Atom-thin Walls Could Smash Size, Memory Barriers in Next-gen Devices

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For all of the unparalleled, parallel-processing, still-indistinguishable-from-magic wizardry packed into the three pounds of an adult human brain, it obeys the same rule as the other living tissue it controls: Oxygen is a must.

So it was with a touch of irony that Evgeny Tsymbal offered his explanation for a technological wonder — movable, data-covered walls mere atoms wide — that may eventually help computers behave more like a brain.

“There was unambiguous evidence that oxygen vacancies are responsible for this,” said Tsymbal, George Holmes University Professor of physics and astronomy at the University of Nebraska–Lincoln.

In partnership with colleagues in China and Singapore, Tsymbal and a few Husker alumni have demonstrated how to construct, control and explain the oxygen-deprived walls of a nanoscopically thin material suited to next-gen electronics.

Unlike most digital data-writing and -reading techniques, which speak only the binary of ones and zeroes, these walls can talk in several electronic dialects that could allow the devices housing them to store even more data. Like synapses in the brain, the passage of electrical spikes sent via the walls can depend on which signals have passed through before, lending them an adaptability and energy-efficiency more akin to human memory. And much as brains maintain memories even when their users sleep, the walls can retain their data states even if their devices turn off — a precursor to electronics that power back on with the speed and simplicity of a light.

The team investigated the barrier-smashing walls in a nanomaterial, named bismuth ferrite, that can be sliced thousands of times thinner than a human hair. Bismuth ferrite also boasts a rare quality known as ferroelectricity: The polarization, or separation, of its positive and negative electric charges can be flipped by applying just a pinch of voltage, writing a one or zero in the process. Contrary to conventional DRAM, a dynamic random-access memory that needs to be refreshed every few milliseconds, that one or zero remains even when the voltage is removed, granting it the equivalent of long-term memory that DRAM lacks.

Usually, that polarization is read as a one or zero, and flipped to rewrite it as a zero or one, in a region of material called a domain. Two oppositely polarized domains meet to form a wall, which occupies just a fraction of the space dedicated to the domains themselves. The few-atom thickness of those walls, and the unusual properties that sometimes emerge in or around them, have cast them as prime suspects in the search for new ways to squeeze ever-more functionality and storage into shrinking devices.

Still, walls that run parallel to the surface of a ferroelectric material — and net an electric charge usable in data processing and storage — have proven difficult to find, let alone regulate or create. But about four years ago, Tsymbal began talking with Jingsheng Chen from the National University of Singapore and He Tian from China's Zhejiang University. At the time, Tian and some colleagues were pioneering a technique that allowed them to apply voltage on an atomic scale, even as they recorded atom-by-atom displacements and dynamics in real time.

Ultimately, the team found that applying just 1.5 volts to a bismuth ferrite film yielded a domain wall parallel to the material's surface — one with a specific resistance to electricity whose value could be read as a data state. When voltage was withdrawn, the wall, and its data state, remained.

When the team cranked up the voltage, the domain wall began migrating down the material, a behavior seen in other ferroelectrics. Whereas the walls in those other materials had then propagated perpendicular to the surface, though, this one remained parallel. And unlike any of its predecessors, the wall adopted a glacial pace, migrating just one atomic layer at a time.

Its position, in turn, corresponded with changes in its electrical resistance, which dropped in three distinct steps — three more readable data states — that emerged between the application of 8 and 10 volts.

Renderings of a neutral domain wall perpendicular to the surface of a ferroelectric material (left) and a charged wall parallel to the surface (right). Red arrows represent positive charges, with blue signifying the negative.

The researchers had nailed down a few W's — the what, the where, the when — critical to eventually employing the phenomenon in electronic devices. But they were still missing one. Tsymbal, as it happened, was among the few people qualified to address it.

"There was a puzzle," Tsymbal said. "Why does it happen? And this is where theory helped."

Most domain walls are electrically neutral, possessing neither a positive nor a negative charge. That's with good reason: A neutral wall requires little energy to maintain its electric state, effectively making it the default. The domain wall the team identified in the ultra-thin bismuth ferrite, by contrast, possessed a substantial charge. And that, Tsymbal knew, should have kept it from stabilizing and persisting. Yet somehow, it was managing to do just that, seeming to flout the rules of condensed-matter physics.

There had to be an explanation. In his prior research, Tsymbal and colleagues had found that the departure of negatively charged oxygen atoms, and the positively charged vacancies they left in their wake, could impede a technologically useful outcome. This time, Tsymbal's theory-backed calculations suggested the opposite — that the positively charged vacancies were compensating for other negative charges accumulating at the wall, essentially fortifying it in the process.

Experimental measurements from the team would later show that the distribution of charges in the material lined up almost exactly with the location of the domain wall, exactly as the calculations had predicted. If oxygen vacancies turn up in other ferroelectric playgrounds, Tsymbal said, they could prove vital to better understanding and engineering devices that incorporate the prized class of materials.

“From my perspective, that was the most exciting,” said Tsymbal, who undertook the research with support from the university’s quantum-focused EQUTE project. “This links ferroelectricity with electrochemistry. We have some kind of electrochemical processes — namely, the motion of oxygen vacancies — which basically control the motion of these domain walls.

“I think that this mechanism is very important, because what most people are doing — including us, theoretically — is looking at pristine materials, where polarization switches up and down, and studying what happens with the resistance. All the experimental interpretations of this behavior were based on this simple picture of polarization. But here, it’s not only the polarization. It involves some chemical processes inside of it.”

Read the original article on University of Nebraska–Lincoln.