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Materials and Mechanics for Stretchable Electronics

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REVIEW

Materials and Mechanics for Stretchable Electronics

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Recent advances in mechanics and materials provide routes to integrated circuits that can offer the electrical properties of conventional, rigid wafer-based technologies but with the ability to be stretched, compressed, twisted, bent, and deformed into arbitrary shapes. Inorganic and organic electronic materials in microstructured and nanostructured forms, intimately integrated with elastomeric substrates, offer particularly attractive characteristics, with realistic pathways to sophisticated embodiments. Here, we review these strategies and describe applications of them in systems ranging from electronic eyeball cameras to deformable light-emitting displays. We conclude with some perspectives on routes to commercialization, new device opportunities, and remaining challenges for research.

Biology is soft, elastic, and curved; silicon wafers are not. An electronics technology that overcomes this fundamental mismatch in mechanics and form will enable applications that are impossible to achieve with hard, planar integrated circuits that exist today. Examples range from surgical and diagnostic implements that naturally integrate with the human body to provide advanced therapeutic capabilities, to cameras that use biologically inspired designs to achieve superior performance. Sensory skins for robotics, structural health monitors, wearable communication devices, and other systems that require lightweight, rugged construction in thin, conformal formats will also be possible. Establishing the foundations for this future in electronics represents an emerging direction for research, much different from the one dictated by the ongoing push toward smaller and faster devices that are still confined to the planar surfaces of silicon wafers.

Work toward mechanically unconventional forms of electronics began, in earnest, ~15 years ago with polymer transistors formed on bendable sheets of plastic (*1*, *2*), where paperlike displays (*3*, *4*) represented the main target application. Advances in printing and related patterning techniques (*5*) and in organic semiconductors (*6*) were key to much of the initial progress in this field. Research in the past few years on ultrathin inorganics, nanotubes, and nanowires promises further improvements, as described in recent review articles (*7*–*9*). Many successes, in the form of working demonstration devices with hundreds to thousands of active components, have already been achieved; several, including displays, are nearing commercial reality.

More recently, the scope of research has expanded dramatically to include more compelling, and more technically challenging, opportunities in soft, biointegrated devices; in curved, bioinspired designs; and in other areas. Here, the electronics must not only bend but also stretch, compress, twist, and deform into complex, curvilinear shapes while maintaining levels of performance, reliability, and integration that approach those of well-developed wafer-based systems. Stretchable electronics can be achieved in two conceptually different, but complementary, ways. One relies on the use of new structural layouts in conventional materials (*10*), the other on new materials in conventional layouts (*11*). We focus first on approaches that have yielded the most sophisticated devices and then present a more comprehensive summary of options.

Structures That Stretch

Two simple ideas underlie the strategy based on structure. The first exploits an elementary result in mechanics: Any material in sufficiently thin form is flexible, by virtue of bending strains that decrease linearly with thickness. A silicon wafer is brittle and rigid, but nanoscale ribbons, wires, or membranes of silicon are flexible. For example, ribbons with thicknesses of 100 nm experience peak strains of only 0.0005% upon bending to radii of curvature of 1 cm. Even when mounted on sheets of plastic with thicknesses of 20 μm, the strains (~0.1%) at similar bend radii remain well below the fracture limits (~1%) (*12*). Circumstances can be improved further by moving the silicon away from the surface of the plastic, where the bending strains are largest, to the point in its depth where these strains are zero. Ultrathin circuits that use silicon nanoribbons in this type of neutral mechanical plane design can be bent to radii of ~150 μm, with strains in the silicon that are less than ~0.1% (*12*, *13*).

