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- Making Rollable Displays
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- In-Cell Polarizers
- TFT-LCD Fabs: Is Bigger Always Better?
- Electrowetting Light Values

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The first piece of Gen 7 motherglass coated with a-Si was shown by production-tool maker Unaxis at FPD International in Yokohama in October 2003. The 2100 × 1800-mm glass can accommodate 18 26-in. wide-format TFT-LCDs. The first Gen 7 factory is being built by Samsung. How large can next-generation fabs get? See Sweta Dash's article beginning on page 32.

Ken Werner

Next Month in
Information Display

The Big Business of Small Displays
- Optimizing Small Displays
- Vivid Colors on Mobile Displays
- Backlights for Small Displays
- Electronic Paper
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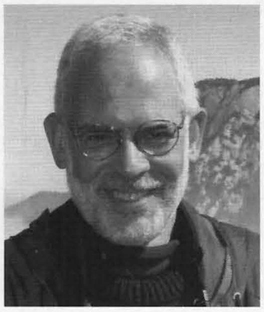
editorial



If You Can't Make It, You Can't Sell It

I have a lot of admiration for manufacturing engineers. That stems from my first real engineering job designing semiconductor devices for the old RCA Solid State Division. (This statement tells you I'm no longer a teen-ager, but so does the photo at the head of this column.)

My time with RCA started off with an extensive training period, most of it at the manufacturing facilities that would fabricate the devices I would design, so I got to know the line engineers pretty well. Our design and development group worked with two factories, one fairly close by and the other quite far away. The engineers at the near-by factory called us design engineers in for support on even fairly routine manufacturing problems. At the time I thought they were lazy, but now I think they were clever.

By involving us in the problems of manufacturing the devices we designed, the factory engineers were implementing an early form of "design for manufacturing." We might have fussed a bit about making the two-hour drive from New Jersey to Pennsylvania, but we certainly thought more about the manufacturability of our designs. For my part, I enjoyed spending part of my time as a sort-of part-time manufacturing engineer. And I learned that there are many ways to manufacture the same device design, and that designing factories to implement processes efficiently and reliably is an art.

In the case of displays, the 26-in. wide display that is manufactured one-up on a Gen 3 substrate may look a lot like the similar display that will be manufactured 18-up on a Gen 7 line, but the factories are very different. Just delivering 1800×2100-mm substrates to a factory is a very different activity from delivering 550×650-mm substrates. And the machines and fixtures for transporting, coating, and patterning those substrates can be very different, indeed.

Manufacturers have sought, and found, ways of significantly reducing the cost of making displays through manufacturing economies. Simply – although "simply" is hardly the word for it – manufacturing on larger substrates is bringing unit costs of TFT-LCDs down substantially. One Gen 7 fab is currently under construction and, as Sweta Dash comments in her article in this issue, LCD-panel makers are beginning to discuss the possibility of building eighth-, ninth- and even tenth-generation facilities.

Equally powerful is implementing design changes to make manufacturing less expensive. Over the last seven years, for instance, designers at LG.Philips LCD have reduced the number of mask steps required to make TFT-LCDs from eight to four, with substantial cost reductions, and they are not alone.

Some manufacturing processes are inherently less expensive than others. Plasma displays, for example, owe their current cost advantage over similarly sized TFT-LCDs to their substantially less expensive backplanes. A new technology that is substantially less expensive to manufacture would be attractive for that reason alone. That is part of the case Heikenfeld and Steckl make for electrowetting technology in this issue.

It may be less revolutionary than developing an entirely new technology, but replacing an expensive step in the manufacture of a current display technology with a less expensive one offers substantial savings. In this issue, Iki, Lazarev,

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guest column

Organic TFTs: The Backplane Technology of the Future?

by Michael Kane

There is a buzz about organic thin-film transistors (OTFTs) that is starting to rival the excitement about organic light-emitting diodes (OLEDs). But it is more difficult for OTFT technology to make its case than it is for OLED technology. OLED displays look better than LCDs, and it is just a question of the willingness of consumers to pay – or manufacturers to absorb – the additional cost for a more appealing display, at least in the early, low-volume stages of OLED technology when the manufacturing costs are high.

In contrast, OTFTs go into display backplanes, and backplanes are a hidden technology not directly visible to the consumer. As a result, OTFT displays do not have the same consumer appeal as OLEDs. What features will push the technology into products?

One answer that is commonly given is that OTFTs will allow us to have flexible displays that can be wrapped around curved objects like soda cans. That is because OTFTs are made using a very-low-temperature process, not much above room temperature, which allows TFT backplanes to be made on inexpensive plastics similar to the material used for overhead transparencies. However, there is something wrong with this argument. Inexpensive, thin, glass LCDs are not currently being used in equivalent applications where the product is flat. For example, we do not see small glass LCDs on CD and DVD packaging. It is unlikely that an electronic revolution in product packaging will take place as soon as curved objects can be accommodated.

Other advantages of flexible displays have been suggested, such as the possibility of rolling up the display. But I am skeptical. A rollable plastic display will not easily lie flat for viewing, and scratches on a plastic display can be prevented only by applying a hard coating that will crack when flexed.

If flexibility is not a feature that can push OTFTs into products, does the technology have a future? It does, but for other reasons. The cost of display fabrication has a number of components that can be significantly less when OTFT backplanes are used. The manufacturing cost depends on process temperatures, because, in general, higher-temperature processing entails higher capital costs, lower throughput because of the time required for temperature ramping, and more expensive substrate materials.

The fact that OTFT backplanes can be fabricated at low temperatures leads to low manufacturing costs, even if they are made on rigid glass substrates. Indeed, OTFT fabrication on glass substrates is a way for the technology to be gracefully and incrementally introduced into standard TFT-display manufacturing lines, with plasma-enhanced chemical-vapor deposition (PECVD) cluster tools replaced by organic-film-deposition equipment. Furthermore, if additive, printing-like processes are used for some or all of the layers, the costs associated with materials and photolithography, two of the most expensive components of TFT-backplane manufacturing, are reduced or eliminated.

Down the road, as OTFT-backplane technology becomes mainstream, the often-predicted roll-to-roll OTFT manufacturing line might become a reality. Low-cost displays from this line will probably be laminated onto a hard, rigid

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Making Rollable Displays

Recent advances in the field of organic electronics are enabling the production of ultra-thin highly flexible active-matrix "system-on-plastic" electrophoretic displays.

by Gerwin Gelinck, Edzer Huitema, Erik van Veenendaal, Fred Touwslager, and Pieter van Lieshout

ONGOING MINIATURIZATION in electronic systems is dramatically reducing the size of computers, mobile telephones, and portable audio equipment. But miniaturization has its drawbacks since, even though the functionality of a mobile telephone can now be squeezed into a watch or a pen, such devices are too small for a decent-sized display. Further reduction in the size of mobile devices is now being hindered by the volume required for the display. Not only does the viewing area take up the major share of a mobile telephone's surface, but the housing that protects the display from shocks adds significantly to the device's thickness.

Displays on plastic offer a solution to both the area and thickness problems. A plastic display is thin and flexible enough to be rolled up in a tube. When the display is needed, it can be unrolled to a size that is considerably larger than the telephone displays we are familiar with today. Besides, plastic displays are robust and do need the additional protection essential for displays on glass.

One dream of these displays is that they will form the core of a pen-like Bluetooth-enabled device that serves as an add-on display for a data carrier. Such a display can also be integrated in the data carrier itself – into the side of a mobile telephone, for example, where the screen could display e-mail, SMS text, office documents, newspapers, and

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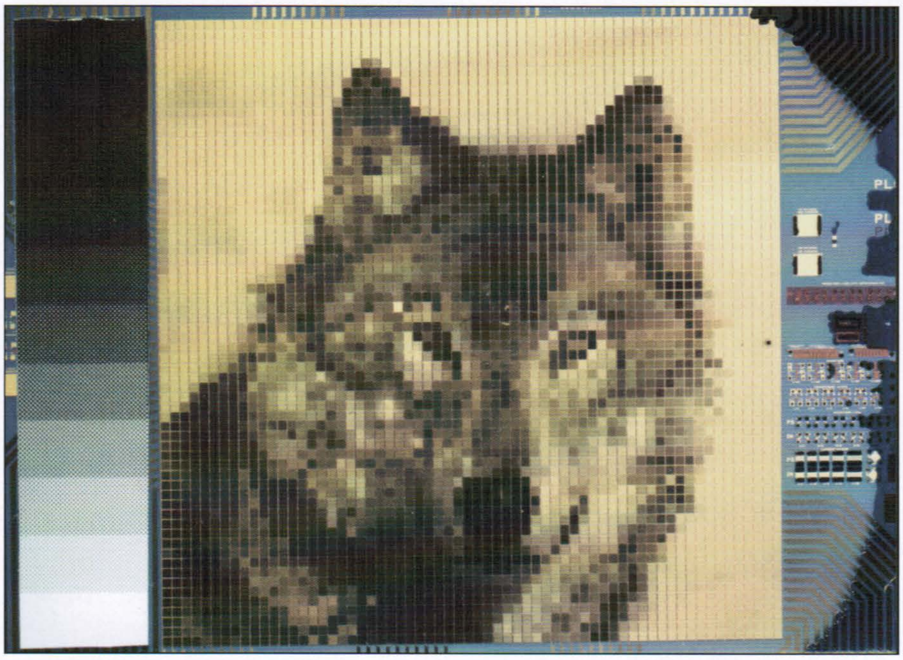

Philips Research Eindhoven

Fig. 1: *This 64 × 64-pixel display on a glass substrate is driven by 4096 polymer TFTs fabricated using a solution-processed semiconductor material. An image containing 256 gray levels is shown; the display was being refreshed at 50 Hz.*

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even books. In an MP3 player, it could show detailed play lists; and when used with a PC, it could even serve as a secondary display that partially replaces print-outs.

Technologies for Highly Flexible Displays

Displays with plastic substrates have been on the market for some time. These are mainly passive-matrix LCDs, however, and since these displays do not use transistors in the pixel drive circuitry, they are easy and inexpensive to manufacture. Their disadvantages include limited size – a few hundred rows – and relatively low image quality because of high crosstalk. In contrast, active-matrix displays are characterized by low crosstalk, which results in much better image quality. And the advanced addressing system of active-matrix displays means they can be much larger.

