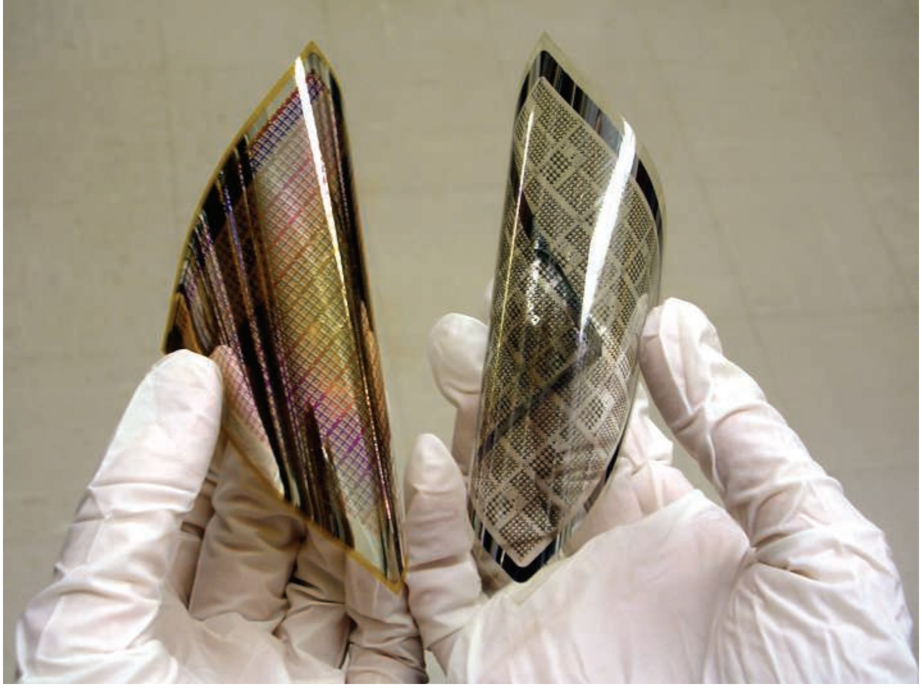


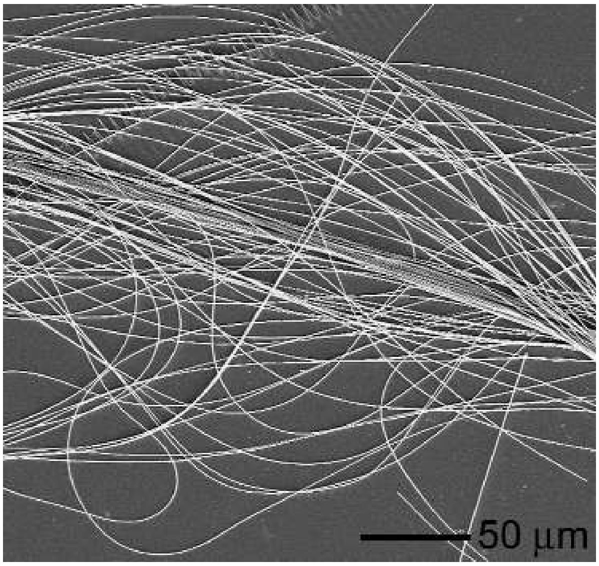
MATERIALS SCIENCE

Inorganic Electronics Begin to Flex Their Muscle

A dark-horse technology bids to overtake plastics in the race to make circuits that can twist and stretch

Like a desert mirage, the promise of organic electronics seems to shimmer always on the horizon. Plastic and other types of organics can form the backbone of electronic components that are cheap, thin, lightweight, and flexible, a combination that makes them sought after for applications as diverse as cheap solar cells and roll-up displays. Yet despite a few commercial successes such as small mobile phone displays, organic electronics have had trouble overcoming nagging problems, such as the slow speed at which electrical charges move through the devices and the fact that exposure to air often degrades their performance. Now, organics have something else to worry about: competition from more traditional inorganic electronics now being made to work on top of flexible materials.

In recent years, several research teams have shown that by making inorganic devices thin enough and layering them on flexible sheets of metal or plastic, they can create circuits that bend and flex much like organics. That approach has enabled researchers to take advantage of the high speed and reliability of inorganic devices and the decades of manufacturing experience that has made them the bedrock of the electronics industry. Now, the two technologies are poised to battle for new electronics applications, such as outfitting robots and medical prostheses with a human-like "skin" complete with flexible temperature and touch sensors. The number of researchers trying to marry inorganic electronic devices with flexible substrates remains a fraction of the crowd working on organic circuitry. "But it's picking up steam," says John Rogers, a flexible-electronics expert at the University of Illinois, Urbana-Champaign (UIUC).