Configuring such structures into "wavy" shapes and bonding them to elastomeric substrates yields systems that can not only flex but also stretch and compress, with a mechanics similar to that of an accordion bellows. Figure 1, A and B, shows two possibilities, illustrated with ultrathin sheets of silicon integrated on slabs of the elastomer poly(dimethylsiloxane) (PDMS). The first case (Fig. 1A) corresponds to a sheet formatted into waves with a herringbone configuration by a controlled buckling process (*14*), as a two-dimensional analog of a similar effect first observed in ribbons (*15*). The resulting Si/PDMS construct can be stretched and compressed reversibly, with a linear elastic response to applied force. The amplitudes and wavelengths of the waves change in response to induced deformations

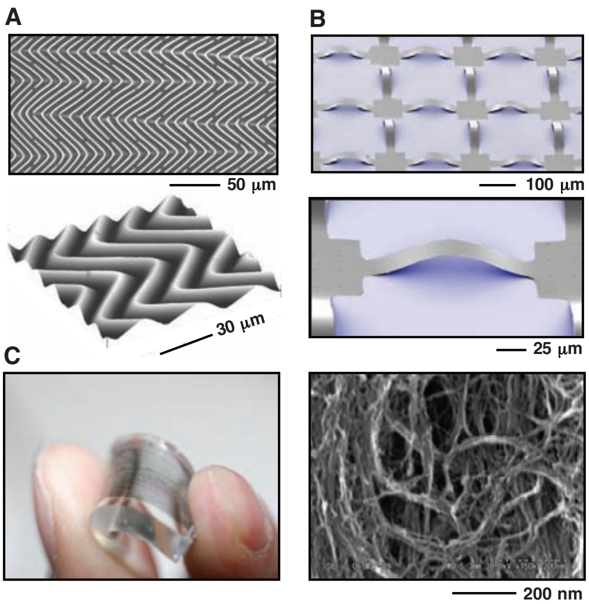

Fig. 1. Concepts for stretchable electronic materials. (**A**) Stretchable silicon membrane (~100-nm thickness) configured in a wavy shape and bonded to a piece of rubber, presented in optical (top) and atomic force (bottom) microscope images. (**B**) Extremely stretchable silicon membrane (~100-nm thickness) patterned into a mesh geometry and bonded to a rubber substrate only at square pads located between arc-shaped bridge structures, presented in moderate (top) and high (bottom) magnification scanning electron microscope (SEM) images. The PDMS is colorized blue. (**C**) Stretchable conductive lines of a SWNT gel printed on a slab of rubber (left) and SEM of the networks of SWNTs that provide electrical pathways in these composites.

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in a way that involves considerable strains in the PDMS, but not in the silicon. In particular, mechanics modeling reveals that the peak strains in the silicon can be 10 to 20 times as small as the applied strains (*16*). Such designs represent, then, a stretchable form of silicon with a strain range of 10 to 20%, that is, 10 to 20 times as large as the intrinsic fracture limits of the silicon.

A related strategy improves this range by structuring the sheet into a mesh and bonding it to the PDMS only at the nodes. The buckled, arc-shaped interconnecting structures (Fig. 1B) can move freely out of the plane to accommodate applied strains of 100% or more, even to values that approach the fracture limits of the PDMS (*17*). Related approaches that use mesh layouts with planar leaf-arm (*18*, *19*), coiled spring (*20*), and noncopolanar serpentine (*17*) interconnects also have attractive features. Alternative, simpler designs (*21*) provide stretchability in certain directions; they, like the arc-shaped layouts of Fig. 1B and related serpentine configurations (*17*), have been used to achieve integrated systems, as discussed in a following section.

