Big and Bendable

By: **Babu R. Chalamala** and **Dorota Temple**

ILLUSTRATION: BRYAN CHRISTIE

Over the past four decades, integrated circuits have worked their way into our computers, televisions, phones, automobiles, appliances, and toys. They're in our air conditioners and airplanes, our cameras and copiers.

Now imagine where else they could go if they weren't small and rigid.

If integrated electronics could be big, flexible, and lightweight, they would be suitable for a dazzling array of items that technologists have long dreamed of. Flexible displays, many meters across, would be sharp, bright, and vivid, and yet they would roll up like

window shades when not in use. Radio frequency identification tags could follow the contours of the products they identified. Light, portable, and powerful antennas would unfurl in space, on the battlefield, or at the beach. Similar lightweight sheets of sensors and circuits, large and pliable, could cover airplane fuselages or nuclear-reactor pipes—and someday, space-station or moon-base exteriors—continually monitoring their physical integrity and triggering an alarm the instant a tiny crack forms.

Indeed, lightweight flexible electronics, in the form of small display screens for wristwatches and the like, are at last taking their first tentative steps into a few niche markets. But as with many novel technologies, greater commercial success awaits cheaper manufacturing methods. And now, engineers are close to delivering one: by adapting the ubiquitous, low-cost technologies of inkjet printing, they have already managed to produce simple flexible circuits of up to 50 square centimeters. In fact, the research division of Royal Philips Electronics NV is now working with Dimatix Inc., which makes inkjet printheads, to produce light-emitting-diode displays for cellphones using an inkjet process.

If this and similar work live up to their promise, it could herald a radical advance in the electronics industry: the cheap and fast fabrication of high-quality, even custom, plastic-based ICs with equipment not much bigger than a microwave oven.

Today, the few flexible plastic-based circuits trickling out commercially are produced in ordinary chip fabrication facilities, using a modification of the standard technique that produces conventional ICs in silicon. Kimberly Allen, director of display technology and strategy for market analyst iSuppli, El Segundo, Calif., says that most of these units are being used in electronic signs [see photo, "Sign of the Future"]. E Ink Corp., in Cambridge, Mass., produces a low- to medium-resolution monochrome plastic display for signs and portable electronics that changes from dark to light when voltage is applied [see "A Bright New Page in Portable Displays," *IEEE Spectrum*, October 2000]. And Nike sells the Triax sports watch, which has a liquid-crystal display (LCD) on plastic; the Japanese wristwatch companies Citizen and Seiko Epson are reportedly readying models for introduction [see photo, "Watch It Bend"].

In Japan and Korea, two countries with large concentrations of display manufacturers, work on big flexible displays is intense. Earlier this year, researchers at Samsung Electronics Co.'s production facility in Tanjeong, South Korea, claimed to have built the world's largest transparent plastic display—an active-matrix LCD with a diagonal measuring 5 inches [see photo, "On Display"].

Other companies, including Acellent Technologies, Nanosolar, and the Palo Alto Research Center, all in California, are developing flexible-circuit technologies for structural monitoring, solar energy conversion, and X-ray imagers, respectively [see photo, "Pixel Perfect"]. And Philips Research, in Eindhoven, the Netherlands, along with E Ink, continues its promising work on flexible, paperlike displays. These displays could soon be used in electronic books and newspapers, as shown in the opening illustration.

Encouraging as these advances are, researchers still have obstacles to overcome in their quest to make large-scale flexible electronics the next big thing. Besides getting the cost for producing plastic circuits down to pennies, rather than dollars, per square centimeter, they also need to find a plastic-compatible transistor technology that can switch millions of times a second, rather than thousands of times a second. Faster transistors would allow a broader range of applications for flexible electronics.

Large-scale flexible electronics are similar in some respects to the active-matrix LCDs found nowadays on virtually every laptop computer, PDA, and cellphone. Like those displays, many types of flexible electronics are much larger than conventional ICs, and they are not built on silicon. The main difference is that the conventional displays are built on brittle, rigid glass plates, while flexible circuits are built on thin, pliable sheets of plastic. Transistors that can bend along with the plastic would have to be very thin—just a fraction of a micrometer. On silicon chips, it isn't the transistors themselves that are inflexible, it's the relatively thick silicon wafer in which the transistors are fabricated.

Two basic alternative materials have the potential to make thin transistors on flexible substrates: amorphous silicon (the technology used in the Samsung display mentioned above) and organic polymers. To understand how the flexible circuits are made, first consider the standard lithography-based process that creates ICs, of both the silicon and plastic varieties.