The active-matrix circuitry itself is usually fabricated in amorphous silicon (a-Si). Although a-Si transistors have been successfully processed directly on plastic substrates, the technology is still unproven [see J. N. Sandoe, *SID Intl. Symp. Digest Tech. Papers*, 293–296 (1998) and S. Polach *et al.*, *Proc. IDW '00*, 203–206 (2000)]. Problems include the difficulty of forming high-quality layers at temperatures sufficiently low to prevent the plastic substrate from degrading and reducing transistor performance.

The flexibility and expansion and shrinkage of plastic films introduce problems with mask alignment in the photolithography process and in the handling of the films. An alternative to fabricating transistors directly on the plastic substrate is embodied in substrate-transfer technologies, in which silicon-based transistors are first manufactured on rigid substrates, then transferred to a plastic substrate [S. Inoue *et al.*, *SID Intl. Symp. Digest Tech Papers*, 984 (2003)]. Although this approach overcomes some of the problems of direct processing, the use of dedicated substrates makes it a relatively expensive process.

A far more effective approach is the use of organic semiconductors [B. Crone *et al.*, *Nature* **403**, 521–532 (2000) and M. G. Kane *et al.*, *IEEE Electron Dev. Lett.* **21**, 534–536 (2000)]. This is the approach adopted by Philips Polymer Vision, an internal venture within the Philips Technology Incubator that has been formed with the aim of bringing the rollable display to market.

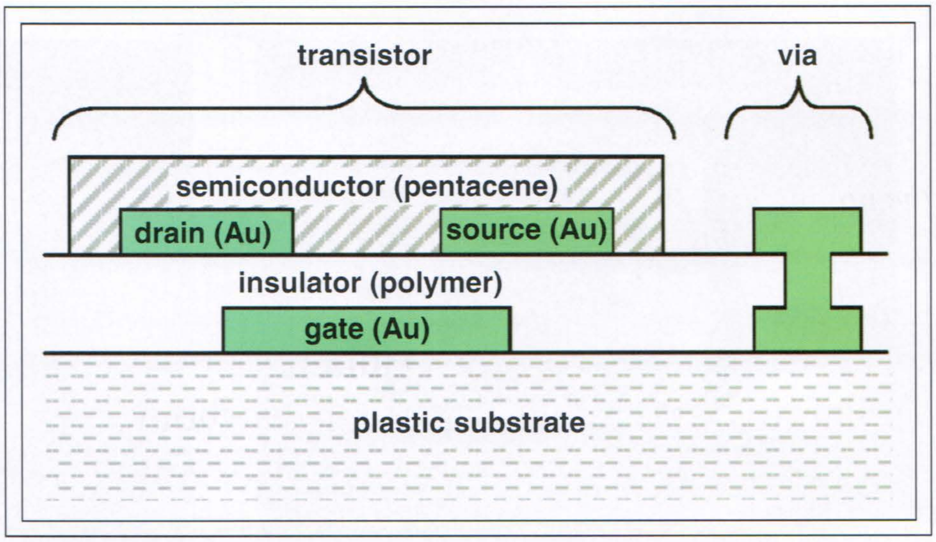


Fig. 2: *Recently, active-matrix displays on ultra-thin foil have been fabricated using solution-processed organic TFTs based on a bottom-gate device architecture. The illustration shows cross sections of such a TFT and of a vertical interconnect (via).*

Organic electronics – the use of organic material as a semiconductor – emerged in the 1990s as a promising thin-film technology for large-area integrated circuits (ICs). In recent years, field-effect mobilities comparable to those of a-Si have been reported using a variety of organic semiconductors.

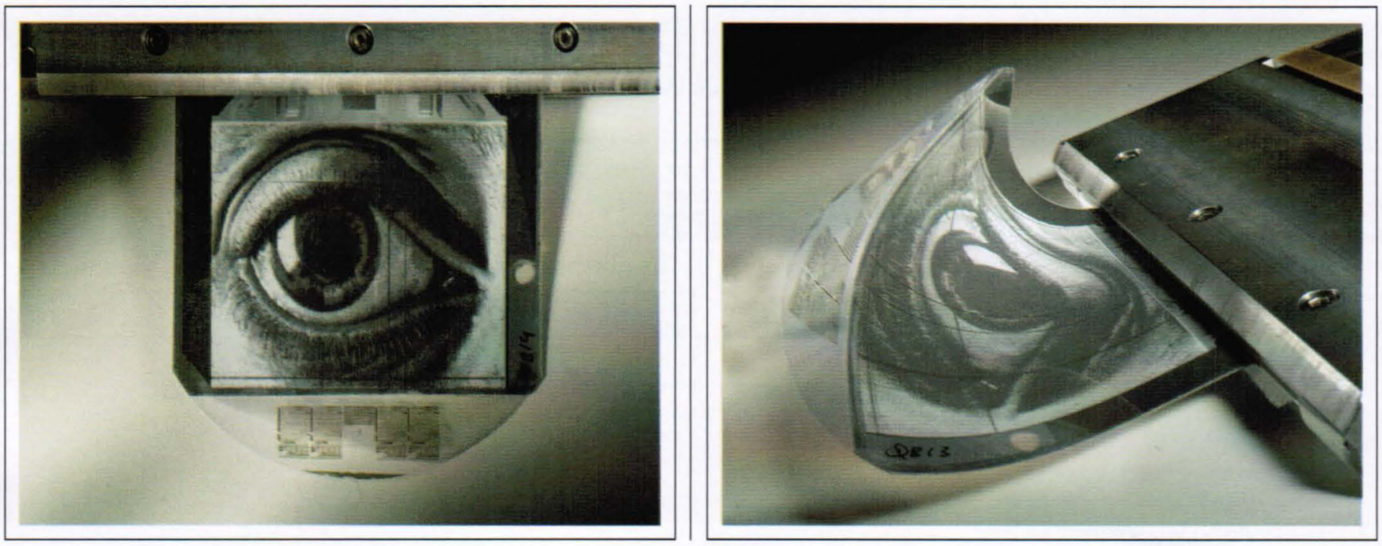
Organic electronics offers several important advantages over conventional techniques that use mainly silicon-based materials [D. Voss, *Nature* **407**, 442–444 (2000)]. Organic materials can be processed from solution, which means that a range of technologies can be used for cost-effective deposition. Examples are simple spin-coating, reel-to-reel coating, and spray deposition for the application of unstructured thin layers. Advanced printing techniques such as ink-jet, micro-contact, or tampon printing are suitable for the direct application of patterned films.

Such deposition technologies make display manufacturing much simpler than it is with the chemical-vapor-deposition (CVD) techniques currently used [T. Tsukada, *Springer Series Mater. Sci.* **37**, 7–93 (2000)], and the processing temperature of the deposition techniques for organic materials is below 170°C. This opens the possibility of using a wide range of plastic substrates instead of glass, which can save weight and make the display thinner and virtually unbreakable [A. R. Brown *et al.*, *Science* **270**, 972–974 (1995)]. Moreover, since the mechanical properties of polymer materials are compatible with plastic substrates, this technology opens the way to plastic displays that are truly rollable. As a result, a range of technologies is being explored to fabricate organic-based TFTs, both as discrete transistors and integrated into active-matrix displays and ICs.

Organic-Based Active-Matrix Displays

The first active-matrix display with an organic semiconductor was reported in 2000 by Philips Research Eindhoven. The display was processed on glass and used a solution-processed semiconductor (Fig. 1). The display contained 4096 pixels and was able to show monochrome images. This was rapidly followed by the first active-matrix displays with organic semiconductors on plastic substrates produced by Philips Research Eindhoven and other research groups such as Lucent Technologies, together with E-Ink Corp. and a joint team from Penn State University and Sarnoff Laboratories.

Recently, Philips Polymer Vision took the next important step towards rollable displays by perfecting the fabrication of solution-processed organic-TFT-based active-matrix displays on ultra-thin foil. These displays use a TFT technology based on a bottom-gate device architecture (Fig. 2). This geometry is comparable to the inverted staggered-electrode structure commonly used in a-Si TFTs. The TFTs are processed on 150-mm-diameter



(a) (b)

Fig. 3: (a) The flexible QVGA active-matrix display with organic TFTs and electrophoretic foil supplied by E-Ink Corp. is displaying an image with four gray levels. (b) The display is flexible.

25-μm-thin polyethylene naphthalate (PEN) films laminated on a removable silicon support.

The organic semiconductor and gate dielectric are processed from solution, and metallic electrodes are used. In this technology, a thin flexible foil is first glued onto a rigid support, then the functional-layer stack is processed, and finally the foil containing the microelectronic devices is delaminated from its support without degrading the devices. The rigid support can be re-used.

This approach permits the use of standard off-the-shelf patterning and deposition equipment. Typically, a registration better than 2.5 μm over a 150-mm wafer for a four-mask process is achieved. The integration of transistors over large areas with a relatively low overlap of 5 μm is possible. This allows transistors to be produced with sufficiently small parasitic stray capacitances for active-matrix displays and row-driver circuits.

After the backplanes are processed, an "electronic ink" film is laminated onto the TFT backplane. This film consists of electrophoretic microcapsules in a polymer binder, coated onto a polyester/indium-tin-oxide (ITO) sheet. Optical contrast is achieved by moving oppositely charged black and white submicron particles in a transparent fluid contained in a microcapsule. Depending on which submicron particles are closest to the viewer, light is scattered back (white state) or absorbed (black state). The electrophoretic effect is bistable, so no electric field is required to maintain the microcapsules in their switched state. This greatly reduces the power consumption of the display.

Using this process, Philips Polymer Vision has fabricated organic-based QVGA (320 × 240-pixel) active-matrix displays with a diagonal of 5 in. and a pixel density of 85 dpi (Fig. 3). The displays combine a 25-μm-thick active-matrix backplane containing the polymer-electronics-based pixel drivers with a 200-μm frontplane of E-Ink's reflective "electronic ink." The resulting displays are the thinnest and most flexible active-matrix displays reported to date. With close to 80,000 TFTs, they are the largest organic-electronics-based displays yet fabricated and have the smallest pixel pitch reported to date. The displays can be bent to a radius less than 2 cm more than 100 times without image degradation. After 2 months at ambient conditions, the contrast degradation was only 10%, while the field-effect mobility was reduced by only 30%. These numbers represent significant advances over previous results. No image degradation has been measured after 100 hours operation at a 10% duty cycle.