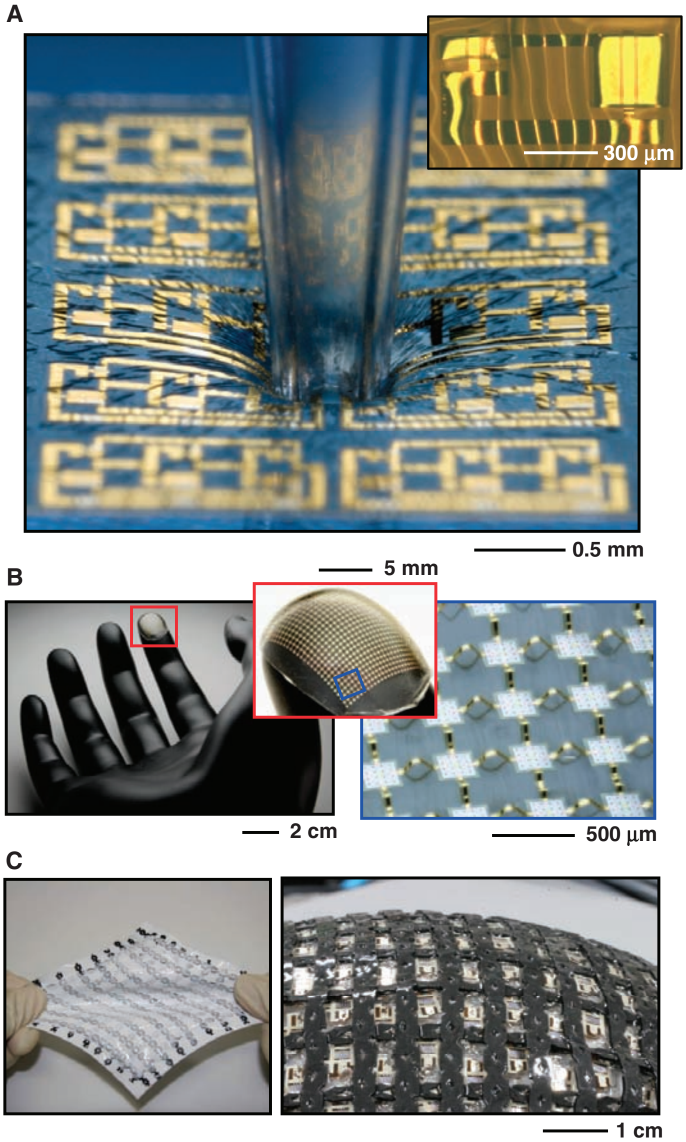

Fig. 2. Examples of stretchable electronics. (**A**) Stretchable silicon circuit in a wavy geometry, compressed in its center by a glass capillary tube (main) and wavy logic gate built with two transistors (top right inset). (**B**) Stretchable silicon circuit with a mesh design, wrapped onto a model of a fingertip, shown at low (left), moderate (center) and high (right) magnification. The red (left) and blue (center) boxes indicate the regions of magnified views in the center and right, respectively. The image on the right was collected with an automated camera system that combines images at different focal depths to achieve a large depth of field. (**C**) Array of organic transistors interconnected by elastic conductors on a sheet of PDMS in a stretched (left) and curvilinear (right) configuration.

Materials That Stretch

New materials provide an alternative route to stretchable electronics. The most successful approaches use elastic conductors as electrical interconnects between active devices that are rigid or only bendable. Although conductive rubbers based on elastomers loaded with carbon black have been known for decades, the resistances and their dependence on strain are both too large to be useful. In a much more promising and recent approach, long, single-walled carbon nanotubes (SWNTs) serve as conductive dopants in a rubber matrix (*22*, *23*). Here, SWNTs processed by grinding in an ionic liquid and then mixing with a fluorinated copolymer yield a black, pastelike conductive substance, referred to as a bucky gel (*22*, *23*). Individual SWNTs form tangled mats in these gels, with the capacity to reconfigure in response to applied strain in a manner that preserves highly conductive pathways for charge transport. This material can be printed onto sheets of PDMS to yield elastic conducting traces with stretchablility in the range of 100%. Figure 1C shows a picture of such a sample and a micrograph of the associated network of SWNTs. Alternative, related approaches use SWNTs in thin film networks formed by solution casting or other means (*24*–*26*).