In logic ICs, transistors act like switches. A voltage on a terminal called the gate turns the transistor on, allowing charge to flow in a "channel" between the other two terminals, which are called the source and the drain. Removing the voltage stops the flow.

As with silicon ICs, large-scale flexible electronics are built up layer by layer. First, the plastic substrate is uniformly coated with a film of the material—either amorphous silicon or an organic polymer—that will form the sources, drains, and channels of the transistors. That layer is covered with a layer of insulation, which is covered in turn by a layer of metal or semiconductor to form the gate. The material on top of this three-layer sandwich is covered with a photosensitive material, or photoresist, which is exposed to a pattern of light that represents the gates in the flexible circuit. Areas of photoresist exposed to the light become soluble. The unexposed regions remain insoluble.

If more than one circuit is to be built on a single substrate, a movable stage that holds the substrate shifts it to a new site, which is exposed to the light pattern next. For conventional silicon ICs, hundreds of chips, each about a square centimeter, are typically made on a single silicon wafer. But because large-scale flexible circuits can be tens of centimeters on a side, a single flexible substrate will usually hold fewer than 10 of them—and, for very large circuits, perhaps just one.

After all of the circuit sites have been exposed, the soluble photoresist is rinsed off, leaving a pattern where the gates are to be located. An etching process takes away all of the gate material not covered by photoresist, leaving the gate pattern. The remaining unexposed photoresist is removed next, exposing the uniform layers of insulator and semiconductor into which the sources and drains will go, along with the gates.

The same basic expose-and-etch process is repeated several times with different patterns of light: first to remove the insulation where the source and drain contacts will go, then to pattern the semiconductor into individual transistors, and finally to create the wires that connect the transistors into circuits.

There are several important differences between this process for making flexible circuits and the one used to make silicon ICs. In the first case, the sources, drains, and channels sit on top of the flexible substrate. But in silicon chips, they are built right into the silicon wafer. For flexible electronics, the gate insulation is deposited onto the flexible substrate, then etched to shape. For silicon wafers, silicon dioxide is used to insulate the gate; it is grown by exposing the silicon wafer to oxygen.

A third important difference is that silicon wafers undergo several heating steps that reduce the resistance of the transistors so they will switch faster. During these steps, temperatures can exceed 1000 ºC. Such heat could melt plastic.

In theory, at least, plastic circuits can be made more cheaply than conventional silicon ICs because the circuits and manufacturing processes are simpler. For example, to get a good yield of working chips, conventional semiconductor plants must essentially rid the air of particles down to sizes of only a few nanometers—about the dimensions of a virus. But because the transistors in flexible electronic circuits are much larger—up to 25 m as opposed to 0.1 m—the allowable particle size is also much larger, which makes the air-filtration task a lot easier and cheaper. Also, an IC can have more than 30 layers of patterned material; flexible circuits—for example, in a flexible display—would typically have only about 10. These differences, however, bring the costs down by perhaps 80 percent, but not to the factor-of-10 reduction that analysts say is needed to make plastic circuits ubiquitous. The tradeoff, of course, is slower circuitry.
Happily enough, the essential fabrication steps for many types of flexible circuits—etching the circuit layers, adding a layer of metal for the wiring, and etching that to shape—can all be accomplished with the relatively cheap, and widely available, technologies used to print ink on paper. In fact, technologists are now working on several flexible-circuit manufacturing processes based on printing on paper. One is a modification of inkjet printing, the process at the heart of countless desktop printers [see photo, "Cut and Print"]. Another adapts roll-to-roll processing, a technique commonly used to print fabrics and newspapers. A roll of unprocessed plastic is put through a processing step and is rolled up again after the step is completed—like movie film passing through a projector.

Tantalized by the prospect of a new, multibillion-dollar market, inkjet-printing companies like Dimatix, in Santa Clara, Calif., and Litrex Corp., in Pleasanton, Calif., are developing processes that could replicate the basic steps of IC manufacturing—in machines not much bigger than desktop printers. How big is the commercial potential of an inkjet process for making circuits? Big enough to have inspired Dimatix recently to change its name from Spectra Inc., its headquarters from Lebanon, N.H., and its focus from printing posters to printing electronics.

