Semiconducting Polymers on Display

FEATURE

by Jennifer Ouellette

Companies ready polymer-based LEDs, transistors, and smart labels for market

Semiconducting polymers have intrigued researchers since their discovery 20 years ago because of their unique electronic properties, which straddle the fence between those of traditional inorganic materials and organics such as photoactive biomolecular materials. Now these polymers are poised to enter the commercial marketplace as active elements in light-emitting diodes (LEDs) for displays. The technology is also being developed for the manufacture of inexpensive plastic transistors with applications envisioned in smart cards and smart labels (which can electronically change prices or warn of sell-date expiration), sensing devices, and other cutting-edge technologies such as electronic paper.

Known more colloquially as plastics, semiconducting polymers are part of a broader class of organic materials that includes small molecules and oligomers. Semiconducting polymers in particular are generating excitement among scientists because of their potential commercial electronic applications. Ananth Dodabalapur, a researcher at Lucent Technologies' Bell Laboratories (Murray Hill, NJ), defines these polymers as long-chain molecules consisting of more than eight units.

There are four specific types of semiconducting polymers. *Filled polymers* are loaded with conductive fillers, such as carbon black, graphite fiber, or metal oxide particles, and have the broadest application in electronic devices. However, they are inhomogeneous materials, which makes them heavily process-dependent, harder to reproduce, and weaker in dielectric strength. *Ionically conducting polymers* are used in such consumer electronic applications as rechargeable batteries, fuel cells, and polymer light-emitting devices, although their conductivity is highly sensitive to humidity. *Conjugated polymers* use polyaniline and its modifications; their major demand is in the manufacture of conducting filled polymers. *Charge-transport polymers* have become the most established semiconducting organic system because of their commercial use in xerographic photoreceptors.

To generate light with these materials, a thin film of semiconducting polymer is deposited on a glass or plastic substrate and sandwiched between two electrodes. Electrons and holes are then injected from the electrodes, and the recombination of these charge-carriers results in luminescence. The bandgap—the energy difference between the valence and conduction bands of the polymer—determines the wavelength of the emitted light.

Displacing LCDs

By far the most lucrative near-term application for light-emitting polymers (LEPs) is as small flat-panel displays. Estimates of the total market for flat-panel displays vary, but Stewart Hough, who heads business development and marketing for Cambridge Display Technologies (CDT) in Cambridge, England, estimates that it is currently between \$30 and \$35 billion and is projected by some analysts to top \$70 billion by 2005.

Organic materials are already beginning to make inroads into the industry. The market for organic light-emitting displays is expected to increase from \$18 million in 2000 to more than \$714 million by 2005, with significant additional growth expected between 2006 and 2010, according to market research by Stanford Resources (San Jose, CA). Those figures include displays for mobile phones, personal digital assistants, digital cameras, camcorders, and eventually personal computers and other consumer products.

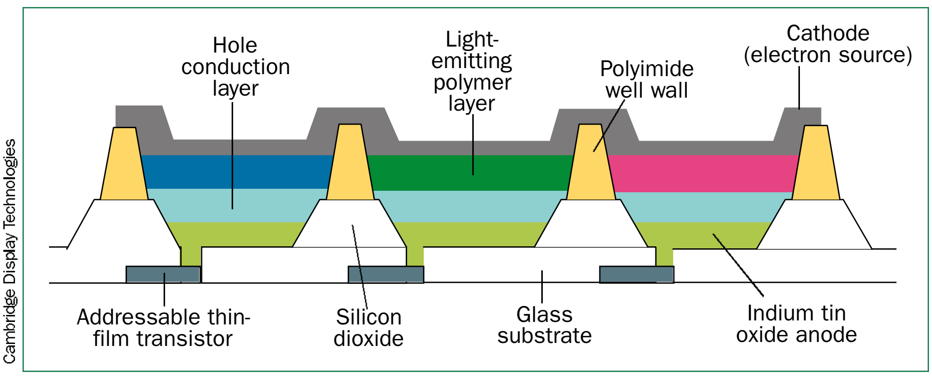

Figure 1. Cross section of three addressable subpixels (red, green, and blue) in a flat-panel display less than 100 µm thick, with a thin film of semiconducting polymer sandwiched between electrodes.