Stretchable Electronics, Optoelectronics, and Integrated Systems

The ideas of Fig. 1 can be exploited to yield stretchable, integrated systems. Figure 2A presents an example of the design approach of Fig. 1A applied to an ultrathin, neutral mechanical circuit sheet that supports an array of silicon transistors, logic gates, and ring oscillators (*13*). A pair of transistors in an inverter appears in the upper inset. The waves are influenced by variations in thicknesses and material compositions across the area of the circuit to yield layouts that are much more complex than those in Fig. 1A. The mechanical responses that enable stretchability, however, are the same: The wavy shapes change to accommodate applied strains, and the underlying PDMS substrate provides an elastic restoring force. The main image shows the circuit deformed in its center with a glass pipette to illustrate the "soft," elastic nature of this system. Figure 2B presents an example with a layout similar to that of Fig. 1B. Here, microscale arc-shaped "ribbon cables" of metal and plastic in neutral mechanical layouts interconnect silicon devices located at the nodes of the mesh (*17*). The circuit is conformally integrated onto a model of a fingertip (*27*), as an example of a surface whose nonzero Gaussian curvature would be impossible to wrap with a system that is only flexible. Figure 2C shows a similar outcome achieved with stretchable conductors (*22*). This circuit consists of arrays of organic transistors interconnected by printed bucky gels (Fig. 1C) and supported by a thin sheet of PDMS in stretched and curvilinear configurations. During deformation, only the interconnection lines stretch, such that negligible changes in transistor characteristics occur even for strains up to 70%.

The left frame of Fig. 3A shows an image of an integrated system that exploits the concepts of Fig. 1B and Fig. 2B, that is, a digital camera based on an array of silicon photodetectors in the approximate size and curved layout of the human retina (*28*). This design offers enhanced field of view and uniformity in illumination compared to a comparable planar detector, when simple imaging optics are used (*28*, *29*, *19*). Fabrication of such an "eyeball" camera starts with an array of silicon photodiodes and blocking diodes formed in a planar but stretchable configuration. Conformal wrapping onto a concave, hemispherical glass substrate, followed by integration with an imaging lens and a printed circuit board interface to a computer for data acquisition, completes the device. A picture of an eye, captured with a camera whose detector curvature (i.e., elliptical paraboloid) matches the image surface formed with a plano-convex lens, appears on the right in Fig. 3A (*29*). The top and bottom frames correspond to the image rendered in the curved format of the camera and a planar projection, respectively; the inset illustrates the picture that was imaged. These ideas create new engineering options in imaging devices, where the geometry of the detector array can be optimized together with the lens configuration. The most promising initial application opportunities are in surveillance, night vision, and endoscopy, where considerations of cost, size, and/or weight can be addressed by introducing curvature in the detector to enable dramatic reductions in the complexity of the optics. The same concepts have the potential to allow other, more complex biologically inspired designs. Ultimately, such devices might be used as retinal implants or as active components on the eye to restore or enhance vision.

Light-emitting devices are also possible using the same approaches. Figure 3B shows an image of a stretchable inorganic light-emitting diode (LED) display that uses ultrathin, microscale AlInGaP LEDs interconnected in a mesh layout and bonded to a PDMS substrate (*30*). Figure 3C provides an example of a related demonstrator produced with stretchable conductors and organic LEDs (*23*). Both types of display can be stretched by 30 to 50% and wrapped onto curvilinear supports without any mechanical damage or change in operating characteristics. This class of technology could, of course, be useful as a flexible lighting or display system, with extreme levels of bendability and mechanical robustness. More interesting opportunities in the future might lie in optogenetics, where programmable light sources wrapped onto the convoluted surface of the brain could provide insights into brain function. Light-based therapies and diagnostics in other parts of the body might also be achievable in similar tissue-integrated modes.

Stretchable Electrodes

Work in stretchable electrodes, as opposed to electronics, has a comparatively long history and broad range of materials and design options. In fact, the field of stretchable electronics owes its origins to observations that films of gold formed by physical vapor deposition directly onto PDMS spontaneously adopt microstructured or nanostructured forms (*31*) and that these structures (Fig. 4A) provide electrodes that can accommodate large applied strains without fracture (*32*). Detailed studies suggest that stretchability in this case derives from a physics similar to that of the silicon structures of Fig. 1A but with additional contributions from the motion of microscopic cracks that form in the films during fabrication and subsequent deformation (*33*). Figure 4B shows a different, but related, example in which direct writing with a silver nanoparticle ink yields a wavy metallic microwire (*34*), able to accommodate stretching through changes in wavelength and amplitude. Similar one-dimensional wavy shapes can be achieved in conducting and semiconducting nanomaterials. Figure 4C presents atomic force microscope measurements on an individual SWNT (*35*), formed in a wavy configuration on PDMS using the techniques that yielded the structure of Fig. 1A. Newtonian mechanics models like those that describe similar deformations in silicon nanoribbons (*15*) can capture the physics even at the molecular scale of the nanotube (*35*). With nanowires, related types of wavy deformations form in the plane of the substrate. Lithography can yield similar structures in micron-scale metal wires, as illustrated with a stretchable, high-frequency interconnect shown in Fig. 4D (*36*). Such traces can serve as interconnects between integrated circuit chips as a route to stretchable devices (*37*) with a type of spatially discrete functionality that can complement the capabilities of the distributed systems of Figs. 2 and 3.