Bend me, shape me. Semiconducting wires from inorganic compounds such as gallium arsenide can form the heart of high-performance circuitry atop flexible substrates.

Researchers worked on thin inorganic electronic devices decades before organic electronics presented a challenge. Labs in the United States first made thin-film inorganic transistors in the 1960s, and today the devices are found everywhere from flat-panel televisions to solar cells. But the devices are still typically deposited on top of glass and other rigid substrates. When organic electronics first entered the picture 30 years ago, the new technology captured the imagination of many groups hoping to create devices atop curved surfaces as well as give electronics the ability to flex and bend. "In the late 1990s, there was a notion by materials and chemical companies that it would be easiest to go with all organics," says Sigurd Wagner, an electrical engineer at Princeton University. But although many successful prototype products have been developed, organics have proven challenging to turn into a robust and reliable manufacturing technology. "There are so many problems, [people] are returning to an inorganic transistor technology used in industry," Wagner says.

Not everybody is returning, of course, and those who make the switch have faced major hurdles. But several groups have recently been showcasing the kinds of things that can be done by putting inorganic electronics on flexible substrates.

The first challenge was to make a workable device at all. To lay down successive atom-thin layers of material, standard semiconductor technology starts by heating slabs of material to a vapor at several hundred degrees Celsius. The white-hot vapor then condenses atop the substrate at temperatures far higher than most flexible materials, such as plastics, can handle. To create usable circuits, researchers had to find ways to deposit those thin organic layers at temperatures only slightly above the boiling point of water.

In 2003, for example, Charles Lieber and colleagues at Harvard University reported in *Nano Letters* that they had deposited a 100-nanometer thin layer of conducting indium tin oxide (ITO) atop a plastic substrate and then patterned an initial set of "gate" electrodes in the ITO using either photolithography or electron beam lithography. The researchers then flowed a solution containing silicon nanowires over the electrodes, depositing the nanowires atop the electrodes when the solvent evaporates. Finally, another lithography step enabled them to pattern the additional metal electrodes needed to create thin-film transistors with a performance comparable to those grown atop crystalline silicon. That same year, Xiangfeng Duan and colleagues at

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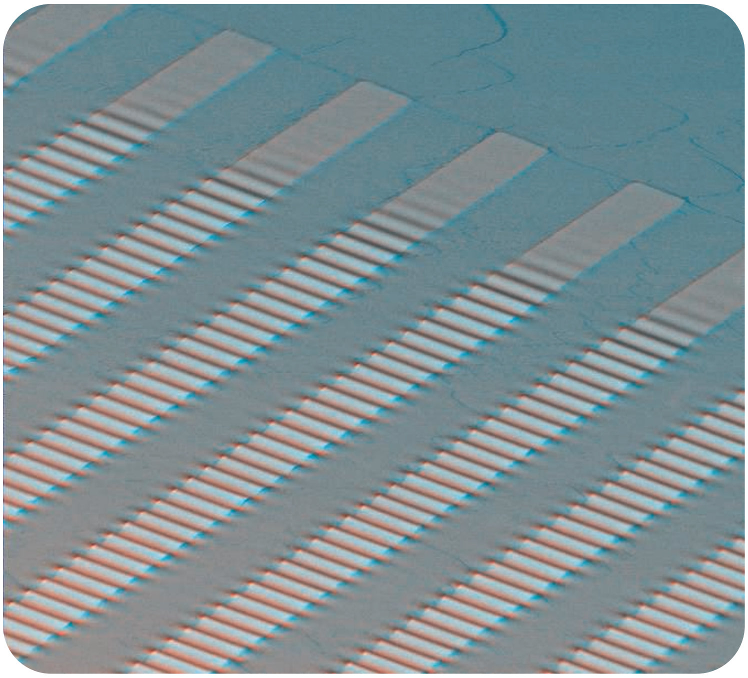
the nanotechnology start-up company Nanosys in Palo Alto, California, reported in *Nature* a similar scheme for suspending inorganic silicon nanowires and cadmium-selenide nanoribbons in a solution and patterning them into thin-film transistors perched atop plastics and other flexible substrates. The speed of charges in those devices and the voltages at which they switched on and off easily outperformed organic devices.

