Pretty as You Please, Curling Films Turn Themselves Into Nanodevices

Nanometer-thick films that roll themselves into tubes and fold up into elegant shapes promise a highly controllable way to make tiny gadgets

Sometimes the results of an experiment are so beautiful that researchers assume they must be useful, too. Just ask Detlev Grützmacher. Six years ago at a conference in St. Petersburg, Russia, Grützmacher, a physicist at the Paul Scherrer Institute in Villigen, Switzerland, spied images of the nanometer-sized tubes and helices a Russian colleague had fashioned from films of semiconductor, the stuff of microchips. The gracefully curling objects resembled modern sculpture.

"Immediately, I started fantasizing about what kind of things one could do with these," Grützmacher says. "Can I make a capacitor? Can I make an inductor? A sensor?" Now, he and a small but growing number of other researchers hope to turn the curlicues into a new form of nanotechnology.

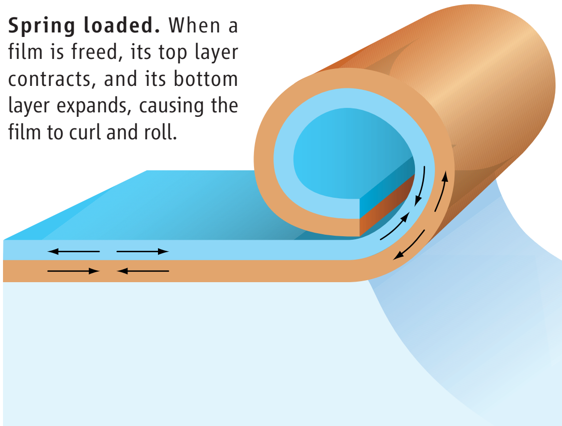
For more than a decade, physicists and engineers have strived to make nanometer-sized gizmos. Some etch ever-smaller devices out of semiconductors, a "top-down" approach that seeks to raise three-dimensional (3D) structures from a succession of layers. Many are exploring a "bottom-up" approach that aims to assemble devices out of individual molecules, such as super-strong carbon nanotubes. To make a practical technology, however, researchers must coax the molecules to piece themselves together, and such self-assembly remains a distant goal.

But a handful of researchers think they can enjoy the best of both worlds. They are experimenting with films that roll themselves into delicate tubes or fold like minuscule cardboard boxes. The budding technology—known as strain architecture, rolled-up nanotech, or nano-origami—offers lithography's ability to put things exactly where they're needed. At the same time, the films curl themselves into novel 3D structures, adding an element of self-assembly.

"It's a whole new direction," says Max Lagally, a materials physicist at the University of Wisconsin, Madison. "Here you really have a way to make the same thing over and over with interesting properties that you can control."

Pablo Vaccaro, a physicist with the Advanced Telecommunications Research Institute International (ATR) in Kyoto, Japan, says the relatively simple and flexible technology will surely find applications. "I feel that we are just at the beginning of a big wave that will revitalize the field of semiconductors," he says.

That wave is still more of a ripple than a whitecap. Rolled-up nanotech probably won't wind its way into production lines for years.



Spring loaded. When a film is freed, its top layer contracts, and its bottom layer expands, causing the film to curl and roll.

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But proponents say the self-rolling tubes and helices may have more potential than competitors such as carbon nanotubes. Force sensors, tiny inkjet printers, and other experimental devices based on the wound-up technology may be around the corner.

Rolling out of Siberia

The technology was born by accident, in the laboratory of Victor Prinz, a physicist at the Russian Academy of Sciences Institute for Semiconductor Physics in Novosibirsk. In 1995, Prinz and colleagues were studying how electrons hop across a crack in a suspended film of semiconductor. They knew that a film consisting of two layers of different materials should bow, potentially allowing researchers to control the width of the crack. To their surprise, the "bilayer" curled into a tube.

That happens because the layers contain atoms of different sizes. For example, to form a film, researchers may lay down a layer of silicon mixed with germanium and top it with a layer of pure silicon, depositing the layers on a soluble "substrate." The atoms in the film arrange themselves in orderly arrays like oranges stacked neatly at a fruit stand. But because germanium atoms are bigger than silicon atoms, atoms in the silicon and germanium layer have to squeeze together and the atoms in the silicon layer have to stretch apart. So when researchers etch away the substrate, atoms in the upper layer snap back toward one another and those in the lower layer spring apart, causing the film to curl upward.

