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Stretchable Electronics: Materials Strategies and Devices**

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New electronic materials have the potential to enable wearable computers, personal health monitors, wall-scale displays and other systems that are not easily achieved with established wafer based technologies. A traditional focus of this field is on the development of materials for circuits that can be formed on bendable substrates, such as sheets of plastic or steel foil. More recent efforts seek to achieve similar systems on fully elastic substrates for electronics that can be stretched, compressed, twisted and deformed in ways that are much more extreme than simple bending. This article highlights some recent progress in this area, with an emphasis on materials approaches and demonstrated devices.

1. Introduction

Electronic devices fabricated on lightweight, bendable plastic substrates are widely believed to have great potential for applications in unconventional electronics.[1] Historically, research in this area has focused mainly on the development of conducting and semiconducting materials based on small molecule organics and polymers.[2] This approach embodies a materials-centric vision of system design, in which one accomplishes bendable electronics through the development of materials that are themselves considered to be bendable (e.g., plastics), in some qualitative sense. Notable successes have been achieved, as demonstrated in many impressive devices and circuits, ranging from electronic paperlike display devices,[3–5] to sensor skins[6] and sheet scanners[7] to circuits suitable for radio frequency identification tags,[8,9] non-volatile memories[10] and photovoltaics.[11–13] In fact, certain of these systems appear close to commercial reality,[5,8,9] in spite of modest electrical performance compared to more well developed, rigid inorganic devices. Stretchable electronics represents a much more challenging class of system, of interest for applications where circuits must be wrapped conformally around complex curvilinear shapes or integrated with biological tissues in ways that are impossible using devices that offer only simple bendability. Biomedical systems such as personal health monitors and smart prosthesics as well as devices that use bio-inspired designs such as electronic eye cameras provide some representative examples. Stretchability demands that the circuits have the capacity to absorb large levels of strain ($\gg$1%) without fracture or significant degradation in their electronic properties. Extreme difficulties associated with the development of complete sets of stretchable electronic materials force one to contemplate hybrid possibilities, such as combinations of stretchable conductors as electrical interconnects between other elements of that are rigid or only bendable. Even this strategy has challenges, however, because all known stretchable conductors, most prominently those based on carbon[14] or nanoparticle filled[15] elastomers, have relatively high resistivities and properties that change significantly with strain and temperature. Recent work

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in stretchable nanotube composites, however, appears very promising.[16]

A completely different conceptual approach to stretchable electronics emerges from certain research on bendable inorganic electronics.[17,18] Here, desired mechanical properties are realized not through new materials but instead through new structural configurations of established ones. For example, bendability can be achieved in intrinsically brittle materials, such as single-crystalline silicon,[18] by implementing them in ultrathin formats (e.g., as nanowires,[19] nanoribbons,[20] or nanomembranes[21]) and, in some cases, in advanced neutral mechanical plane designs.[22] An attractive feature of this strategy is that it leads naturally to systems with electrical performance and reliability comparable to those of wafer-scale electronics, far surpassing anything that is possible with known organic active materials. For example, transistor devices with field effect mobilities up to several hundred $cm^2 V^{-1} s^{-1}$ in complementary circuits with bendability to radii of curvature as small as 0.05 mm can be achieved in this fashion.[21,22] The extension to stretchable is remarkably straightforward: ultrathin material structures formed into 'wavy' or buckled geometries offer stretchability with a physics similar to an accordion bellows, without inducing significant strains in the materials themselves.[18,24] This approach has recently been used to create stretchable conductors, transistors, diodes, photodetectors, circuits of various sorts and even fully integrated systems such as hemispherical electronic eye cameras.[25] A separate body of work uses material structures in a different way to yield a similar outcome. Here, open meshes[6] constructed in bendable materials provide large, reversible levels of deformability for strains applied along certain axes, for systems such as sensitive robotic skins.[27] Cantilever-spring structures in silicon exploit a related physics.[27,28] In this paper, we review these strategies, provide examples of device level demonstrations of them and conclude with some perspectives on future research opportunities.