LEP-based display technology is widely accepted as the most likely replacement for the cathode-ray tube and liquid-crystal diode (LCD). It offers several significant advantages over both technologies, according to Hough, such as enhanced clarity, unlimited viewing angles, faster image-refresh rates, thinner profile, lighter weight, and the availability of all colors of the visible spectrum. In addition, LEPs can achieve high brightness at low drive

Figure 2. The world's first full-color, ink-jet-printed, active-matrix LEP display, developed by Seiko-Epson and CDT, measures 150 × 200 mm and is 2 mm thick.

voltages and current densities, which results in lower power consumption than other technologies. Moreover, polymer materials can be processed into large-area thin films using simple and inexpensive technology, unlike inorganic LEDs, which require a highly doped semiconductor layer for ohmic contact. Hence, large-area pixellated displays made from a single sheet are possible.

CDT is initially targeting its LEP technology for small display applications, including those that require simple patterning, such as dot matrix alphanumeric displays. The company hopes to eventually produce larger area displays, a market for which there is no established commercial technology and where the LEP approach promises an inexpensive solution.

"If you look at the evolution of display technologies, they always start out simple and small," says Hough. As an example, he points out that LCDs began with applications in wristwatches and small calculators, and eventually came to dominate the notebook and desktop markets. "Polymers will follow a similar path, only it won't take 30 years. It may only take 5 to 10 years to realize their full potential," he says. The biggest challenge is scaling up the manufacturing process to handle larger commercial production of these materials and devices.

CDT has joint development agreements with several major manufacturing companies, including one with DuPont for the development of flexible substrates for large area displays, and other agreements with Philips, Seiko-Epson, Hewlett-Packard, Bayer AG, and Hoechst, drawing on the expertise of each. The partnership with Seiko-Epson has resulted in the recent demonstration of a full-color video display based on CDT's polymers and Seiko-Epson's inkjet expertise. The two companies have developed an innovative manufacturing method that uses inkjet printing to deposit individual pixels—made up of red, green, and blue LEP materials—directly onto the substrate. With this technology, potential display size is limited only by the size of the available wafer, and the technology has no adverse impact on throughput when deployed in existing manufacturing lines, says Hough.

"One thing that is happening in the LCD market is that profitability has been squeezed," says Hough. "Consequently, many companies are looking for something new and improved to differentiate their products."

CDT has signed a licensing agreement for electronic applications of its technology with Delta Electronics, a major manufacturer of video displays, electronic components, and networking products. Another CDT licensee is Philips Research Components (Eindhoven, The Netherlands), which set up a separate business unit to develop, manufacture, and sell LEP displays and LEP backlights for LCDs. Pilot production began in 1998.

Last December, CDT announced that it would spend $25 million to build a manufacturing facility in Godmanchester, about 15 miles from its headquarters, to help drive its LEP commercialization strategy. That same month, Covion—one of the first companies dedicated to commercial manufacture of both polymer and small-molecule semiconducting materials for use in flat-panel electronic displays—invested $5 million to boost capacity at its plant in Frankfurt, Germany. This expansion created a solution volume of more than 40,000 liters of conjugated polymers annually. There is also considerable interest in LEPs for display applications in Japan, Korea, and Taiwan.

Improving performance

Advancements continue to be made in performance. Valy Vardeny of the University of Utah conducted experiments on enhanced photoluminescence and predicted that electroluminescence is possible in LEDs. This prediction has been borne out by experiments at several laboratories, which demonstrated an internal quantum efficiency of electroluminescence in polymer-based LEDs of about 50%—thus making them capable of converting between 41 and 63% of incoming energy into light, in contrast to the 10% conversion rate for conventional LEDs.

These results were achieved by placing conducting plastics in a magnetic field at extremely low temperatures and then using a laser—rather than electricity—to make them emit light. The materials were also bombarded with

IBM–Alias/Wavefront

Figure 3. This award-winning baby mobile uses lightweight organic light-emitting diodes to realize images and sounds in response to gestures and speech of the infant.

microwaves, which scientists believe randomize the spins of the incoming electrons and holes so that they combine more quickly. Although this approach works well in the laboratory, bringing such a process into the marketplace is more complicated. However, Vardeny believes a practical alternative to microwaves might be to dope light-emitting plastics with iron compounds, for example, which have the same randomizing effects.

"If this were realized, it could mean more efficient light emitters for lasers, displays, and domestic applications ranging from room lights to TV screens," he says. The method can also be used as a test to predict which polymers and oligomers are most efficient at converting electricity into light.

