

aren't many geometric configurations that you can conceive of where nearly all of the elements are in either tension or compression."

In this case, the researchers chose one of the known geometric configurations that satisfies this requirement, the octet truss, for their experiments, as reported in the June 20 issue of *Science* (DOI: 10.1126/science.1252291; p. 1373). The unit cell of the octet truss has a regular octahedron at its core, with eight regular tetrahedra on its faces, which lead to a face-centered-cubic (fcc) structure. Using projection microstereolithography, they were able to produce highly ordered, nearly isotropic microlattices within these fcc, stretch-dominated architectures. Critical features in the 20  $\mu\text{m}$  to 40 nm range created lots of void space for ultralightweight properties.

One key to their success was the ability to use projection microstereolithography to fabricate arbitrary, three-dimensional (3D) microscale structures. This additive manufacturing technique is based on building patterns of photocured polymer resins (HDDA or PEGDA) layer

by layer. The pattern is generated slice by slice from a 3D CAD model, and projected through a liquid-crystal-on-silicon chip, which acts as a reconfigurable digital photomask, onto the surface of a bath of UV-curable resin. After a layer hardens, the sample is lowered in the polymer bath, new resin coats the surface, and the next layer of the 3D structure is projected and polymerized onto the layer beneath.

The result is an extended microlattice of octet truss unit cells made of solid polymer struts. By coating these struts with a nickel-phosphorus alloy through electroless nickel plating, and removing the polymer struts through thermal decomposition, a hollow-tube metallic Ni-P microlattice can be formed. Similarly, by depositing the ceramic  $\text{Al}_2\text{O}_3$  by atomic layer deposition onto the polymer struts and removing the polymer, a hollow ceramic  $\text{Al}_2\text{O}_3$  microlattice is formed. For yet another configuration,  $\text{Al}_2\text{O}_3$  nanopowder is mixed in with the polymer before the process begins, resulting in a structure consisting of a polymer-ceramic hybrid core. Subsequent heat treatment decomposes

the polymer and sinters the  $\text{Al}_2\text{O}_3$  to form a solid ceramic microlattice.

In each case (polymer, metallic, hollow ceramic, solid ceramic), uniaxial compression studies yielded plots of relative compressive stiffness and relative compressive strength versus relative density. These plots showed the stiffness and strength to be linear functions of the relative density of the material for each of these stretch-dominated lattices. In contrast, a bend-dominated, solid polymer Kelvin foam made by the same process for comparison decreased in strength and stiffness by a power of two with decreasing density.

"We fabricated an ultrastrong, ultrastrong material that is primarily void space, which makes it very light weight," Spadaccini said. "Then we took that a step further by combining additive micromanufacturing processes with nanoscale coating processes to give us a material that is about as light as an aerogel. The mechanical properties, relative to the material's density, go through the roof."

**Tim Palucka**

**Fast electronic switching of ultrathin films of phase-change materials render nonvolatile color changes**

Phase-change materials (PCMs) switch between amorphous and crystalline solid states. The process can occur at ultrahigh speeds (on the order of MHz), and may be driven thermally, optically, or electrically. Controlling the associated changes in the PCM's optoelectronic properties is a great motivator to investigate and characterize such systems. As reported in the July 10 issue of *Nature* (DOI: 10.1038/nature13487; p. 206), Peiman Hosseini and Harish Bhaskaran at the University of Oxford and C. David Wright at the University of Exeter induced phase switching within sputtered  $\text{Ge}_2\text{Sb}_2\text{Te}_5$  (GST) films. These phase changes take place within low-dimensional

nanoscale-sized regions, and the optical properties (e.g., color) in these regions change in a reversible, stable manner.

The researchers started by sandwiching GST between two layers of indium tin oxide (ITO), and depositing it on a reflective platinum surface. Crystallization of the GST changes its refractive index, which in turn changes the color of the multilayered stack when illuminated with "white" light. No energy is required after a switching event to maintain the new color, which is a distinct advantage in low-power display applications. In short, the group demonstrated the principle behind a PCM-based, nonvolatile reflective display.

The researchers modeled the stack using a transfer matrix optical computational method, and calculated optoelectronic properties such as color, reflectance, internal electric field, and transmittance. The model simulates the stack's optical properties for GST in its as-sputtered amorphous state, and also in its crystalline

state. Hosseini and colleagues found excellent agreement between their model data and the experimentally measured reflectivity spectra of the films.

The researchers next turned their attention to how the thickness of each of the three films affects the properties of the overall stack. They confirmed a strong dependence of color on film thicknesses. Furthermore, smaller GST thickness enhanced the reflectivity contrast between the amorphous and crystalline states, and fortuitously for display applications, required less power to switch. The researchers also tailored the thickness of the ITO layers to enhance the reflectivity of specific wavelengths; in effect, they demonstrated that it is possible to create a pixel of a specific color for a reflective display.

