

Materials Competition for Flat-Panel Displays

Materials issues constitute many of the remaining challenges to the development of new technologies for the multibillion-dollar flat-panel display (FPD) market. Despite the current dominance of liquid-crystal displays (LCDs), strong interest remains in exploring alternative technologies for a growing variety of display applications, as well as in scaling up LCDs to larger sizes.

Certainly business is booming, causing some to tout FPDs as the next semiconductor industry. Motorola pegs the current FPD market value at \$16 billion and predicts that sales will reach \$30 billion by 2002. FPDs also continue to attract heavy federal investment, according to Bruce Gnade, program director for the Defense Advanced Research Projects Agency's (DARPA's) FPD initiative. That agency alone has invested more than \$500 million in FPD-related research since 1993.

Basic FPD technologies consist of essentially four types: LCDs, plasma-display panels (PDPs), field-emission displays (FEDs), and electroluminescent displays. LCDs account for as much as 99% of all FPDs shipped, according to David Slobodin, a scientist with In Focus Systems (Wilsonville, OR), a leading manufacturer of projection displays. PDPs, which operate much like a large array of tiny red, green, and blue fluorescent light bulbs, are just beginning to appear on the commercial market. However, Japanese manufacturers expect that by the year 2000, more than 1 million such displays will be sold annually.

No one technology will meet the needs of the many emerging markets for FPDs, each of which requires different sizes, brightnesses, temperature ranges, weights, and costs. LCDs work well commercially in laptop displays and in desktop monitors up to about 20 in. diagonal, and good performance has been achieved in 25-in. diagonal desktop prototypes. However, it is difficult to scale the technology up to larger sizes, although Sharp Microelectronics has demonstrated a 40-in. tiled LCD, in which the image as a

whole appears on two displays, as in a video-wall but without the visible separations between the individual displays. "It's the classic semiconductor problem," says Kevin Lyons, business development manager for Symyx Technologies (Sunnyvale, CA). "The larger the piece you're trying to make, the lower your defect rate needs to be per square inch to have an effective device."

FEDs currently operate best at very small sizes and don't scale

prove useful for microdisplays used in lenses or goggles.

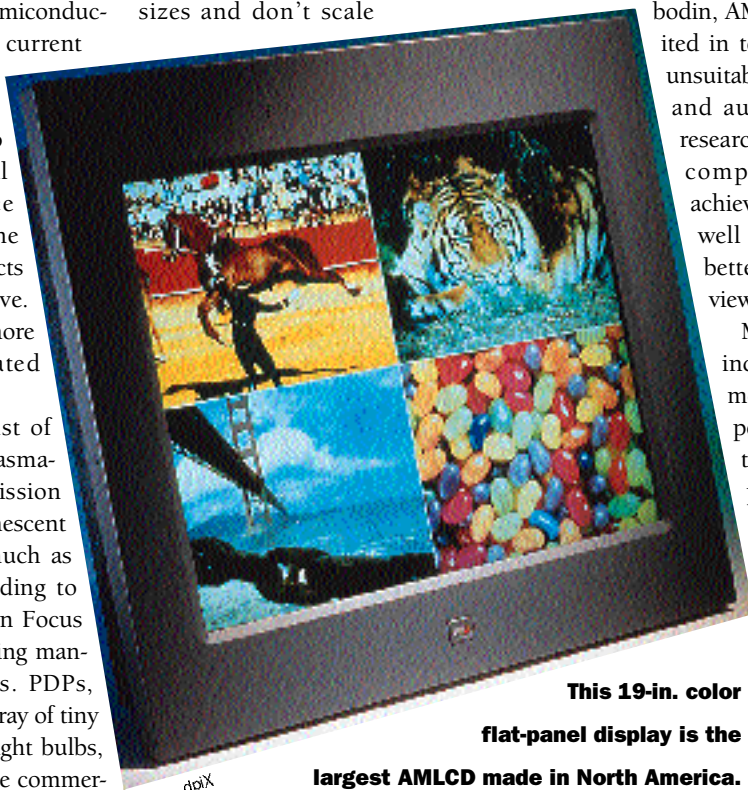
Active-matrix LCDs

One of the more popular types of LCDs is an active-matrix LCD (AMLCD), in which each pixel has a built-in thin-film transistor to drive the on-and-off shuttering of the liquid crystal, resulting in sharper contrast and quicker control. However, according to Slobodin, AMLCDs, like most LCDs, are limited in temperature range, making them unsuitable for many military, aerospace, and automotive applications. A key research goal is to alter the molecular composition of liquid crystals to achieve a wider temperature range, as well as faster switching speeds and better optical properties for a wider viewing angle.

