midgut (small intestine) provides the major site of digestion and nutrient absorption, and the hindgut (large intestine) resorbs water and expels waste. To fulfill these functions, the

[1]Cavendish Laboratory, Department of Physics, J. J. Thomson Avenue, University of Cambridge, Cambridge CB3 0HE, UK. [2]The Wellcome Trust/Cancer Research UK Gurdon Institute, University of Cambridge, Tennis Court Road, Cambridge CB2 1QN, UK. [3]Wellcome Trust-Medical Research Council Stem Cell Institute, University of Cambridge, UK. E-mail: bds10@cam.ac.uk