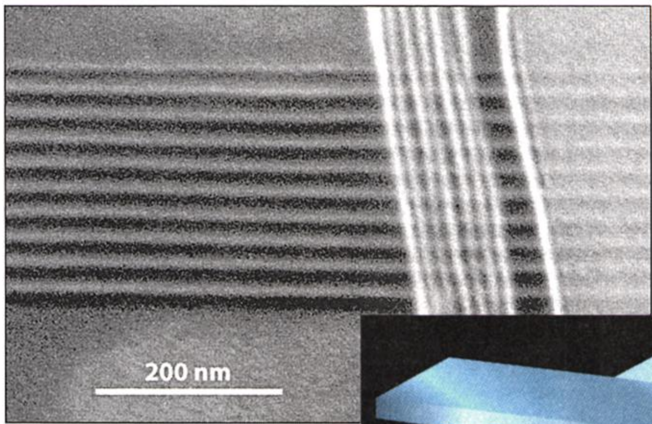
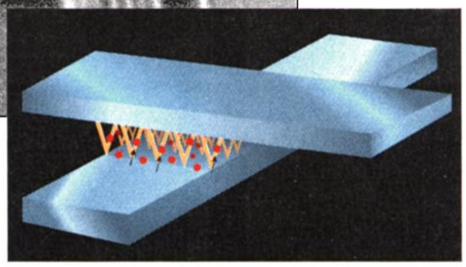
NEWS

Can Chemists Assemble a Future For Molecular Electronics?

Researchers hope to create a new technology by finding ways to get molecule-sized circuits to put themselves together

2001 was a banner year for molecular electronics, the nascent effort to make electronic circuitry from molecule-sized components. Several teams wired up their first molecular-scale logic and memory circuits, a feat that earned them *Science*'s Breakthrough of the Year (*Science*, 21 December 2001, p. 2442). But the field's pioneers have always had a bigger dream: to make chips useful for applications such as cheap, throwaway electronics that silicon can't touch. To do so, they must find a new way to pattern the millions of transistors, wires, and other devices needed to make complex circuitry. Without that breakthrough, molecular electronics could slide from being one of the hottest fields in nanoscience to a mere curiosity.





On track. Nanowires are assembled into crossbars (*above*). Organic molecules between crossing wires serve as transistors (*right*).

The solution, many researchers believe, lies in the idea of self-assembly, making individual molecular components so that each plugs itself into a structure just where it's needed. After years of making individual devices, researchers are now beginning to tackle that challenge. "One of the next big things is making big advances in the assembly area," says Charles Lieber, a chemist and molecular electronics expert at Harvard University in Cambridge, Massachusetts.

The goal of chemically programming millions of molecules evokes everything from smirks to outright scorn from conventional electronics makers, who view its technological prospects as a long shot at best. "Two years ago, everyone thought we were idiots," admits James Heath, a chemist who heads a molecular electronics effort at the University of California, Los Angeles (UCLA). But new results suggest that researchers looking to self-assemble molecular electronics are beginning to make headway. In January, at a meeting in Phoenix, Arizona, Heath was one of several team leaders presenting progress reports on using self-assembly together with other techniques to help make the most complex molecular electronic circuitry ever constructed. "This isn't at the stage where you can shake something in a beaker and pull it out and presto," he says. "But there is some self-assembly involved."

Heath reported that his UCLA group, along with Pierre Petroff's group at the University of California, Santa Barbara, has developed an assembly process to create a framework for molecule-based circuitry more than 1000 times as dense as what current chip-patterning techniques can achieve. The key step is to create small groups of parallel nanowires stacked atop each other like tiny crossbars. Heath's group, together with that of Fraser Stoddart at UCLA and colleagues at Hewlett-Packard in Palo Alto, California, previously showed that tiny, switchlike organic molecules trapped at the intersections of similar crossbars could act like molecular-scale transistors, and that crossbar circuits, in which each junction contains a layer of molecular switches, could function as a type of rewriteable memory. In that case the wires were much larger, each a couple of micrometers across. The researchers' new technique may enable them to fabricate similar memory circuits but at a density of molecular-based memory bits that takes advantage of their ultrasmall molecular switches.