In inkjet printing, tiny nozzles squirt droplets of ink onto a sheet of paper. There are two types of inkjet printers—those that use heat from resistors to form tiny bubbles to push the ink out of the nozzles and those that use a piezoelectric material inside each nozzle, which deforms when a voltage is applied. Under voltage, the piezoelectric material vibrates, pushing the ink out of the nozzle. These same mechanical vibrations pull more ink into the nozzle to replace the ink that was squirted out. The digital data for the document tells the piezoelectric material where and when to vibrate to get the drops in just the right places. In the heat method, the data sends current through the resistors to achieve the same result.

According to Dimatix scientists, only the piezoelectric process is suitable for making plastic electronic circuits, because the hot resistors used in the other method would damage both the polymers that make the transistors and the plastic substrates themselves. However, Hewlett-Packard is developing a process for printing circuits using the thermal process.

To print circuits instead of documents, Dimatix researchers replace the ink with a liquid containing an organic semiconductor or a metallic conductor. Today, inkjet-compatible liquids are also available for printing organic polymers to make the semiconducting components, and for laying down silver to make the connective wires. But at the moment no suitable liquid has been found for printing amorphous silicon with inkjets.

As you might expect, the printhead that Dimatix engineers developed for printing circuits is more complicated than the ones in desktop inkjet printers. There are more nozzles—over 100 on a circuit printer, compared with 30 on a desktop machine. Adding to the complexity, the direction in which each nozzle fires and the amount of ink in each drop are individually controlled—features not found on desktop printers.

These capabilities are needed to achieve the resolution and precision required for useful circuits. Today, the Dimatix jet heads can print lines and spaces 50 m wide with 5-m accuracy. Soon engineers expect to be able to bring line widths down to less than 10 mm.

In the Philips project, specialists at the Netherlands-based giant are working with Dimatix jet heads to print plastic organic-light-emitting-diode (OLED) displays for cellphones and other applications. By spraying solutions of red, blue, and green organic light-emitting material onto the display substrate, they have produced displays of up to 2 inches measured diagonally that are every bit as crisp and bright as displays made on glass substrates. Other researchers are using the inkjet technique to apply the color filters for LCDs.

Litrex Corp., which makes inkjet printers using Dimatix printheads, is also getting into circuit printing. It has already built inkjet printers for making flat-panel displays on both glass and plastic substrates. Including printers installed in R&D labs, Litrex has sold more than 50, mostly for making OLED arrays.

For making circuits, the failure rate of the inkjet nozzles must not be more than about a thousandth of the 1 percent or so allowed for printing documents. Litrex developers have achieved this level of reliability by including a high-speed camera in each printer that visually inspects the drops from each nozzle. It can capture images of single drops fired at a rate of up to 20 000 per second. The display substrate is loaded into the printer only after the inspection shows that all nozzles are firing correctly.

Litrex engineers are now testing a printer for large 2.4- by 2.4-meter substrates, now a standard size used by display makers. Although it is technically possible to build a single 2.4- by 2.4-meter display, most manufacturers build six separate displays within that area.

One important advantage of the inkjet print process over conventional techniques is that the jet process puts the circuit material only where it is needed, whereas the conventional process puts the material down over the whole substrate and then etches most of it away. But the fluids used to make electronics are pricey—up to US $10 000 per liter. A 7-inch-diagonal display printed conventionally might require a milliliter of these fluids, costing about $10. But an inkjet process would use only half a milliliter, saving the manufacturer $5. Multiply this by millions of displays, and it amounts to considerable savings.

At Motorola Inc., in Schaumburg, Ill., senior manager Daniel Gamota and his colleagues are taking printed electronics one step further. They are using conventional printing presses—the same ones that make posters and consumer product labels—to make circuits. These presses typically use metallic, rubber, or plastic cylinders 30 cm wide and 45 cm around, in which the patterns to be printed are etched.

Gamota and his team rent time on such printers from graphics arts companies and replace the standard printing inks with an assortment of electrically functional inks, which could be conducting, semiconducting, or insulating and organic or inorganic. So far they have produced more than 50 kilometers of circuitry, mostly timing and control circuits that switch at tens of hertz. These still-experimental circuits are too slow, even for displays. But they are fast enough to make electronically active labels for consumer packaging. So, for example, a timing circuit could switch on an indicator when a product reaches its expiration date. Or a sensor could detect when a package of food has spoiled.

Engineers are just starting to look into making flexible electronics with the roll-to-roll process. By eliminating the high-temperature, high-vacuum steps used in conventional circuit manufacture, it holds the promise of cutting the manufacturing cost by that magic factor of 10 or better.