Careful process optimization and attention to material purity, including the use of an ion-removal system, have resulted in major improvements in operational lifetime and product uniformity. New glue compositions have been developed that combine strong adhesion to maintain alignment of the flexible layers to within a few microns during processing with easy delamination to allow the display to be removed from the silicon support substrate without any degradation of the display and electronics. This has resulted in exceptional uniformity and high yield.

Driver Integration

A further challenge lies in reducing the module cost of displays. To achieve this goal, the footprint of the display should be reduced and the number of silicon-based driver ICs required for the module minimized. An efficient way to achieve this is by monolithic integration of the driving electronics using organic transistors integrated on the backplane.

Using the same technology as that employed in the active-matrix backplane, Philips Polymer Vision has fabricated 120-stage shift registers that can operate as row drivers. The largest functional circuits based on organic electronics produced to date, these shift registers function at a clock frequency of

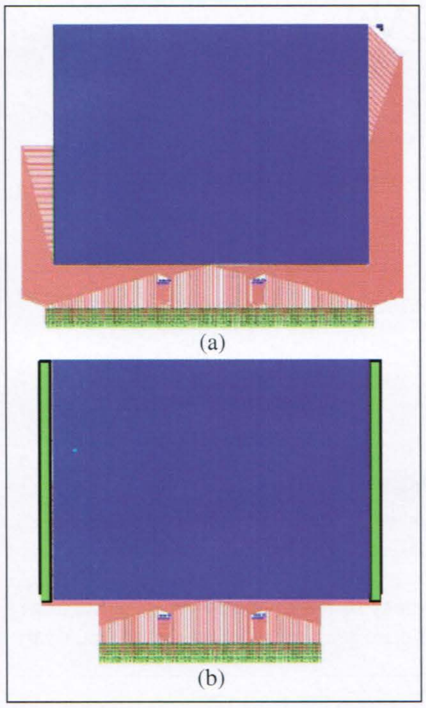


Fig. 4: The footprint of the flexible display without integrated drivers (a) is significantly greater than one with integrated drivers (b).

up to 2 kHz. This corresponds to a maximum refresh rate of 8 Hz for the QVGA display, which experience indicates is more than acceptable for e-reading applications.

The shift registers need only clock signals, data lines, and supply lines – a total of 10 lines – to perform line-at-a-time selection of all rows. The use of integrated drivers reduces the number of contacts by at least 200, resulting in higher contact reliability and ruggedness. It also substantially reduces the footprint of the display (Fig. 4).

Tests have shown promising operational lifetime under the exacting conditions needed for continuous display updating. Because the displays and shift registers are fabricated by the same technology, the results of the shelf-life tests and bending tests of the displays should also be valid for the shift registers.

Industrializing Technology Innovations

Solution processing opens a host of alternative patterning technologies, such as thermal printing, stamping, selective de-wetting, and ink-jet printing. The ultimate goal in all these technologies is the development of a low-cost roll-to-roll process. At present, though, Philips has chosen to use standard photolithographic techniques for patterning the layers. This allows fabrication on the standard semiconductor-manufacturing equipment used in the AMLCD industry, permitting faster development time without the need to create new fabrication tools and techniques. We believe this will ultimately provide lower costs thanks to faster ramp-up to volume production.

Whatever deposition/patterning technology is used, challenges that need to be addressed include process reliability and, more fundamentally, the limited shelf life of the organic semiconductor – currently a matter of months.

Our goal is not only to prove the feasibility of such displays but also to move rapidly towards the development of a consumer product and an industrially feasible production process. Philips Polymer Vision recently set up a semi-automated pilot line to produce samples for process optimization and product development. Products incorporating ultra-thin highly flexible displays could be available to consumers as early as 2008, and for niche applications even earlier. To further speed up industrialization and product development, Philips Polymer Vision is currently seeking cooperation with technology partners and major customers in the mobile-telephone and PDA markets, among others. ■

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The Resurgence of LCOS Displays

Technology advances and ten years of hard-won manufacturing expertise are driving the resurgence of liquid-crystal–on–silicon (LCOS) displays.

by Henning C. Stauss

AFTER MORE THAN A DECADE OF R&D and limited commercialization, liquid-crystal–on–silicon (LCOS) technology is fast becoming a compelling display-technology option for applications that require excellent image quality and price/performance standards. These applications range from large-screen rear-projection high-definition televisions (HDTVs) and front-projection home-theater systems to a multitude of head-mounted-display devices for gaming, commercial, and government applications. The ascendance of LCOS technology is a consequence of innovations, burgeoning market opportunities, and significant advances in the manufacturability of panels.

At Brillian Corp., for example, the Gen II LCoS™ technology unveiled in 2003 features contrast levels of over 2000:1. A fill factor of 92% or higher eliminates pixelation, or the "screen door" effect, and the technology delivers a vivid dark state and excellent dynamic range. Microdisplays based on this technology are currently being used by Brillian and its original-equipment-manufacturer (OEM) customers to produce large-screen rear-projection HDTVs, front projectors, commercial digital photo printers, and near-to-eye (NTE) devices.

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The Rise of LCOS Technology

LCOS technology has long been considered to be promising, but until just a few years ago, it was long on promise and short on delivery. That is because the decade-old technology lacked a supporting industry infrastructure and, unlike Texas Instruments' Digital Light Processing™ (DLP™) technology, LCOS technology suffered from a dispersed investment climate comprising many players and rival

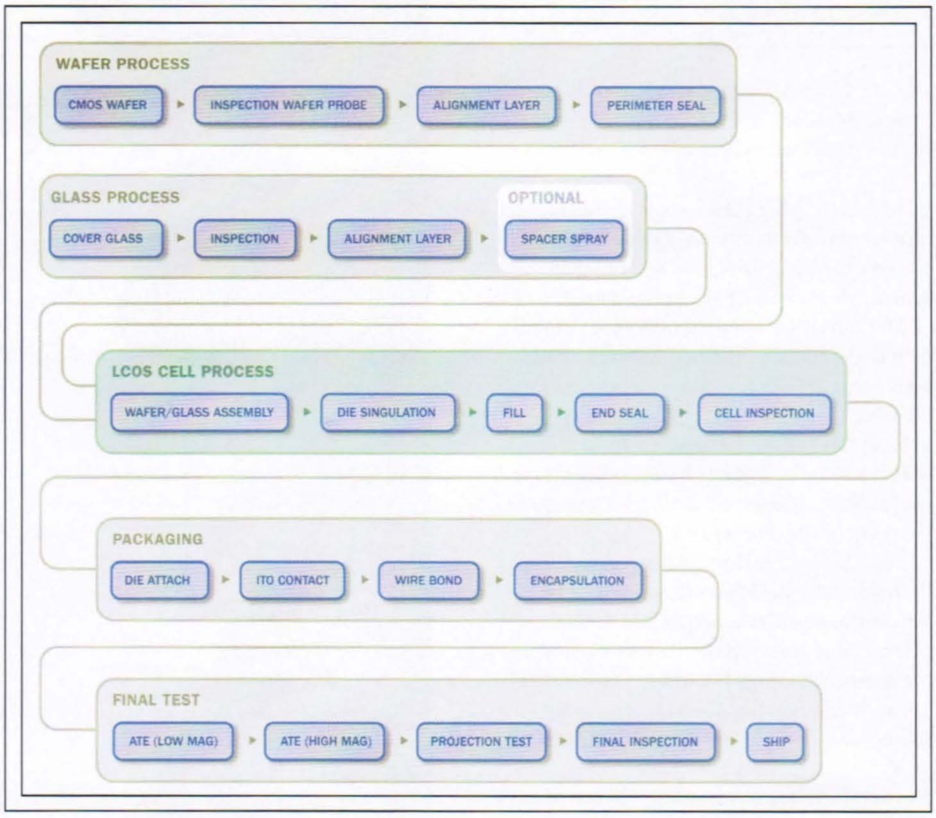

Fig. 1: *Achieving high yields in the manufacture of LCOS microdisplays requires a process flow that features wafer-scale manufacturing techniques; automated, production-proven equipment; and expertise in moving products smoothly through a rigorous multistage manufacturing, packaging, and testing process.*

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approaches. In the 1990s, LCOS manufacturers pursued different approaches to virtually every facet of panel design and production: digital versus analog backplanes, varying techniques for managing the cell gap, different types of liquid-crystal material, and different alignment-layer approaches. As a result, there were no common industry standards for materials, and no common light-engine designs, optical elements, or screens.

In addition, many of the early LCOS players, who had extensive semiconductor expertise, were not as well versed in overcoming the unique manufacturing challenges of combining liquid-crystal-cell technology with a silicon backplane and achieving consistent yields. For these reasons, among others, many of the LCOS panels that appeared in the mid-to-late 1990s never moved beyond the prototype phase.

In the past several years, much of this has changed. An infrastructure of key support components is now in place and accessible to LCOS companies. While the light engine must be customized for each vendor's LCOS device, x-cubes, polarizing beam splitters, Moxtek polarizers, arc lamps, lenses, and screens can be leveraged for all LCOS applications. In addition, the development of production-proven manufacturing and test equipment for LCOS has matured, enabling more consistent and reliable production yields. Finally, new technologies designed specifically for LCOS have evolved to further boost product performance. A good example is the Moxtek polarizer (winner of the SID/*Information Display* 2001 Display Material or Component of the Year Silver Award), designed specifically to enhance performance in reflective high-light-flux applications such as LCOS-based HDTVs.