Finally, in addition to structured wires of Fig. 4, A to D, similar levels of stretchability can be achieved directly in electrodes of suitable materials, like the SWNT-based conductors of Fig. 1C. Figure 4E shows, as an example, a low-melting-point metal solder housed in sealed microchannels in PDMS (*38*). Here, the metal can plastically deform and flow in response to large strain deformations, while the PDMS provides an elastic restoring force. More recently, work shows that graphene on PDMS exhibits reversible responses to large applied strain (*39*), perhaps involving a mechanics similar to that of the gold electrodes of Fig. 4A. An image appears in Fig. 4E.

Paths to Commercialization

Although nearly all current activities in stretchable electronics are centered in academic laboratories, there is growing interest at small and large companies. A path to commercialization might begin with stretchable electrodes, followed by devices with discrete configurations, and culminating in highly functional, distributed systems. An important perspective is that many of the underlying concepts are aligned well with the incremental, but collectively substantial, developments in silicon packaging. Three examples are noteworthy. First, the commercial success of ultrathin cell phones and laptop computers with hinged displays, sliding keyboards, and related components continues to motivate the development of sophisticated, multilayer flexible interconnection cables and printed circuit boards that can accommodate bending to small radii of curvature. Second, technology for thinning silicon chips to thicknesses in the range of tens of microns is of increasing importance for advanced thermal management and three-dimensional, stacked integration schemes. A third effort in industry seeks to evolve chips into forms that seamlessly integrate with printed circuit boards, in a manner that blurs

