Shedding Light on Oxide Interfaces

German Hammerl, *et al.*
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ductor diode) and boost its power with fiber amplifiers up to kilowatts.

The exquisite control offered by fiber at high power makes coherent beam combination an extremely exciting possibility for extending the power further, perhaps to the megawatt regime. There are a range of different methods through which the output beams of individual fiber sources can be combined (*8*, *9*), primarily to reach higher power and brightness than is possible from a single-fiber emitter. However, coherent combination in a phased-array laser configuration, rather like a radar antenna with active phase control of the individual beams, provides control of the spatial beam profile and a degree of beam steering and tracking (*10*). Digital holography is another version in which electronic means are used to control the beam profile (*11*). These are expensive systems, but costs can be reduced with simpler phase-control systems, provided that the laser phase noise is sufficiently low. Furthermore, although coherent beam combination has been restricted to continuous-wave systems, it is now being extended to the femtosecond pulsed regime (*12*).

Building on these results, the possibility of using coherently combined femtosecond fiber sources to drive wakefield accelerators for particle colliders is being explored (*13*). The multi-megawatt average power makes the efficiency levels that fibers offer a necessity. Although many thousands of fiber channels will have to be combined, the volume manufacturability, scalability, and reliability of active fiber technology makes this a tremendously exciting proposition for the next few decades.

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PHYSICS

Shedding Light on Oxide Interfaces

The properties of a metallic oxide can be altered when it is confined as an ultrathin layer by layers of an insulating oxide.

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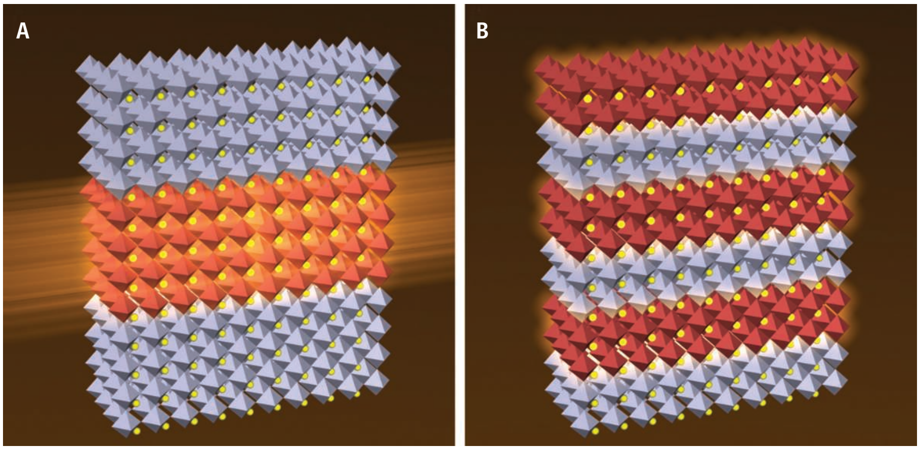
In the stable of solid-state materials, silicon is the workhorse. Its semiconductor properties are actually quite ordinary, but when other materials are harnessed to it to form interfaces, remarkable devices can be made that control the flow of electrical current with low applied voltages. In contrast, some transition metal oxides would be the stable's racehorses. Remarkable functional behaviors of this group include the ability to change from a metal to an insulator with a slight change in temperature, unusual magnetic properties, and even high-temperature superconductivity (*1*). Further novel properties are expected to emerge at interfaces created between transition metal oxides that already exhibit functional behavior, and these properties could be tuned through small changes in composition or by simply applying a bias voltage (*2*). However, like temperamental racehorses, the interfaces in these complex oxides can be more difficult to control than those formed by silicon. On page 937 of this issue, Boris *et al.* (*3*) report progress toward this goal by confining an ultrathin layer of lanthanum nickelate ($LaNiO_3$), normally a paramagnetic metal, between insulating lanthanum aluminate ($LaAlO_3$) layers, which leads to changes in its properties.



Thinner is different. Artistic illustration of two different electronic phases in heterostructures of $LaNiO_3$ (red), which is metallic as a bulk material, confined by $LaAlO_3$ (gray), which is a bulk insulator. (**A**) A confined $LaNiO_3$ layer that is four unit cells in thickness still shows metallic behavior. (**B**) When the thickness is reduced to two unit cells, a temperature-driven metal-insulator transition emerges.

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The difference between semiconductors such as silicon and exotic transition metal oxides lies in the nature of the interactions between the constituent electrons. The electronic states of semiconductors are well described by conventional, single-particle band theory, in which individual electrons act independently. Contact between energy bands at interfaces can bend the bands or create energy barriers, which in turn can generate quasi-electric fields (which act on the charge carriers differently from true electric fields) or cause accumulation of charge carriers. In the complex oxides, however, there are strong correlations between the tightly

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bound transition metal d electrons, and single electrons are no longer independent but influence the behavior of all other electrons in the crystal. The large electrical polarizability of oxygen also enhances the response of these materials to electric fields causing ferroelectric (a net electric dipole moment) or multiferroic (both ferroelectric and ferromagnetic) properties (*4*).