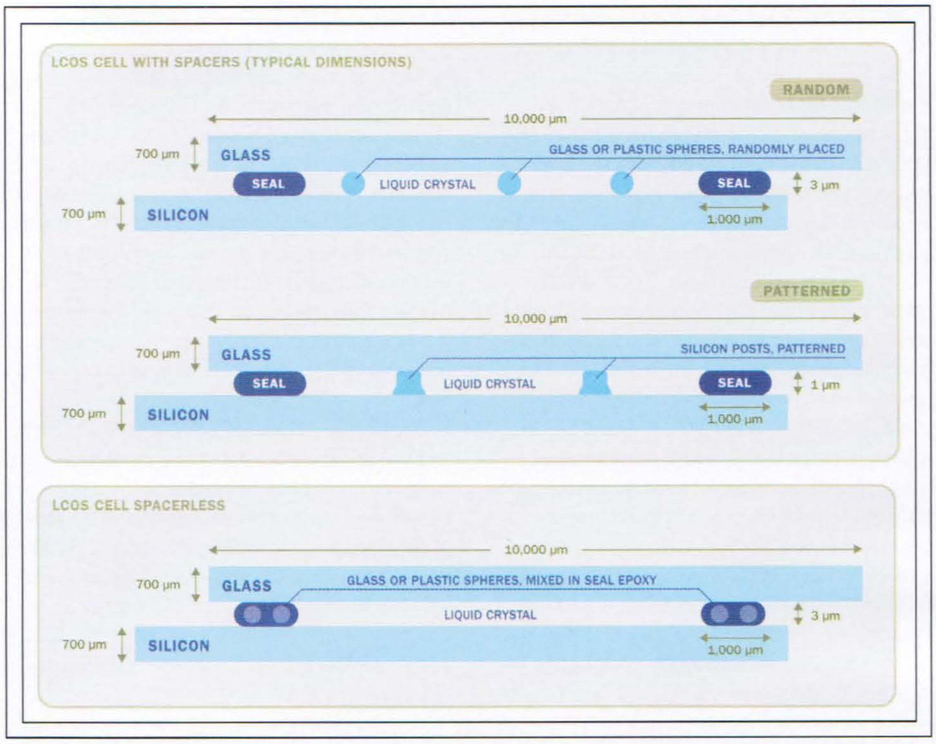


Fig. 2: *Spacers, either randomly placed glass spheres (top) or patterned silicon posts (middle), are used to control the cell gap. But in three-panel LCOS architectures, spacers create unacceptable artifacts, so "spacerless" cell-gap techniques (bottom) have been developed that place spacers only in the non-active part of the cell, typically in the seal.*

More than a Decade of Learning

LCOS manufacturers have made significant inroads in overcoming problems in volume production, such as cell-gap control, high-volume packaging design, and alignment-layer issues in reflective technologies with high light flux.

Wafer-scale manufacturing. Early on, virtually all LCOS displays were built on a single chip. This single-cell manufacturing approach created prototypes that generated a great deal of attention in the industry but no production-worthy mass-market products. Today, LCOS manufacturers rely primarily on wafer-scale manufacturing techniques for cost efficiency. Typically, they will pair a complete 8-in. complementary-metal-oxide-semiconductor (CMOS) silicon wafer having a highly reflective and smooth mirror surface with an 8-in. round of specially treated cover glass. All critical manufacturing steps are completed at the wafer level – including the application of the alignment layer, spacer technology, and perimeter seal – before singulation into individual chips. LCOS manufacturers are able to leverage solid, robust, and production-proven wafer handling, cleaning, and processing equipment for LCD processes. As a result, the industry has been able to successfully move toward cost-effective mass production of reliable LCOS panels (Fig. 1).

Spacerless technology. An extremely important advance has also been realized in cell-gap control for high-contrast projection applications. Spacers (3–4-µm glass spheres) were conventionally used to precisely control the space between the silicon backplane and glass plate (Fig. 2, top).

For extremely thin cell gaps, below 1.5 µm, a different spacer process relying on posts was developed and incorporated during the manufacture of the silicon wafers (Fig. 2, middle). These minuscule posts are spaced at either every pixel or every x number of pixels to tightly control the cell gap. The post-based-spacer process for thin-cell-gap control is successfully used today in single-panel applications. In three-panel light-engine architectures, however, spacers of any kind have proved themselves unacceptable in LCOS cells because the cell gap is larger and the spacers become visible. So, successful spacerless cell-gap-control methods have been developed (Fig. 2, bottom). In three-panel LCOS architectures, spacers are placed only in the non-active part of the cell, typically in the seal, and a novel seal process ensures that the required gap precision is maintained in the cell.

Spacerless LCOS displays offer outstanding dark-state performance and clean unobstructed images without the pixelation effect found in high-temperature-polysilicon-based displays.

Alignment-layer innovations. Developed over decades for conventional liquid-crystal applications, polyimides were also used for the alignment layer in most microdisplay applications as a cost-effective and controllable part of the production process. In projection-type LCOS designs, however, organic alignment layers have proven unsuitable. The high-intensity light to which these LCOS displays are exposed, particularly the short-wavelength blue light, degrades organic alignment layers over time. The impact on three-panel architectures is severe because the panel devoted to blue light degrades faster than those devoted to red or green, which produces a change in the end product's color balance. Single-panel architectures face the same problem, but require organic alignment layers because of the liquid-crystal modes used.

Significant technical innovation has been required to develop an inorganic-alignment-layer process suitable for production environments because of the complex techniques required to apply the layer and the lack of proven processes and production equipment. In fact, inorganic alignment layers have never been leveraged widely for classic liquid-crystal applications because of the technical difficulty (and cost) of applying them to large surfaces. Since microdisplays are developed on relatively small 8-in.-diagonal wafers, the cost per area of an inorganic alignment layer is not prohibitive. Brillian has developed a process for applying an inorganic alignment layer, which is in the company's high-end three-panel Gen II LCoS™ projection applications.

Packaging advances. Because of the early technology and manufacturing challenges associated with LCOS production, most LCOS developers invested greater resources in the design of the LCOS cell than in packaging. As the industry matures, however, packaging is becoming a critical element in a successful, volume-production product. Package design greatly affects LCOS-display performance. Packages must be very flat, the heat characteristics must be known, and cost must be factored into the overall equation. Great advances have occurred on this front, thanks in large part to semiconductor-packaging technologies.

Brillian Corp.

Fig. 3: *Among the modern manufacturing facilities required for LCOS manufacturing are Class-100-or-better cleanrooms, such as this one in the Brillian Corp. Tempe, Arizona, facility.*

Key Steps and Critical Choices

Each LCOS developer faces a number of unique challenges and choices. Arguably, the most fundamental decision involves how much of the manufacturing process is controlled in-house. Brillian Corp., for example, made a strategic decision to keep a large percentage of its manufacturing internal at the company's Tempe, Arizona, manufacturing site. In particular, the company wanted hands-on control of processes that involve proprietary techniques related to the application of the alignment layer and the liquid-crystal-cell process. By using modern equipment and a highly automated production line, Brillian believes it is able to cost-effectively control its key production processes (Figs. 3 and 4).

This approach contrasts with fabless semiconductor business models in which contractors are used to perform certain parts of the manufacturing process. The fabless model may offer advantages in lower capital requirements; however, it increases the risk of dissemination of intellectual property and process know-how, and gives the micro-display contract manufacturer a more controlling position.

Manufacturing-Process Flow

The following is a manufacturing-process flow for Brillian's Gen II LCoS™ micro-display imagers. Although each LCOS vendor's manufacturing process – and strategy – will differ at certain points, the key steps are consistent across the industry.

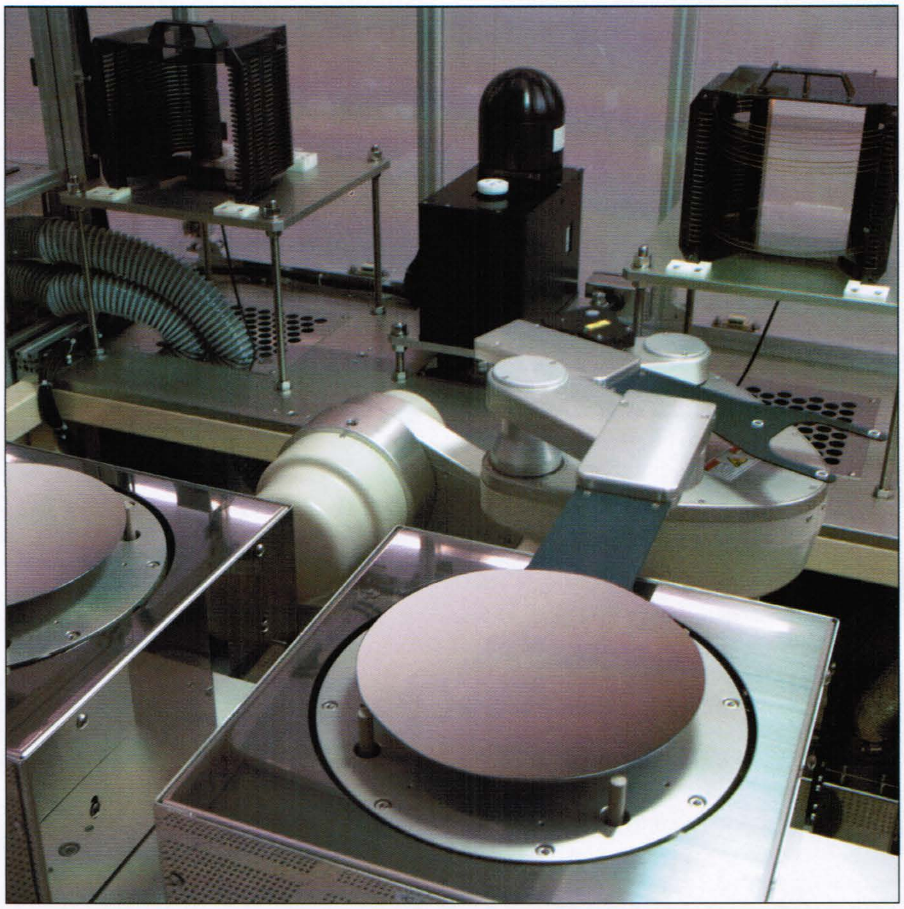
1. Receipt of CMOS Wafers. CMOS silicon wafers with a highly reflective mirrored surface are received at the manufacturing facility. In LCOS displays, the wafers must provide an extremely flat, smooth, scratch-free, and residue-free surface. The foundry must ensure precise gap fill between every mirror and a surface finish that will yield highly reflective panels after the LCD processes are completed. The wafers are optically inspected and can be electrically probed, if desired, before they are entered onto the line.