2. Material Structures for Stretchability

Compatibility with well developed, high performance electronic materials represents a key advantage of stretchable electronics systems that are enabled by unusual material structures rather than unusual materials. Two different designs seem to offer the most promise and have so far enabled the most sophisticated device demonstrations. One uses material micro/nanostructures in 'wavy' layouts, where the amplitudes and wavelengths can change in response to applied strains.[29–31] The other divides the circuits into open meshes, such that in-plane rotations of bridging elements enable mechanical deformations at large effective strains.[6] Structures that incorporate both of these layouts are also, of course, possible. This section presents representative illustrations of these various strategies, with images of some experimentally demonstrated examples.

2.1. 'Wavy' Layouts of Nanowires, Nanoribbons, and Nanoribbons

Figure 1a and b schematically illustrate nanoribbons (gray) of brittle materials in two types of wavy layouts on stretchable supports (light blue). The first (Fig. 1a) involves intimate mechanical coupling at all points along the ribbon-substrate interface. For the case of silicon and the elastomer poly (dimethylsiloxane) (PDMS), such coupling can be accomplished through covalent –O–Si–O– linkages that form due to condensation reactions between surface –OH groups on the PDMS surface and the native oxide of the silicon.[24,29] When formed with the substrate in a pre-stretched configuration, mechanical relaxation creates a non-linear buckling instability that leads to sinusoidal, or 'wavy' configurations, with wavelengths and amplitudes that depend primarily (but not exclusively) on the elastic properties of the silicon and PDMS, and the thickness of the silicon.[32] Under applied strain, the wavelengths and amplitudes of these structures change in a manner that avoids substantial strains in the silicon itself.[29,32] Although the detailed physics is non-trivial,[32] the basic responses can be shown to be nearly identical, conceptually, to those of an accordion bellows. The resulting mechanical advantage provides practical levels of stretchability up to ~15%, exceeding by ~15 times the intrinsic fracture limit of the silicon.[29] This type of approach depends only on relatively simple, linear elastic mechanical responses, and can be applied to wide ranging classes of materials, in various geometries, from inorganic nanoribbons[29] and nanomembranes[33] to carbon monolayers[34] and nanotubes.[35] Some of the earliest results used spontaneous patterns of buckling formed due to the evaporation of thin films of gold onto PDMS,[37] although in this case microcracking often also plays an important role in the mechanics of stretching.[37]

Figure 1b shows the second type of wavy configuration.[31] Here, patterned sites of adhesion on the substrate and/or the ribbon create localized positions of bonding. The non-bonded regions can delaminate, or 'pop-up', from the substrate as the

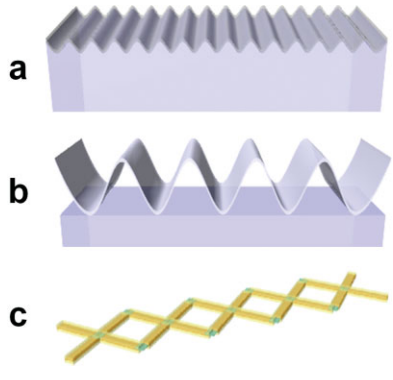

Figure 1. Three classes of material structure that can offer end-to-end stretchability/compressibility in brittle materials. a) Schematic illustration of wavy bucked structure of thin ribbon of a brittle material (gray), fully bonded to an elastic support (light blue). b) Similar type of structure, bonded only in selected locations. c) Mesh shaped ribbon.

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substrate prestrain is released, in an overall process that is otherwise similar to the case of the structures in Figure 1a. The main advantage of this second type of structure is that it offers engineering control over the buckling period in a way that allows its optimization for levels of stretchability. With such an approach, it is possible, in fact, to achieve reversible stretching to strains of 100% or more, often limited only by cohesive fracture of the elastomeric substrate.[31] As with the case of Figure 1a, these structures can be implemented in ribbons, membranes or wires of various materials.

