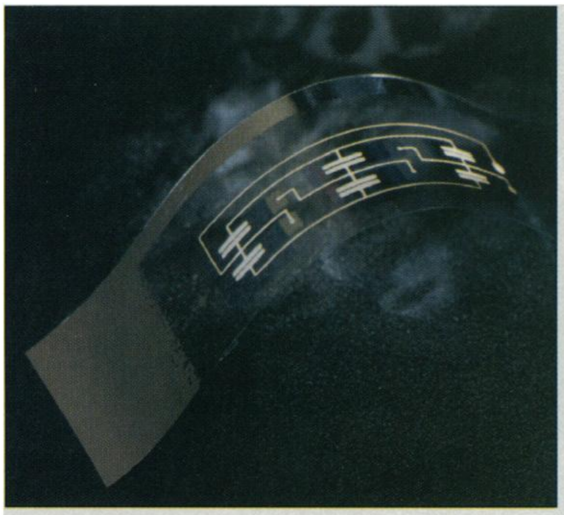
Patterning Electronics on the Cheap

The reigning way to carve microcircuitry, photolithography, is ill-suited to low-end chips and displays. Tomorrow's throwaway electronics may be stamped, sprayed, or screen printed

From industry to communication to entertainment, the microchip is king today. But the power behind the throne is a technique called photolithography, the method used to pattern the chips' tiny features. Since it was invented in 1959, it has shrunk the size of circuit features some 400-fold. Computing power—in smaller and smaller packages—has gone through the roof.

But all is not well in the Lilliputian land of lithography. It is expensive and, because it is designed to work on crystalline silicon, which comes in wafers of limited size, it can pattern only small areas at a time. Researchers have been looking for alternatives that are cheaper, faster, and better suited to patterning the new semiconducting plastics now emerging from the laboratory. Lately, they have been turning to a host of new patterning methods, some with a decidedly low-tech flavor: stamping, screen printing, or ink-jet printing. And as a recent spate of meeting reports and journal articles—many of them still in press—shows, these techniques have begun to move out of the tinkering stage and toward real-world devices.



Z. BAO/LUCENT TECHNOLOGIES' BELL LABS

Print it. Researchers are turning to simple printing techniques to pattern electronic devices such as these screen-printed, centimeter-sized polymer circuits.

"It may not be a question of plastic-based microelectronics catching up [with silicon], but making something different instead."

—George Whitesides

The new techniques are now getting so good, says Princeton University electrical engineer Jim Sturm, that "it's now realistic to think about using them commercially" to create simple electronic devices such as throwaway plastic "smart" cards and data-packed checkout labels. And down the road, researchers expect that the techniques could improve enough to meet demanding patterning applications, such as making large, flat-screen displays.

Particularly for the low-end applications, photolithography is far too complex to be cost-effective. It typically begins with a single flat wafer of silicon coated with a thin, light-sensitive polymer layer, called a photoresist. Manufacturers then place a stencillike mask over the resist and shine light through its slits, exposing select regions of the polymer to light and changing the chemical properties in those regions. The resist is doused with an etchant that removes either the exposed or unexposed regions as well as a thin section of the underlying silicon. To create transistors and other electronic devices, these steps must be repeated over and over as additional layers of insulators and conductors are successively laid down.

The technique can carve features hundreds of times smaller than most of the alternatives can, at least so far, so it is not likely to be displaced anytime soon as the mainstay for making computer chips. "However, there are applications that [this technology] can't touch," says Harvard University chemist George Whitesides, such as plastic-based electronics and cheap, large-area silicon devices. And for these cheaper, larger scale applications, researchers would like to eliminate some or all of the "subtractive" steps of masking and etching, and simply lay down the features they want.

For example, a team at Philips Research Laboratories in Eindhoven, the Netherlands, reported last month at the European Conference on Molecular Electronics in Cambridge, England, that it has managed to use light itself, without etching, to pattern an electronic circuit composed of 40 polymer-based transistors, the largest of its kind to date. The device replaces the components of present-day electronics with different flexible polymers. In place of a transistor's source, drain, and gate electrodes—which control the flow of electrons through the device and are normally made of aluminum—is a conductive polymer; a semiconducting polymer replaces silicon as the electron-carrying channel between the source and the drain; and an insulating polymer substitutes for the silicon oxide insulator in conventional chips.

