ELECTRONICS

New Age Semiconductors Pick Up the Pace

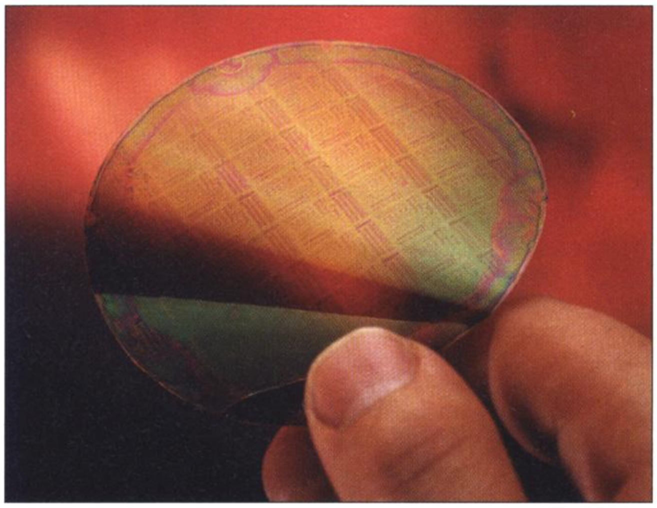
Long hampered by poor electrical qualities, low-cost electronics are now moving fast toward real applications, with the help of some clever chemistry

If prices for consumer electronics seem cheap now, just wait. Researchers around the globe are closing in on a Holy Grail of electronics: making circuits out of cheap, throwaway materials like plastics. And if they succeed they'll likely launch a whole bevy of new applications, such as wall-sized flexible plastic displays and computerized merchandise tags that would allow shoppers to walk an entire cart of goods through a scanner and have their purchases recorded automatically.

These experimental electronics have been on the drawing boards since the mid-1980s. That's when researchers discovered polymers able to conduct electric currents under certain conditions and not others—just as silicon and other inorganic semiconductors do. Since then, research into cheap, large-area electronics has been dominated by organic materials, which can be easily layered over large surfaces. But until recently, devices made with organics have been painfully slow in their ability to shuffle an electric current, a big problem in meeting today's demands for lightning-fast computation.

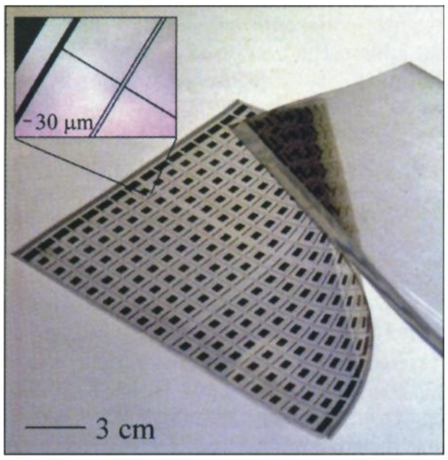
Now, in a series of journal articles and meeting reports over the past few months, researchers have come up with several swifter alternatives, comparable in speed to the type of low-grade silicon transistors used to run laptop displays. Some are organics, others either incorporate inorganic components or are entirely inorganic. "There's a new richness of chemistries being brought to bear on this," says chemist Howard Katz of Bell Laboratories, the R&D arm of Lucent Technologies in Murray Hill, New Jersey.

The improvements have not just been in speed. Researchers have also made headway in creating electronic materials that would be reliable, stable over long periods, and cheap and easy to manufacture—essential attributes for commercial devices. "There has been a lot of progress in this field," says Bell Labs chemist Zhenan Bao. Still, no one group has managed to put all these attributes into one material. "At this point, people are trying to put all the pieces together," says Cherie Kagan, a materials scientist at IBM's T. J. Watson Research Laboratory in Yorktown Heights, New York. Nevertheless, there's growing optimism in the field that progress is beginning to gather pace. "It's starting to happen," says Ananth Dodabalapur, a device physicist at Bell Labs who has helped push the field since the beginning.



Roll 'em. New flexible electronics promise to power roll-up displays.

That's a big change for an area that until recently was struggling to find organic materials that could pass juice at even one 10-thousandth the speed attained by silicon, the stock material of the electronics age. Crystalline silicon, the material used to make the processing chips that serve as the brains of computers, can push charges at a blinding speed—1000 square centimeters per volt second (cm^2/Vs), the standard measure of mobility in electronics. But the material is delicate and expensive to make, it must be handled in clean rooms to avoid contamination, and it can't be used to cover large areas such as displays. Amorphous silicon is cheaper and can be spread thinly to control laptop displays, but it only conducts at between 0.1 and 1 cm^2/Vs. And films of this material must be grown in a vacuum, making it too expensive for cheap, throwaway circuitry.