2.2. Open Mesh Geometries

For the cases of Figure 1a and b, strains applied in the plane of the substrate are accommodated through out-of-plane displacements in the wavy structures.[29–32] In open mesh geometries, accommodation is provided by in-plane rotations, with a motion similar to that of a scissors.[6] Figure 1c shows a narrow strip with such a mesh design. Tensile strains applied at the ends of this structure cause the bridges to rotate in a manner that transforms the open squares into rhombuses: the strip lengthens and narrows as a result. Circuits that exploit this principle can use, for example, the bridges for electrical interconnects between device islands that lie at the vertices. In this design, mechanical failure at the limits of operation typically occurs at the bridges. To maximize robustness, the bridge size is usually designed to be longer than the island width (square island with 2 mm width and bridge with 4 mm length) and the size of device remains smaller than bridge intersection area, approximately 1 mm square width.[6]

2.3. Experimental Results

The concepts of Figure 1 have been implemented in several classes of materials, and even in fully formed devices and circuits. Figure 2 presents images of some examples of the former, embodied in two dimensional layouts as straightforward extensions of the simpler one dimensional versions of Figure 1. The top frames show a nanomembrane of single crystalline silicon on PDMS, in a 'wavy' herringbone layout that forms spontaneously during release of biaxial prestrain (in this case, 3.8%) in the PDMS.[33] The overall fabrication followed a sequence similar to that described in the previous section. The frame on the right of Figure 2a presents an atomic force microscope (AFM) image, revealing characteristic wavelengths of 12.8 μm and amplitudes of 0.66 μm. In this system, strains applied in any direction in the plane of the membrane, or those that arise from bending and other deformations out of the plane, are accommodated by corresponding changes in the wavelengths, amplitudes and spatial layouts of the wave structures, in a manner that avoids destructive strains in the silicon itself.

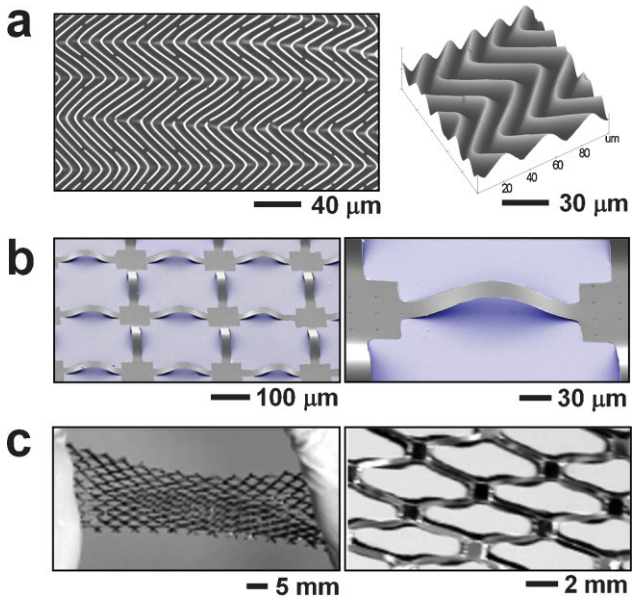

Figure 2. a) Silicon nanomembrane in a 'wavy' herringbone layout, bonded to an underlying piece of PDMS (left) and its surface topography measured by AFM (right). Figures were adapted and reproduced with permission from [33]. Copyright 2007, American Chemical Society. b) Array of square silicon nanomembranes interconnected by 'pop-up' nanoribbons on PDMS (left) with magnified view (right). c) Plastic mesh stretched in a direction angled relative to the bridge structures (left) with magnified view (right). Figures were adapted and reproduced with permission from [6]. Copyright 2005, National Academy of Sciences.

The two dimensional analog to the 'pop-up' wave geometry of Figure 1b appears in Figure 2b. This structure involves square islands of silicon (100×100 μm and 290 nm thick) connected by narrow (30×150 μm and 290 nm thick) silicon bridges. Relaxing biaxial prestrain (in this case, 30%) in the PDMS substrate leads to the configuration of Figure 2b. The bridges move up and down in response to compressive and tensile strains, respectively. This type of system, which often includes an encapsulating layer of PDMS to embed and protect the pop-up bridges, is of interest partly because it offers ranges of stretchability that are 5–10 times larger than those that are easily achieved using the design of Figure 2a.

