

Electrochemical morphing

Silicon anodes in lithium batteries expand during discharge, causing failure. This expansion has been used constructively in a material whose architecture controllably and reversibly changes to alter its function. [SEE ARTICLE P.205](#)

SEUNG-YEOL JEON & SUNG HOON KANG

If pressure is applied to a block of rubber, it flattens, but reverts to its original form once the pressure is removed — the shape transformation is said to be volatile. But if the same pressure is applied to Play-Doh, the new shape persists even without the pressure. Such a difference is due to inherent dissimilarities in each material's properties, rather than in the nature of the shape produced, and it has not been possible to turn the volatility of a material's shape changes on or off on demand. On page 205, Xia *et al.*¹ report a type of 'architected' material for which the shape-transformation volatility can be modulated by controlling an applied charge and the geometry of substructures in the material, using electrochemical reactions that occur in batteries.

Architected materials are a new class of material in which desirable properties are achieved through careful arrangement of substructural elements, such as beams and plates². Many researchers are attempting to engineer normal (non-architected) materials to produce architected materials that have the exceptional characteristics of natural materials made from other compounds or elements, or that exhibit unusual properties not found in nature. Architected materials can have very different properties from those of their analogous non-architected materials.

Many studies on architected materials have sought to develop 'smart' materials that change their shape, and therefore their function, by responding to stimuli such as temperature, humidity or magnetic fields — similar to the capabilities of the robots in the *Transformers* films. The buckling of railway tracks in hot weather has inspired a strategy for inducing large shape and property changes: similar buckling of constrained substructures in materials has been triggered by applying mechanical loads³ or by controlled swelling caused by the absorption of a solvent⁴.

However, previously reported approaches for generating buckling-induced shape changes involve a finite number of shape configurations (usually two), and cannot switch the shape-transformation volatility of a material. That is, either an external stimulus must

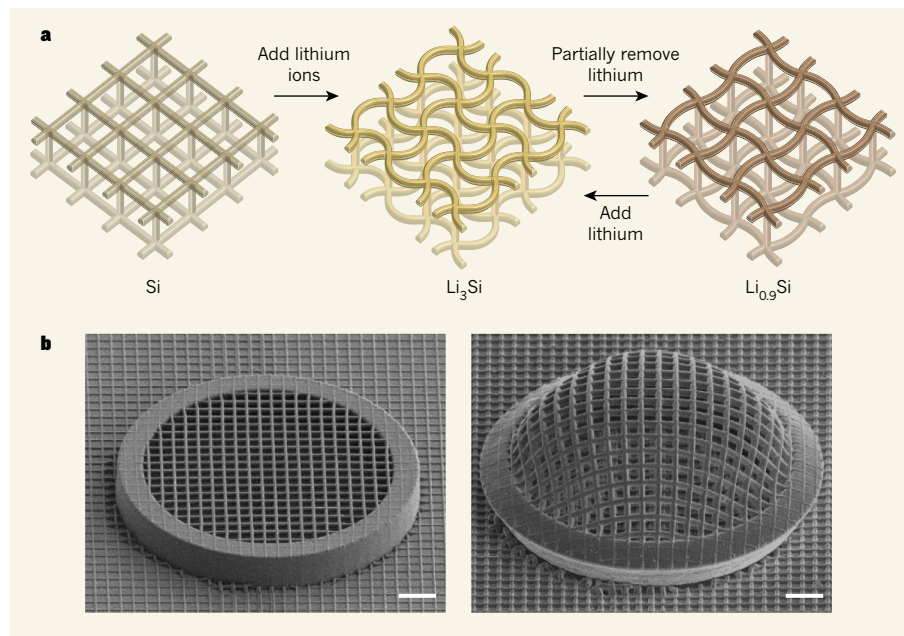


Figure 1 | Structural reconfiguration of a material through electrochemical reactions. a, Xia *et al.*¹ report an 'architected' material whose microscopic structure consists of a 3D cage-like lattice, which has an outer coating of silicon. When lithium ions are loaded into the silicon through electrochemical reactions, the silicon expands, causing the lattice to buckle. The buckling is reversible, and the extent of buckling depends on the amount of lithium trapped in the silicon. b, The buckling can be precisely controlled to produce changes in the shape of the architected material. Scale bars: 15 micrometres. Micrographs reproduced from ref. 1.

be maintained to retain the new shapes (as in the rubber-block example), or else the architected materials do not recover their original form when the external stimulus is removed (as with Play-Doh).