Boris *et al*. used pulsed laser deposition to grow superlattices—precise numbers of oxide layers with atomically sharp interfaces (see the figure). Samples with four-unit-cell thick $LaNiO_3$ layers grown between $LaAlO_3$ layers were metallic at temperatures from 8 to 300 K, just like bulk $LaNiO_3$. Samples with only two layers of $LaNiO_3$, in which each $LaNiO_3$ layer is next to a $LaAlO_3$ layer, showed a metal-to-insulator transition with subsequent magnetic ordering as the temperature was lowered.

Such effects might be mainly the result of strain in the layers, which can be induced by the substrate used for growth. To check whether this was the case, Boris *et al*. grew the same layer structures on strontium titanate ($SrTiO_3$), which has a larger lattice constant than the superlattice, and on lanthanum strontium aluminate ($LaSrAlO_4$), in which the lattice constant is smaller. The same behavior was seen in both cases, except for a shift of transition temperature (100 and 150 K, respectively), ruling out strain as the cause.

To demonstrate further that these effects were intrinsic to the superlattice structure, Boris *et al*. applied state-of-the-art surface probes. They used ellipsometry to measure the changes in the sample's electrical conductivity. Ellipsometry is not influenced by extrinsic impurities, particularly interdiffusion of ions between the layers, nor is it influenced by misfit dislocations resulting from inexact matching of the lattice constants at the interface, which can occur in oxide superlattices. They also used low-energy muon spin rotation to identify a change in the magnetic order accompanying the transition from the metallic to the insulating state. Here, spin-polarized muons with well-defined energies are implanted within the oxide heterostructure, where they align their magnetic moments parallel to those of the surrounding electrons. The measured directions of the subsequent positron decay products yield the local magnetic order of the electronic phase. The bilayered $LaNiO_3$ samples showed a clear magnetic transition, but the superlattices with thicker layers did not.

Deposition techniques such as pulsed laser deposition or molecular beam epitaxy are now well developed, so nearly defect-free superlattices with atomically sharp interfaces can be routinely grown. Unanticipated phenomena such as the metal-insulator transition described here, or conductivity at interfaces between the insulating oxides such as $LaAlO_3$ and $SrTiO_3$ (*5*) or interfacial superconductivity (*6*), are now regularly reported. However, there is still much work to be done before oxide materials reach the level of sophistication achieved in semiconductor heterostructures. Improved control and understanding of the role of defects is necessary, as well as systematic incorporation of multiple interfaces with different electronic properties (*2*).

From a practical point of view, demonstrations of integration with conventional semiconductors would be helpful, as would a detailed understanding of the behavior at interfaces with metallic electrodes (*7*). On the theoretical front, the aspects that make complex oxides desirable—in particular the strong correlations, the large polarizability, and the sensitive dependence on crystal chemistry and structure—also make them challenging to describe accurately. Improved techniques must combine many-body physics methods for describing strong correlations with computational materials methods, such as density functional theory, that can account for chemistry and structure. With these developments, which the community is poised to make over the next few years, true predictive capability and layer-by-layer construction of designer oxide superlattices should be achievable.

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CELL BIOLOGY

The TASCC of Secretion

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Cells can spatially couple cellular degradation and protein synthesis to boost protein secretion.

The oncogene-induced activation of signaling pathways involving the tumor suppressor proteins p53 and retinoblastoma is likely an important mechanism for preventing the proliferation of potential cancer cells (*1*, *2*). This activation causes cells to exit the cell division cycle and enter a senescent state, which is characterized by major changes in chromatin structure that are thought to render senescence irreversible. Despite the absence of proliferation, senescent cells are not as quiescent as first thought, as they signal to their surrounding environment by activating a protein secretion program (*3*, *4*). On page 966 of this issue, Narita *et al*. (*5*) show that to enable this secretory state, a senescent cell profoundly reorganizes its endomembrane system.

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The secretory program leads to the massive production of factors [collectively called the senescence-messaging secretome (SMS) or senescence-associated secretory phenotype (SASP)] that are released into the surrounding microenvironment (*3*, *4*). The composition of the SMS is heterogeneous. It includes growth factors, inflammatory cytokines, and modulators of the extracellular matrix, and its precise physiological role is highly controversial. For example, inflammation can modify the microenvironment in ways that favor cancer cell invasion and tumor growth (*6*, *7*); however, in the context of oncogene-induced cell senescence, inflammatory cytokines can also exert an autocrine, tumor-suppressive action (*8*–*11*).

Narita *et al*. found that expression of the oncogenic protein H-RasV12 in a senescent mammalian cell triggers a reorganization of its endomembrane system, which results in the formation of a membrane compartment that carries out the secretory program. They named this structure the TOR-autophagy spatial coupling compartment (TASCC). As the name suggests, the key components

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