To lay out these features, the Eindhoven team starts with a flexible substrate and lays down a thin, uniform layer of a conducting polymer on top. The researchers then pattern the source and drain electrodes into this layer by exposing it to light through a mask. The light, explains the group's leader, Emiel Staring, creates reactive compounds known as free radicals in the polymer, which convert the material from a conductor into a nonconducting insulator. So, just as the unexposed areas remain bright in a photographic negative, the regions left unexposed remain conducting, and hence become the electrodes.

This step is repeated for the very top layer of the device, which contains the gate electrodes. In between, before the top layer is laid down, the researchers lay down uniform layers of a semiconducting polymer followed by an insulating polymer. These layers need not be patterned, because the patterned electrodes above and below control the electronic properties of the materials in these layers.

Staring says the performance of the all-polymer circuit "is not up to the usual standards of [silicon] integrated circuits," primarily because the current-carrying speed of today's polymers still lags well behind that of crystalline silicon. Nevertheless, says Zhenan Bao, a chemist at Lucent Technologies' Bell Laboratories in Murray Hill, New Jersey, "it's a very important result," because the circuit's complex pattern of interconnected transistors is a big step toward applications. And because the polymers are cheap and easy to lay down over large areas, unlike crystalline silicon, the Philips researchers hope to be able to use them one day to drive large-area flexible devices such as flat-screen displays that can be rolled up and stored in a drawer.

In press

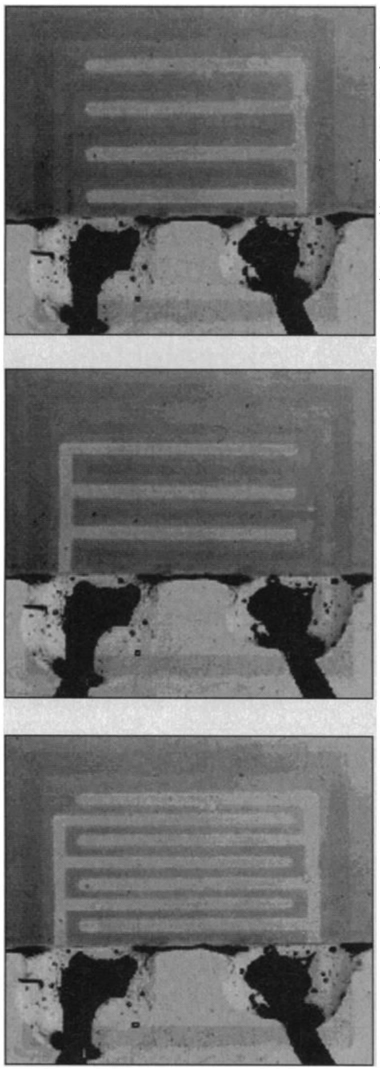
The Philips group is not alone in pursuing that goal. At last month's American Chemical Society (ACS) meeting in Las Vegas, Bao reported that she and her Bell Labs colleagues have made simpler all-polymer circuits by using an entirely different patterning approach: a screen-printing technique akin to the prosaic method for imprinting t-shirts. But instead of laying down a series of colored inks, the group prints successive layers of conducting, semiconducting, and insulating polymers that start out as liquids but quickly cure to form flexible plastics.

To make the master patterns for this printing process, the team has borrowed a little from photolithography. They coat a metal mesh with a light-sensitive film, then expose the film to a pattern of light shining through a mask and etch away the exposed polymer. The result is a plastic pattern that can then be used repeatedly to print one layer of their circuits. By making a different master pattern for each layer, the researchers can build up complete microcircuits, made up of features as small as the width of a human hair.

Bao says that like the polymer circuits made by Philips, her team's devices can't match the performance of comparable silicon circuits. But for low-end applications such as memories for smart cards, she thinks their performance "may be good enough already."

