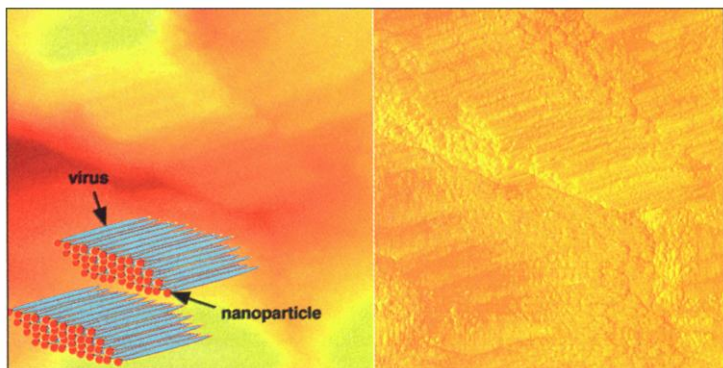


# Assembling the Supersmall And Ultrasensitive

BOSTON, MASSACHUSETTS—Graced by unseasonably mild temperatures, about 3500 materials scientists, chemists, and physicists gathered here for the semiannual Materials Research Society (MRS) meeting.\* Hot topics included reports of using viruses to assemble nanoparticles and of novel composites that pave the way for ultrasensitive sensors.

## Liquid Crystals Via Virus

Angela Belcher doesn't just borrow ideas from biology in making new materials—she borrows whole organisms. At the MRS meeting, Belcher, a chemist at the University of Texas, Austin, described making liquid crystalline films out of viruses engineered to tote tiny inorganic nanoparticles. Polymer-based liquid crystalline films already form the heart of flat-screen computer displays. And although the viral liquid crystals aren't likely to displace their polymer counterparts anytime soon, they point the way forward in one of the hottest areas of materials science, merging the organizational prowess of biology with the electronic, magnetic, and structural properties of inorganic compounds.



**Self-assembly.** An atomic-force microscope image (right) shows that pencil-shaped viruses toting nanoparticles have stacked themselves like cordwood.

Liquid crystals, first discovered in 1888, have molecular structures that are poised between the rigid order of solid crystals and the bumper-car chaos of liquids. Displaymakers use this malleability to their advantage: By applying an electric field, they reorient the liquid crystal, a change that switches the material from transparent to opaque. In Belcher's experiments, the viruses take on the ordering duties themselves. "The virus is making the liquid crystal and orienting it," says materials scientist Samuel Stupp of Northwestern University in Evanston, Illinois.

Viral films aren't Belcher's first foray

into using living organisms to make materials. Two years ago, Belcher and her Texas colleagues reported that viruses could be engineered to express, for example, proteins that bind semiconductor nanoparticles made from gallium arsenide but not silicon or cadmium selenide (*Science*, 24 December 1999, p. 2442). That work held out hope that microbes could eventually help researchers shepherd nanoparticles into complex arrangements that are possibly useful for storing electronic data or wiring up molecule-sized electronic devices. The new work brings such potential applications much closer, as it shows for the first time that biological systems can organize nanoparticles into macrosized structures.

To make the films, Belcher and her graduate student Seung-Wuk Lee started by inserting random mutations into the viral DNA for a protein that sits on one outer tip of long, pencil-shaped viruses. When the viruses infected their bacterial hosts, they reproduced and expressed the engineered protein on their coat. The researchers then turned the viruses loose in a solution containing nano-

particles made of zinc selenide. The best nanoparticle-binding virus was then allowed to reproduce, making billions of copies. Finally, by simply changing the concentration of the viruses in solution, Belcher and Lee found that they could coax the viruses to pack themselves and their nanoparticle cargoes together in different liquid crystalline arrangements. The viruses' ability to form films "was a surprise to us," says Belcher.