More recently, researchers have started taking larger strides. Rogers and colleagues at UIUC and Wright-Patterson Air Force Base in Ohio, for example, reported in the 1 May issue of *Applied Physics Letters* that they had created ultrahigh-speed gallium arsenide (GaAs) transistors on cheap, flexible plastic substrates. To do so, the Illinois researchers initially fabricated GaAs wires from an inorganic wafer using conventional semiconductor manufacturing techniques. They then applied a thin layer of glue beneath the devices and used a stamping technique to place them atop a plastic film, with additional lithographic steps to create the needed electrodes. The final devices, Rogers's team reported, could switch on and off more than 1 billion times a second, far faster than organic devices and a speed that makes them candidates for use in high-speed communications equipment.

The newfound prowess of inorganic flexible electronics is also making them attractive for other potentially lucrative markets, such as displays that conform to car dashboards and other contoured surfaces. In December, for example, Wagner and former postdoctoral candidate Stephanie Lacour reported at the International Electron Devices Meeting in Washington, D.C., that they had fabricated amorphous silicon-based circuitry atop tiny islands of rigid silicon nitride. They placed the devices on a flexible substrate of silicone rubber and connected them with ultrathin flexible gold wires. Because both the substrate and the wires between the devices could flex, the researchers could use them to create the flexible equivalent of the electronic "backplane" that controls current liquid-crystal flat-screen displays.

Rogers and his Illinois team report a similar feat in this month's *IEEE Electron Device Letters*. They fabricated their circuitry out of ultrathin bendable single-crystalline silicon ribbons. They initially created the ribbons atop a rigid support called "silicon on insulator" (SOI). They then etched away the underlying support and used a printing technique to transfer the silicon ribbons to a flexible polyimide substrate. Finally, they used low-temperature computer chip patterning techniques to lay down the additional layers of metal and insulators needed to complete their circuitry. The result: circuits that performed nearly as well on a flexible substrate as those grown atop crystalline silicon wafers.

Rogers and his Illinois team also recently detailed an approach that could make inorganic electronics not only fast and flexible, but cheap as well. They set out to bring down the high cost of relying on wafers made from SOI, which can cost $300 each. In the 22 May issue of *Applied Physics Letters*, the Illinois researchers showed how to carry out the same process using standard bulk crystalline silicon wafers that cost only one-tenth as much as SOI wafers. Marrying conventional crystalline silicon with a flexible substrate "allows us to think about ways to put single-crystal silicon in places you couldn't before," Rogers says.



Next wave. Undulating ribbons of silicon atop a flexible substrate can be stretched without damage. Such stretchable semiconductors could pave the way for high-speed flexible circuitry in fabrics.

One of those new places could be in fabrics that not only flex but also stretch, a particularly challenging environment for electronics. Earlier this year, Rogers and a team of Illinois colleagues reported in *Science* (13 January, p. 208) that they had laid down thin silicon ribbons atop a stretched-out plastic sheet. When they then released the tension on the plastic, the sheet snapped back to its original shape, causing the silicon ribbons to buckle in regular waves. When the researchers then stretched the plastic back out again, the silicon ribbons elongated and continued to function normally as transistors. "It's a very powerful approach," says Lacour, who is now at Cambridge University in the United Kingdom. Since publication of their *Science* paper, Rogers says, the team has vastly increased the amount of stretching their devices can tolerate, extended the work to other types of inorganic materials, and allowed materials to stretch in all directions instead of just one.

Wagner and colleagues have also been looking to take inorganic electronics in new directions, such as integrating them with biological systems. Chunks of rocklike semiconductors aren't typically thought of as biocompatible. But the way they work can make them an ideal choice, Wagner explains. That's because unlike many organic devices, silicon and other standard inorganic semiconductors can be used to make devices that turn on and off with tiny amounts of applied voltage. That's critical, Wagner says, because when large voltages have to be applied they invariably dissipate power as heat. "You can't put them close to biological tissue because that raises the temperature too much," Wagner says.

In November, Wagner and colleagues at Princeton and at Columbia University reported at the IEEE Sensors Conference in Irvine, California, that they had made an array of stretchable silicon transistors atop a plastic substrate capable of recording the activity of brain neurons in vitro. The immediate goal of this ongoing project is to understand how neurons respond to rapid stretching, a petri dish analogy to what happens during a car crash or other types of brain trauma.

But Lacour is already planning to take the next step. At Cambridge, she is helping direct an effort to use flexible circuitry in regenerating severed nerves of accident victims. When nerves are severed, Lacour explains, they quickly die unless they receive consistent electrical inputs, as they would from sensory cells. So Lacour has created flexible gold electrodes on plastic that she hopes to use to integrate with regrowing tissue. By integrating transistors and sensors onto such circuitry, researchers may even be able to create prostheses that communicate touch and temperature to the body's nervous system much as a real limb does, Lacour says. With the progress in flexible inorganic electronics, it's a vision that's beginning to look more real all the time.

–ROBERT F. SERVICE

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