Working both with a continuous ITO/GST/ITO/Pt film and a similar film with lithographically defined pixels, they used the conductive tip of an atomic

force microscope (CAFM) to switch the GST's phase within nanoscale areas. They changed the color of the affected area, and created images that demonstrate the working principle of a reflective micro-display.

Next, the group moved on from reflective devices to deposit ITO/GST/ITO sandwiches on transparent substrates (quartz). They modulated the optical transmission of such a stack by electrically

stimulating the crystallization of the GST layer. The researchers again used a CAFM to serially render high-resolution images, now demonstrating the principle behind a transmissive micro-display. Potential uses of fast, low-power, semi-transparent displays include wavelength-tunable windows, windshield displays, or even synthetic retina devices.

The layered films are very thin, and

the techniques described were also demonstrated on flexible substrates and displays, enabling the creation of PCM-based pliable, electronic paper. Harish Bhaskaran, who led the work, said, "This optoelectronic framework has many like-ly applications, such as ultrafast, entirely solid-state displays, or supple, 'smart' contact lenses."

**Rich Louie**

### Optical sensors swell when exposed to a target gas

Using microscopic polymer light resonators that expand in the presence of specific gases, Dirk Englund's research team at the Massachusetts Institute of Technology has developed optical sensors with predicted detection levels in the parts-per-billion range. Optical sensors are ideal for detecting trace gas concentrations due to their high signal-to-noise ratio, compact, lightweight nature, and immunity to electromagnetic interference.

Although other optical gas sensors have been developed before, Englund's team conceived an extremely sensitive, compact way to detect vanishingly small amounts of target molecules. As reported

in the June 16 issue of *Applied Physics Letters* (DOI: 10.1063/1.4879735; 241108), the researchers fabricated wavelength-scale photonic crystal cavities from PMMA, an inexpensive and flexible polymer that swells when it comes into contact with a target gas. The polymer is infused with a fluorescent dye, which emits selectively at the resonant wavelength of the cavity through a process called the Purcell effect. At this resonance, a specific color of light reflects back and forth a few thousand times before eventually leaking out. A spectral filter detects this small color shift, which can occur at even subnanometer level swelling of the cavity, and in turn reveals the gas concentration.

"These polymers are often used as coatings on other materials, so they're abundant and safe to handle. Because of their deformation in response to

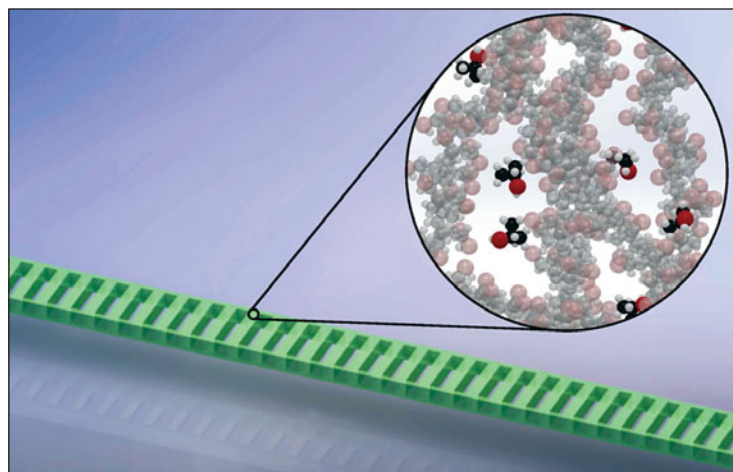
biochemical substances, cavity sensors made entirely of this polymer lead to a sensor with faster response and much higher sensitivity," said PhD student Hannah Clevenson, who led the experimental effort in Englund's laboratory.

PMMA can be treated to interact specifically with a wide range of different target chemicals, making the researchers' sensor design highly versatile. There's a wide range of potential applications for the sensor, said Clevenson, "from industrial sensing in large chemical plants for safety applications, to environmental sensing out in the field, to homeland security applications for detecting toxic gases, to medical settings, where the polymer could be treated for specific antibodies."

The thin PMMA polymer films, which are 400 nm thick, are patterned with structures that are 8–10  $\mu\text{m}$  long by 600 nm wide and suspended in air. In one experiment, the films were embedded on tissue paper, which allowed 80% of the sensors to be suspended over the air gaps in the paper. Surrounding the PMMA film with air is important, Clevenson said, both because it allows the device to swell when exposed to the target gas, and because the optical properties of air allow the device to be designed to trap light traveling in the polymer film.

The researchers, including Pierre Desjardins and Xuetao Gan, found that these sensors are easily reusable since the polymer shrinks back to its original length once the targeted gas has been removed.

The current experimental sensitivity of the devices is 10 parts per million, but the team predicts that with further refinement, they could detect gases with part-per-billion concentration levels.



High-sensitivity detection of dilute gases is demonstrated by monitoring the resonance of a suspended polymer nanocavity. The inset shows the target gas molecules (darker) interacting with the polymer material (lighter). This interaction causes the nanocavity to swell, resulting in a shift of its resonance. Credit: H. Clevenson/MIT.