Print it. A quick and easy rubber-stamping technique produces transistor arrays.

Organic semiconductors first burst on the scene in the late 1980s. They appeared to offer researchers the promise of electronic circuitry without the hassle and cost of silicon, because organics could be dissolved in solution and spun out into thin films on virtually any substrate. But the performance of early materials was anything but impressive. The first semiconducting polymer transistors conducted at only 10^{-5} cm^2/Vs.

Since then, researchers have created a wide variety of more promising semiconducting organics. Among the first of this new breed was a polymer called regioregular polythiophene that could move charges as fast as 0.1 cm^2/Vs, just matching the pace of the slowest amorphous silicon. And researchers soon found that if they moved from long-chain polymers to shorter organic molecules, such as one called pentacene, they could reach speeds of nearly 2 cm^2/Vs.

But these newer materials were far from perfect. Over time, polythiophene is contaminated by air. Oxygen reacts with the material and converts the polymer from a semiconductor, in which the electric current can be turned on or off, into a rather poor conductor with no switching ability. That means the material cannot be used to make transistors without going to the added expense of encapsulating finished devices in a sealant. Pentacene brought added costs as well. To make the best semiconductors, pentacene molecules must be lined up in perfectly ordered crystals, which can only be done in a vacuum, making it a poor choice for cheap, large-area electronics.

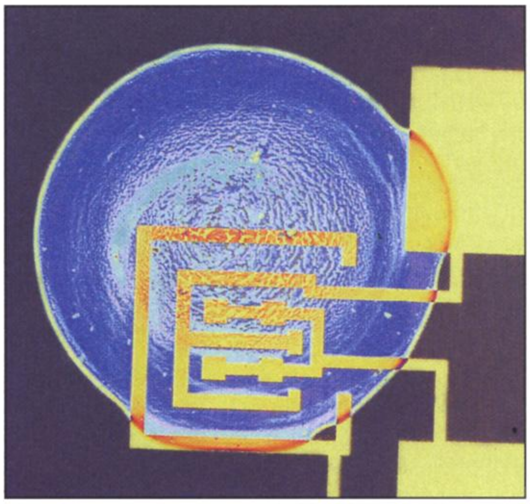
That left researchers wondering how to make a material with the speed of pentacene and the ease of handling of polymers. Independent teams at Bell Labs, IBM, and the Massachusetts Institute of Technology (MIT)

CREDITS: (TOP TO BOTTOM) ROYAL PHILIPS ELECTRONICS; J. ROGERS/LUCENT TECHNOLOGIES' BELL LABORATORIES have recently reported that they are well on the way, but each group took a very different path to reach this goal.

Perhaps the widest ranging of this new generation of materials is the one from Bell Labs. Katz reported at last month's Materials Research Society meeting in Boston that he and his colleagues have come up with a new approach to making short organic molecules that can be processed in solution like polymers. They turned to a pair of organics that harbor carbon- and sulfur-containing thiophene rings used to make the polythiophene polymer semiconductors. Abbreviated as dihexyl alpha 5T and 6T, these organics contain a core row of five or six thiophenes that are polar, meaning they are capable of separating positive and negative charges. The ring chains are flanked on either end by short nonpolar hydrocarbon tails. When spun from solution into films, the molecules tend to stand on end. And because polar and nonpolar groups tend to separate, the film automatically forms alternating layers of thiophene rings and hydrocarbon chains. After experimenting with various solvents and processing conditions, Katz's team found a set of conditions that gave them high-quality films that they used to make devices with mobilities up to 0.1 cm^2/Vs. What's more, notes Katz, these organics are stable in air and thus are compatible with cheap, large-scale processing. And like inorganic semiconductors, they switch automatically from nonconducting to conducting when primed with a bit of juice from a control electrode in the heart of a transistor.

The IBM team decided that, rather than modify their organics, they would enlist the help of inorganic materials. In the 29 October 1999 issue of *Science* (p. 945), Cherie Kagan, David Mitzi, and Christos Dimitrakopoulos reported creating transistors harboring a new semiconductor made from a hybrid of organic and inorganic materials. The team's goal, says Dimitrakopoulos, was "to get the best of both worlds," with the ease of processing from organics and the high charge mobility of inorganics.