The possibility of plastic solid-state lasers intrigues Vardeny, who believes they will be easier, safer, and less expensive to manufacture than conventional semiconductor lasers. These lasers, of which a few prototypes have been made, would have several performance advantages. For example, the plastics act as their own cavities. Thus, they not only emit laser light but also contain and focus it. Plastic lasers are also flexible enough to be fashioned into thin films or "microdisks" suitable for use in display devices, or lined up in a computer chip to switch and transmit optical signals. Plastic-laser materials also could be dissolved in solvents and applied as coatings to optical fibers to amplify light moving through them. Finally, almost all existing solid-state lasers can emit only red and infrared light. Plastic lasers could emit green or blue light, which have shorter wavelengths and, hence, could be used to write more information on storage disks.

Semiconducting-polymer transistors are well suited for use as chemical sensors in such devices as electronic noses (see *The Industrial Physicist*, February 1999, pp. 26–29) because the polymers, being chemicals, can interact with other chemicals and translate information from the gas phase into electronic data. In another applications area, scientists at Advanced Research Development, Inc. (Athol, MA), have manufactured plastic solar cells by combining two different polymers: polyvinyl alcohol and polyacetylene. The resulting copolymer film is marketed under the trade name Lumeloid. It can polarize light and, theoretically, convert nearly three-quarters of it into electricity, compared to the up to 20% conversion rate achieved by present-day photovoltaic cells. The company is now working on a complementary polymer capable of storing electricity because photovoltaics must be able to operate day and night to be competitive.

The future is plastics

Because of the lower cost of manufacturing organic transistors, another major potential application is for large-scale integrated circuits for low-cost generic applications, such as radio-frequency electronic wireless tags, or smart labels, to track merchandise, baggage, or express packages. Other potential uses include roll-up computer screens and smart cards. Bell Labs has focused much of its research in this area, according to Dodabalapur. Among its recent achievements is the demonstration of a prototype electronic paper developed jointly with E-Ink Corp. (Boston, MA). The device is a 256-transistor flexible display, in which each transistor controls a single pixel.

Researchers at Philips Research Laboratories have developed "all-polymer" transistors in which every part is made from plastic. Other companies working in this area include IBM, DuPont, Xerox, and a start-up venture in Cambridge, England, called Plastic Logic, founded by Richard Friend, a professor of physics at Cambridge University whose research also spawned CDT. Unlike silicon processors, which are fabricated on flat wafers, Plastic Logic's fabrication process prints the chips on rolls of film that can be applied as smart labels to various surfaces, even clothing.

"It is all about transferring low-level intelligence to everyday products," says Friend, adding that in the not-too-distant-future, "Your yogurt container will be able to tell the yogurt it should have been eaten a few days ago."

Even more applications are possible as the underlying science behind semiconducting polymers becomes more advanced. "The potential for a radically different semiconductor technology in the future is great," says Friend.

Plastic Logic has already received $2.48 million in start-up funds to further develop and commercialize its technology. The company hopes to produce the world's first commercial microchips made of plastic, which would sell for perhaps one-tenth the price of silicon chips. Viable prototypes are expected by the end of the year.

However, the future of semiconducting-polymer technology has its naysayers. Some industry analysts argue that the savings from switching to semiconducting polymers from silicon would likely be minimal because the vast majority of chips are small silicon processors that cost less than $1, of which the raw silicon component is but a fraction of the total cost. Furthermore, global investment in silicon-processor fabrication plants is approaching $100 billion, making it extremely difficult for a small start-up such as Plastic Logic to compete in an industry so firmly fixed in silicon.

Nevertheless, Friend and other researchers in the field remain optimistic about the technology's future potential, particularly because of important new breakthroughs in recent years. In March, Bell Labs scientists announced that they had discovered that some polymer semiconductor-based transistors can become superconducting under certain conditions and detailed their work with one such material (see "Briefs," p.11). This finding could pave the way to combining semiconducting plastics with conventional silicon transistors to make circuits for quantum-computing applications, although a workable prototype of such a device would be further into the future.

"It's a promising technology, not just because of its application in existing commercial markets, but also in the creation of new markets," says Dodabalapur of LEPs. "Polymer-based semiconductors have so many novel properties, we will certainly hear much more about them in the years to come."

Further reading

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