a reduction in lithium-sulfur battery performance. To combat this, researchers have engineered many ways to trap the polysulfide intermediates, developing trapping layers or separators to keep the intermediates on the sulfur cathode. Understanding how these intermediates form and how they interact with the materials used to contain them could lead to the development of better trapping layers.

"Characterizing the polysulfides, which is required to figure out ways to mitigate their formation or trap them, has been a challenge," says Michael Toney, of the Stanford Synchrotron Light Source. Toney also uses XRD and imaging techniques to characterize electrochemical materials, but was not connected with this work. Scientists have used x-ray and UV-visible absorption spectroscopy to try to capture the formation and migration of these intermediates, but such methods lack precise characterization of their location and quantity in the cell. XRD has been used to study the structure of the solid components of the battery in great detail, but it would not have been possible to see the polysulfides, which lack long-range order when they are dissolved in the electrolyte.

Because of this, Villevieille's group anticipated only observing the solid electrodes in the XRD experiment and seeing how changing the separator layer between them would alter their structure. They started using silica fibers as a simple separator material. They were surprised to see two unknown peaks appearing in their XRD diffractograms when they expected to see none.

"If the liquid [polysulfides] are visible," Villevieille says, "[this means that] it's deposited as a layer somewhere." Further characterization of the separator using electron microscopy revealed that the polysulfides had adsorbed onto the silica fibers of the separator. Suspecting an interaction between the silica and the polysulfides, Villevieille's group used a polymer separator. The peaks disappeared when the polymer separator was used but reappeared when fumed silica was added to the electrolyte solution. "When there is silicon dioxide, we see the signature," Villevieille says.

Villevieille does not think that this effect is limited to silicon dioxide alone and is currently testing other oxides to scavenge the polysulfide intermediates. Her next step is to demonstrate how this technique can be used to optimize the battery cycling stability. These future measurements and others like it are "going to be valuable for informing the community on how to move forward," Toney says.

Lauren Borja

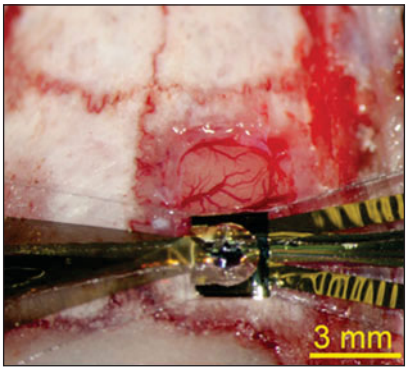
Bio Focus

Microfluidic device delivers drugs directly to brain

Various neurological disorders, from Parkinson's disease to major depression, are treated using drugs that are delivered systematically, ultimately affecting tissues throughout the body indiscriminately. To avoid the inevitable side effects of these drugs, researchers are developing implantable devices that deliver drugs locally to the brain and nervous system. In a step forward, an international team of researchers has developed an implantable microfluidic ion pump system that can deliver large amounts of drugs to the brain with a low voltage and exceptionally high on-off ratio. In preliminary *in vivo* experiments in rats, which were described recently in *Advanced Materials* (doi:10.1002/adma.201701217), the researchers showed that the device could effectively alter the state of the brain.

"It's a hybrid technology between a convection-enhanced delivery device and an ion pump," says study lead author George Malliaras of France's École Nationale Supérieure des Mines, referring to two approaches for localized cortical drug delivery. "Our main achievement was to take an ion pump device, which is very promising for drug delivery, and to make it practical."

Convection-enhanced delivery devices, or CEDs, use high pressure to deliver drugs with intracranial needles or catheters. Though the fluid-delivery systems can bypass the blood-brain barrier and deliver high local drug concentrations, they increase the local pressure around the target area, potentially deforming tissue and causing neural damage. An alternative platform for cortical drug delivery is the organic electronic ion pump (OEIP), which transports ions from a source solution to a target solution (within the brain) through a selective ion bridge such as a polyelectrolyte film. Unlike CEDs, OEIPs use dry delivery—only the drug and not the solution is delivered—and do not require high pressure. However, because the ion bridge that connects the drug reservoir outside the body to the target in the skull is a centimeter long, OEIPs require voltages of tens of volts to deliver adequate amounts of drugs, leading to possible harmful electrolysis of the brain, Malliaras says.



Microfluidic ion pump system placed on the surface of a rat's cortex. Image courtesy of George Malliaras/*Advanced Materials*.

To get around the limitation of OEIPs, Malliaras and his colleagues sought to combine a microfluidic system with an ion pump. The resulting microfluidic system would bring the drug molecules close to the delivery point, where they are pumped to the target area through small holes coated with ion bridge material. The microfluidic channel acts as a passive drug reservoir, and for fully implantable applications, this channel can be replenished as needed using a connected subcutaneous

reservoir that is refilled with a syringe—a design similar to some CEDs.