They achieved just that by choosing inorganic and organic components that assemble themselves into layered sheets. The organic component, called phenethyl ammonium, is deficient in electrons, creating vacancies in its electronic structure that behave like positively charged particles, while the inorganic portion—tin iodide—has an excess of electrons. The result is that when the two materials are mixed in solution at room temperature and allowed to settle as a film, the negatively and positively charged components assemble themselves into alternating negatively and positively charged layers that hold each other in place. And in devices made with the films, charges seem to be taking the fast lane through the inorganics: They've measured current speeds up to 0.6 cm^2/Vs, "which is really getting into the heart of where you want to be," says Kagan. What's more, Dimitrakopoulos notes that previous work has shown that transistors made with just tin iodide can reach mobilities as high as 50 cm^2/Vs. "We're just scratching the surface with these materials," he says.



Back to basics. A dollop of inorganic semiconductor forms the heart of this transistor.

The IBM hybrid, too, is still a work in progress. These films also quickly degrade in air and therefore must be protected. But Kagan and Dimitrakopoulos say they're not worried. "We can change the organic and inorganic layers to improve the properties of the films," says Dimitrakopoulos, adding that such attempts are already under way.

The MIT team, led by physicist Joseph Jacobson, went full circle, using organics to help them make films of high-mobility inorganics that they then used for their transistors. To make thin crystalline films, inorganics such as silicon traditionally must be deposited from a gaseous vapor. But Jacobson's team wondered whether they could get good electronic properties by putting down a layer of nanometer-sized crystallites on a surface and then heating them up so that they bonded together. Much to their delight, as the team reported in the 22 October 1999 issue of *Science* (p. 746), the approach worked. The team surrounded nanoclusters of cadmium and selenium—each of which had just 1000 or so atoms—

Setting the Benchmark for Plastic Electronics

If you made an ideal organic conductor, pure and virtually free of defects, how fast could it conduct charges? Physicists Bertram Batlogg, Jan Hendrik Schoen, and Steffen Berg and crystal grower Kloc Christain—all researchers at Bell Laboratories, the R&D arm of Lucent Technologies in Murray Hill, New Jersey—decided to find out. At the Materials Research Society meeting last month in Boston, the team reported that they had grown nearly perfect crystals of some 10 different organic materials, all made from small-molecule components rather than spaghettilike polymers, and put them through their paces. Such materials wouldn't be suitable for commercial devices—they would be too expensive and delicate—but they could help define the limits of the possible for cheap plastic circuitry.

According to Batlogg, the best crystal they came up with—made from pentacene—moved charges at about 3 cm^2/Vs. And the others were not far behind. By contrast, notes Batlogg, crystalline silicon can reach 1000 cm^2/Vs. The difference, he says, seems to be in the bonding between neighbors in the material. Silicon atoms form strong covalent bonds with their neighbors. This allows the quantum mechanical waves of electrons on neighboring atoms to overlap, which helps grease the pathway for charges to flow. By contrast, even in nearly perfect pentacene crystals, individual molecules are only weakly bonded to one another. The result is that the heat at room temperature causes them to jostle back and forth. "It's a jumble," says Batlogg. In that jumble, the overlap of quantum mechanical waves varies, "so the probability of [a charge] hopping from one molecule to the next is reduced," he says.

Francis Garnier, a pioneer in the field of organic electronics at the CNRS Laboratory of Molecular Materials in Thiais, France, calls the new work "very important," because it helps researchers in the field know how much higher speeds they can hope to achieve. The good news is that researchers working with small organics like pentacene as well as polymers have already produced devices that show speeds between 0.1 and 2 cm^2/Vs, not far from the best case scenario. Some would say, however, that this is also the bad news, as it means there's not much room for improvement with organics. In the last few months, researchers at IBM and the Massachusetts Institute of Technology have begun experimenting with making easily processed devices with inorganic materials or organic-inorganic hybrids, which have the potential to push current much faster. These new results might wind up encouraging more researchers to follow that lead.

—R.F.S.

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with organic groups that allowed them to dissolve in an organic solvent. That enabled them to lay down a thin liquid film of the clusters. When the researchers then heated their film up to 350 degrees Celsius, the organic groups essentially burned off and neighboring clusters sintered together in larger aggregates 10 to 15 nanometers across.

Jacobson and his colleagues reported that devices made with the films moved charges at 1 cm^2/Vs, 10 times as fast as Bell Labs' new organic material. Moreover, the MIT researchers have devised a potentially cheap and easy scheme for printing circuits made from this material. "This is nice work and could be a good track to follow," says Francis Garnier, a pioneer in conducting organics at the CNRS Laboratory of Molecular Materials in Thiais, France.