2. Receipt of Cover Glass. Virtually all LCOS manufacturers rely on 1.1–0.7-mm Corning 1737F glass counter substrates. Corning 1737F glass has a thermal-expansion coefficient similar to that of silicon, which reduces stress after the glass is mated with the silicon wafer. The glass is polished and made free of waviness, warp, scratches, or voids. It is then coated with indium tin oxide (ITO) with a refractive-index match on the inside and a broadband anti-reflective coating on the outside. The glass has the same dimensions as the silicon, which permits the use of special wafer-handling equipment that automates the manufacturing process for both substrates and achieves greater cost efficiencies across the production line. The equipment has been slightly modified to process the glass, which has delicate active layers on both surfaces.

3. Cleaning. De-ionized water is used to clean the silicon and glass wafers *via* rinser-dryers and/or spray-cleaning equipment. The surface of the substrate is activated by UV ozone or plasma ashing to prepare it for the application of the alignment layer.

4. Application of the Alignment Layer. After cleaning, a spin-coating process is used to apply the polyimide (organic) alignment layer to the silicon and glass; the polyimide is then cured and rubbed with classical LCD tools. The inorganic alignment layer is manufactured by a proprietary evaporation or sputtering process on silicon and glass by using SiO_x, SiO_2, diamond-like carbon, or other oxides. Additional treatment of the surface, such as by alcohol vapor, may be required to stabilize the layer for subsequent processing.

5. Perimeter Seal. The perimeter seal determines the outside of the cell and defines the cell gap in the spacerless process. The general method for creating the perimeter seal is to dispense either thermally curable or UV-curable epoxy material on the silicon or glass substrates. Screen- and offset-printing methods are also being leveraged in the industry to apply the perimeter seal because these are seen as economical wafer-scale application processes. After the perimeter seal is applied, the glass is precisely aligned to the wafer, the substrates are pressed together with a mechanical or vacuum-bag process, and the epoxy is cured via heat or UV light. In the spacerless process, this is the most critical step for obtaining a uniform cell gap. The cell gap is measured on the wafer/glass assembly and closely monitored.



Brillian Corp.

Fig. 4: *In a modern LCOS plant, robotic handling ensures product cleanliness and low-cost manufacturing.*

6. Die Singulation. At this stage, the silicon and glass assembly is separated into single chips using a scriber, a dicing saw, or a laser, depending on the company's heritage (LCD or wafer fab). Because of the crystalline structure of the silicon, scribing the wafer with a wheel is difficult and therefore not the preferred method. At Brillian Corp., a dedicated dicing saw for silicon and another one for glass are used to scribe the substrates and then break the cells out of the wafer/glass assembly.

7. Fill Process. A classic LCD fill process is employed to fill each microdisplay with liquid crystal. The microdisplays are placed in a holder within a vacuum system, fill hole down. A vacuum is created, the cell is filled by lowering it to the liquid-crystal level, and the vacuum system is then vented to drive the liquid crystal into the cell. Complete immersion is generally avoided because of contamination issues.

8. End Seal. Fast-curing UV epoxy, which is compatible with the liquid crystal, is applied to the fill port. This step is critical for setting the cell gap. At Brillian, all cells of a wafer are filled and end-sealed at the same time to maintain wafer integrity and provide a matching throughput to the wafer-scale manufacturing process. A thorough wet clean, usually combined with a step to remove the alignment layer (organic or inorganic) from the glass ledge, is used to wash off liquid-crystal residue.

The alignment of liquid crystals can be altered (and severely impacted) by the choice of materials used for the perimeter and end seals. That is why the choice of materials and application techniques are closely held secrets among manufacturers.

9. Packaging. Packaging processes including die attach, wire bonding of the silicon to the package, ITO contact, encapsulation, and application of an aperture complete the manufacturing process. The packaging process generally uses readily available semiconductor equipment and is easily transferable to a typical contract manufacturing operation, if required. Brillian uses a standard package from Silicon Bandwidth (SBI) which can be connected *via* a semicustom flex to the drive electronics, a tester, a customer's projector, or Brillian's own HDTV.

10. Final Test. The bar for testing continues to move upwards for LCOS manufacturers. Higher contrast and brightness and better optical systems for larger magnification in the customer's projector require more-stringent tests and more-precise test equipment.

At Brillian, projection testing and automated test equipment (ATE) are used to assess parametric values and cosmetic defects. In low-magnification mode, ATE is used to measure the contrast, brightness, and uniformity of the bright and dark states and for several gray shades.

In high-magnification mode, ATE is used to scan the display for dot defects and bright, dark, and gray states, and provides a detailed map of defects for every single imager. The threshold for a pass/fail decision at test is correlated to the final application and depends on the color channel for which the imager will be used, the application (front projection is more tolerant than rear projection), and the product type. (NTE and electronic printer applications have requirements different from those of projectors.)

The ATE data is uploaded to a server so a complete data set can be provided to the customer along with the finished imager. All finished imagers are characterized and documented. At Brillian, no imager leaves the factory without passing a projection test in which an operator in a darkroom assesses image quality in rear-projection mode before the imager is labeled and shipped.

A Promising Future

As many industry watchers have stated, the next several years are the make-or-break opportunity for LCOS displays. This promising display technology has come far in the past decade, overcoming many obstacles and increasingly appearing as the foundation for some of today's most exciting new applications. Enhanced design techniques, advanced and predictable manufacturing processes, new automated test procedures, and improved production yields point to a future in which LCOS displays will play a significant role in delivering outstanding image quality at a competitive cost.

Notes

"LCoS" is a registered trademark of Brillian Corp.

"LCOS" is used as the general acronym for liquid-crystal on silicon. – *Editor* ■

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In-Cell Polarizers

Despite the success of conventional sheet polarizers in LCDs, they are costly, labor intensive, and one of the LCD components that most frequently require repair. For some applications, there is a durable, lower-cost alternative.

by Tei Iki, Pavel Lazarev, and Michael Paukshto

THE EXPLODING liquid-crystal-display (LCD) market will reach about $40 billion in 2004, and continuous growth of 21% is expected over the next 5 years. Part of this demand comes from the consumer-television market, which is fueled by the increasing affordability of LCD panels.

Significant cost reductions have been made in LCD manufacturing in recent years through massive capital investment in highly efficient ultra-large panel lines, along with process and yield improvements. But the use of the conventional sheet polarizer remains a costly and labor-intensive component of the LCD-manufacturing process. Until fairly recently, there was no practical alternative to sheet polarizers for direct-view LCDs, but a new aqueous material invented by Optiva, Inc., which can be applied to the LCD substrate, is a potential replacement for the sheet polarizer. Although further research and improvement are required, it is now possible to create an "in-cell" polarizer that is coated onto the interior surfaces of the LCD's front and back plates. This development promises a fully automated, cost-effective LCD-manufacturing process.

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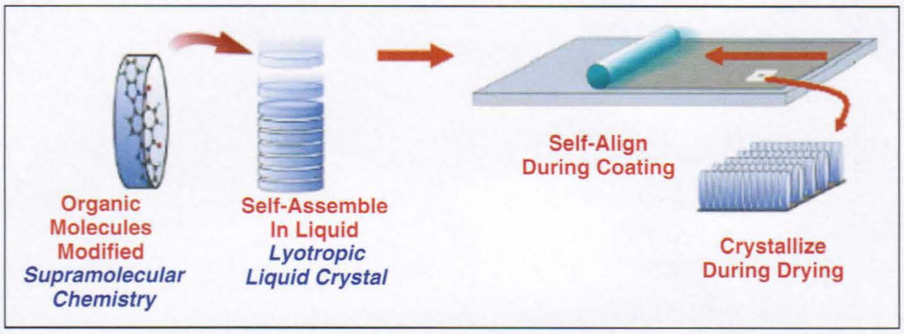

Fig. 1: *The Cascade Crystallization process forming thin crystalline films consists of a chemical-modification step and four steps of ordering that form the crystal film.*

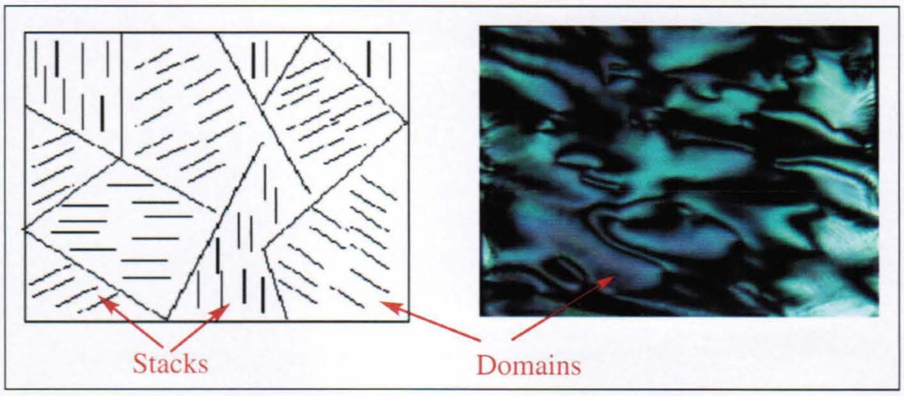

Fig. 2: *In the second stage of the ordering process, supramolecules are converted into a lyotropic liquid-crystalline state. This nematic phase is shown in a schematic drawing (left) and in a 100× microscopic image between crossed polarizers (right).*