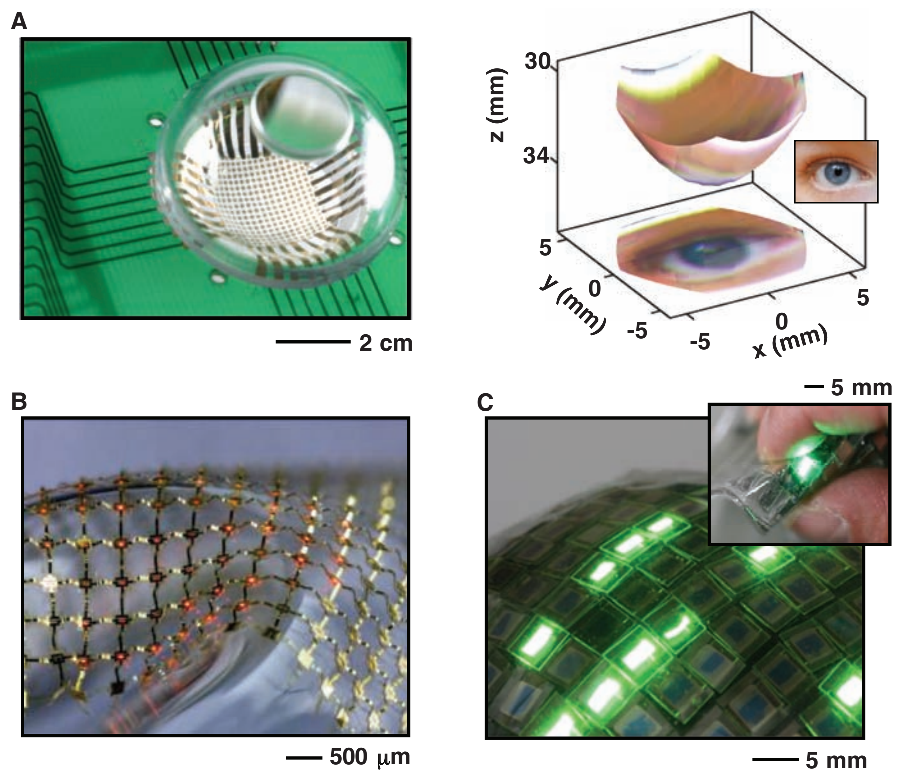

Fig. 3. Examples of stretchable electronic systems. (**A**) Electronic eyeball camera (left) that uses a hemispherically curved array of silicon photodetectors and picture collected with a similar camera that uses a paraboloid design (right). The image in the top is rendered in a form consistent with the curvature of the detector. A planar projection appears on the bottom, with the actual object in the center right inset. (**B** and **C**) Stretchable LED display devices that use mesh designs with microscale inorganic LEDs (B) and stretchable interconnects with organic LEDs (C).

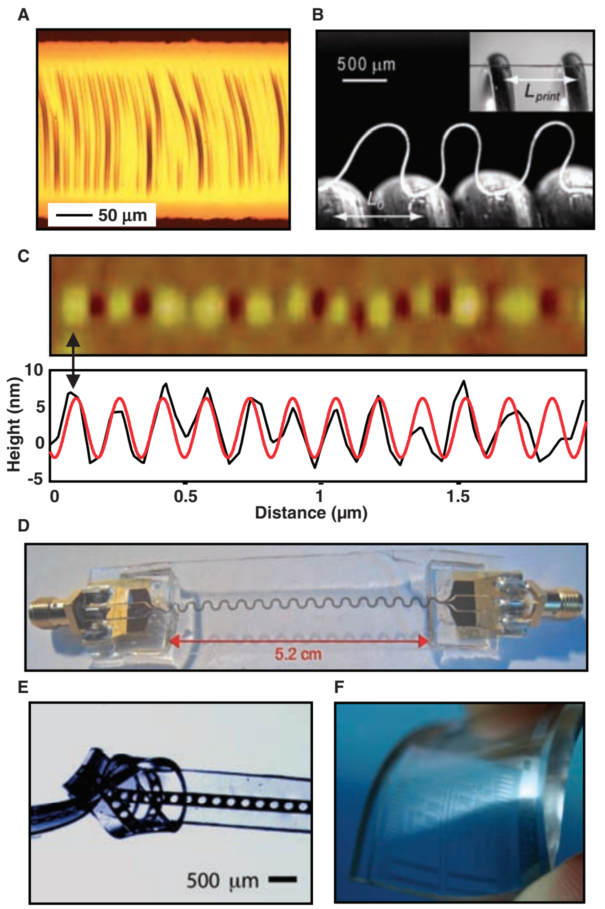

Fig. 4. Structures and materials for stretchable electrodes. (**A**) Thin gold film formed by physical vapor deposition onto a PDMS substrate, with stretchability provided by wavy shapes and networks of micro- and nanocracks. (**B**) Wavy silver microwire formed by direct write printing onto the surface of a metal spring. The inset shows the structure in its original configuration. (**C**) Atomic force micrograph (top) and surface relief profile (bottom; black: data; red: sinusoidal fit) of an individual SWNT formed into a wavy shape by transfer to a prestrained substrate of PDMS followed by release. (**D**) Serpentine metal coplanar waveguide embedded in a slab of PDMS and attached to standard SMA connectors for a stretchable, high-frequency cable. (**E**) Stretchable metal wire consisting of a low-melting-temperature solder sealed in channels in PDMS. (**F**) Patterned layer of graphene on a PDMS substrate.

the distinction between the two. Interest in such configurations is motivated by their ability to eliminate parasitic effects that reduce performance. The design and manufacturing strategies associated with these and other trends in packaging are highly relevant to certain approaches in stretchable electronics, and the reverse is also true. This situation creates promising paths to commercialization, with time scales that have the potential to be much shorter than those typically associated with new technologies derived from academic research.

