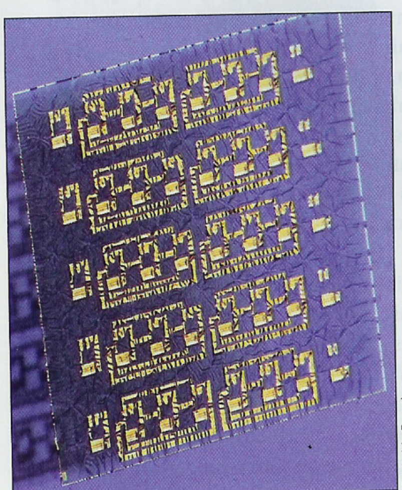
Foldable and stretchable circuits: teaching silicon new tricks

Researchers led by John Rogers, a professor of materials science and engineering at the University of Illinois at Urbana-Champaign, have developed a new form of flexible, stretchable silicon integrated circuit.

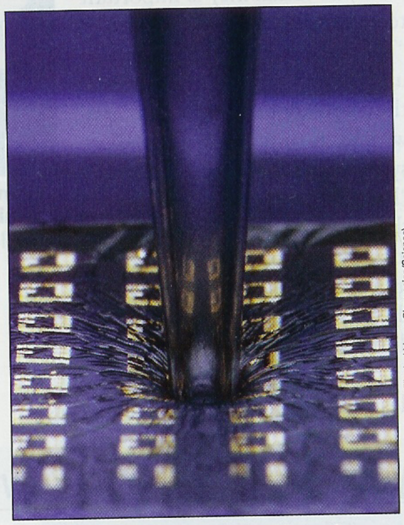
Not only can these new silicon circuits wrap around complex shapes, but they can do so without sacrificing electrical performance while stretching, compressing and folding is taking place, the researchers say.

"The notion that silicon cannot be used in such applications because it is intrinsically brittle and rigid has been tossed out the window," says Rogers, whose findings have been published in *Science* magazine and posted on its *Science Express* website.

"Through carefully optimized mechanical layouts and structural configurations, we can now use silicon in integrated circuits that are fully foldable and stretchable," Rogers says. The development could lead to new types of sensors that can be integrated into artificial muscles, wearable health-monitoring systems or electrical devices that can wrap around aircraft wings and fuselages to monitor structural properties.


(Credit: John Rogers)

Mechanically stretchable "wavy" silicon integrated circuit on a rubber substrate.


(Credit Beckman Inst., Univ. Illinois, Urbana-Champaign/Science)

Researchers have now developed a way to combine silicon with thin plastic or rubbery substrates to create robust, flexible and bendable electronics that do not sacrifice electronic performance. The electronics' layer resides in the neutral bending plane that experiences almost no strain, even when the overall device is substantially bent.

'Wavy' electronics

Rogers and his UI research team had previously reported the development of a one-dimensional, stretchable form of single-crystal silicon with micron-sized, wavelike geometries in 2005. He says then that the configuration allowed reversible stretching in one direction without significantly altering electrical properties, but only at the level of individual material elements and devices.

Now Rogers and collaborators at the UI, Northwestern University and the Institute of High Performance Computing in Singapore are reporting the extension of this earlier "wavy" development to two dimensions capable of yielding functional integrated circuit systems.

Rogers reports constructing integrated circuits consisting of transistors, oscillators, logic gates and amplifiers and notes that these circuits exhibited extreme levels of bendability and stretchability, demonstrating electronic properties comparable with those of similar circuits built on conventional silicon wafers.

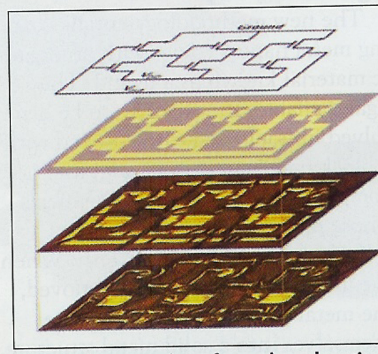
"We've gone way beyond just isolated material elements and individual devices to complete, fully integrated circuits in a manner that is applicable to systems with nearly arbitrary levels of complexity," Rogers says.

Methodology

To create fully stretchable integrated circuits, the researchers apply a sacrificial layer of polymer to a rigid carrier substrate, Rogers says. On top of the sacrificial layer, they deposit a very thin plastic coating that supports the integrated circuit. He notes that the circuit components are then crafted using conventional techniques for planar-device fabrication, along with printing methods for integrating aligned arrays of nanoribbons of single-crystal silicon.

The researchers' next step, according to Rogers, is to wash away the sacrificial polymer layer and bond the plastic coating and integrated circuit to a piece of prestrained silicone rubber.