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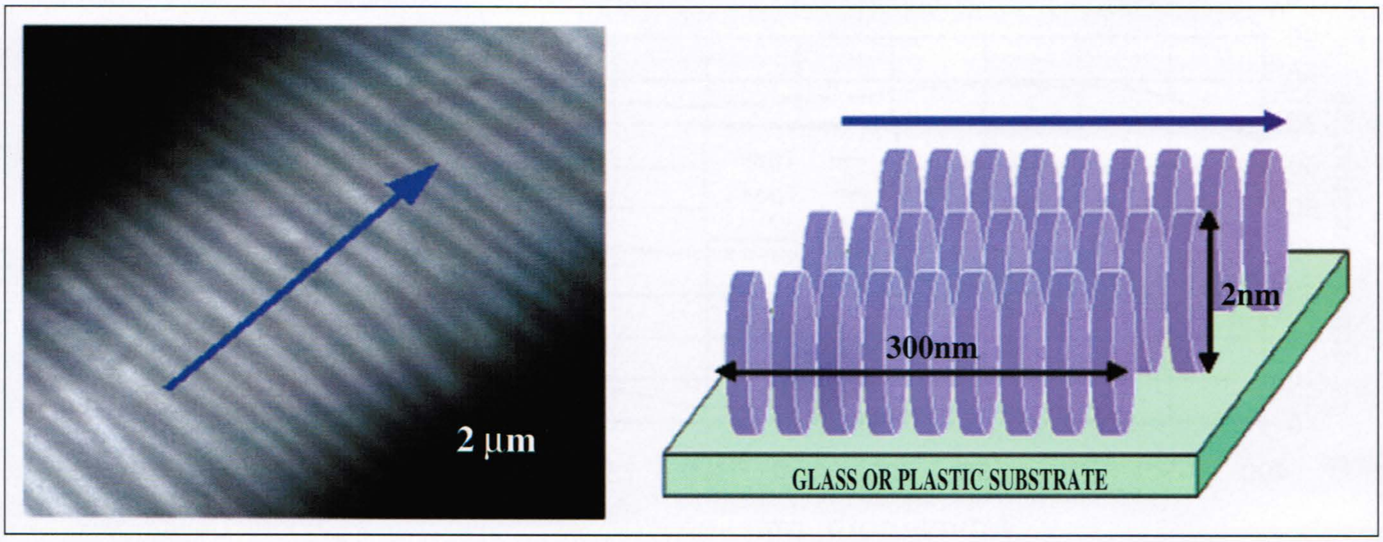

Fig. 3: The lyotropic liquid crystal is deposited under the action of a shear force onto a substrate so that the shear-force direction determines the crystal-axis direction in the resulting solid-crystal film. The TCF™ monolayer is shown in a schematic drawing (right) and in a scanning transmission x-ray photomicrograph (left). The blue arrow indicates the coating direction.

Cascade Crystallization

The family of coatable, self-assembling materials invented by Optiva, Inc., is based on aqueous solutions of polycyclic organic compounds. At Optiva, we call the method for manufacturing Thin Crystal Film™ (TCF™) Cascade Crystallization ("Method and Materials for Thermostable and Lightfast Dichroic Light Polarizers," U.S. Patent 5739296, 1998; "Dichroic Light Polarizers," U.S. Patent 6049428, 2000).

The Cascade Crystallization process consists of a chemical-modification step and four steps of ordering that form the crystal film (Fig. 1). The chemical-modification step introduces hydrophilic groups on the periphery of the polycyclic molecule to impart amphiphilic properties to the molecule. Amphiphilic molecules stack together into supramolecules, which is the first step of ordering.

In a specific concentration, supramolecules can be converted into a liquid-crystalline state to form a lyotropic liquid crystal, which is the second step of ordering (Fig. 2). The lyotropic liquid crystal is deposited under the action of a shear force (or meniscus force) onto a substrate, so that the shear-force (or the meniscus) direction determines the crystal-axis direction in the resulting solid-crystal film. This shear-force-assisted directional deposition is the third step of ordering, representing the global ordering of the crystalline or polycrystalline structure on the substrate surface (Fig. 3).

The fourth and last step of the Cascade Crystallization process is drying/crystallization, which converts the lyotropic liquid crystal into a solid-crystal film.

The optical properties of TCF™ depend on the particular polycyclic self-assembling planar molecule being used. For example, there is good correlation between the absorption spectrum of the precursor dye solution and that of the TCF™ for light transmitted in a polarization direction perpendicular to the coating direction.

The Optiva N015 broadband polarizer consists of three basic components (Fig. 4) and has a promising transmission spectrum (Fig. 5). The transmission axis of the polarizer is parallel to the coating direction, and absorption in the direction orthogonal to the coating direction has its origin in the absorption characteristics of the original components.

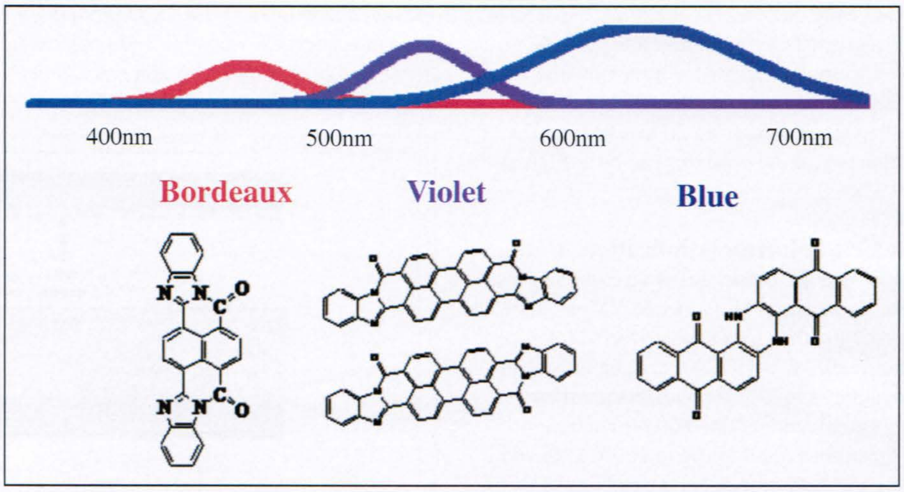

Fig. 4: Optiva's broadband N015 polarizer is based on a mixture of three precursors, which are shown along with their absorption spectra.

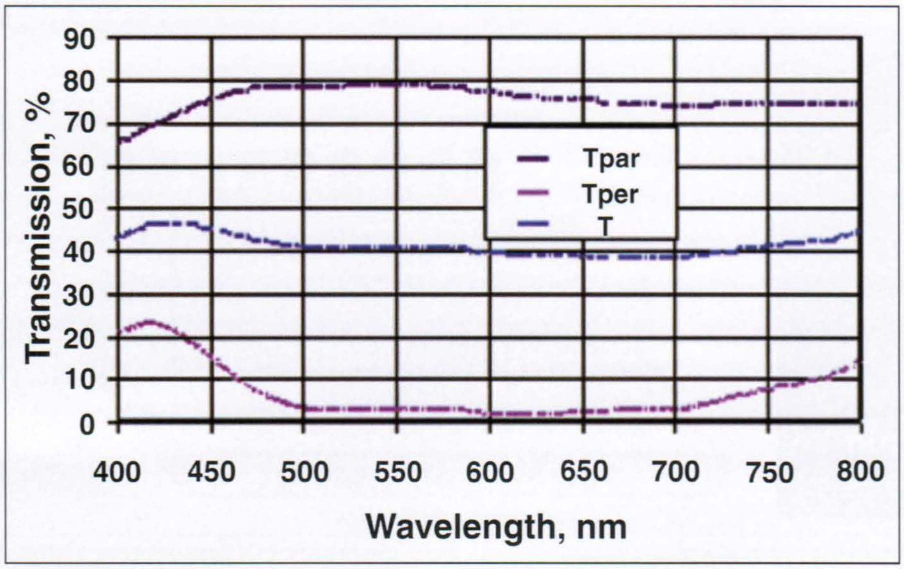

Fig. 5: The transmission spectrum of the N015 polarizer in polarized light is basically attractive, but does have some light leakage at short (blue) wavelengths. T is the transmittance of unpolarized light, T_{par} is the transmittance of polarized light along the coating direction, and T_{per} is the transmittance of polarized light perpendicular to the coating direction.

Another example of a TCF™ polarizer is a colorless version based on polycyclic compounds having no absorption in the visible spectrum. Such a coating can be used to produce a negative A-plate – a type of compensation film for enhancing the LCD viewing-angle performance. Several TCF™ materials demonstrate very high birefringence (optical anisotropy) between 0.3 and 0.8. The coating technology allows manufacturers to easily change the thickness of the TCF™. Therefore, for a given TCF™ material, it is possible to produce polarizers with a transmittance *T* anywhere in the range of 30–60% or a retarder with a retardation from 20 to 300 nm. The efficiency of the polarizer can be as high as 99.9%.

In-Cell-Polarizer Application

TCF™ has the properties of an E-mode polarizer [P. Yeh and M. Paukshto, "Molecular crystalline thin-film E-polarizer," *Molecular Materials* **14**, 1–19 (2001)]. The important advantages of TCF™ polarizers are their extreme thinness (200–800 nm) and high temperature stability (up to 250°C). In addition, the fully automated water-based TCF™-coating process provides an environmentally harmless solution [Y. Bobrov *et al.*, "Environmental and Optical Testing of Thin Crystal Film™ Polarizers," *JSID* **11**, No. 1, 63–70 (2003)].

TCF™ can be coated on a wide variety of glass and plastic substrates. The thinness of TCFs and their ability to be coated directly on glass make them useful for in-cell application. Several types of passive-matrix twisted-nematic (TN) and supertwisted-nematic (STN) LCDs with a TCF™ coating inside the LC cell have been made at Tecdis, Philips, Picvue, and Wintek. STN-LCD production lines utilizing TCF™-coating equipment were developed by Nakan Corp. Recently, Sony made the first transflective TFT-LCD employing one internal TCF™ polarizer and two external conventional sheet polarizers (Fig. 6), which was demonstrated at SID 2004 [T. Ohyama *et al.*, "TN-Mode TFT-LCD with In-Cell Polarizer," *SID Intl. Symp. Digest Tech. Papers*, 1106–1109 (2004)]. In another possible configuration, the TCF™ polarizer is positioned under the ITO electrode layer (Fig. 7).

The advantages of in-cell-polarizer design are a high contrast ratio, a simple cell structure, and good color reproduction in the reflective mode. Although it was not a problem in some applications, the initial TCF N015 polarizer was subject to light leakage at short wavelengths (blue region), which gave color images a yellow cast. This can now be corrected by the addition of a TCFY105 film. In the new TCF N025 polarizer, there is no blue-light leakage and the crossed state is now quite achromatic. The performance of today's TCF™ material is suitable for transflective TFT-LCD designs with one internal polarizer. Transmissive and transflective designs with two internal polarizers are even more attractive. For both transmissive and reflective displays, the thickness of TCF™ polarizers is typically in the range of 300–700 nm, depending on the optical requirements of the display. These thicknesses are in the range of the wavelengths of visible light. Because TCF™ material is highly birefringent – $n_{\parallel}$ is approximately 1.5 along the transmitting axis and $n_{\perp}$ is approximately 1.85 along the absorbing axis – the design must take into account possible thin-film-interference effects at interfaces between materials of differing indices.

