

Inspired by the anisotropy and self-assembly of liquid-crystalline materials, Yang and Gogotsi's groups converted  $Ti_3C_2T_x$  ( $T_x$ : surface functional groups) nanosheets, the most widely studied MXene, into liquid-crystal phases. They hoped to vertically align  $Ti_3C_2T_x$  in the specific liquid-crystal phase. However, this was not a trivial task, according to Yu Xia, first author of the article: "The biggest challenge is that very little is known in the field of two-dimensional materials-based liquid crystals... Everything had to start from scratch."

A solution came soon. The researchers attached a surfactant, hexaethylene glycol monododecyl ether ( $C_{12}E_6$ ), onto the surface of  $Ti_3C_2T_x$  through hydrogen bonds, which turned the  $Ti_3C_2T_x$  nanosheets into high-order liquid crystals, coined lamellar nematics. Upon applying a shear force, these surface-modified  $Ti_3C_2T_x$  sheets

"stand" straight on the substrate, forming orderly distributed arrays, as suggested by liquid-crystal theory. These vertical arrays were maintained after the  $C_{12}E_6$  surfactants were removed. This structure contains abundant inter-sheet slits that serve as ion-movement "expressways" to allow quick ion diffusion.

Electrochemical testing revealed that the vertically aligned  $Ti_3C_2T_x$  nanosheets are capable of being charged rapidly. Cyclic voltammetry tests showed that the 200- $\mu\text{m}$ -thick film electrode lost little of its charge-storage capacity at a fast charging rate of  $1000\text{ mV s}^{-1}$ . This behavior was observed in electrodes that were 40–320  $\mu\text{m}$  thick. The control sample, the same  $Ti_3C_2T_x$  nanosheets but stacked parallel to the substrate, abruptly lost its charge-storage capability starting at an intermediate rate of  $10\text{ mV s}^{-1}$ , even though the thickness was only 35  $\mu\text{m}$ . The results unambiguously

highlight the advantage of the vertical arrangement in retaining the fast charge-storage characteristic of MXene-based supercapacitor electrodes.

"It is amazing that simply making MXenes 'stand up' leads to such a big difference," says Yat Li of the University of California, Santa Cruz. "This work shows an innovative method of controlling the alignment of electrochemically active materials to achieve ultrafast directional ion diffusion in thick electrodes," he says. Li was not involved in this study.

This method may encourage a plethora of future work. Gogotsi says, "Alignment of mechanically strong and electrically conductive MXene layers may lead to manufacturing of MXene fibers, membranes, coatings, and other forms with unique and anisotropic properties for various applications beyond energy storage."

**Tianyu Liu**

### Ductility observed in flash-sintered yttria-stabilized zirconia

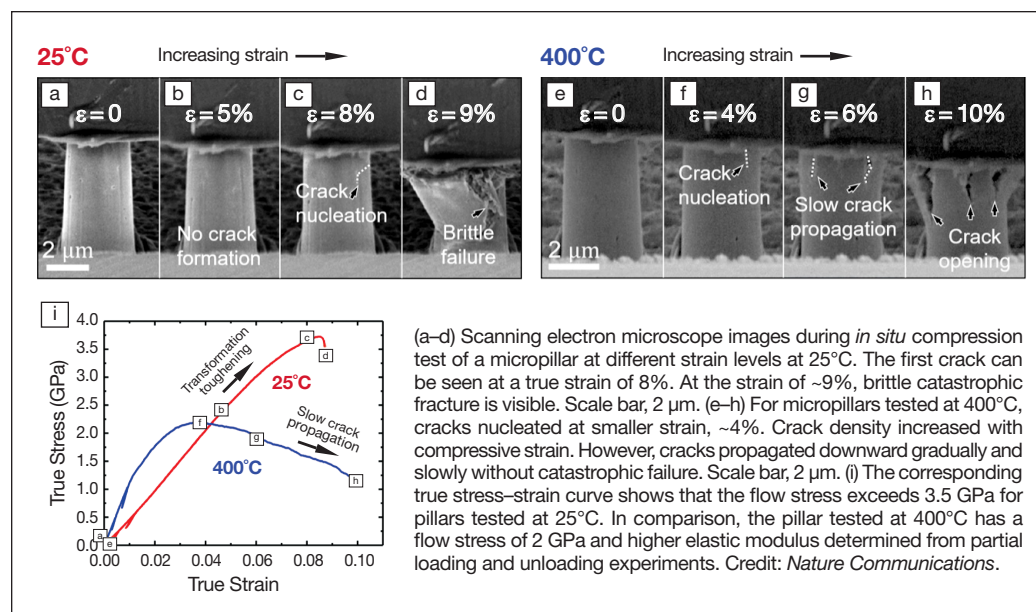
Ceramics have many important high-temperature industrial applications but are exemplars of brittle failure. Yttria-stabilized zirconia (YSZ) is a ceramic that undergoes a stress-induced phase

transformation that grants it limited ductility as crack propagation is slowed. However, further increases in ductility remain elusive as ceramics lack the ability to support a high-enough dislocation density. In a recent issue of *Nature Communications* (doi:10.1038/s41467-018-04333-2), Jaehun Cho, Qiang Li, Haiyan Wang, and Xinghang Zhang of Purdue University and

their colleagues detail their study of flash-sintered YSZ with improved ductility.