Heath's team, led by postdoc Nick Melosh, used materials called quantum well superlattices as a template for growing a variety of different types of conducting nanowires. The wires were then transferred to a substrate. In a superlattice, researchers use a technique called molecular beam epitaxy to essentially spray-paint atomically thin layers of different semiconductors one atop another. Heath's team turned the superlattice on its side and selectively deposited the nanowires onto just one component of the superlattice, thereby translating the atomic control over film thickness into atomic control over nanowire diameter and spacing between neighboring wires. Then the researchers used a still-proprietary technique to transfer the parallel nanowires to a substrate. Finally, they repeated the process with a second set of nanowires and deposited them on top of and perpendicular to the first set. The result: a group of about 100 nanowire junctions patterned at a density of about 300 billion junctions per square centimeter.

"It's really beautiful stuff," says Lieber of the new result. But Heath readily admits that his team is far from turning the tiny crossbars into useful devices. "Now we have to figure out how to wire them up," Heath says. He's looking for a better approach than the painstaking method of connecting the wires one at a time.

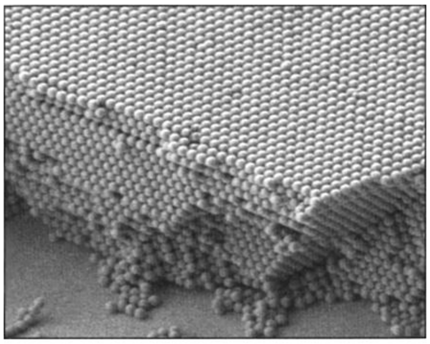
Lieber's Harvard team has also made dramatic progress in fabricating crossbars. For their work, which they described in Phoenix, researchers used a combination of flowing fluids and other techniques to self-assemble similar crossbar structures with nanowires less than 100 nanometers apart. Lieber also declines to offer more details until the work is published. But he says that the field's new focus on using self-assembly to construct complex circuitry opens the door to commercial applications. "I'm more optimistic than I was even 6 to 8 months ago," Lieber says.

Other groups are taking biological routes in hopes of achieving similar goals. At Pennsylvania State University, University Park, for example, chemist Christine Keating is working to use DNA to guide the assembly of nanorods in precise arrangements. The approach links one sequence of single-stranded DNA to a nanorod and the other to a surface, allowing the complementary strands to find each other in solution and knit themselves together. Keating's team hopes to coax circuits to wire themselves up

CREDIT: (TOP) J. HEATH/UCLA

Building Better Photonic Crystals

Self-assembly has the potential to transform not only electronics but photonics as well. Researchers are using self-assembly techniques to grow photonic crystals, devices in which a regular array of tiny holes or other features patterned into a material steer light beams exactly where researchers want them to go. By building such beam-steering devices into computer chips, technologists hope to simplify and speed the conversion of digital information from photons—used to carry data over communications networks—into electrons, which process information on chips.

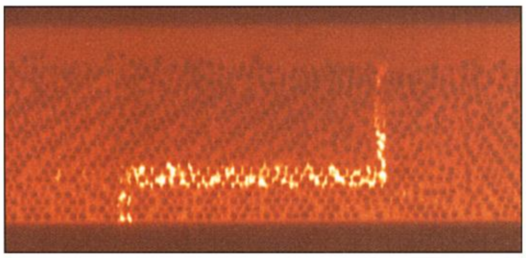


Packed. This stack of tiny glass spheres can be used to create a photonic crystal.

To make photonic crystals, many researchers currently employ the same lithographic chip-patterning techniques used in advanced electronics. But lithography has trouble making thick three-dimensional (3D) photonic crystals, which are potentially the best performers. Self-assembly, by contrast, has an easier time of making thick devices, and the process can be dirt cheap. But it's hard to create self-assembled devices free from debilitating defects and to add light-guiding features. Recent progress is bringing renewed hope, however. "The field is really beginning to pick up steam," says Paul Braun, a materials scientist at the University of Illinois, Urbana-Champaign.