Designers can take advantage of these optical characteristics to enhance transmission, reflection, or contrast. For example, increas-

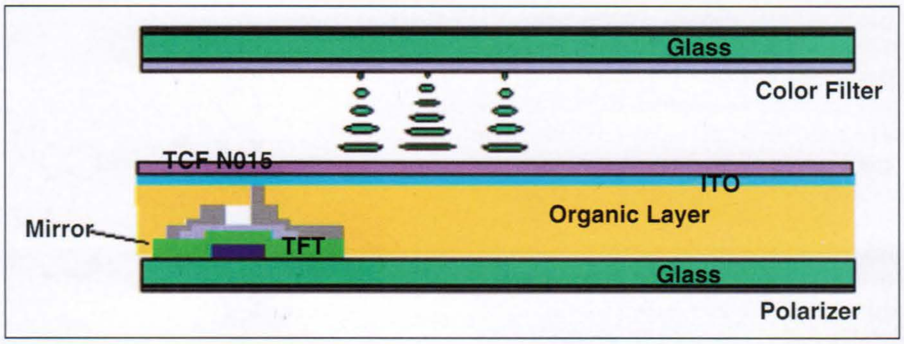

Fig. 6: Sony demonstrated this transflective TFT-LCD employing one internal TCF™ polarizer and two external conventional sheet polarizers at SID 2004.

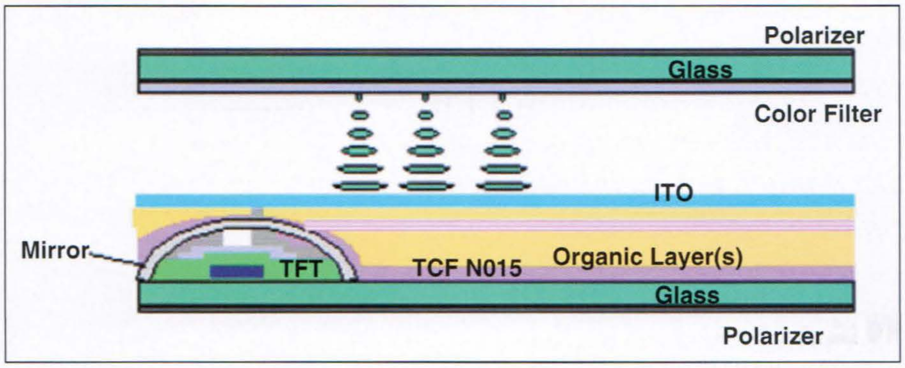

Fig. 7: *A transflective TFT-LCD can also employ an internal TCF™ polarizer positioned under the ITO electrode layer.*

ing the thickness of these TCF™ polarizers tends to decrease the transmittance of unpolarized light through two parallel polarizers and increase contrast. But thin-film interference can modify this tendency.

When using TCF™ polarizers, it is important that all the light management of the LCD be within the gap between the front and back glass – or plastic. In plastic displays, low-cost plastics, which are typically birefringent, can be used to form the cell instead of a higher-cost isotropic plastic. But full-scale use of internal polarizers in TFT-LCDs will be possible only after there is substantial improvement of the stack orientation in TCF™ material, which will enhance contrast ratio.

The contrast-ratio enhancement will come from improvements in the lyotropic liquid-crystal formulation, in coating technology, and in the drying process, which are interrelated factors in TCF™ formation.

Where Are We Now?

The development of Thin Crystal Film™ has presented new opportunities to LCD designers. Optical-film components can now be coated directly on glass and placed inside the glass envelope of an LCD cell. It promises advantages in optical performance (parallax is minimal), in manufacturing cost (optical-film components are produced by printing *in situ*), in form factor (optical functions are implemented in very thin films), and in materials costs (new materials promising lower cost for the same function).

We are currently developing LCD designs enabled by these new components, along with design tools that can simulate the performance of new devices. ■

Liquid Light

Amidst the LCD's increasing dominance, the new technology of electrowetting is attempting to make a place for itself based on superior light utilization and manufacturing simplicity.

by Jason C. Heikenfeld and Andrew J. Steckl

WHY DEVELOP a new flat-panel-display (FPD) technology? Why try to change a technological landscape already deeply embedded with liquid-crystal displays (LCDs)? These are weighty questions as the LCD strengthens its reputation for dominance by fending off the best advances of many alternative display technologies. However, it is important to note that the present dominance of any display technology is not due to perfected performance or true simplicity in manufacturing. Rather, the currently leading display technologies are simply the "best available" options.

One need only consider that most reflective displays reflect only about one-third of incident light or that backlit LCDs have a power efficiency of only about 1%. Is there room for new technologies? Certainly. And electrowetting light valves (ELVs) for displays are a candidate that has captured the attention of "old display hands." A nascent technology, ELVs promise to deliver record performance in light utilization for *both* reflective and emissive displays. Furthermore, early results are revealing that ELV devices are so inherently simple in fabrication and operation that impressive cost advantages might be gained over existing display technologies.

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An Ultra-Simple Light Valve

The fundamental mechanism behind all electrowetting devices is shown pictorially in Fig. 1. The liquid-repelling nature of an electrically insulating hydrophobic film can be counteracted by applying an electric field across the film. As shown in Fig. 1 (top), a highly polar (high surface tension) liquid such as water beads up on a clear, hydrophobic (low surface energy) insulator of amorphous Teflon® that is less than 1 μm thick. By applying a voltage between the droplet and a transparent electrode beneath the hydrophobic insulator, the droplet rapidly (in about 1 msec) wets the surface (Fig. 1, bottom). The process is fully reversible and capacitive, so no power is consumed while the droplet is held in either the wetted or de-wetted state of actuation.

This droplet form of electrowetting is not applicable to displays, but is presented to provide an initial understanding of the basic electrowetting mechanism. Interestingly, in the field of imaging, Varioptic [B. Berge and J. Peseux, *Eur. Phys. J. E.* **3**, 159–163 (2000)] and Philips [S. Kuiper and B. H. W. Hendriks, *Appl. Phys. Lett.* **85**, No. 7, 1128–1130, (2004)] are nearing commercialization of variable-focus electrowetting liquid lenses that do use this basic mechanism.

Other exciting applications of electrowetting include laterally moving droplets (at hundreds of Hz!) on patterned electrodes for lab-on-chip applications [M. G. Pollack *et al.*, *Appl. Phys. Lett.* **77**, No. 11, 1725–1726 (2000)] and optical switches for high-speed fiber-optic communications systems [P. Mach *et al.*, *Appl. Phys. Lett.* **81**, No. 2, 202–204 (2002)]. It is only very recently that the viability of electrowetting for displays was demonstrated [R. A. Hayes and B. J. Feenstra, *Nature* **425**, 383–385 (2003)].

An ELV for displays includes an oil film and a hydrophilic grid that defines the pixels

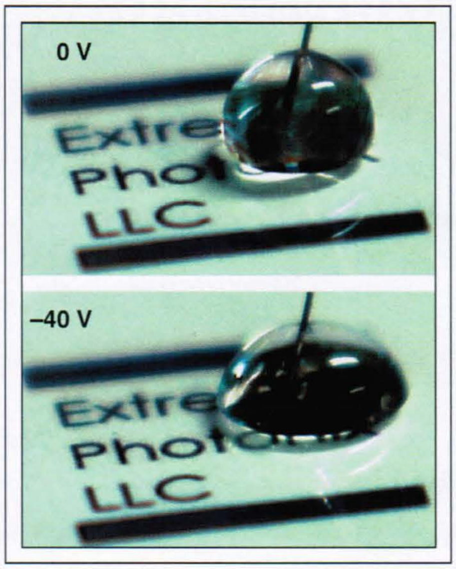

Fig. 1: *In the basic electrowetting principle, the application of voltage to a glass/ITO/fluoropolymer/water-drop structure effectively changes a hydrophobic surface (top) into a less hydrophobic surface (bottom).*

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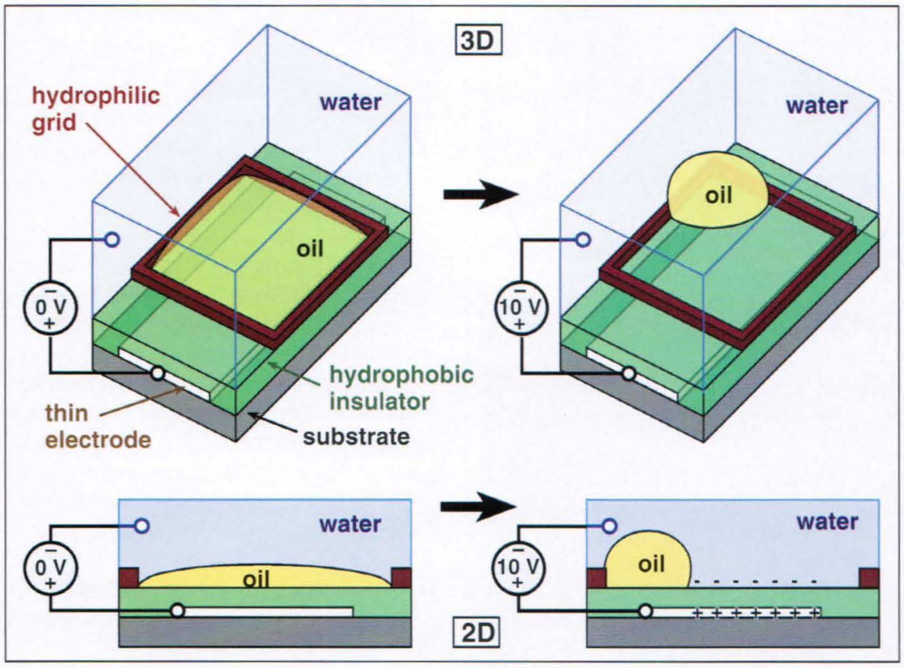


Fig. 2: A generic ELV device structure and its basic operation for displays is shown in 3-D (top) and 2-D (bottom) views. Typical oil volume for a 100 × 100-μm cell is only a few tenths of a nanoliter.

(Fig. 2). Interfacial surface-tension relationships between the polar water (high surface tension), non-polar oil (low surface tension), and hydrophobic insulator (low surface energy) cause the oil to naturally locate as a film between the water and the hydrophobic insulator. The oil is also confined laterally by a water-attracting hydrophilic grid.