Figure 2c shows the route to stretchable represented in Figure 1c. Selective cutting of rectangular opening areas in a plastic substrate with a numerically controlled cutting plotter or drilling machine forms a net shape structure,[6] in this case in a 75 mm thick sheet of poly(ethylenenaphthalate) or polyimide. The bridge size is 0.4×4 mm, allowing the systems (12×12 transistor networks) to be stretched to strains up to 25%, for directions at 45 degrees to the bridges. Strains applied in a direction not aligned to the connecting bridges leads to rotations of the bridges in a manner that enables the end-to-end length of the system to change. Electronic materials supported by such a mesh can be used to form active circuits and devices that offer a type of stretchability. Demonstrations in electronic skin and pressure sensors have been reported,[6] in which the mesh substrate supports layers of various electronic

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materials such as Au (50 nm thick) for electrodes, polyimide (750 nm thick) for dielectrics, pentacene as an organic semiconductor (50 nm thick) and parylene (2 μm thick) for passivation. Systems examples of the other classes of stretchable devices are summarized in the following section.

3. Systems Examples

The strategies of Figure 1 are each notable because of their successful application to devices, circuits and even entire systems with meaningful levels of integration. Of the 'wavy' or buckled class of system, the first and simplest demonstrations consisted of stretchable wires of Au as interconnects between devices on rigid or bendable islands.[36] Inverters based on n-type amorphous silicon transistors on thin polyimide sheets bonded to PDMS substrates and interconnected with wavy Au wires represent examples.[36] Somewhat later, different procedures enabled isolated high performance single crystalline devices, such as pn junction diodes and field effect transistors, both with integrated metal electrodes.[29–31] The most sophisticated, and most recent, examples involve semiconductor nanoribbons/nanomembranes on ultrathin plastic substrates, configured in optimized neutral mechanical plane designs, for fully integrated, complementary silicon circuits in 'wavy' layouts.[22] These procedures represent a realistic and scalable pathway to stretchable electronics. Figure 3a shows an example consisting of an array of three stage complementary ring oscillators and some isolated devices. Unlike the simple sinusoidal and herringbone geometries of Figures 1a and 2a, these systems buckle in complex spatial configurations, due to the materials and thickness heterogeneity of the circuits. The physics of the response to applied strain, however, is conceptually similar: the wavelengths, amplitudes and spatial layouts of the wave structures change to accommodate applied strains in a manner that avoids fracture in any of the materials. The inset of Figure 3a shows, as an example, part of the circuit under strain applied in the horizontal direction (red arrow). In this condition, waves with wavevectors in the horizontal direction decrease in amplitude and increase in wavelength, while the opposite occurs for waves oriented in the orthogonal direction due to the Poisson effect. The result is a wavy layout predominantly composed of vertically oriented waves. Systems with this design might be useful as conformal electronics for health monitors, where stretching naturally occurs during use.

