applied to the donut-shaped translucent film. Finally, a lathe turns the cylindrical methafilcon-PLGA/latanoprost-methafilcon sandwich into a lens.

To track the *in vitro* drug release kinetics, the research team assayed daily aliquots of phosphate buffer solution (PBS) into which they had placed the lenses. After an initial burst, the latanoprost release rate steadied. The researchers also fitted lenses to rabbit eyes and periodically checked the concentration of latanoprost in the aqueous humor. The concentration of absorbed medication remained constant from the 3rd until the 28th day, after which time the lenses were removed. The latanoprost concentration in the aqueous humor was the same as for eye drop use.

Earlier studies by the research team demonstrated that both the PLGA and encapsulation within the polymer hydrogel contribute to the release kinetics. PLGA is FDA-approved; it biodegrades into components found naturally in the human body and has well-known release kinetics. The device's function is not materials-dependent, Kohane said. "Unlike other approaches where the drug was distributed throughout the lens, in our design there was a real advantage from its macroscopic nature. The larger an object is, the smaller its surface area to volume ratio and therefore the slower and more controlled its release is going to be. The key concept here is the design rather than the specific materials." While one concern for commercialization of the contact lens is degradation during storage, the PLGA can in principle be switched with a polymer with a longer shelf life.

Nor is the lens substrate materials-critical. In the long term the team may switch to contemporary silicone hydrogel lenses. For now they will try to increase the size of the film "window." Currently the aperture is equivalent to that of eye-color-changing contact lenses, but the researchers want the light transmission to be close to that of vision-correcting lenses.

"Here you have a contact lens that could be built with the patient's refractive correction, so that the patient would be seeing better using the lens.... Right now patients don't have much incentive to be compliant with their glaucoma medications. Glaucoma is commonly asymptomatic so most patients don't appreciate any vision loss until it's too late. So I think something that adds an incentive that is currently not there would be beneficial to improving compliance," said Ciolino.

Anuj Chauhan of the University of Florida uses vitamin E to slow contact lens drug release. "The strength of [the Boston] work is that you can release the medication for a month at zero-order release rates. Vitamin E is not zero order, it's diffusion-controlled. The advantage of the thin films is that you get close to zero-order release. Other methods have their own advantages, and it's good that multiple people are working on the problem."

Jen Gordon

Energy Focus

Skin pigment enables edible battery for biodegradable devices

By using the skin pigment melanin as an electrode material, researchers have made batteries that people could swallow. Such edible batteries could potentially power medical implants that disintegrate in the body instead of having to be surgically removed.

The idea behind biodegradable electronics is to make devices that go into the body, for example, to measure temperature, monitor wounds, or deliver drugs. Once their job is done, the devices could crumble into smaller pieces that are easily eliminated by the gastrointestinal tract, said Christopher Bettinger, a materials science and engineering professor at Carnegie Mellon University (CMU). "Unlike a pacemaker that has to last for five years, such edible electronics only need to last about 20 hours," he said. "So we want simple devices that are cheap and biocompatible."

Bettinger and others have already made biodegradable transistors and capacitors using various natural and synthetic materials. But the essential power sources for edible electronics were missing. Lithium-ion batteries could be used in the body if they are packaged safely, said Bettinger, but the toxic lithium and electrolytes in them could be a problem if the battery leaks or gets stuck in the body.

So he teamed up with materials science and engineering professor Jay Whitacre to use melanin electrodes in the sodium-ion battery chemistry that Whitacre has developed. Melanin shares some key properties with conventional electrode materials: it binds reversibly with ions, it generates electrons, and it is composed of uniform nanoscale granules that give it a very high surface area.

The sodium-ion battery relies on a water-based electrolyte to move sodium ions between its electrodes. The researchers replaced the activated carbon anode with those made of melanin. To make the anodes, they extracted melanin from cuttlefish, loaded it with sodium ions, and encased it in a steel mesh. The result is a battery that uses benign, abundant materials such as water, sodium, and melanin. "The cathode is manganese, which people need in their diets," Bettinger said. "We're using materials that are found in the body or that we eat anyway."

The battery could power a body temperature sensor for five hours, although its power output was less than that of a traditional battery. The melanin anodes, meanwhile, could provide as much current per mass as some well-known anode materials. Bettinger, Whitacre, W.J. Kim, and W. Wu of CMU and S.-E. Chun of the University of Oregon reported their results in the December 24 issue of the *Proceedings of the National Academy of Sciences* (DOI:10.1073/pnas.1314345110; p. 20912).