Many researchers are seeking to incorporate very-high-conductivity metals, such as aluminum or copper, into the anodes. In addition, the effort to replace the amorphous-silicon thin-film transistors (TFTs) with polycrystalline silicon—and to develop polysilicon processes that are fast enough and cheap enough to use in large-scale LCD fabrication—represents one of the most significant materials-processing issues facing the FPD industry today.

Because of the fairly low electron mobility of amorphous-silicon TFTs, AMLCDs manufactured with this technology can be expensive, prone to defects, and rather limited in switching speed, according to John Batey, manager of process engineering at dpiX (Palo Alto, CA), a Xerox-affiliated start-up company. In contrast, polycrystalline silicon can sustain higher currents, resulting in faster transition speed. "The combination of high-conductivity anodes and polysilicon-transistor technology would be a radical paradigm change in the LCD industry," he says.

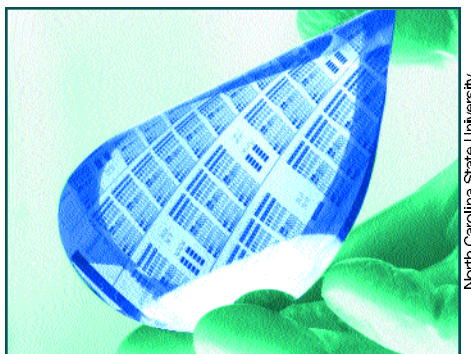
There is also considerable interest in fabri-



This 19-in. color flat-panel display is the largest AMLCD made in North America.

up well beyond a 10-in. diagonal screen. In contrast, PDPs are exceptionally well suited for very large screen displays, on the order of 25- to 60-in. diagonals, but their relatively large pixels make it difficult to scale them down to smaller screens. Electroluminescent displays are completely solid-state devices, in which a phosphor is sandwiched directly between two electrodes. They are rugged and exhibit excellent temperature ranges, according to Gnade, although they are expensive to manufacture and fairly inefficient in terms of power. This makes them generally unsuited for portable displays, although they may

Amorphous-silicon thin-film transistor array on transparent polyethylene terephthalate.



North Carolina State University

cating an entire computer—including the display, memory, and microprocessor—on top of a glass substrate in a single-step process. Slobodin calls this objective the Holy Grail of the AMLCD industry, saying that low-temperature polycrystalline silicon appears to be the most promising material for this application.

“If you want to do this, you must integrate instead of having a hybrid technology with a plate and separate integrated circuits,” says Sigurd Wagner of Princeton University. He points out that amorphous silicon is not a fast enough semiconductor for the driver transistors. “With polycrystalline silicon, you could make both the drivers and the matrix transistors out of the same semiconductor and fabricate everything in a single process.” However, while amorphous silicon can be easily deposited over large areas to get the necessary economies of scale, polycrystalline-silicon films are deposited as amorphous films and then annealed, a process difficult to scale up to high volume.

Nader Kalkhoran, a researcher at Spire Corp. (Bedford, MA), believes that his discovery of visible emission in certain nanocrystalline forms of silicon may help pave the way for this new class of FPDs. His design features monolithic integration of light-emitting pixels and associated driver electronics on a single substrate, using relatively simple and cost-effective silicon fabrication processes. “Essentially there is no reason why display pixels with the same resolution as those used in the integrated circuit industry cannot be fabricated,” he says.

Reflective displays

The desire for lower power is fueling research in three major types of reflective display technology: liquid-crystal polymer dispersions and cholesteric materials in the United States, and certain dye-based materials in Japan. These eliminate the need for a backlight, which saves power and volume, resulting in a much thinner display. “They’re not going to replace the high-end tabletop machines currently on the market, but they do have a significant potential market for

portable computers,” says Greg Crawford of Brown University.

“I think everyone who makes LCDs is looking at reflective displays because of the potential for very low power, very long battery life, and ultraportable displays,” says Batey, adding that dpiX has an active R&D program in reflective display technology. Kent Displays (Kent, OH), a spin-off company of Kent State University’s Liquid Crystal Institute, currently manufactures monochrome reflective displays for small handheld devices, such as cellular telephones and pagers, using these cholesteric materials.

Because cholesterics have bistable memory capabilities, an image will remain on the display screen without being refreshed until it is changed, unlike standard transmissive displays that must renew the image 60 times per second. This feature would enable Kent Displays to make high-resolution displays on low-cost passive substrates without the need for an active matrix, thus simplifying the manufacturing process. The company is now developing full-color reflective displays as well as improving the speed of existing displays. Ultimately, it wants to produce electronic books and newspapers.

