

## From SIMES: A Future with Smart Rock?

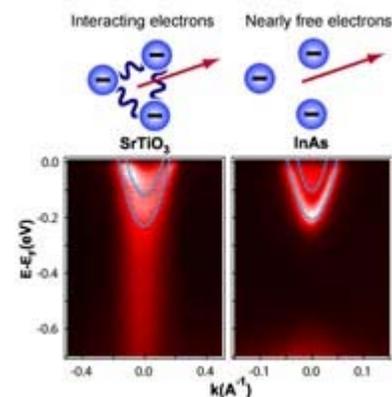
As materials researchers, the first things that come to mind when we talk about oxides are rocks and sand—hardly anything we associate with the smart materials sought for future electronic devices. Indeed the idea of smart oxides sounds very farfetched. However, this may change.

Today's electronic devices largely rely on a single property of semiconductors—the remarkable tunability of their conductivity. The use of this property in devices was made possible by the extraordinary progress in materials science that now routinely permits growth of extremely high-purity compounds. For decades, it was thought that the chemical complexity of oxides would result in devices much inferior to those based on conventional semiconductors.

Now, thanks to two decades of research on high-temperature superconductivity and related oxides, semiconductor-level purities can be achieved in transition-metal oxides, so that device engineering can finally be contemplated. Given this, there are two good reasons to imagine smart functions that cannot be realized in semiconductors. Oxides exhibit very rich and often extreme properties—they exist as metals, insulators, semiconductors or even transparent conductors, and show ferromagnetism, ferrimagnetism, antiferromagnetism and low- or high-temperature superconductivity. Furthermore, they show giant responses to small external stimuli—the conductivity of some oxides can change by several orders of magnitude if a modest magnetic field is applied (colossal magnetoresistance) or if the temperature is changed slightly (Mott metal-insulator transition). Given their abundance and the relative ease of integrating multiple oxides together, one can imagine devices with functionalities well beyond what we have experienced to date.

For the above reason, the surfaces and interfaces of oxide systems have become an exciting field for exploration. Indeed, in his Nobel lecture, Herbert Kroemer remarked that "the interface is the device." Although the merits are clear, progress has been limited until recently. In particular, it was unclear whether thin conducting layers supporting two-dimensional electron gases, or 2DEGs—which form the back-bone of today's semiconductor devices—can be created at all in oxides. As such, it took much of the community by surprise when, in 2004, Ohtomo and Hwang discovered a conducting electron layer at the interface between the two insulating oxides strontium titanate and lanthanum aluminate. Surprisingly, the electrons at this interface have a high mobility, comparable to those of semiconducting devices. Moreover, the conductivity of the interface electron gas can be controlled and exotic properties such as superconductivity and large magnetoresistance have been demonstrated, setting the scene for a new generation of multifunctional all-oxide devices.

Despite these advances, the understanding of the conditions needed to form such an electron gas in oxides is still limited. One of the most obvious open questions is whether the interface between two different insulators is necessary. Our recent study shows that it is not. By using angle-resolved photoemission spectroscopy, we were able to see the same two-dimensional conducting electron layer at the bare strontium titanate surface after simply exposing it to intense ultraviolet light. Furthermore, we showed that the electron density in the 2DEG can be controlled by the light irradiation dose. This demonstrates a completely new way to create a 2-D conducting channel independent of an interface.



Comparison of ARPES data from strontium titanate (SrTiO<sub>3</sub>) and indium arsenide (InAs). The long tail in the strontium titanate data is a signature of strong electronic interaction. Its dispersion (blue lines) nevertheless reveals the interacting electrons with relatively fast velocity.

Moreover, it opens a route to fast and inexpensive creation of patterns of varying conductivity similar to those used in conventional semiconductor-based chips.

Intriguingly, our data also show that the electrons in this layer interact strongly, but nevertheless move at very high speeds. To grasp how surprising this is you only need to imagine a crowded cocktail party; it is not hard to see that you must move slowly if you do not want to bump into too many other people in the party. Similarly, interacting electrons are usually also found to move slowly while we find exactly the opposite, revealing another facet of interacting electrons in oxides. While the answer to this paradox is still open, one scenario could be that the fundamental energy landscape of the underlying bulk electronic structure changes when the system develops the conducting layer near the surface (and possible interfaces), where the energy levels are "bended." Due to a process called quantum confinement, this would provide extra energy to the electrons and make them travel faster than expected. Regardless of its final interpretation, the discovery of this unusual co-existence of interacting but very mobile electrons may hold the key to understand the unique properties observed in oxide 2DEGs, and their potential for novel device applications.

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*ARPES measurements were performed at the Advanced Light Source and preliminarily at Stanford Synchrotron Radiation Lightsource (US), calculations of the electronic structure were performed at the University of St Andrews (UK) and the transport measurement was performed at the Synchrotron Light Research Institute (Thailand).*



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