"This introduces a route to batteries built with biodegradable organic

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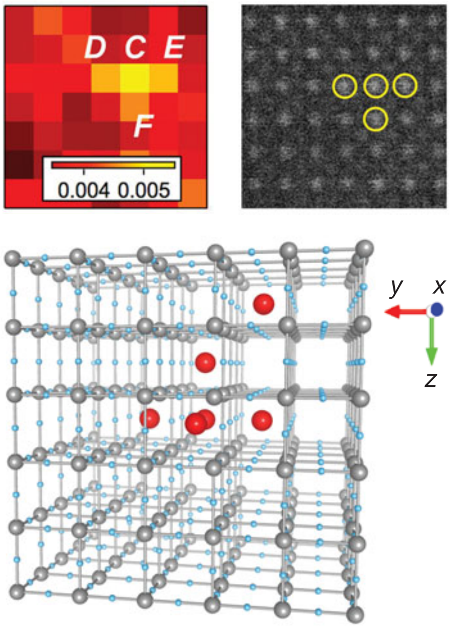
materials," said John Rogers, a materials science and engineering professor at the University of Illinois at Urbana-Champaign commenting on this study. Other possibilities to power edible electronics have been demonstrated recently, he said. These include mechanical energy harvesters; degradable solar cells; and RF antennas and rectifiers that could be used to power devices from outside the body. But, he said, batteries are an important power supply option.

"This new system appears to offer a scalable route to high power output," Rogers said. "Successful integration of these batteries with electronics and sensors and wireless communication components, all of which now appear possible due to rapid advances in chemistries and materials, can enable devices that go into the body and then naturally disappear."

Prachi Patel

Quantitative STEM technique extracts 3D atom stacking information from 2D image



From two to three dimensions: 2D projected Sr column intensity (I_{Sr}) map (top left) and high-angle annular dark-field (HAADF) image (top right) of a Gd-doped $SrTiO_3$ crystal area. Bottom figure gives a 3D reconstruction of the most probable Gd dopant configuration in columns C–F perpendicular to the surface (indicated by yellow circles in the HAADF image). Reproduced with permission from *Phys. Rev. Lett.* **111** (2013), DOI: 10.1103/PhysRevLett.111.266101. © 2013 American Physical Society.

The properties of electronic devices are often affected by the positioning of dopant atoms, where these may be evenly distributed or present in the form of small clusters. The ability to determine the exact locations of dopant atoms in a host lattice is one example of the three-dimensional (3D) structural information that can facilitate the optimization of new electronic devices, particularly nanoscale devices.

Obtaining 3D information with atom-scale resolution is a real challenge in conventional scanning transmission electron microscopy (STEM). "The typical method to obtain 3D information is 3D tomography, but this requires taking different images and tilting of the sample which is difficult to do and limits resolution to a few nanometers. While people have used that technique to make computer-reconstructed images of, e.g., nanoparticles, it does not give truly quantitative atomic resolution," said Jinwoo Hwang, first author on an article published in the December 27, 2013 issue of *Physical Review Letters* (DOI:10.1103/PhysRevLett.111.266101).

Currently a postdoctoral researcher in Suzanne Stemmer's group at the University of California–Santa Barbara (UCSB), Hwang and his co-authors from UCSB and the University of Melbourne, Australia, used a different method based on a quantitative STEM technique. Their experimental system can measure absolute intensity in the STEM image, which is dependent on the number and depth of the dopant atoms in each atomic column lying perpendicular to the image plane. By comparing the measured intensities with simulated images, they were able to determine the detailed 3D atomic arrangement of Gd dopants in a Gd-doped $SrTiO_3$ sample with an uncertainty less than one unit cell.

$SrTiO_3$ was used as the model system for the electron microscopy study performed at UCSB. While an interesting material in itself, the method could also be used for other materials. Hwang said, "Applications could be the study of dopant atoms in Si transistors or of dopant distributions in nanoparticles and nanowires, where it would be of strong interest to know if they segregate to surfaces or interfaces."

One of the issues is that only samples a few nanometers thick can be analyzed in this way. This requirement comes from maximizing the dopant visibility, and also from electron channeling effects that cause oscillations of the intensity; both scale with the atomic numbers of the lattice constituents. To get to this thickness and to avoid surface damage (that would be induced by ion-beam milling), mechanical polishing was used. The good news is that for Si, thicker films of 10–12.5 nm can be used because of its lower atomic number.

However, applying this technique to device characterization may still prove challenging. According to Wilfried Vandervorst, Head of the Materials and Components Analysis Department of IMEC, Belgium, "In a real device structure, we want to look at different regions which typically are inhomogeneous. The technique is in essence equivalent to 3D tomography, only instead of different images there is a need now to make different material slices out of the sample. So it will be interesting to compare with other techniques, [such] as the 3D atom probe, that may get the same result without that requirement."

Dirk Wouters

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