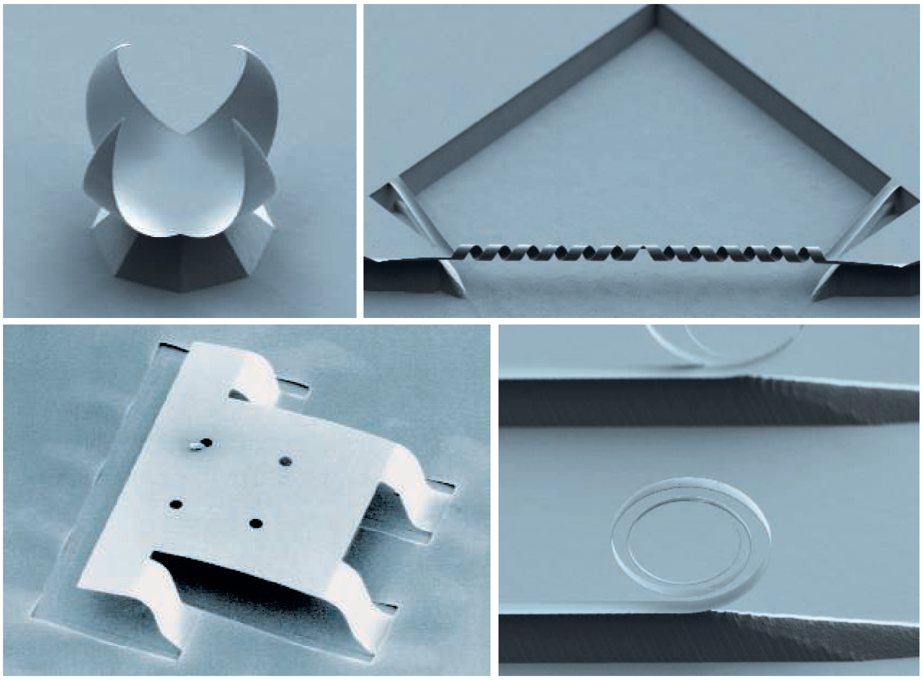
Theorists predicted that it would be impossible to etch away the substrate without damaging the film, or that films only a few layers of atoms thick would quickly oxidize, Prinz says. Yet, within a few years, he and his team had wound up tubes, coils, and helices with widths ranging from a few micrometers down to a few nanometers. "Never trust theorists in novel fields," Prinz says. "Trust only in your experiments."

As unlikely as it sounds, such films wind themselves into tight spirals resembling carpet rolls, with successive windings binding neatly to each other. Researchers can form more complex shapes such as helices by exploiting the fact that the films tend to curl perpendicular to certain rows of atoms, just as a carpet might roll most easily perpendicular to its warp. If researchers lay down a thin strip of film that's canted relative to the easy-rolling direction, it will curl into a helix instead of a tube.

The roll-up technique offers several advantages, proponents say. The approach begins with standard lithography to pattern films and etch away substrates, so it provides the exquisite control of that tried-and-true technology. The basic physics is so simple that the approach should work with a wide variety of materials. And because the technique works with semiconductors, it should be possible to roll up electronic circuits in the film or to integrate tiny tubes, coils, and other devices directly into microchips—at least that's the hope.

What's it good for?

For the moment, researchers are primarily studying the electrical, optical, and mechanical properties of the tubes and other shapes they've made. Two years ago, physicist Oliver Schmidt and colleagues at the Max Planck Institute for Solid State Research in Stuttgart, Germany,



Les objets. Using the curling films and a little ingenuity, researchers can create a wide variety of potentially useful shapes, such as a grasping claw, a suspended spiral, and a delicate coil spring. The same basic physics can be used to make larger folding or pop-up structures, such as a microstage.

CREDITS (GROUP, TOP ROW AND BOTTOM RIGHT): L. ZHANG AND D. GRÜTZMACHER/PAUL SCHERRER INSTITUTE; (GROUP, BOTTOM LEFT) T. LEISCHMANN, K. KUBOTA, P. O. VACCARO, AND S. SARAVANAN; (BOTTOM) L. ZHANG *ET AL., NANO LETT.* **6** (2006), ACS

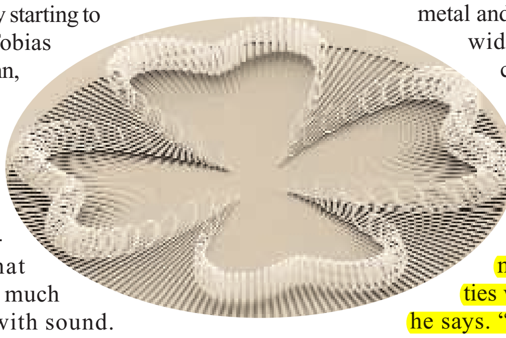
showed that a rolled-up nanotube can convey liquid like a tiny pipe. Earlier this year, they reported in *Applied Physics Letters* that the tubes also guide light like optical fibers.