The Fraunhofer Institute for Reliability and Microintegration, in Munich, Germany, has set up a laboratory to develop roll-to-roll processing of circuits on plastic. There, Karlheinz Bock and his group have produced thin-film transistors from organic semiconductors. They have measured individual transistors that switch at speeds up to 2 kilohertz. The first applications are likely to be low-tech and inexpensive electronics for things like radio-frequency identification tags and smart cards, though they can't say when the process will be commercially viable.

The biggest problem with the direct printing and roll-to-roll processes is that at best they produce transistors that switch only a few thousand times a second. That speed is adequate for displays. But it's much too slow for radio transmitters and radar detectors, which must run at speeds of a gigahertz or faster.

The sluggish performance of plastic transistors built on plastic sheets is a function of large transistor size, poor alignment of circuit layers, and material limitations. Alignment problems make electrical properties like resistance and capacitance more difficult to control. The transistors with the largest resistance and capacitance switch most slowly. A large variation in switching speeds means that some transistors will switch much more slowly than others. And circuits can work only as fast as their slowest transistors.

The alignment problem is exacerbated by the fact that plastics expand and shrink during processing because of changes in substrate temperature. Those size changes make it even harder to align one circuit layer with another. Misalignment limits how small their transistors can be—and larger transistors are slower than smaller ones, all other factors being equal. On the bright side, however, the inkjet process can compensate for the changing substrate area because the nozzles can be programmed to adjust for it.

Another factor that limits speed is the low melting temperature of plastic. The processes must be kept below about 300 ºC, which also results in slower transistor speed. That's because electrons move faster through a crystalline material, in which the atoms form a repeating three-dimensional pattern, than through one in which many of the atoms are out of place. Higher processing temperatures allow atoms to move into their orderly crystalline positions.

Materials come in a range of crystalline order: basically, the more closely the atoms occupy their crystalline positions, the faster the charge carriers can move. At the speedy end of the range are single-crystal materials, in which there is essentially perfect order, with all the atoms forming one repeating pattern. Polysilicon has many small regions in which all the atoms are in the proper crystalline locations, but the regions are oriented randomly with respect to one another. Electrons move quickly through each region. But passing through the boundaries between one region and another slows them down considerably. So transistors made with polysilicon are slower than those made with single-crystal silicon.

Creating single crystals can require temperatures up to 1000 ºC, far beyond the melting point of plastic substrates. So to get the speed advantage of single crystals in a flexible medium, some researchers are turning to ordinary single-crystal wafers. These are the raw materials used for the substrates of conventional ICs; they are disks less than a millimeter thick sliced from big single-crystal ingots. The idea is to get thin, narrow strips of single-crystal silicon with which to make transistors. The strips can then be placed on a plastic backing and rolled up with the plastic.

This approach is being investigated at the University of Illinois at Urbana-Champaign, where engineering professor John A. Rogers and his team start out with a single-crystal silicon wafer that has a thin layer of silicon dioxide buried just below the surface. Here's how their approach works. Using standard techniques, they create narrow lines of photosensitive material on the silicon wafer. Then they etch away the silicon not covered by the photoresist. The photoresist protects the underlying silicon from the etching process. But where there is no coating, the silicon is etched away, down to the silicon dioxide. Then they etch away the silicon dioxide, leaving a bunch of parallel wires of single-crystal silicon sitting on the wafer surface.

To get the narrow strips of silicon off the wafer and onto the plastic, the researchers first cover the strips with a thin layer of rubbery material. As they pull the rubber off the wafer, the strips of silicon come off with it. Then they put the rubber, with the strips, on top of a plastic substrate. They use a solvent to detach the wires from the rubber and leave them sitting on the plastic. An adhesive layer on the surface of the plastic fixes the wires in place.

One approach to building transistors using the silicon strips is to deposit the gate electrode material on the plastic substrate and then to pattern it using conventional, but low-temperature, lithographic techniques. A thin polymer layer added over the gate electrodes forms the gate insulation. Then the silicon strips are transferred on top of this insulation. All that remains is to attach an electrode at each end of the strip to supply power. Because the transistor is made from crystalline silicon, its switching speed can be as fast as that of a transistor with the same dimensions built on a single-crystal silicon wafer.

Using this material, which they call nanostructured silicon, Rogers and his co-workers have successfully built transistors on plastic that switch at almost 300 megahertz—more than a thousand times as fast as transistors made directly on plastic substrates, whether by conventional lithographic techniques or printing methods. They are now trying to build simple circuits.
Rogers's nanostructured technique almost completely avoids the temperature restrictions by doing the high-temperature processing on the silicon wafer rather than on the plastic. His technique cannot produce the cheapest electronics, because it uses single-crystal wafers and conventional lithography. But for high-speed applications, particularly military and aerospace ones, performance is more important than cost.