In the 15 November 2001 issue of *Nature*, for example, David Norris and colleagues at the NEC Research Institute in Princeton, New Jersey, Princeton University, and the A. F. Ioffe Physical-Technical Institute in St. Petersburg, Russia, described a way to make large, defect-free photonic crystals. Norris—now at the University of Minnesota, Twin Cities—simply dipped one end of a vertical silicon wafer into a solvent containing a suspension of tiny glass spheres. As the solvent evaporated, the surface of the liquid slowly traveled down the wafer, coating it with spheres that assembled themselves into a perfect crystalline arrangement.

To turn this collection of spheres into a photonic crystal, Norris's team exposed it to hot silicon vapor, which slowly diffused into the crevices between the spheres, filling them with silicon. Then they dissolved the spheres with hydrofluoric acid, leaving the silicon dotted with air-filled holes. The silicon network and the air have very different indexes of refraction (a measure of the speed of light in each material), which combine to form an optical filter that transmits only certain wavelengths of light, reflecting all others.



Guiding light. A laser-cured polymer (yellow) creates a path for photons to travel through a photonic crystal.

Braun calls the NEC work "tremendous," in part because photonic crystals wind up atop a silicon wafer—just the place to integrate photonic devices with electronic components. So far, these photonic crystals are more like perfect mirrors than devices in themselves. But "the mirror is a starting point," Braun says. "If you don't have it, the rest is academic." To make light-steering devices, researchers must doctor the crystals to allow precise wavelengths of light to enter and then maneuver them through the material, a process akin to making a wire for light inside the crystal.

That's where Braun's group has recently been making progress. In the 4 February 2002 issue of *Advanced Materials*, Braun, postdoc Wonmok Lee, and graduate student Stephanie Pruzinsky reported using a laser to thread a type of light wire called a waveguide through a photonic crystal. Like the Norris group, they used self-assembly to create a 3D array of tiny spheres. They then filled the space around the spheres with a plastic precursor called a monomer. Finally, they focused a pair of lasers on a spot within the crystal. Where the lasers met, their combined energy cured the monomer into a rigid polymer. By sweeping the focus of the two beams through the crystal, the researchers patterned their waveguide where they wanted it to go. Braun cautions that the polymer light pipe is still untested. But Norris calls it "an intriguing first step."

Another first recently came from a team led by Peter Mach and Pierre Wilzius at Bell Laboratories, the research arm of Lucent Technologies in Murray Hill, New Jersey. In the March issue of *Physical Review E*, they reported progress in converting self-assembled photonic crystals into switches that can redirect light in different directions. This effort started out like the NEC effort, creating a solid framework around air-filled holes. But then the Lucent team, together with team members at Harvard and the University of Pennsylvania, filled the holes with liquid crystals, tiny rod-shaped molecules that swivel in unison in response to an applied electrical field. When the researchers switched on a field, this caused a light beam hitting the crystal to diffract, altering its direction. Eventually, Mach says, such switches may prove useful for creating chip-sized devices capable of routing photonic data for optical networking.

The recent reports show that self-assembled photonic crystals can be made defect-free, incorporate waveguides, and switch light beams. Now comes the hard part, Braun says: "to combine all three." –R.F.S.

in predesigned arrangements.

Physicist Ranganathan Shashidhar and colleagues at the Naval Research Laboratory in Washington, D.C., also are taking a page from nature. They're decorating tiny viral particles with metal nanoparticles and switching molecules in the hopes of getting each one to act like an individual device. Then they plan to allow the viruses to assemble themselves into arrays—something they do automatically—in hopes of creating complex interconnected circuit networks. The effort remains in the preliminary stages, Shashidhar says, but hopes are high because biology has already solved the self-assembly problem.

Efforts to use self-assembly for molecular electronics are nowhere near mature enough to be called a technology. "We're still in the land of science here," says Heath. But researchers are growing more confident that self-assembly can boost molecular electronics to sufficient levels of complexity to result in practical applications. "I do think self-assembly is up to the task," says Lieber. Even if molecular electronics circuitry never matches the speed and reliability of silicon, those applications will undoubtedly bring an end to the smirks.

–ROBERT F. SERVICE

CREDITS: (TOP TO BOTTOM) D. J. NORRIS/NEC RESEARCH INSTITUTE; W. LEE *ET AL.*, *ADVANCED MATERIALS* 14, 271 (2002)