MATERIALS SCIENCE

Primed to Remember

Dan Hewak and Behrad Gholipour

Human memory can be primed. Expose the brain, even unconsciously, to a word or object, and in subsequent exposures, the memory synapses are faster, and more details are remembered for longer times (1). Why not do the same with the electronic memories in our computers, phones, digital cameras, and game consoles? On page 1566 of this issue, Loke et al. (2) show that writing speeds in next-generation electronic memory—ones based on changing a material’s phase from a crystal to a glass—have increased substantially through a preswitching incubation process. This priming enabled them to break the 1-ns barrier for electronic switching. On page 1561, Nam et al. (3) remarkably provide images and recordings of the electronic changes that occur in memory cells only a few nanometers in size that allow us to watch the switching mechanism. Both of these studies provide valuable information on the physics of phase-change memory (PCM) and also clues on how this technology could change computer architectures.

The most common nonvolatile memory (one that retains data with the power off) used in laptop computers, smartphones, and video-game consoles is flash memory, which traps a few electrons within an electronic “gate”; the charged state represents a bit of information. However, the size of flash memory cells has been shrunk to near fundamental limits; smaller cells would lose memory information from electrons leaking through the gate into neighboring cells.

Unlike flash memory, PCM does not depend on trapped electrons, and memory cells can be reduced to much smaller sizes. Phase-change materials for memory applications are typically metallic alloys, commonly based on germanium, antimony, and tellurium (Ge₅Sb₅Te₅, or GST). These compounds can easily be switched between the amorphous and crystalline phase, by heating with a laser (as in a DVD or CD disk), or with a small electrical current when the GST is part of an electronic memory chip. Like flash memory, PCM is nonvolatile, and once switched, the phase remains stable until the cell is rewritten. In addition to smaller cell sizes, PCM is inherently faster and can switch repeatedly tens of millions of times, versus only several thousand times for flash memory. Electronic PCM could allow computers to boot instantaneously and greatly enhance the overall performance of computer networks. Many researchers argue that these materials will provide a universal memory technology that could replace both magnetic hard drive and dynamic random-access memory, and even mimic the human brain (4).

Breaking the speed limits of PCM is how Loke et al. describe their recent advances. Priming of human memory works best when the two stimuli are in the same modality (e.g., visual priming works best with visual cues). A weak electric current primed the cell, then a short higher-intensity pulse stored the bit of information. This tandem process significantly sped up crystallization; with the potential to mimic the human brain, phase-change memories are operating faster, while imaging provides further insight into the switching mechanism.
switching speeds of 500 ps were reached for the smallest cells. They used computer simulations to help identify a structural origin to this speed increase, which they believe is induced through thermal prestructuring (see the figure, panel A). As measured during this electronic priming, a resistance dip suggests some permanent preswitching structural modification.

The effects of priming the human brain can be imaged by monitoring the brain’s frontal region activity using an electroencephalogram (5). In an analogous fashion, Nam et al. extend our understanding of the phase-change mechanism by using in situ transmission electron microscopy (TEM) to watch switching directly. By using single-crystal GST nanowires, which provide an open geometry, they viewed the material during the actual switching process (see the figure, panel B). Their direct observation of amorphization in a crystalline phase-change material revealed astonishing insight into the phase-change mechanism. When a voltage was applied across the nanowire, the TEM imaging showed visible contrast changes associated with the now characteristic resistance dip. With a continuously increasing current, defects became mobile and began to propagate along the direction of hole-carrier motion.

At the point of lowest resistance, the movement jammed and a tangled region of highly accumulated dislocations formed, which was followed by switching into an amorphous state. This glassy state appeared as a clear bright line and was confirmed as amorphous by electron diffraction measurements. Nam et al. make the analogy of traffic on a highway, in which a simple analytical model predicts a sharp catastrophic jamming transition when the vehicle density exceeds a certain fraction of the maximum packing density (6). In an inspired next step, they created a notch in their nanowire, akin to closing a lane on a busy highway. Defects piled up and an amorphous band appeared at the restriction (see the figure, panel C).

Recently, it has been argued that PCM materials do not change from glass to crystal by melting to a liquid and resolidifying, but rather transform via an all solid-state process. Nam et al. may have provided visual evidence of this hypothesis. As Kolobov et al. (7) explained, “distortions in the crystalline phase may trigger a collapse of long-range order, generating the amorphous phase without going through the liquid state, upsetting yet another commonly held belief that attributes the change in properties to the loss of long-range order.”

Unlike human brains, today’s computers deal with processing and memory separately. Data are constantly moved around, resulting in a speed and power “bottleneck.” Kuzum et al. (8) describe brain-inspired computing and identified phase-change materials as ideal for the implementation of synaptic plasticity. Unlike binary memory applications, they used the continuous transition between resistance levels of phase-change states in an analog manner to emulate biological synapses. Wright et al. demonstrated that phase-change materials can both store and process information simultaneously (9) and could be used to make artificial neurons and synapses. Another major hurdle is power consumption; supercomputers consume substantially more energy than the human brain while “thinking” (10). These studies, along with recent new PCM designs by Xiong et al. (11), show that there is promise for power reductions through the use of PCM technology.

The studies by Loke et al. and Nam et al., along with related work in other labs, should not only pave the way for phase-change memories with ultrafast switching speeds, low-energy consumption, and reduced memory cell sizes, but also lead to a better understanding of the mechanisms responsible for the phase-change phenomena that could further improve switching speeds. The potential to emulate the human nervous system is gaining increasing attention, as these combined works provide further evidence that phase-change materials could be used to make artificial neurons and synapses.

References


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ECOLOGY

Biotic Multipliers of Climate Change

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A focus on species interactions may improve predictions of the effects of climate change on ecosystems.

Many species face uncertain fates under climate change. Some will persist by shifting their range or adapting to local conditions, whereas others will be lost to extinction. Efforts to lessen the impacts of climate change on biodiversity depend on accurate forecasts. Most studies aiming to identify likely winners and losers consider species one at a time with a “climate envelope” approach that correlates species’ occurrences with climatic and environmental variables. Using this method, researchers have predicted that by 2050, 15 to 37% of species will be faced with extinction (1). But which species are most likely to be under threat? And how will their loss affect the broader ecological community?

The climate envelope approach ignores a core truth of ecology: Species interact with each other in ways that deeply affect their viability. Certain species impart particularly strong effects on others. Consequently, climate change impacts on these species could initiate cascading effects on other species. In effect, these species act as biotic multipliers of climate change. The inherent complexity of species interaction networks has discouraged their consideration in predictions. Emerging research illustrates that trophic interactions are especially strong candidates for biotic multipliers of climatic change. Focusing on these species and their interactions is one path through the complexity.

Recent findings highlight the importance of undisturbed vertical interactions involv-
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Editor's Summary

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