Lastly, he says, they relieve the strain and – as the rubber springs back to its initial shape – apply compressive


(Credit: John Rogers)

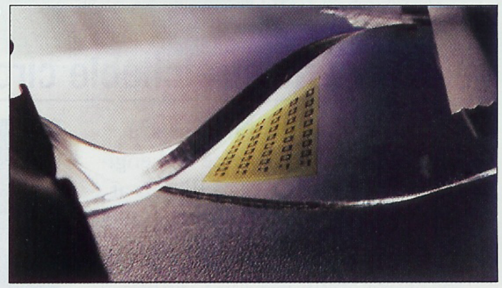
Circuit diagram (top frame) and optical images of a stretchable "wavy" silicon ring oscillator circuit on a rubber substrate in the "as fabricated" flat state (top micrograph) and in moderate and high states of biaxial compression (middle and bottom micrographs, respectively).

stresses to the circuit sheet. These stresses spontaneously lead to a complex pattern of buckling, creating a geometry that then allows the circuit to be folded or stretched in different directions, giving it the ability to conform to complex shapes or to accommodate to the mechanical deformations that occur during use.

"The wavy concept now incorporates optimized mechanical designs and diverse sets of materials, all integrated together in systems that involve spatially varying thicknesses and material types," he explains, adding that the "overall buckling process yields wavy shapes that vary from place to place on the integrated circuit, in a complex but theoretically predictable fashion."

Rogers stresses that attaining high degrees of mechanical flexibility or foldability is important to sustaining the wavy shapes. "The more robust the circuits are under bending, the more easily they will adopt the wavy shapes which, in turn, allows overall system stretchability," he says. "For this purpose, we use ultrathin circuit sheets designed to locate the most fragile materials in a neutral plane, minimizing their exposure to mechanical strains during bending."

"We're opening an engineering design space for electronics and opto-



Attaining high degrees of mechanical flexibility or foldability are key to sustaining wavy shapes that enable the circuits to be stretched.

electronics that goes well beyond what planar configurations on semiconductor wafers can offer," Rogers states, indicating that NSF and DOE are funding his research. (Visit: jrogers@uiuc.edu) ■

Improving fuel-cell catalysts and chip conductivity

For more than 5,000 years, man has been shaping metal by "heating and beating." Even with nanotechnology's emergence, metals still have required "carving" with electron beams or etching with acids.

Now, however, researchers at Cornell University have found a way to self-assemble metals into complex nanostructures that may lead to more efficient and cheaper fuel-cell catalysts and conductors capable of carrying more information across microchips.

Ligands are key

The new methodology entails coating metal nanoparticles with an organic material known as a ligand. The ligand enables the particles to be dissolved in liquid and, then, mixed with a block copolymer, a material that is comprised of two different chemicals whose molecules link together to solidify in a predictable pattern. When the material and ligand are removed, the metal particles left behind fuse themselves into a solid metal structure.

Ulrich Wiesner, a Cornell professor of materials science and engineering, explains the process in the June 27, 2008, edition of *Science* magazine. "Metals have a tendency to cluster into uncontrolled structures," Wiesner says. "The new thing we have added is the ligand, which creates high solubility in an organic solvent and allows the particles to flow even at high density."

Another key factor, he adds, is making the layer of ligand surrounding each particle relatively thin, so the volume of metal in the final structure is large enough to hold its shape when the other materials are removed.

'Novel playground' opens

Wiesner says the new process is exciting because "it opens a completely novel playground" where no one previously "has been able to structure metals in bulk ways." He says that, in principle, "if you can do it with one metal, you can do it with mixtures of metals."

Science reports that Wiesner, two CU colleagues and other researchers, used the new methodology to create a platinum structure with uniform hexagonal pores about 10 nm wide. The porous structure enables fuel to flow through and react over a larger surface area.

The new process begins by mixing a solution of ligand-coated platinum nanoparticles with a block copolymer. The nanoparticle solution combines with one of two polymers. The two polymers assemble themselves into a structure that alternates between small regions of one and the other, producing clusters of metal nanoparticles suspended in the one polymer. Many other patterns are possible, the researchers say, depending on selection of polymers.

The material is then annealed in the absence of air, turning it into a carbon scaffold that continues to support the shape into which the metal particles had been formed.

The final step entails heating the material to a higher temperature in air to burn away the carbon. Because metal nanoparticles have a very low melting point at their surface, Wiesner says, they sinter into a solid structure, and chunks of porous platinum at least a 0.5 cm across can be made in this manner.

In addition to making porous materials, the new technique also can be used to create finely structured surfaces, Wiesner says. This is a key factor, he notes, in the field of plasmonics, where waves of electrons move across a conductor's surface with the information-carrying capacity of fiber optics but in spaces small enough to fit on a microchip. (Visit: news.cornel.edu) ■