Challenges and Outlook

Collectively, the advances in materials and mechanics described here provide several promising engineering options for stretchable, curvilinear electronic and optoelectronic components and complete, integrated systems in discrete, distributed, or hybrid forms. The underlying science encompasses many research topics of fundamental interest, from materials growth, processing, and heterogeneous integration, to micromechanics and nanomechanics, to charge transport and its coupling to strain and geometry, to adhesion and interface science. To appreciate how some of these topics relate to engineering challenges, consider that the modulus of silicon is ~100,000 times as high as a typical elastomer; the thermal conductivity is ~1000 times as great, and the thermal expansion coefficient is ~100 times as small. Such extreme mismatches in properties lead to interesting, and similarly extreme, behavior in systems that intimately integrate these dissimilar materials. As an example, research on nonlinear behavior in hard and soft laminates is providing new insights into the mechanics of their deformation (*16*, *33*, *40*, *41*), particularly their nonlinear behavior in buckling modes, with explicit relevance to stretchable electronics. The challenges are even more pronounced for SWNTs (*22*–*26*) and graphene (*39*), where larger mismatches in properties occur and little is known about even the basic foundational mechanics responsible for stretchability. Other areas for study in these and other heterogeneous systems include the physics of heat transport, to enable efficient thermal management, and the materials science of interfaces, to ensure mechanical reliability. From an engineering standpoint, these and related issues must be understood clearly before levels of integration in stretchable electronics, which currently range, in distributed forms, from hundreds to thousands of transistors, can begin to reach those of established devices.

Successful outcomes from these efforts have the potential to change fundamentally our conception of electronics, from hard, rigid, planar chips to soft, stretchable, curvilinear sheets. Here, mechanics design will be as important as electrical design in the formulation of new systems. Of the many potential areas of application, some of the most compelling are in biomedical devices that address important problems in human health. Soft, elastic mechanical properties and curvilinear layouts can provide both mechanical modulus and shape matching to biological tissues. Such "tissue-like" devices, particularly when implemented with biocompatible materials, will facilitate solutions to long-standing challenges in the establishment of viable, intimate biotic-abiotic interfaces with high levels of functionality. Recent work in this direction using passive, stretchable electrodes for research applications (*42*) and diagnostic systems with discrete designs (*37*), both with modest degrees of deformability, will rapidly expand into fully distributed, biointegrated, multifunctional devices for clinical use.

Beyond biology, stretchable electronics will find utility in conformal, active antennas and other components for communications, perhaps even in cellular telephones of the future, as envisioned recently by a large company in this industry. In other possibilities, stretchable sensor tapes will provide thin, conformal monitors of the structural health in the wings of aircraft or the blades of windmills, as examples. The basic ideas can also be exploited in other semiconductor technologies, including photovoltaics and thermoelectrics. In the latter case, devices for scavenging power will be available in the form of sheets that can wrap the complex surfaces of engine parts for efficient thermal coupling. These and related opportunities for engineering in areas of application with important societal implications, taken together with the broad range of interesting scientific topics, provide strong motivation for continued and expanded efforts in this emerging field.

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REVIEW

Oxide Interfaces—An Opportunity for Electronics

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Extraordinary electron systems can be generated at well-defined interfaces between complex oxides. In recent years, progress has been achieved in exploring and making use of the fundamental properties of such interfaces, and it has become clear that these electron systems offer the potential for possible future devices. We trace the state of the art of this emerging field of electronics and discuss some of the challenges and pitfalls that may lie ahead.

Herbert Kroemer began his Nobel lecture by stating, "Often, it may be said that the interface is the device" (*1*). Transistors, lasers, and solar cells all exploit interfacial phenomena. Interfaces enable data processing, memory, and electronic communication. Moreover, interfaces in semiconductor structures are the birthplace of a multitude of fascinating discoveries in fundamental science. Curiously, away from interfaces, in the bulk of the material, the behavior of electrons in semiconductors such as silicon is less exciting. The electrons zip through the crystal lattice essentially as independent, free particles, barely interacting with one another. In contrast, there are other materials (e.g., many oxides) in which electron interactions in the bulk of the material give rise to spectacular phenomena, including colossal magnetoresistance and high-temperature superconductivity. These phenomena arise in oxides from regularly spaced ions interacting with the electrons, from the unique electronic character of oxygen ions, and from the electronic correlations—interactions among the electrons, which make them deviate from free-particle behavior.