Schmidt and colleagues have recently rolled up films of a single material. They grow the film so thick that the atoms near the bottom squeeze together but those near the top feel no pinch. That's because faults develop in the stacking that allow the upper atoms to shift apart, Schmidt reported at a meeting of the American Physical Society in March. The advance could lead to a handier all-silicon technology. The tubes can also emit light, Schmidt says, a trait that could lead to rolled-up lasers on a chip, a potential boon for "optoelectronics."

Researchers have rolled up a variety of materials, including metals and insulators. The technique even works with polymers, physicist Manfred Stamm of the Leibniz Institute of Polymer Research Dresden in Germany and colleagues reported last year in *Advanced Materials*. They lay down a polymer that absorbs a solvent and swells, then top it with one that does not; the swelling curls the film. "Millions of different polymers exist with all sorts of functionalities," Stamm says, "and interfacing to biological systems may be easier because most biomaterials are polymers." Stamm hopes to use a polymer nanotube as the nozzle for a nano–inkjet printer that might spit out one macromolecule at a time.

Some researchers use curling films to connect larger plates and fold them into micrometer-sized devices in an approach known as nano- or micro-origami. ATR's Vaccaro and colleagues have used semiconductor films to make an array of pop-up mirrors and other structures without complex hinges or moving parts. Optics engineer George Barbastathis and colleagues at the Massachusetts Institute of Technology in Cambridge have made tiny fold-over capacitors, as they described in *Applied Physics Letters* in February, and the team's ultimate goal is to fold up accordionlike devices that manipulate light in novel ways. "We see this as an enabling technology," Barbastathis says. "We're trying to make it as manufacturing applicable as possible."

Experimental widgets based on the new technology are already starting to emerge. Physicists Tobias Kipp, Detlef Heitmann, and colleagues at the University of Hamburg in Germany have turned a semiconductor tube into an optical ring resonator, a device that resonates with light much as a whistle rings with sound. Described in *Physical Review Letters* in February, the resonator isn't yet as good as those made by other techniques. But the researchers think rolled-up resonators could someday play a part in quantum information technologies.



Employed like a probing finger, a drill-like helix should also make a good force sensor, says Bradley Nelson, a roboticist at the Swiss Federal Institute of Technology (ETH) in Zurich. Because the tubes bend much more easily than the probes used on atomic force microscopes, such a sensor should be extremely sensitive, says Nelson, who is collaborating with Grützmacher of the Paul Scherrer Institute. The team should have a working sensor within 6 months, Nelson says.

Perhaps most ambitiously, applied physicist Robert Blick and colleagues at the University of Wisconsin, Madison, hope to use free-floating silicon germanium tubes as chemical sensors that unwind when they encounter their target molecule. Researchers already do something similar with fluorescent quantum dots, whose light changes when the dots bind to their chemical target. The tubes "are a bit bigger, but they're a lot more flexible in that they can change their shape and you can incorporate electronics," Blick says. The project is in its early stages, but the researchers have shown that they can wind and unwind a tube by changing the salinity of the solution surrounding it.

Tube versus tube

Amid the parade of grand visions, some researchers say it's too early to tell whether the roll-your-own approach will pay off. "I don't see how one can claim it has any advantages versus bottom-up approaches, since neither has been demonstrated," says Charles Lieber, a chemist at Harvard University. Even the optimists acknowledge that technical hurdles lie ahead. For example, affixing electrical contacts to rolled-up devices can be tricky.

Researchers working with the curling films disagree on how they stack up against other forms of nanotechnology, in particular carbon nanotubes. The bizarre, elongated molecules of carbon possess electrical and mechanical properties that the larger semiconductor nanotubes cannot hope to match, says Wolfgang Hansen, a physicist at the University of Hamburg whose team has rolled up tubes containing layers of metal and insulator. "The bandwidth for applications is certainly larger" for carbon nanotubes, he says. ETH's Nelson, who works on both types of tube, sees it the opposite way. "There's just a lot more design possibilities with these little coils," he says. "There are a lot more materials and interesting geometries that you can produce."

All agree that finding a few killer applications would go a long way toward transforming vision into reality. Researchers can't yet say what those could be—perhaps something as simple as tiny inductive coils for electronics—but most are hopeful that they will come. The tale of this technology, they say, has only begun to unwind.

–ADRIAN CHO