Xia and colleagues overcome this issue by using a new approach to induce shape transformations. They began by fabricating a cage-like 3D lattice (Fig. 1a) from a polymer using a 3D printer, then coated the lattice sequentially with a nickel layer and a silicon layer. Silicon is used as an anode material in lithium-ion batteries, which discharge by moving lithium ions from their cathode to the anode. Silicon anodes expand by about 300% when fully loaded with lithium⁵, and the authors used this electrochemical transformation as an external stimulus to trigger buckling in their architected material. Xia and colleagues' approach builds on previously reported work⁶ in which honeycomb-like silicon structures were observed to buckle on loading with lithium ions.

The authors observed that the silicon-coated lattice undergoes shape transformations on discharging that can be reversed by recharging, and vice versa. Unlike architected materials based on soft materials, this shape change can be continuously modulated by electricity, and the new shape is maintained when discharging and/or charging is stopped — that is, the shape transformation is non-volatile. Moreover, Xia *et al.* carried out a numerical analysis to show that their approach can be used to switch the architected material between volatile and non-volatile shape-transformation states. They did not demonstrate such switching experimentally, but they did show that volatile and non-volatile states can be produced individually.

The researchers could control where in the lattice buckling occurred, thus enabling complex shape changes to be produced (Fig. 1b; see also Fig. 4h and Figs 6d–k of the paper¹). These complex changes were engineered by introducing precisely positioned imperfections into

the lattice, to provide a slight bias that caused buckling to occur in a particular direction. Such imperfections would generally be undesirable in other contexts.

One of the current limitations of Xia and colleagues' work is that it takes a long time to make a tiny amount of the architected material — we estimate that it would take about a day to produce 1 cubic millimetre of material, although the exact timing will vary depending on the printing conditions and the geometries of the material involved. A new 3D-printing approach known as volumetric additive manufacturing⁷ might help to accelerate and scale up the process, but it currently has limited spatial resolution and works with only a small range of materials.

Xia and colleagues' findings have a variety of potential applications. For example, in micrometre-scale robots, which have limited room for components, the use of materials that can change shape to perform multiple functions would be most helpful. The technology might also find uses in autonomous micro-devices that perform desired functions by changing shape in response to stimuli such as changes in ion concentration, or in devices known as microactuators⁸ that 'snap'⁹ between two configurations in response to electrical signals or electrochemical stimuli.

The study also demonstrates a means of releasing the stress that builds up in silicon anodes of lithium batteries as they change volume during discharge, to prevent failure of the anodes — which is one of the key challenges in the development of next-generation silicon–lithium batteries. Moreover, the work opens up opportunities for controlling the propagation of high-frequency vibrations (known as phonons) using electricity, which might enable the development of potentially useful microelectromechanical systems.

Future research into electrochemically reconfigurable materials could benefit from the use of computational methods, such as machine learning, to optimize the topology of architected materials and the shapes produced for different applications. Such methods might increase the lifetime and/or the number of possible lithium loading–unloading cycles of architected materials by decreasing the strains required to induce buckling. They might also reduce the time taken for materials to respond to an electrochemical stimulus (currently 5 to 10 minutes), by increasing the surface area at which electrochemical reactions can occur, for example by using hierarchical substructures.