Researchers at Nanosys Inc., a Palo Alto, Calif., start-up, are using a different method for making fast circuits on plastic. They are building transistors out of incredibly narrow freestanding pieces of single-crystal silicon, called nanowires. But they do not start, as Rogers does, with a silicon wafer. They make the wires by combining a silicon-bearing gas, such as silane (SiH_4), with oxygen in a reactor. The result is a cylindrical thread of single-crystal silicon tens of nanometers in diameter and hundreds of micrometers long.

Their process can also produce a thin outer layer of silicon dioxide, which forms the gate insulation. The wires are then suspended in a solution, and the plastic is coated with the solution. The company's proprietary method for coating the plastic ensures that all the nanowires are parallel. The result is basically a sheet of plastic coated with single-crystal silicon nanowires covered with silicon dioxide. Low-temperature deposition and etching steps similar to those used in making conventional circuits finish the transistor-manufacturing process.

Researchers at Seiko Epson Corp., in Tokyo, have come up with a slightly different method for putting faster transistors on plastic. Like Rogers, they begin with a silicon wafer. They coat the wafer with a thin layer of polysilicon, on top of which they build an array of polysilicon transistors. Once the transistor array is complete, they cover it with a temporary glass substrate and heat the silicon wafer from the back side. The heat causes the original polysilicon coating to separate from the layer of transistors. The circuitry, now attached to the temporary glass substrate, can be transferred to the plastic substrate and fixed in place with a permanent adhesive. At this year's IEEE International Solid-State Circuits Conference, held 6 to 9 February in San Francisco, Seiko Epson researcher Nobuo Karaki and his colleagues described a microprocessor on a plastic substrate that was made with their technique. It contained 32 000 transistors and ran at rates up to 500 kHz.

There are, however, other ways than relying on single-crystal silicon strips or nanowires to avoid the heat issue. One way is to look for the odd material for which switching speed doesn't depend on crystalline characteristics. At Phiar Corp., in Boulder, Colo., researchers are doing away with semiconductors completely, instead using a sandwich of metals and insulators to make transistors that exploit a quantum-mechanical phenomenon called tunneling.

Another approach is to look for plastic substrates that are less sensitive to heat than those currently in use. In particular, plastics made from liquid crystals or silicone resins are showing promise. And for applications that don't need transparent substrates, thin metal foils coated with a layer of insulation can replace the plastic. At Lehigh University, in Bethlehem, Pa., engineering professor Miltiadis K. Hatalis and his team have made polysilicon circuits on metal foil that switch at rates of 100 MHz.

For military applications, circuits built on flexible substrates start to get really interesting when their transistors switch at speeds above a gigahertz. At those frequencies, antennas made with lightweight and conformable plastic electronics are possible. Such antennas would be a great advantage for soldiers on the battlefield, who have to carry loads weighing more than 25 kilograms. The ultimate goal, an admittedly long-term one, is to weave the flexible radio circuits right into the fabric of the soldiers' uniforms, to let officers not only communicate with soldiers but also monitor their vital signs.

Other futuristic possibilities include space-based radar receivers. They would be built around a two-dimensional array of RF circuits on a substrate that would detect and amplify radar echoes from a target. These arrays would be sizable, because the distance from one detector circuit to another would equal one half the wavelength of the radar signal. For a 500-MHz radar signal and an array of 1600 detectors, the receiver would measure 10 meters on a side.

But for radar systems in space, bigger is better, because a bigger receiver can detect weaker signals. And NASA has plans for space-based radar receivers 20 meters on a side. Of course, getting conventional rigid receivers into space isn't easy. Even a 10- by 10-meter array wouldn't fit in one piece into the cargo bay of today's space shuttles. It would have to be sent up in parts and assembled outside the spacecraft. On the other hand, a receiver made on a flexible plastic backing could be rolled up for the ride into space and unfurled in orbit.

In addition to the high-speed circuits, space-based radar antennas and telescopes will also need robust structural health monitoring built into the plastic receivers. The very fact that they are flexible means their shape could be influenced by differences in temperature across these large panels. Thus, the low-speed monitoring and control of the shape of the optical or radar receivers will have to accompany the high-speed reception and processing of high-speed signals; for this, too, flexible circuits will be needed.

