Flexible circuits could lead to bendable sensors in many apps
Flexible electronics

High-performance ICs learn to bend and stretch

By Sunny Bains

IN ELECTRONICS, rigid and flat is normal. In the real world, not so much.

There are many applications in which it would be useful for electronics to conform to curvilinear surfaces or to deform with use, especially in sensing. A detector array could be made to encircle the heart, stretching with each beat. An artificial skin could be stretched around the wing of an aircraft, relaying detailed local information while in flight. An artificial retina could fit in the curved space at the back of the eye like the biological sensor it replaced. Thus far, however, flexible technologies have lacked the performance, manufacturability or, well ... flexibility to make such applications feasible.

But a new technology demonstrated at the University of Illinois at Urbana-Champaign (UIUC) may be able to fill this niche—one that is certain to widen once engineers are allowed to think beyond flat and rigid. The new circuits are designed to have long, thin interconnects, fabricated using standard semiconductors (silicon, gallium arsenide and so on) and conventional techniques, and then transferred onto a stretched elastic sheet (see box below). Once the substrate is relaxed, the interconnects—which are thin enough to bend without breaking—buckle under the strain. If designed correctly, they can then buckle further if compressed or flatten if stretched. Thus, an elastic circuit fabric can be created using more-or-less ordinary electronics.

Alternatively, the elastic fabric can be used to form the electronics into 3D shapes that can be transferred onto a rigid substrate. This is how the UIUC team was able to create the first hemispherical silicon camera.

Whether flexibility or shape is the goal, the approach has the advantage of leveraging conventional microlithography and semiconductor processing. John Rogers, who led the

THE TECHNOLOGY EVOLVES

Researchers first demonstrated a kind of elastic silicon in which thin ribbons of the material were directly attached to polydimethylsiloxane (PDMS) while it was being stretched. Once allowed to relax, the incorporated ribbons formed sine waves that varied in wavelength and amplitude when the elastic material was subsequently deformed. With this system, stretch and compression of a few percent each could be accommodated. The ribbons shown here are 20-µm wide and 100-nm thick.
UIUC research, has set up a company—Semprius—to commercialize the technology. "The most important advantage," Rogers said, "is that we use known, established materials and processing techniques to achieve levels of performance in the circuits as high as comparably designed wafer-based systems, but with levels of stretchability approaching that of a rubber band [up to 100 percent strains and even larger]. An associated advantage is that we can fully exploit all existing electronics knowledge and fabrication facilities."

Bob Reuss—an independent consultant and former DARPA program manager and Motorola senior technologist—also suggests the technology will, at the very least, find a niche. "To achieve conformal and/or flexible electronics with at least moderate functionality, I believe the technology will be valuable, if not essential. So success will mean creation of a new market segment," he said.

ARTIFICIAL EYEBALL: Thanks to the design of circuits with bendable interconnects and an elastic transfer step, this hemispherical detector array was fabricated using conventional 2D lithography.

Further, he added, "Elastic S is in my opinion an example of 'more than Moore.' It is not on the International Technology Roadmap for Semiconductors and perhaps never will be. Rather, it is one of a variety of technologies being created either to more effectively utilize IC technology for applications beyond computing and communications, or to actually...

HOWEVER, RESEARCHERS found they could get a more predictable ribbon shape, and more flexibility, by patterning the adhesive on the elastic substrate so the semiconductor ribbons could buckle without constraint by the PDMS. This produced patterns with free-standing sine waves and a greater ability to stretch and compress. The ribbons shown here, 50-μm wide and 290-nm thick, were deposited on a substrate with an initial strain of 50 percent. Using these techniques, the team achieved stretchability of 100 percent and compressibility of 25 percent.