In one such film, for example, the viruses lined up in successive rows, like rows of pencils all with zinc selenide erasers at one end (see figure above). Other films have viruses lining up in either a zigzag pattern or all facing the same direction but not organized into

orderly rows. And each arrangement, Belcher's team found, produced unique iridescent patterns when viewed with a microscope under polarized light, a common characteristic of liquid crystalline films. Unlike polymer liquid crystals, however, the viral films cannot yet be easily switched between different configurations.

Although the new films' optical properties make them visually striking, their ability to align nanoparticles over relatively large distances could be even more important in the long run. Stupp points out that nanoscience researchers have developed numerous techniques to pattern nanoparticles and other nanosized objects at small-length scales. Extending such patterns to the macroscale has proven difficult. But because the Texas team's viruses can assemble themselves into films that can be picked up with a pair of tweezers, they may offer researchers new ways to stack metallic nanoparticles into nanowires or magnetic nanoparticles for data storage.

## Swell New Sensor

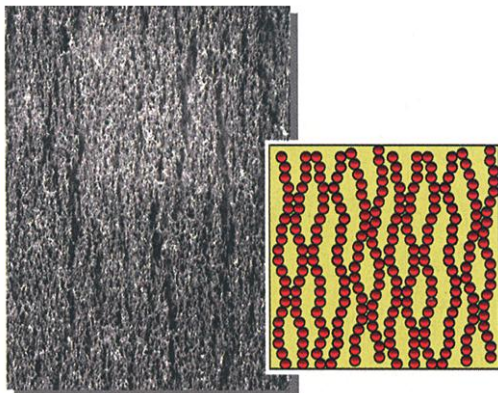
Whether we notice them or not, sensors that detect small changes in temperature, pressure, and even the presence of chemicals are all around us. Many of them spot changes in their environment by tracking the effect on a material's ability to conduct electricity. Increase the temperature or pressure of the material, for example, and the conductivity can drop by about 50% to 90%. At the meeting, Jim Martin, a physical chemist at Sandia National Laboratories in Albuquerque, New Mexico, unveiled a plastic material embedded with magnetic particles that does quite a bit better, changing its conductivity as much as 100-billion-fold. And it's versatile, responding not only to temperature and pressure changes but to the presence of some chemicals as well.

That sensitivity is "off the charts," says Todd Christenson, an electrical engineer and sensors expert at Sandia who is not affiliated with Martin's group. "It's incredible." That could ultimately make the new materials useful in a wide range of ultrasensitive detectors.

Martin got interested in the sensing ability of plastic composites after hearing a talk about the way some commercial sensors work. Those sensors harbor a random mixture of tiny conductive carbon particles in an insulating polymer matrix sandwiched between two electrodes. Flip the switch, and current hops between connecting carbon particles. But jack up levels of a property such as temperature and the polymer swells, breaking the contact between some of the carbon particles and causing the conductivity to drop. Such devices can vary widely and unpredictably in performance, however, because each winds up with a different or-

CREDIT: ANGELA BELCHER/UNIVERSITY OF TEXAS

\* 26–30 November.



**Power lines.** Conducting particles aligned by a magnetic field offer sharp warnings of changes that break their connections.

dering of carbon particles, Martin says.

Martin suspected that researchers could make the sensors more sensitive and reliable by stringing the conducting particles between

the electrodes like tiny wires. In that arrangement even slight environmental changes would change the polymer enough to knock the particle chains out of alignment. To get that alignment, Martin's team decided to use a magnetic field, which causes magnetic particles to line up in the direction of the field lines (see figure at left). Because carbon particles aren't magnetic, the Sandia researchers used nickel particles, each about 2 millionths of a meter across. They electroplated each particle with a thin layer of gold to prevent the nickel from oxidizing when exposed to air, a change that would destroy the particle's conductivity. They then embedded their gold-coated nickel particles in an uncured polymer and exposed the combo to an external magnetic field. Once the particles were aligned in chains, the researchers cured the polymer and began their tests.

