

surfaces, which can be used as enantioselective catalysts or for sensing chiral molecules (*Nature* 2003, DOI: 10.1038/nature01990). The two images, created in the lab of Jay A. Switzer at Missouri University of Science & Technology, are graphical representations of X-ray diffraction data. The peaks are stereographic projections—so-called pole figures—showing the crystal orientation of enantiomeric copper oxide films electrodeposited on achiral gold substrates. Switzer's team used right- or left-handed tartrate molecules in the deposition solution as templates to orient the films with right- or left-handed chirality.

Since 2003, Switzer's group has deposited chiral copper oxide on different substrates and shown that the enantiospecificity can be enhanced by etching the films using chiral etchants (*J. Am. Chem. Soc.* 2007, DOI: 10.1021/ja073640b). "I am sad to announce that I have not formed a start-up company and made billions of dollars—yet," Switzer informs C&EN. Switzer's lab is still working on electrodeposition of metal oxide and metal hydroxide films, with an eye toward developing oxygen-evolving catalysts for splitting water to produce hydrogen (*Chem. Mater.* 2013, DOI: 10.1021/cm400579k) and to make switches for solid-state memory devices being designed for smartphones and tablet computers (*ACS Nano* 2013, DOI: 10.1021/nn4038207).—STEVE RITTER

## DNA SEQUENCING: ZERO-MODE WAVEGUIDES TURN 10

A decade ago, researchers at Cornell University reported an analytical device, which they called a zero-mode waveguide, for using light to detect single biomolecules in samples of any concentration. That device was remarkably simple—just an array of nanometer-scale holes in a metal film on a fused-silica surface (*Science* 2003, DOI: 10.1126/science.1079700). Today, that unpretentious device is the basis of the DNA-sequencing technology from Pacific Biosciences, based in Menlo Park, Calif.

Waveguides are devices that are used to direct light and sound waves—optical fibers are one example. Zero-mode waveguides are so named because the holes, which serve as the waveguides, are smaller than the wavelength of light used, so the light doesn't pass through the holes.

From the beginning, the Cornell team's waveguides were intended to be used for

optically monitoring the progress of DNA sequencing. "We knew the fundamental limitation in fluorescence-based sequencing would be background noise caused by other nucleotides," says Stephen W. Turner, founder and chief technology officer of Pacific Biosciences, who was on the team that invented the zero-mode waveguides. "We needed to reduce the observation volume."

Turner and his Cornell colleagues tried several approaches. "Most of them worked to some degree, but the zero-mode waveguide worked so well and was so much better and simpler than the others that it was the hands-down winner," Turner says. The technology is now the heart of Pacific Biosciences' PacBio RS II sequencing instrument.

Each waveguide in a disposable PacBio RS II reaction cell serves as a tiny vessel for a DNA-sequencing reaction. Single polymerase enzymes are immobilized in a waveguide, which provides

*These reaction cells for the PacBio RS II DNA sequencer contain 150,000 zero-mode waveguides (holes not visible).*



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a window to observe sequencing in real time by precisely following the incorporation of fluorescently labeled nucleotides. The prototype device had a few thousand waveguides, but today's PacBio RS II uses reaction vessels with 150,000 waveguides that can be monitored simultaneously. The combination of the waveguide and specially designed DNA polymerases allows sequence read lengths that are thousands of base pairs long—some longer than 30,000 base pairs, which is the most among DNA sequencers.

Other sequencing devices sometimes have trouble working through DNA regions containing a lot of guanine and cytosine (GC) bases, but not the PacBio RS II. "The place where PacBio is truly amazing is its lack of GC bias," comments Jay Shendure, associate professor of genome sciences at

the University of Washington. "That, along with the long read lengths, is enabling its utility in niche applications such as accurate assembly of microbial genomes with high or low GC content, as well as accurate assembly of challenging regions of mammalian genomes."—CELIA ARNAUD

## MATERIALS CHEMISTRY: METAL-ORGANIC FRAMEWORKS GO COMMERCIAL

Record-breaking surface areas, exceptional pore sizes, and cavernous internal channels are properties that thrust metal-organic framework (MOF) materials into the scientific spotlight just over a decade ago. Researchers quickly predicted that these porous crystals—built from metal ions or metal clusters bridged by organic linking groups—would prove useful for gas separation and storage and other applications.

Then in 2003, a team led by Omar M. Yaghi, now at the University of California,

Berkeley, reported that a zinc-based MOF could reversibly store a few percent by weight of hydrogen at room temperature and more at lower temperatures (*Science* 2003, DOI: 10.1126/science.1083440). That development was considered a step toward the practical use of hydrogen as a fuel for electric cars, and it sparked a flurry of activity by scientists working on hydrogen storage, which continues today. A hydrogen uptake as high as 10% by weight has been reported for a copper-based MOF at high pressure and cryogenic temperature.

Researchers today have synthesized thousands of MOFs and related types of framework compounds and demonstrated that many of them are useful for storing and purifying gases, separating hydrocarbons, capturing carbon dioxide from

exhaust gas streams, mediating catalytic reactions, and soaking up uranium from seawater. Most of the reports—especially ones detailing the structures and compositions of new MOFs—come from academic research groups. But MOFs are no longer just academic curiosities. A few companies, including Sigma-Aldrich, now sell lab quantities of MOFs. And BASF makes a handful of the compounds on a ton scale, although commercial applications for them remain scarce.

“We manufacture double-digit-ton quantities of some MOFs per production run,” says BASF Senior Vice President Ulrich Müller. He adds that the company’s manufacturing capabilities have already been optimized, so no additional development work is needed; the company is just waiting for demand to pick up.

One application for BASF’s MOFs is to boost the storage capacity of natural gas fuel tanks for vehicles such as buses. The



*BASF now manufactures a few types of MOFs on a multiton scale at its facilities in Germany (above). The porous crystals are starting to be used in commercial applications, including sorbent materials that increase the gas storage capacity and driving range of natural-gas-burning vehicles, such as this truck (left).*

extreme surface area of a MOF—thousands of square meters per gram—and its ability to adsorb methane and other natural gas molecules mean that cylinders packed with MOFs can store roughly twice as much natural gas as unfilled cylinders.



BASF (BOTH)

The technology has been road tested on passenger vehicles and large trucks.

Müller has been closely following MOF developments coming out of academic labs since the end of the 1990s. Yet these materials continue to amaze him.

“It’s fascinating to see the way tuning and tweaking the metals and linkers can lead to new materials with properties that would have been unimaginable just a few years ago,” Müller says. Translating some of these newer materials into real-world applications seems inevitable, he adds. But as with any new technology, Müller concedes, commercialization takes time. —MITCH JACOBY

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