Finally, if the material systems that are compatible with this approach can be expanded, it would open the way for sensors and smart actuators to be used in many other applications, including medical devices. Given that our bodies contain various ion-containing, water-based fluids, it might be possible to devise micro-devices that sense physiological variables without external power, or to make

smart implants that adapt to local conditions by modulating their shapes. ■

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STRUCTURAL BIOLOGY

A mechanism for touch

Piezo proteins mediate the sense of touch. A near-complete structure of one such protein has been obtained, and the mechanism for converting mechanical signals into electrical ones has been probed in another. SEE ARTICLES P.225 & P.230

EDWIN W. MCCLESKEY

Our bodies can sense a wide array of mechanical stimuli: our sense of touch can distinguish between a soft breeze floating over the skin and a painful pinch, and other systems can detect the stretch of a muscle or even blood pressure. Our ability to sense these things requires an applied force to be turned into an electrical signal in the tiny endings of sensory neuronal cells that suffuse different tissues. Two related proteins, the Piezo1 and Piezo2 ion channels, mediate many of the mechanically stimulated processes in animals, by allowing positive ions to flow across the surface membrane of cells in response to force applied to the membrane¹. Such mechano-electric transduction is mediated by Piezo2 in sensory neurons and by Piezo1 in non-neuronal cells that respond to forces such

as shear and osmotic force². On page 225, Wang *et al.*³ report a remarkable, almost complete structure of Piezo2, and on page 230, Lin *et al.*⁴ describe experiments that test how transduction occurs in Piezo1.

Piezo ion channels assemble from three identical Piezo proteins, each containing more than 2,500 amino-acid residues⁵. Solving such large structures — finding the location of each atom — is a great technical challenge. Nevertheless, studies in the past couple of years have described partial structures of Piezo1 at near-atomic resolution^{6–8}.

Wang and colleagues now take things further with their near-atomic-resolution structure of Piezo2, resolving each of its 38 transmembrane helices. This is yet another achievement of the 'resolution revolution' in single-particle cryo-electron microscopy

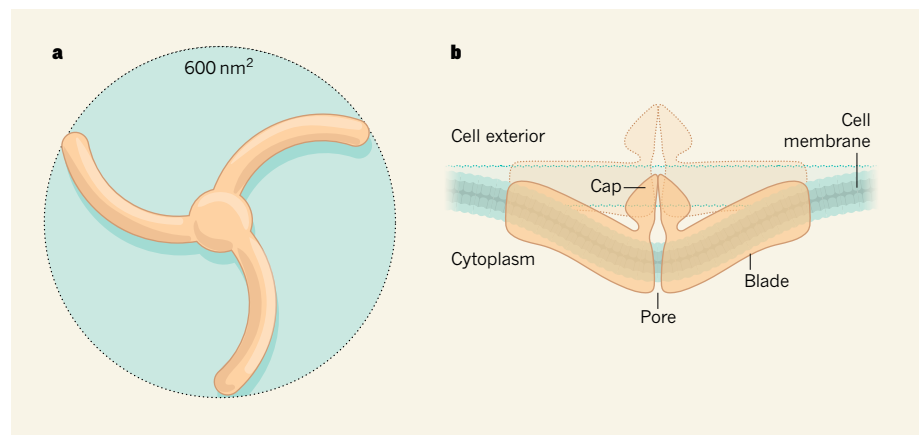


Figure 1 | The structure of Piezo ion channels and their response to forces. Wang *et al.*³ report the near-complete structure of Piezo2, a membrane ion channel that converts mechanical stimuli into electrical signals. Viewed from above or below the membrane, the trimeric channel looks like a three-bladed propeller and defines an extensive membrane area of about 600 square nanometres — in line with the idea that it responds to stretching of the membrane. **b.** Lin *et al.*⁴ report that the bowl-like shape of the Piezo1 channel, viewed here from the side, creates a dimple in the surrounding membrane. The protein and dimple flatten reversibly when a force (not shown) of the size that could cause the channel's pore to open is applied to Piezo1, perpendicular to the membrane.