Flash sintering is a rapid densification process that results in nano-sized grains: heat is increasingly applied to a sample at a constant rate, under a moderate external electric field. When flash sintering was developed by Rishi Raj's group at the University of Colorado Boulder a few

years ago, this process seemed promising as a way to limit the grain growth of ceramics upon sintering, which is one of the standard ways of increasing ductility in metals—following the well-known Hall–Petch relation (doi:10.1111/j.1551-2916.2010.04089.x). Above the flash temperature, nanoparticles undergo densification within a few seconds. Once completed, the sample exhibits a significant and sudden increase in density and electrical conductivity.





Haiyan Wang's group began looking at flash-sintered ceramics and the fundamental sintering mechanisms.

The researchers studied the microstructure of flash-sintered YSZ using a transmission electron microscope. They observed dislocations (as multiple arrays of lines in the sample), which are only seen in metallic materials or ceramics deformed under extremely high temperatures. From there, the researchers began investigating the fundamental mechanism behind the ductility of flash-sintered YSZ: why does flash sintering result in high dislocation densities? They also measured the mechanical

properties of flash-sintered YSZ using an *in situ* nanomechanical testing tool inside a scanning electron microscope. They found that while transformation toughening was the primary deformation mechanism at room temperature—with strains of 8% that led to brittle failure—at 400°C the mechanism changes and dislocations become the primary carriers of deformation—with strains of up to 10% leading to ductile failure.

B. Reeya Jayan of Carnegie Mellon University, not associated with this study, was impressed to see the high density of dislocations in flash-sintered YSZ.

“Understanding such processing–structure–property relationships under external fields is exciting and will be an active area of research,” she says.

In future work, the research team hopes to generalize the results to other ceramic systems by understanding which are key in enabling the ceramics' plastic deformation. This could lead to advances in engineering ceramics for many industrial applications.

Other members of the research team are affiliated with Oak Ridge National Laboratory, Colorado State University, and the University of California, Davis.

**Antonio Cruz**

### Energy Focus

#### Fast-charging 3D battery developed by bottom-up nanofabrication

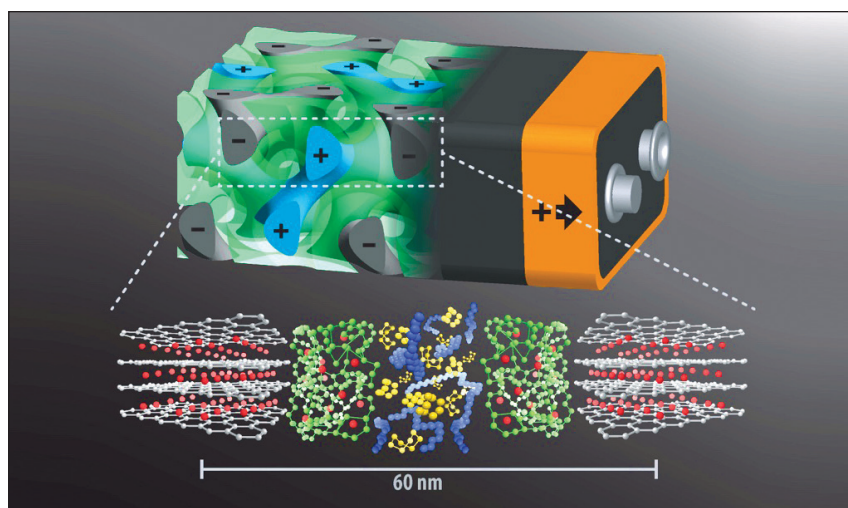
Traditionally, battery architectures include a layered assembly of anodes, cathodes, and a separator. In Li-ion batteries, the thickness of each component, which is typically ~10  $\mu\text{m}$ , dictates the charging rate of the battery governed by the diffusion of lithium ions. Now researchers have designed a so-called three-dimensional (3D) battery fabricated through a novel bottom-up approach, where all of these

components interpenetrate and in which the thickness of each layer is just 10 nm. This makes it three orders of magnitude thinner than the mainstream batteries currently on the market. Since diffusion time significantly depends on the size of each component, this design results in orders of magnitude faster charging times. The 3D battery design is a radical deviation from mainstream battery design concepts. The concept sounds straightforward, but was complicated to achieve in practice.

According to U.B. Wiesner of Cornell University, lead researcher in this study

that was published in a recent issue of *Energy & Environmental Science* (doi:10.1039/c7ee03571c), thinner batteries have been demonstrated previously that have increased power density but reduced energy density. With the 3D design, the thinner components promote fast ion transport while also offering increasing charge storage.

In this bottom-up nanofabrication, approach the porous carbon anode is deposited first. The porous structure of the layer was confirmed through a scanning electron microscope. The polymer electrolyte poly(phenylene oxide) is coated afterward. The last layer (cathode) of two interpenetrating network mesopore channels is deposited, which is a composite of sulfur and poly(3,4-ethylenedioxythiophene)(PEDOT). The redox-active functionality with a discharge voltage of 2–2.5 V versus lithium and infiltration at moderate temperatures (155°C) made the selection of sulfur an easy choice in comparison with the standard lithium cobalt oxide cathode. PEDOT is employed because of its high electronic conductivity. With these components in place and in the interpenetrating configuration, the battery could operate at a stable open-circuit voltage and a well-defined discharge plateau at 2.7 V with a reversible capacity of 0.2 mA h cm<sup>-2</sup>. As an illustrative comparison, a conventional battery design with a similar capacity would occupy an area that is 4700 times larger.



Rendering of the 3D battery design with anode (gray) and cathode (blue) interpenetrating each other separated by the separator layer (green). Bottom: Molecular structures of anode, separator, and cathode (same color code) materials with lithium ions (red) shuttling back and forth. Scale bar indicates that the entire sandwich has a thickness of only about 60 nm. Credit: U. Wiesner.