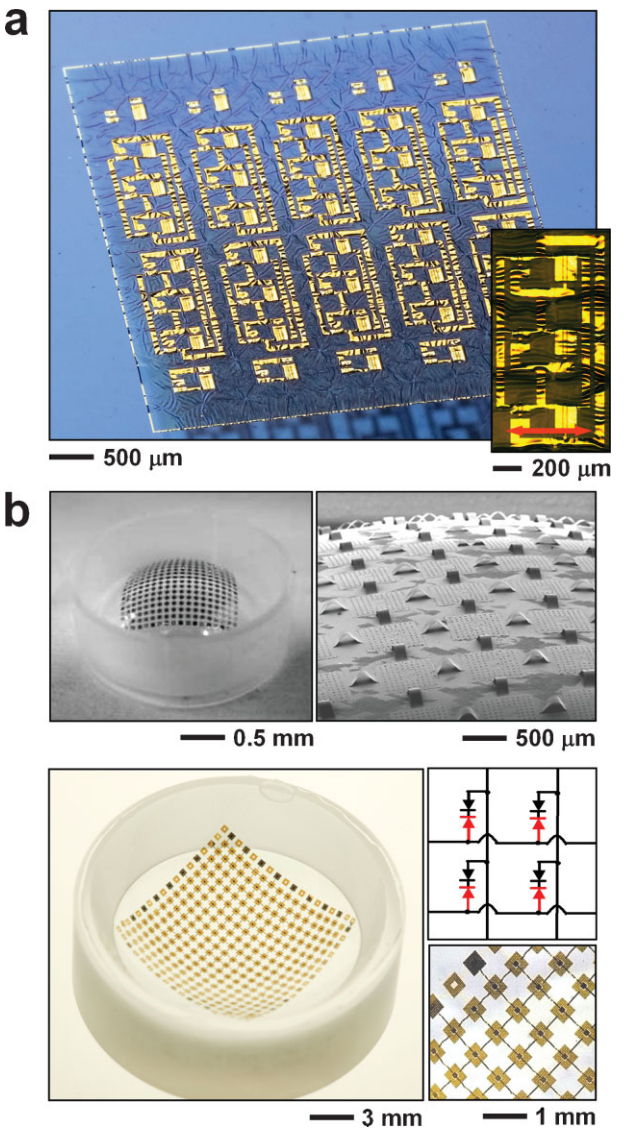

Figure 3. a) Image of fully stretchable silicon integrated circuit, consisting of a set of complementary ring oscillators and isolated transistors; inset shows one of these oscillators under uniaxial stretching in the direction of the red arrow. b) Optical image of an array of interconnected photodetectors and junction diodes in a compressed, hemispherical geometry on an elastomeric transform element (left top) and magnified SEM image (right top). Image of this array after transfer to a hemispherical glass substrate (bottom left), with magnified view (bottom right) and schematic circuit diagram (middle right).

Other classes of systems require stretchability only for integration onto curvilinear substrates, which themselves might be mechanically rigid. One type of device, which appears in Figure 3b, incorporates an array of silicon photodetectors and passive matrix electronics (circuit diagram in the second from bottom frame on the right) on a rigid, hemispherical substrate for a type of camera that has the approximate geometrical layout of the human eye.[25] This design offers larger field of view, better illumination uniformity and improved focusing behavior compared to planar, but otherwise similar, imaging devices with simple, single component imaging optics. Fabrication of the device (bottom left frame of Fig. 3b) used the stretchable concept of Figures 1b and 2b, together with a hemispherical elastomeric element to accomplish the planar to hemispherical geometry transformation needed for integration. (Strains in the range of 20–40% are required for such a transformation; simple bendability is insufficient.) The top frames show images of the array on the

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transform element; the bottom left frame shows the array on a rigid, hemispherical glass substrate. Integration with control electronics and an imaging lens completes the camera. Details of the fabrication can be found elsewhere.[25] Similar layouts, in interesting but nonfunctional demonstrations, can be achieved using cantilever-sprinas that interconnect silicon islands.[27–28]

4. Prospects

The stretchable electronics systems described here all use new material structures, rather than new materials, to accomplish desired mechanical attributes. The capabilities and the underlying mechanics are now reasonably well understood, as an outcome of comprehensive experimental and theoretical studies.[29–33,35–41] Improvements in material layouts, material types and structures appear to offer, however, significant opportunities for improving the range of stretchability, the mechanical robustness and the electronic/optical performance. In addition, further work on applications is likely to lead to important advances. In a first class of device, stretchability enables integration of electronics with systems whose range of motion demands reversible deformation to large levels of strain. Many biomedical applications fall into this category, where fundamental work on biocompatibility will require further research. Different possibilities arise from the conformal integration of electronics on substrates with complex surface curvature. This capability opens up design possibilities that bypass the two dimensional, flatland constraints inherent with conventional flat wafer or glass substrates. Hemispherical electronic eye cameras represent a good example. For these classes of systems, elastic stretchability is an attractive feature, but not a requirement. Irreversibly deformable circuits, such as those that involve spooled interconnects and rotating device islands,[42] provide an alternative route to the same outcome. This broader field of unusual electronics combines, in an appealing manner, interesting fundamental topics in semiconductor nanomaterials and applied nanomechanics with unusual device and system engineering, all in the context of important and wide ranging applications that cannot be addressed using conventional technologies. The result is an area with many exciting research possibilities, and a correspondingly bright future.

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