Still, the approach has its drawbacks, concedes Jacobson. To burn off the organics and sinter the nanocrystals requires heating the devices to a point that would melt transparent plastic substrates envisioned for use in displays. And, like many other such materials, they must remain isolated from air.

Improving the speed and stability of these novel electronic materials aren't the only goals being pursued. Another Bell Labs team, led by physical chemist John Rogers, reported at the meeting that they are making heady progress in printing complex circuits of plastic electronics. To do the printing, Rogers and his colleagues wet preformed stamps with a solution containing gold and then pressed the stamps onto a layer of semiconducting polymer, which itself sits atop a plastic substrate. And although the work remains in its early stages, they've already succeeded in printing a circuit with 300 transistors that they plan to use to control light emission from a flat-screen display. "We've yet to make a functioning display, but we've built the electronics and been able to show that [the transistors] have good characteristics," says Rogers.

For now, Rogers and his colleagues have been making their circuitry out of a variety of semiconductors such as polythiophene. That material has a modest charge mobility, but because variations on the stamping technique can make such small features—down to about 100 nanometers—they can create ultrashort "channels," or pathways for the electrons to follow in the transistors. With a shorter distance to travel, the overall speed isn't such a drawback.

That experience drives home a key lesson that is dawning on researchers in the field, say Bao, Rogers, and others. For any next-generation semiconductor to succeed commercially, it must meet so many demanding criteria that the one that wins may not necessarily be the one that pushes current along the fastest. But then again, it may be. Says Rogers: "It makes for a good horse race."

–ROBERT F. SERVICE

HUMAN RESOURCES

New Incentives Lure Chinese Talent Back Home

China is dangling higher salaries, bigger research budgets, and improved management practices to lure top young scientists now working abroad

BEIJING—At the age of 37, Chinese-born She Zhensu had already carved out a place in the upper ranks of the U.S. research community. A tenured professor of mathematics at the University of California, Los Angeles (UCLA), who studies turbulence, he published regularly in leading journals. But last year, after 12 years in the United States, She returned home to lead a multidisciplinary experimental group at Beijing University that has also been designated a state key laboratory. The salary "cannot be compared with what I earned in the States," She admits, but he has no complaints about the move: "It is an opportunity for me to contribute to higher education and research in my motherland. I think I made the right choice."

That attitude is exactly what Chinese officials were looking for when they selected She to be among the first group of Changjiang Scholars. It's one of several new programs that offer premium salaries, generous research budgets, and other perquisites (see table on next page) to try to bring back—or retain—top-level Chinese researchers who can provide the mentoring that young scientists now often seek overseas. So far, the numbers are small. The special grants have gone to some 150 researchers like She who have shown significant promise overseas, plus dozens of scientists who trained and worked abroad before returning home. But the government sees them as a core that will elevate Chinese science for decades to come. "They are role models for both productivity and good research practices," says Bai Chunli, vice president of the Chinese Academy of Sciences (CAS), which runs the nation's premier research labs.

Homeward bound. Mathematician She Zhensu left UCLA for greater opportunities in China.

These incentive programs are just one part of a broader strategy to reverse the tidal wave of scientific talent that has flowed out of China in the past 2 decades. The Ministry of Education estimates that upward of two-thirds of the 300,000-plus scientists and engineers who went abroad to study during that period remain abroad. In addition to the special incentives, the government is improving research conditions and adopting performance rather than seniority as the basis for funding and professional advancement. The strategy appears to be working. Last year 564 researchers returned to CAS from overseas while only 432 left for foreign positions—the first-ever positive flow. "We're finally turning the tide," says Peng Liling, who oversees the incentive programs at CAS.

The prototype for the new programs was CAS's so-called Hundred People Program, which has given out \$32 million to 177 scientists since it began in 1994. The central government supplemented it in 1998 by the 300 Talents Program, a \$72.5 million program spread over 3 years. Last year the Ministry of Education began its Changjiang Scholars Program with a plan to spend \$15 million annually for 3 to 5 years. Roughly half the cost is being picked up by Li Ka-shing, a Hong Kong business tycoon and philanthropist. In addition to these efforts, some of the bigger universities, including Qinghua and Beijing, have their own incentive programs, as do several cities.

Simple calculation. Mathematician Yuan Ya-xiang says coming back to work in Beijing was an easy decision.

Participants in these programs can do quite well. Changjiang scholars, for example, get a yearly salary of 100,000 yuan (about US\$12,000), a hefty premium over the typi-

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