Other groups are turning to more modern printing techniques for help in simplifying the initial patterning steps in photolithography on silicon. At Princeton, for example, electrical engineer Sigurd Wagner and his colleagues are using a computer-controlled laser printer to create a pattern of toner—a powdered ink—on a flexible substrate topped with a thin layer of semiconducting amorphous silicon. The patterned toner then acts as an etch-masking material, thus eliminating the need to pattern a separate polymer layer for this purpose.

Meanwhile, Princeton's Sturm has been trying to do away with both masks and etching by printing electronic materials only where they are wanted in the first place. With his colleagues, he is using an ink-jet printer to pattern polymers that, when layered and sandwiched with electrodes, become arrays of tiny, light-emitting devices for flexible, full-color displays.



A. MACDIARMID/UNIVERSITY OF PENNSYLVANIA

First impressions. Patterned with an ink-stamping technique, this 2-cm "light valve" transmits a backlight when an electric field is applied to just the right or left electrodes *(top and center)* or to both.

Making a full-color display requires combining large sets of red, green, and blue light-emitting pixels. In polymer-based devices, each of these three colored lights has a core of a different semiconducting polymer. Patterning small dots of these separate polymers very close to one another in a repeated array is Sturm's goal. But thus far he has made only single-color devices, consisting of a single printed layer, to demonstrate the feasibility of the process. One stumbling block is the equipment: Like Wagner, Sturm is using an off-the-shelf printer, designed to pattern ink rather than electronic materials.

Stamp it out

A final set of patterning techniques is based on an even more mundane strategy: stamping out a circuit pattern in the same way as a rubber stamp prints a label. At the ACS meeting, for example, Ralph Nuzzo, a chemist at the University of Illinois, Urbana, reported using the technique to make silicon-based transistors. Nuzzo and his Illinois colleagues, along with Whitesides and his team at Harvard, had previously used a stamping method called microcontact printing to pattern single layers of semiconductors, metals, and polymers (*Science*, 19 July 1996, p. 312; 15 December 1995, p. 1760). At the meeting the groups reported collaborating to print the multiple layers needed for working electronic devices.

The researchers first use conventional photolithography to etch a pattern in a polymer photoresist or in silicon. This serves as a mold for a liquid polymer that is then heated, cured, and peeled off. The polymer now carries a negative image of the photoresist so that it can be repeatedly "inked" with organic molecules and stamped onto a chip material's surface to act as an etch mask layer, thereby eliminating the initial patterning steps for each chip. The Illinois-Harvard researchers have made a series of working devices, using this and related techniques to shape the various layers of semiconductors, metals, and insulators.

Stampers, too, are trying to do away with the need for masks and etching altogether. At the ACS meeting, for example, Alan MacDiarmid of the University of Pennsylvania, Philadelphia, reported that his team, together with Whitesides's group, has used the stamping technique to print "light valves." These devices, which are at the heart of digital displays, electrically alter the transparency of a liquid-crystal layer, changing it from opaque to clear. The Pennsylvania-Harvard team simply stamped out liquid conducting polymers that rapidly cured to form the patterns of electrodes and leads that control the liquid crystal.

It is still too early to tell whether all these new patterning techniques will progress far enough to push electronics into a new realm of cheap, throwaway applications. For one thing, the devices produced to date are relatively primitive. For another, most of the techniques are now limited to creating devices in which the individual features are roughly a tenth of a millimeter across, about 1000 times larger than those made by lithography.

But Nuzzo and others argue that in time, they will be able to reduce feature size dramatically and also turn out the complex architectures needed for real-world applications. Contrasted with the billions of dollars spent over the last decade to engineer the Pentium and other advanced chips made by photolithography, efforts to develop alternative patterning techniques have been modest indeed and rather recent—none has been under way more than a few years. And even if the new patterning approaches don't displace photolithography as the tool of choice for computer chips anytime soon, that might be irrelevant, says Whitesides. "It may not be a question of plastic-based microelectronics catching up [with silicon], but making something different instead."

–Robert F. Service