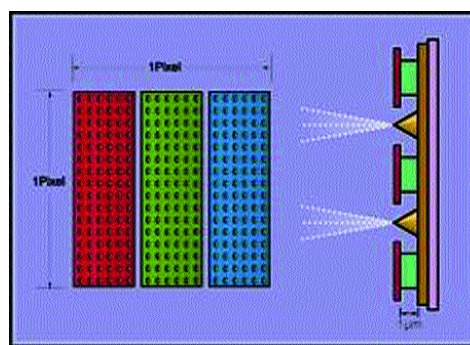
Many reflective displays are adaptable to flexible plastic substrates. This has sparked considerable interest because it reduces weight, although getting the conductor to adhere to the plastic remains a challenge. One good candidate material for plastic reflective LCDs is polypyrrole, a conducting polymer with good chemical and thermal stability that can be deposited in situ on plastic substrates. Kent Displays recently demonstrated the operation of a 2 × 2 fully multiplexed cholesteric LCD, fabricated from conducting polymer-based plastic substrates.

Gregory Parsons of North Carolina State University recently succeeded in forming

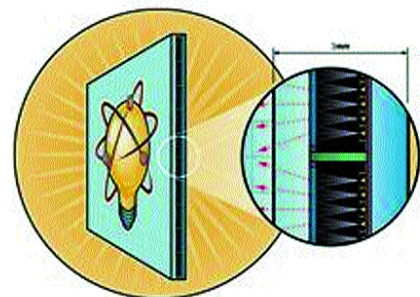
transistors on plastic substrates by reducing the temperature required to achieve the necessary electronic properties. However, Crawford reports that such devices still exhibit transmission and resistivity problems. Batey also expresses disappointment at the rate of progress in this area, despite the manufacture of plastic simple-matrix LCDs in Japan. “I still think there’s a great future there, and I believe we’ll see plastic AMLCDs sometime in the future, but it’s not going to happen in the next couple of years,” he says.

Field-emission displays

FEDs, a relatively new technology that operates on the same principle as cathode-ray tube (CRT) desktop monitors, combine equivalent picture quality with the size and weight advantages of LCDs. Both FEDs and CRTs shoot beams of electrons at an array of color pixels on glass. But CRTs have a single hot-cathode electron source to activate the pixels, whereas FEDs have hundreds of electron sources per pixel emanating from a cold cathode. In addition to being brighter and more efficient than many standard LCDs, FEDs offer full motion and color, and they can be seen clearly from wide viewing angles.



Field-emission displays shoot beams of electrons through a vacuum tube at an array of color pixels on glass.



Motorola Flat Panel Display Div.

Motorola has made FEDs the focus of its display-development efforts. The company is so confident of the technology's prospects that it just completed construction of a 275,000 sq. ft. R&D and pilot production facility in Tempe, Arizona, representing a more than \$100 million commitment to

FEDs. Initially, Motorola will focus on smaller displays of 10 in. or less, for cellular phones, personal pagers, and a variety of medical, testing, and analytical instruments. Motorola unveiled its first 5.1-in. prototype for full-color FEDs in May.

Some obstacles remain, acknowledges

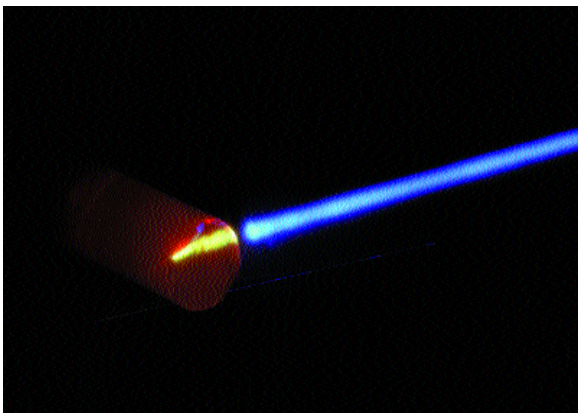
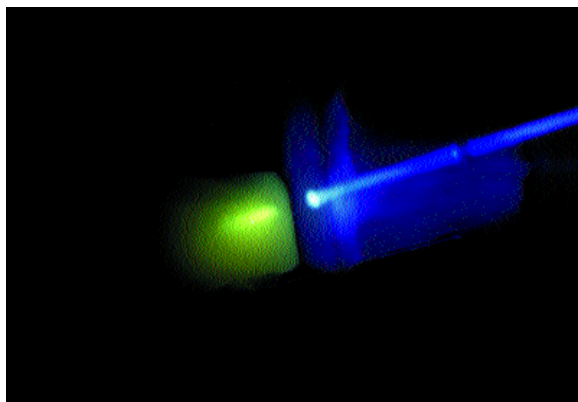
Larry Dworsky, who heads the company's FPD effort. The incorporation of a high-voltage vacuum environment into a very thin structure, for example, limits the materials used to only those with excellent vacuum characteristics, namely low outgassing rates and the capability to withstand thousands of volts across millimeter or even submillimeter distances. "You've got all your surface area but no internal volume," he says. "So we've got to look at surface characteristics, gas absorption and desorption, and sensitivity to contaminants much more stringently than in conventional CRTs."