The results were dramatic. Bumping up

the temperature just 5 degrees Celsius slashed the electrical resistance by five orders of magnitude. An 80-degree change made it plummet by 10 orders of magnitude. Modest pressure changes produced an effect of 11 orders of magnitude. And even exposing the polymer to a chemical vapor of toluene caused the polymer to expand and altered the resistance by nine orders of magnitude. "We were surprised by how well it worked," Martin says.

Martin says he has no immediate plans to commercialize the materials: "We're still at the level of science." Some bugs still remain to be ironed out as well. For example, many of the particles oxidize over time when exposed to air, probably a result of incomplete electroplating. But once the composites are fine-tuned, they are likely to be a hot commercial property, Christenson predicts.

—ROBERT F. SERVICE

## PLANT BIOTECHNOLOGY

# For Plants, Reproduction Without Sex May Be Better

A better understanding of how plants reproduce asexually by apomixis may boost efforts to develop improved crops

Mention embryo formation, and thoughts usually turn to sex: the union of sperm and egg to produce a new individual. But several common plants, including dandelion, citrus, mango, and certain forage grasses, can do without sex, producing their embryos from unfertilized immature sex cells or even from ordinary somatic cells. Although plant biologists have known about this bizarre form of reproduction, called apomixis, for about a century, only recently have they begun to get a glimmer of insight into how plants achieve the feat.

Within the past few years, researchers have identified a variety of genes that may determine whether plants reproduce sexually or asexually by apomixis. Eventually, they hope to use these genes to develop new strains of apomictic crop plants. The payoff could be enormous. Because the progeny of apomixis are identical to the parents, traits transferred into an apomictic plant, whether by classical breeding or genetic engineering, wouldn't be lost in the genetic shuffling that occurs during sexual reproduction.

Apomixis also offers a possible way to avoid the degeneration of breeding stocks of some vegetatively propagated plants, such as potato and cassava, that accumulate pathogens through repeated use. "Apomixis could play a major role in feeding the growing population of our planet," says plant developmental biologist Ueli Grossniklaus of

the University of Zürich, Switzerland. "It could promise social and economic benefits that would challenge those of the Green Revolution." As a result, "apomixis is a very, very hot area of research," says Robert Goldberg, a plant biologist at the University of California, Los Angeles.

Funding agencies are beginning to pay attention. In 2001, for example, the ApoTool European Union funded the \$2 million program, coordinated by Sacco de Vries of the University of Wageningen in the Netherlands, to further the identification of genes that might go into a custom-designed

apomict. In addition, the International Maize and Wheat Improvement Center in Mexico and various funding agencies in the United States—including the Department of Agriculture (USDA), the National Science Foundation, the Department of Energy, and the Rockefeller Foundation—are providing modest, but increasing, support for the research. And several biotech companies—such as Ceres of Malibu, California, which was co-founded by Goldberg, and Apomyx of North Logan, Utah—have research efforts devoted to apomixis, although they are keeping quiet about the number of dollars invested.

A measure of this increased worldwide interest was evident at last April's XVIth International Congress on Sexual Plant Reproduction in Banff, Canada, where 170 people signed up for the apomixis section alone. At the previous meeting, 2 years earlier, just 140 scientists had attended the entire meeting.

One development that helped spark this interest came in 1998 when two teams of classical plant breeders, working independently, demonstrated the feasibility of introducing the apomixis trait into crop plants that normally reproduce sexually. Bryan Kindiger, Phillip Sims, and Chet Dewald of the USDA's Agricultural Research Service (ARS) Southern Plains Range Research Station in Woodward, Oklahoma, developed corn that reproduces by apomixis by crossing the grain with an apomictic relative, eastern gamagrass (*Tripsacum dactyloides*). Their success didn't come easily.

The team had to perform at



**A long slog.** This corn-gamagrass hybrid was one of many produced on way to an apomictic corn strain.

CREDITS: (TOP TO BOTTOM) J. MARTIN/SANDIA NATIONAL LABORATORIES; KEN HAMMOND/USDA