Exotic, space-based applications like these could lead to more mundane, terrestrial applications for fast, flexible circuits. Large, lightweight X-ray detectors could rapidly inspect containers at airports and shipping docks. Portable radar systems, light and compact enough to stow in a soldier's backpack, could detect an enemy hidden in the bushes or locate the source of a mortar attack.

We are well along the road to making flexible large-scale electronics into a thriving industry. All the essential elements are under development. Inkjet printing has successfully made displays with both OLEDs and electrically active inks that change from white to black, or vice versa, when a voltage is applied. The roll-to-roll manufacturing process can be used to make cheap disposable radio-frequency identification tags. The technology for coating plastic substrates with the single-crystal silicon needed for high-speed transistors is rapidly maturing.

If developers pull these technologies together, by the end of the decade the theoretical will become practical. It will be commonplace to see lightweight flexible displays for signs and consumer electronics and instrument panels that conform to a car's dashboard. But high-speed applications like flexible stowable antennas in space to monitor military maneuvers, analyze weather patterns, and predict earthquakes may take another 10 to 15 years.

Flexible electronics will not completely replace standard silicon technology. Rather, there will be two technologies, side by side: conventional silicon ICs for the most demanding applications, like microprocessors and communications network circuits, and flexible macroelectronics wherever large size or low cost outweighs the need for raw, blazing speed.

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To Probe Further

The July and August 2005 issues of Proceedings of the IEEE, Vol. 93, nos. 7 and 8, are both devoted to flexible electronic technology.

For more on inkjet printing of electronics, go to the list of technical papers on the Litrex Corp. Web site: http://www.litrex.com/TechnicalPapers.htm.

Information on how to print circuits is available in *Printed Organic and Molecular Electronics*, edited by Daniel Gamota, Paul Brazis, Krishna Kalyanasundaram, and Jie Zhang (Kluwer Academic Publishers, 2004).

Figure 1

PHOTO: E INK CORP

Figure 2

PHOTO: E INK CORP

Figure 3

PHOTO: SAMSUNG ELECTRONICS

Figure 4

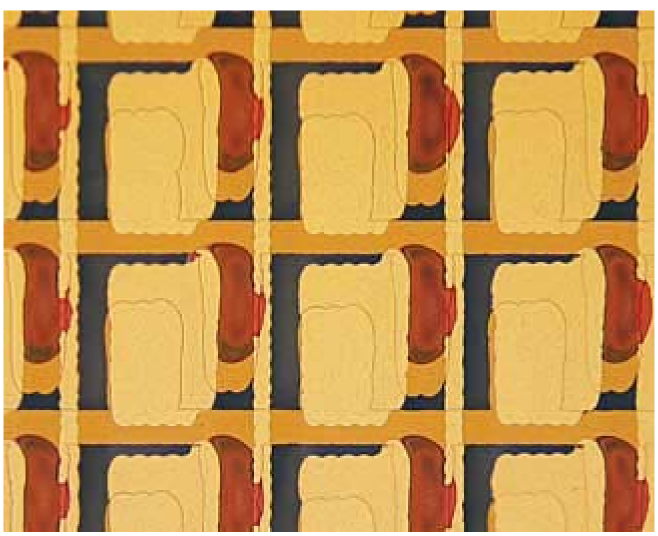
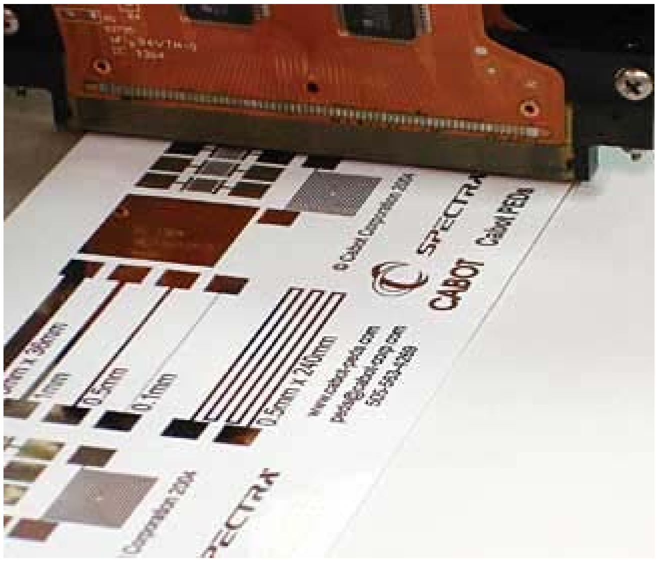


PHOTO: PALO ALTO RESEARCH CENTER

Figure 5



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