NEXT, THE RESEARCHERS demonstrated that the technique could be used with working devices. Ultra-thin circuits were fabricated on a sacrificial layer and then removed using chemical etching, as shown here. They were subsequently transferred to the stretched PDMS with the thin interconnects between circuits free to buckle to accommodate deformation of the substrate. The performance of the circuitry, encapsulated with polyimide for protection, was found largely unaffected by imposed strains within design limits.
Elastic, not plastic

The best known way to create flexible electronics is to print circuits directly onto carbon-based plastics. One target application for this technology is the electronic newspaper, which is in the process of being realized commercially. Though the technology is maturing, it has inherent problems: It relies on organic materials that have much poorer electronic performance than semiconductors. Worse, the development of these materials does not come free as a byproduct of progress in the electronics industry. Finally, although these materials are flexible, they are not elastic: They bend, but they don’t stretch.

Another approach is to fabricate conventional chips and then thin the wafers to make them lighter and less rigid. Again, stretching is not an option, and even bending ability is limited. Yet another option is to attach small chips to an elastic surface and create wires to connect them after the fact. Though this offers both performance and mechanical flexibility, there are many non-conventional (and, therefore, expensive) fabrication steps involved.

The UIUC approach depends on the fact that silicon, gallium arsenide and other semiconductors—all basically brittle—become flexible when deposited in very thin layers. Max Lagally, a materials science and engineering professor at the University of Wisconsin-Madison, works in the area of nanostuctures for electronics, among other things. “Thin, flexible Si [and other semiconductors, including Ge] has tremendous potential,” he says. “There is the flexibility, the ability to take advantage of the third dimension. One can also strain them and thus take advantage of better electronic properties—one can stack them, etc.”

The UIUC approach, in fact, “takes little advantage of these properties, as the carrier is all flexible,” Lagally said. This is in contrast to researchers creating far more sophisticated micro- and nano-mechanical devices by engineering the strain in fabricated layers so, when released, they form complex three-dimensional structures. Rather, he explained, the group’s most important achievement, is the transfer technol-
work closely with theoretical mechanicians and analog circuit designers to pursue this type of outcome.”

**Potential applications**

There is “an entire, untapped world of applications for electronics that demand properties unachievable with conventional technologies based on semiconductor wafers,” Rogers said. “The most prominent examples fall into two categories: bio-inspired devices and biomedical devices. Both rely on systems that have the layouts of biological systems, none of which have the rigid, planar nature of a semiconductor wafer.”

In the biomedical area, Rogers said, “We are working on electronic sensor patches that conformally integrate with the complex, curvilinear surface of the human brain. Our goal, in collaborations with a professor [Brian Litt] in the medical school at University of Pennsylvania, is to provide a system that can detect the onset of a seizure in a person who suffers from epilepsy, before the seizure actually occurs.”

The technology has a good chance of succeeding in these areas, concurs Reuss, who believes it will prove lucrative for investors. “Whether to augment, replace or monitor biological function, flexible/stretchable electronics will be needed to effectively and comfortably achieve human interface,” he said.

> MORE See rogers.mse.uiuc.edu and www.semprius.com

“Given the aging population, as well as the desire to medicate for a variety of debilitating diseases, there seems to be a huge available market for the right technical solutions.” Structural health monitoring and portable electronics, he added, will also be attractive applications.

However, Reuss is not convinced that commercial success can be taken for granted: Industry inertia may be a problem. “There is a well used expression: ‘If it can be done in Si, it will be done in Si,’” he said. “So conventional ICs, perhaps thinned to less than 50μm, should never be ruled out.”

Further, he added, the advantages of the new technology may be offset by the higher cost associated with a process flow more complex than simply printing inks onto a substrate such as plastic. If inks become available that provide performance closer to conventional ICs, cost-vs.-performance trade analysis may become more difficult.

Carmichael Roberts of North Bridge Venture Partners is a lead investor in Rogers’ new technology. Not surprisingly, he has high hopes for it. “Conventional silicon has produced products worth billions of dollars,” he said. “In 10 years or less, this new silicon technology has the potential to be worth billions of dollars as well.”

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