The device is made up of two parylene sheets that are held together with medical-grade, double-sided adhesive tape, forming the microfluidic channel. The bottom parylene sheet layer contains a poly(3,4-ethylenedioxythiophene):poly(styrene sulfonate) (PEDOT:PSS) electrode that traces the bottom of the microfluidic channel. The team created this part of the device by depositing a 3-µm-thick parylene film onto a 1-inch by 3-inch glass slide, then depositing a 10-nm-thick layer of Cr and 100-nm-thick layer of Au, and finally patterning the interconnects using a metal liftoff process with acetone. The slide was then patterned with PEDOT:PSS to form electrodes. The top half of the device required depositing a 1.7-µm-thick parylene film onto a glass slide, followed by patterning with Cr/Au, depositing a second 1.8-µm-thick parylene film layer, etching with AZ9260 photoresist to define the outline of the ion bridge pattern (300 through-holes for the *in vivo* version of the device), and patterning the ion bridge material (chemically bleached PEDOT:PSS). They sandwiched the layers with the adhesive, which was cut to the shape of the fluidic channel.

The researchers conducted a number of *in vitro* tests on their device using GABA, a neurotransmitter that scientists have used to control epileptic activity in *in vitro* models using OEIPs. The researchers measured the current flow through the ion bridge material and found that GABA accounted for 91% of the (cation) charge transport. The rest of the ions transported came from the solution, Malliaras says, adding that the amount of these ions is too low to cause any ill effects in real-world applications. The device showed a nearly 20-fold increase in the flux for GABA at only 1/20th of the voltage of previous reports of traditional OEIPs. And its on-off ratio was exceptionally high—nearly five orders of magnitude between 1 V and 0 V. In *in vivo* tests, which were done mostly to prove the device could be implanted, Malliaras and his team placed the device on the surface of a rat's cortex and filled the microfluidic channel with KCl solution to deliver potassium ions. They found that they could induce hyperactivity within a matter of seconds.

Daniel Simon, a materials scientist at Linköping University in Sweden who researches cortical drug delivery using OEIPs, was impressed with the work, particularly the team's successful merging of the mixed ionic and electric conduction of organic electronics and the easy long-range liquid transport of fluidics. "Indeed, I see their system as a great addition to the organic bioelectronics toolbox, showing the potential of hybrid solutions to the drug delivery challenge," he says. But Simon, who was not involved in the work, doubts the electrolysis danger of traditional OEIPs, as well as the ability of the new microfluidic platform to sustain drug delivery for more than a couple seconds. Still, he looks forward to the team's follow-up research. "And possibly combining their work with our own to overcome the last remaining hurdles in fast, efficient, sustainable, and leak-proof drug delivery components," he says.

Malliaras and his colleagues are now using the platform in animal models of epilepsy to examine whether the microfluidic device can safely and effectively treat seizures. Other potential applications include subcutaneous implantation in diabetics to deliver insulin and microdialysis of the brain, a technique to separate and quantify neurotransmitters, hormones, and other biomolecules from fluid in the brain.

Joseph Bennington-Castro

Bio Focus

Structure of natural materials informs design of graphene-based composites

Numerous ongoing efforts strive to exploit the full potential of graphene—the most fashionable current material in materials science—and rely on its exceptional tensile strength for various structural applications. However, this two-dimensional carbon structure still faces challenging scalability and mass production roadblocks. More importantly, bulk composites cannot seamlessly integrate graphene into their structure without sacrificing many of the beneficial properties of this material. Graphene oxide (GO), which includes various epoxy and hydroxyl groups, is easier to mass-produce and combine with other materials. However, stacked GO sheets are held together by intermolecular hydrogen bonds of adjacent oxygen-containing groups. On their own, without additional reinforcement, these networks stand up poorly to shear stresses and cannot generate composites that are both strong and tough.

In order to solve this challenge, researchers from the Laboratory for Atomistic and Molecular Mechanics at the Massachusetts Institute of Technology turned to mussels for inspiration. They found that the feet of these mollusks contain adhesive proteins with a structure that closely resembles polydopamine (PDA), which is a dopamine molecule that is polymerized under alkaline conditions. The research team, led by Markus J. Buehler, chemically bonded this material with graphene oxide layers and used a combination of experimental and computational approaches to describe the structure and properties of the resulting composites. The team published their results in a recent issue of *Nano Futures* (doi:10.1088/2399-1984/aa6aed).

Buehler says, "We were excited about the opportunities that arise when combining distinct biological material platforms into a new system, such as done here by taking advantage of the great adhesion properties of mussel threads, the intriguing layered geometry of nacre, combined with graphene oxide to realize a synthetic analog of the layered minerals. These concepts allowed us to construct a *de novo* designer material that offers exceptional mechanical properties combined with other useful traits."

The research group assembled the composites into stacks that were modeled after the structure of nacre shells. Much like their biological counterpart, the materials drew their superior strength from the