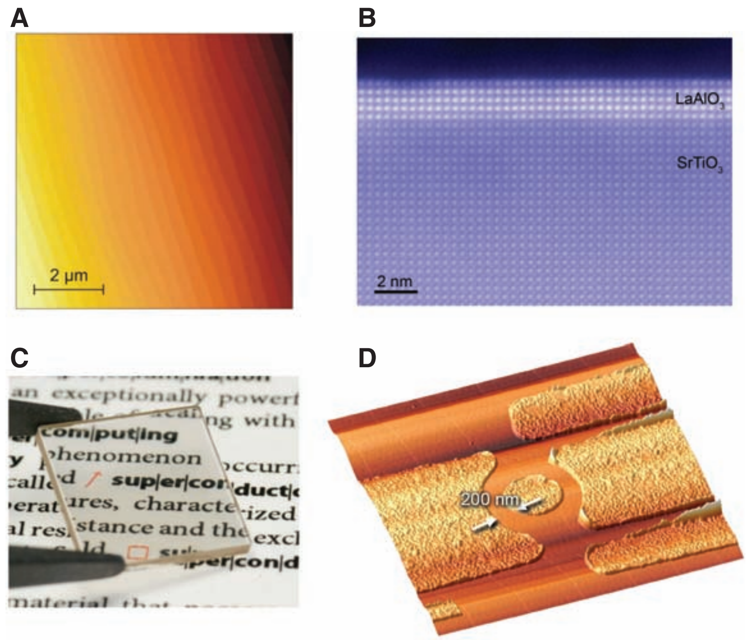

Fig. 1. Micrographs of $LaAlO_3$-$SrTiO_3$ heterostructures. (**A**) Top view of a $LaAlO_3$-$SrTiO_3$ bilayer containing eight monolayers of $LaAlO_3$, taken by scanning force microscopy (figure courtesy of S. Paetel). (**B**) Cross-sectional view of a corresponding sample containing five monolayers of $LaAlO_3$ (figure courtesy of L. Fitting Kourkoutis and D. A. Muller). (**C**) Optical photograph of a complete sample (figure courtesy of G. Hammerl and K. Wiedenmann). (**D**) Scanning force microscopy image of a conducting ring patterned by electron beam lithography into a $LaAlO_3$-$SrTiO_3$ structure [from (*8*)].

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Interfaces Matter

The introduction of interfaces into semiconductor structures spawned numerous semiconductor devices of immense utility and interesting physics. By analogy, it is tantalizing to incorporate well-defined interfaces into oxides to generate novel phenomena. Because oxide multilayers are far more difficult to grow than semiconductor heterostructures, progress in this direction was thwarted for many years. Intensive efforts over the past two decades to grow oxide superconductors, however, led to decisive progress in the growth of oxide multilayers (Fig. 1). Key steps were the ability to terminate oxide substrates at well-defined ionic planes (*2*), the application of pulsed-laser deposition (PLD) (*3*) and molecular-beam epitaxy (MBE) (*4*) to the growth of multicomponent oxides containing difficult-to-oxidize constituents, and the development of high-pressure reflection high-energy electron diffraction (*5*) to monitor the deposition of individual atomic layers. As a result, epitaxial heterostructures of oxides can now be grown with atomic-layer precision. The chemical abruptness and crystalline perfection of oxide multilayers now rival those of semiconductor multilayers; it is possible to change from one material to another over a distance of a single unit cell (*6*, *7*) (Fig. 1B). Such oxide heterostructures can also be patterned laterally (*8*) (Fig. 1D), even with nanometer resolution (*9*). The ability to precisely create interfaces connecting different oxide materials provides a wealth of new possibilities to generate novel electronic phases.

The same phenomena that control interfaces in standard semiconductors, such as the formation of space charge layers, are also relevant at oxide interfaces. Mobilities of charge carriers have reached values so high that the quantum Hall effect (QHE) has been achieved at interfaces between oxides, an effect previously limited to interfaces between high-purity semiconductors and to interfaces involving graphene sheets. As a result of improvements in film growth, the mobility of two-dimensional elec-