Phosphors

By far the most pressing materials challenge for FEDs—as well as for PDPs, electroluminescent displays, and certain CRT projection displays—is the development of low-voltage phosphors. The ones currently in use function reasonably well in higher-voltage displays but lose brightness as voltage decreases. The best TV display phosphors are about 15% efficient, according to Carl Seager of Sandia National Laboratories, and are even less efficient at the lower energies (400-500 V) ultimately desired for FEDs.

An exception is zinc oxide, one of the few phosphors that conducts electricity well. This property makes it possible to build up electric fields inside the phosphor, which are crucial to preventing the loss of surface charges and hence maintaining brightness. However, zinc oxide emits light at a wavelength somewhere between green and blue. Thus it is not useful for the commercial manufacture of three-color displays, as it requires complicated filtering processes that would negate any energy-efficiency advantages.

Motorola is surmounting the challenge by avoiding low-voltage devices and using the same standard phosphors as the TV industry, which are designed to be optimized at roughly 20,000 V. Although Motorola's displays will run at around 5,000 V, Dworsky maintains that the phosphors function reasonably well at that level. Nanocrystals Technology (Briarcliff Manor, NY) is experimenting with doped nanocrystalline phosphors to achieve enhanced transfer rates to the activator ion.



ing to Sally Cahill Glauser of Lawrence Livermore National Laboratory, aerogels are a novel class of open-cell nanoporous materials with remarkable optical, electronic, thermal, and structural properties—which makes them ideal as host matrices for luminescent materials. After investigating the optical properties of silica aerogels doped with a variety of luminescent materials, her group concluded that aerogels would make good hosts for fluorescent dyes and other luminescent substances that are commonly used in display technology.

In the more futuristic area of molecular electronics, Paul Kolodner of AT&T Bell Laboratories/Lucent Technologies (Murray Hill, NJ) is seeking to exploit the

Photoluminescence of silica aerogel doped with organic dyes fluorescein (top) and rhodamine 6G (bottom).

natural electrochromic properties of bacteriorhodopsin for reflective display applications. Bacteriorhodopsin, a protein molecule found in the cell membrane of certain bacteria, can be used to produce metabolic energy. Electric fields cause a low-contrast color change from purple to blue in normal bacteriorhodopsin, but certain mutant varieties change color more dramatically, from blue to pale yellow. “If this property can be enhanced and generalized to other color combinations, the material could be used as an electrically addressable pigment, or electronic ink,” Kolodner says.

Spire Corp. has developed an ion-implantation technique to introduce the activators into the host material using zinc gallide phosphors. This enables the use of a single layer of phosphor material with red, green, and blue activators side-by-side on a film. The current manufacturing process requires the deposition of a different phosphor layer for each primary color.

Seager’s research focuses on developing chemical coating treatments to help reduce the surface charge loss, a difficult task because of the low voltage desired for many of the new FPDs. Furthermore, it is unlikely that the same coating can be used for all phosphors; rather, chemical treatments will have to be individually tuned for each phosphor. “In theory, all you need are three phosphors in the right combination, but there are literally hundreds of them out there,” says Seager. “If we were all working on one phosphor, we would probably have discovered the answer by now.”

Novel materials

The bacteriorhodopsin would be sandwiched between glass plates containing arrays of electrodes. A page of text or a color image would be written electronically on the protein film by applying voltages on the electrodes, as in LCD technology. However, the protein would derive its color by reflecting ambient light rather than by relying on an internal light source. Kolodner acknowledges the need to substantially increase the protein’s sensitivity. “In order for this to be useful, you would need to have 100% change in color with the application of a few volts,” he says. “We’ve got a 25% change in color with the application of a few thousand volts.”

There are also more-novel materials under investigation for use in FPD applications, although these remain very much in the early stages of research and development. Accord-

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