Department of Physics & Astronomy
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Tunnels, Gates, and Switching

Oxide heterostructures hold promise for understanding quantum effects and developing nanoscale electronics

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As everyday tasks are governed more and more by electronic devices such as smartphones and tablets, understanding the nuances of electrons—and the materials they move through—has become increasingly essential. Scientists like UT Distinguished Professors Elbio Dagotto and Takeshi Egami investigate these systems not only to understand the physics, but also to develop a framework where those findings might be adapted for environments where the demand is for ever-faster delivery down to the nanoscale.

While silicon, which has been the workhorse of the microchip industry for decades, nears the limit on how much heat and power it can handle at smaller scales, the quest for new materials in the electronic realm has resulted in some interesting new possibilities. Among these are oxide materials, created from oxygen and elements from the "transition metal" territory of the periodic table (titanium, manganese, and copper, for example). Dagotto and Egami, along with colleagues from Oak Ridge National Laboratory and Southeast University in Nanjing, China, investigated the electronic properties of oxide materials in "Tunneling Electroresistance Induced by Interfacial Phase Transitions in Ultrathin Oxide Heterostructures," published in *Nano Letters* in November 2013. Physics Graduate Student Lu Jiang was first author on the paper, and the collaboration was led by ORNL staff member Ho Nyung Lee.

The Beauty of Misalignment

Solids have a blueprint comprising bands: a conduction band with few if any electrons, and a valence band, which is teeming with them. The energy difference between the two is called the band gap, and it's a key factor in determining the material's conductivity. A large gap, for example, is typical of insulators, while conductors have a very small (or nonexistent) one. Growing artificial materials with these quite different properties layer-by-layer, one over the other, leads to a heterostructure with properties quite different from those of the original components. These efforts have garnered a great deal of interest as candidates for electronics. Their importance when in semiconducting form was recognized with the 2000 Nobel Prize in physics. Dagotto is well-versed in heterostructure research; he is co-editor of the text *Multifunctional Oxide Heterostructures*, published in 2012. In the *Nano Letters* research, he and his colleagues looked at the role of ferroelectricity in these materials.

Ferroelectric materials have spontaneous electric polarization, meaning the locations of the negative and positive charges that cause that polarization can be reversed by applying an electric field. The prospect of controlling that polarization and making it switchable would mean controlling the electric properties of the other components in the heterostructure. One potential means to do that is via FTJs, or ferroelectric tunneling junctions. The importance is that the "other component" (in this case a material called manganite), can switch its properties from metal to insulator due to changes in the number of electrons in the conduction band induced by the ferroelectric material. Then, the electric field that switches the ferroelectric also induces the metal insulator transition in the manganite with a concomitant huge change in resistance.

Electron Tunneling and Resistance

In the world of quantum electronics, a tunneling junction is an ultrathin insulating layer sandwiched between two metallic electrodes. It serves as a tunnel for electrons to pass through. An FTJ is simply a tunneling junction where that insulating layer is ferroelectric. The electrically-induced resistance in FTJs is known as the tunneling electroresistance effect, or TER. Up until now, the electrode has gotten little if any notice in explaining the TER effect. The ORNL-UT team, however, chose to study an oxide heterostructure paying special attention to that role. The material they researched comprised electrode layers of a correlated electron oxide (or CEO) made up of lanthanum, strontium, manganese and oxygen (called manganites). The ferroelectric layers were made of lead zirconium titanate, or PZT. They grew the samples at the nanoscale, with the CEO layers only five nanometers thick and the PZT layers only 10 nanometers thick.

What they found is that at the interface of this heterostructure, ferroelectric polarization induced dramatic phase transitions in the CEO layer: from a ferromagnetic insulator to a ferromagnetic metal with an associated huge change in resistivity (100,000 fold at 50K). This change, induced by ferroelectric polarization, is among the largest ever, and is potentially useful for amplified electroresistance or other electronic devices that require large on/off switching ratios for electric current. The group's combined theory and experimental observations strongly support the idea that the modulated phase in the electrode layer of these samples was the key to controlling the tunneling electroresistance effect. Not only does the research contribute to a more comprehensive understanding of electroresistance in strongly-coupled systems, but it also explores the potential of nanoscale electronic environments.

Gates and Switching

The tunneling research follows an earlier *Nano Letters* that UT physicists published with ORNL colleagues in late July 2013. In that paper, "Electrophoretic-like Gating Used to Control Metal–Insulator Transitions in Electronically Phase Separated Manganite Wires," they explored the promise of switching processes in manganite nanowires, with Physics Graduate Student Hangwen Guo as first author and ORNL staff member Zac Ward as leader of the effort. Complex materials such as these are especially interesting to scientists because not only do they have regions with vastly different resistive and magnetic properties, but those properties can coexist on scales ranging in length from micrometers to nanometers. The smallest change in underlying energies can lead to dramatic phase changes and, consequently, colossal changes in the material's character, particularly its resistance.

In this study, the group showed that when an electric field was applied to gate electrodes on the nanowires, the result was a controllable transition from metal to insulator, with novel switching characteristics. The switching was not only reversible, but also highly resistant to thermal breakdown caused by repeated cycling. The research lays the groundwork for further studies of switching behavior in a wide range of complex materials.

These papers show how UT physicists are advancing efforts to realize the potential of oxide materials. Finding ways to modulate phases and control resistance at the nanoscale opens exciting possibilities in developing new ideas for electronic devices and a richer understanding of quantum physics.

More Information

- *Nano Letters* **"Tunneling Electroresistance Induced by Interfacial Phase Transitions in Ultrathin Oxide Heterostructures" (http://dx.doi.org/10.1021/nl4025598)**
- *Nano Letters* **"Electrophoretic-like Gating Used To Control Metal–Insulator Transitions in Electronically Phase Separated Manganite Wires" (http://dx.doi.org/10.1021/nl4016842)**
- **Condensed Matter Physics at UT (http://www.phys.utk.edu/research/cmp/index.html)**
- **Professor Elbio Dagotto/UT's Correlated Electrons Group (http://sces.phys.utk.edu/)**

  Professor Takeshi Egami (http://web.utk.edu/~mse/faculty/egami/default.html)