Without an applied voltage (Fig. 2, left), the oil forms a continuous film between the water and hydrophobic insulator that is about 10 μm thick. With the application of as little as 5–10 V to the system (Fig. 2, right), the water is *attracted* to the hydrophobic insulator, causing the oil to be displaced and to decrease in lateral area. The removal of the applied voltage returns the oil back to a continuous film inside the hydrophilic grid.

A high-performance light valve can be achieved by making the oil light-absorbing by dyeing it with a colorant; no voltage produces a continuous oil film, which causes light absorption, and the application of more than 5 V produces a displaced oil film and light transmission. Thus, ELV light transmission is approximately equal to the area occupied by the oil film. A large change of more than 70% in area of the oil film can be achieved for high contrast and gray-scale ELV switching (Fig. 3). This simple ELV concept is applicable to reflective displays (with a reflective substrate, as in Fig. 2), transmissive displays (with a backlit glass substrate), and emissive displays (with a UV-light-storage plate as the substrate).

Reflective ELV Displays

The reflective-ELV-display concept was introduced by Hayes and Feenstra at Philips Research Laboratories (Eindhoven, The Netherlands). Philips has a strong initiative in reflective-display development for the emerging electronic-paper market. The Philips reflective-ELV-display approach uses cyan, magenta, or yellow (CMY) dyed-oil film on a reflective substrate (Fig. 4). Without applied voltage, the ELV array reflects only magenta filtered light from the continuous dyed-oil film [Fig. 4(a)]. With the application of –15 V, the dyed-oil film is displaced, and the ELV array begins to reflect white light [Fig. 4(b)]. Since pixel dimensions can be 100 μm or smaller, the human eye averages the appearance of the array as a transition from magenta to white. By increasing the applied voltage to the cell, up to 90% white reflectance can be achieved.

A high-brightness full-color reflective display can be achieved by sandwiching a common water layer between the YMC- and MCY-subpixel ELV arrays and attaching a CYM front color-filter array (Fig. 5). For example, one of the three colored subpixels can consist of cyan and magenta oil layers and a solid-yellow filter (Fig. 5, center). This subpixel can then generate black, green, red, and yellow color based on which of the two oil films is displaced.

This reflective-CMY-ELV-display approach developed by Philips has more than *double* the reflectivity of conventional reflective-display technologies based on liquid-crystal or electrophoretic switching (Table 1). The doubling of reflectivity results from the fact that each of the three colored subpixels comprising a CMY ELV pixel can fully reflect two-thirds of the visible spectrum (for example, yellow is red plus green). Furthermore, two of the three subpixels can both generate saturated red, green, or blue (RGB) reflection. Other reflective-display technologies that use RGB filtering can, at most, reflect only one-third of the visible spectrum at each subpixel and can, at most, provide saturated RGB color at only one out of three subpixels.

Philips has already achieved a 40% reflectivity for full-color cells, with room for improvement to the theoretical limit of just above 60%. It is important to note that the benefit of CMY filtering is *only* applicable to display technologies in which the light transmissivity of the filter medium can be externally switched. Therefore, at this time, only

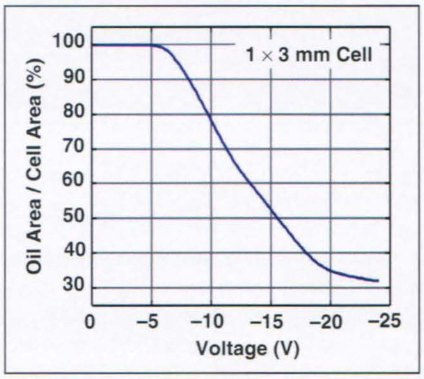
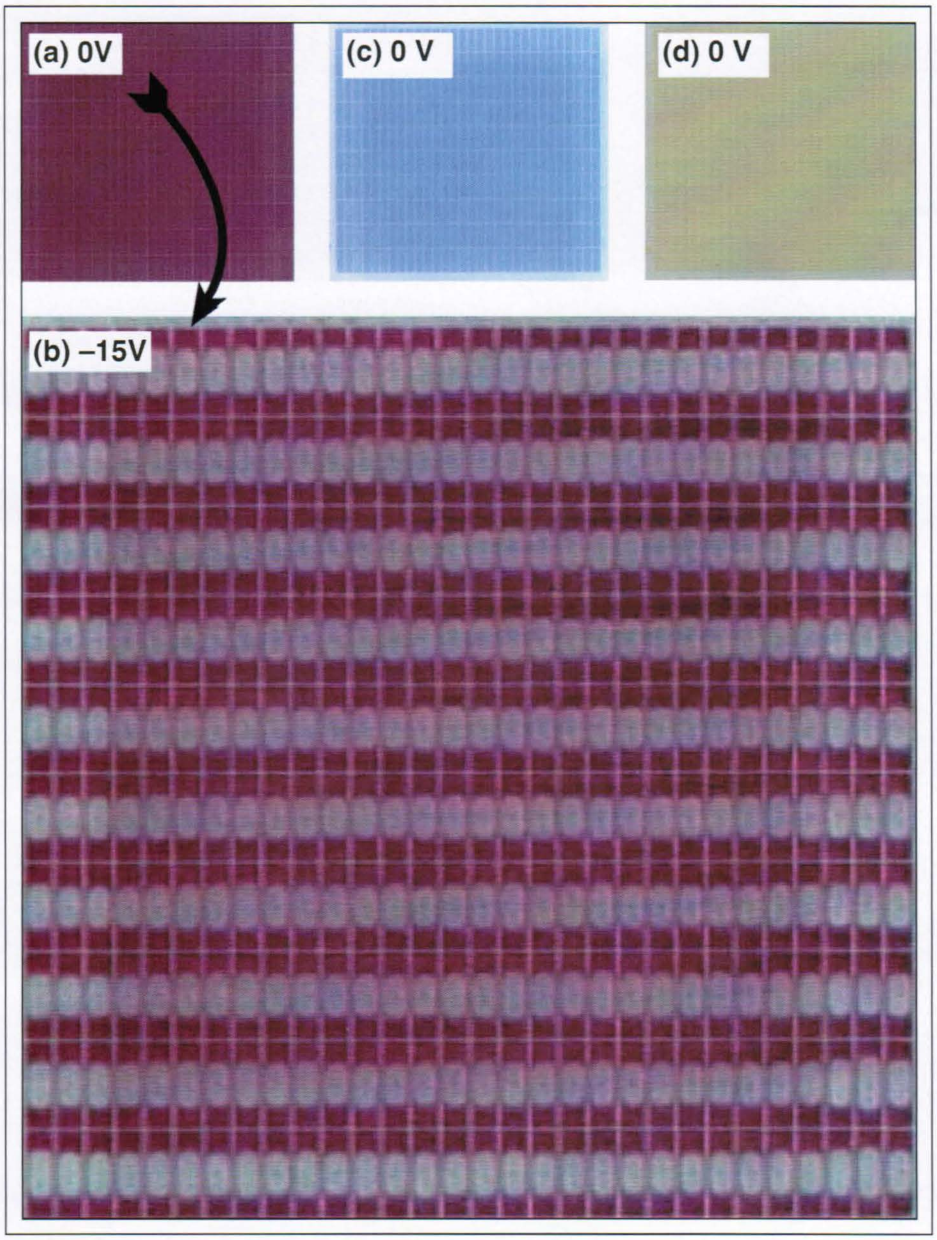


Fig. 3: A typical ELV voltage response is shown. Smaller-sized ELVs can modulate the oil area to as little as 10%. Less than 10-V ELV operation has also been demonstrated.



Philips Research Laboratories

Fig. 4: *A reflective ELV 10 × 30 magenta array of 240 × 80-μm pixels biased at 0 V (a) and –15 V (b), and cyan (c) and yellow (d) arrays at 0 V.*

ELVs can benefit from the high brightness of the CMY-filtering approach.

Because of their high brightness and simple device structure, reflective ELV displays are a strong candidate for electronic-paper applications. Furthermore, the absence of a cell-gap dependence on reflectance permits a straightforward extension of reflective ELV displays to flexible/rollable-display formats. ELVs are not yet suitable for "zero-power" displays because reflective ELV displays are currently not bistable. However, ELVs have a switching capacitance similar to that of LCD cells, which permits a very low power consumption well-suited to video-rate reflective displays in cellular telephones, PDAs, and other portable-display applications.

In terms of display cost, the simplicity of the ELV-device structure should permit reflective ELV displays to be manufactured at a cost comparable to or lower than that of other reflective displays.

Emissive ELV Displays

Following the pioneering reflective-ELV-display work at Philips, Extreme Photonix is developing ELVs for *emissive* displays. The company is now pursuing both color-filtered transmissive and fluorescent emissive ELV displays. The nearly perfect light utilization of reflective ELV displays is also characteristic of emissive ELV devices. The simplest extension of the generic ELV device shown in Fig. 2 to transmissive displays requires that a black oil be used in conjunction with a diffused-white-light backlight located behind a glass substrate. As the black oil is displaced with increasing voltage, light transmittance through the ELV cell is increased to more than 70% (Fig. 6). A standard RGB color-filter plate added to the front of a black-oil ELV array creates the basis for a full-color-display panel.

Extreme Photonix has implemented several other proprietary optical-enhancement techniques that cumulatively lead to a projected panel luminous efficiency of about 10 lm/W, assuming an 80-lm/W backlight with 50% of the pixels on. Use of the previously mentioned CMY-filtering approach with two stacked ELV arrays doubles the average luminous efficiency to about 20 lm/W. This luminous efficiency is an *order of magnitude* greater than the efficiencies achievable for transmissive LCDs. An additional benefit is that, unlike an LCD, a transmissive-ELV-display panel is *inherently* viewable at all angles without variation in image quality.

A transmissive-ELV-display panel should have considerable cost advantages over LCDs because it (1) has no cell-gap dependence, permitting the use of low-cost color-filter arrays; (2) requires no additional films or materials for enhancing viewing angle; and (3) is so efficient that it can use lower-cost and higher-efficiency edge-lit backlights. These potential cost advantages for transmissive ELV displays could be extremely pronounced in high-definition-television (HDTV) applications in which backlight and color-filter-array costs account for approximately one-half of the panel's components and materials cost.

ELVs have also been implemented as a switching mechanism in a novel emissive display developed at Extreme Photonix

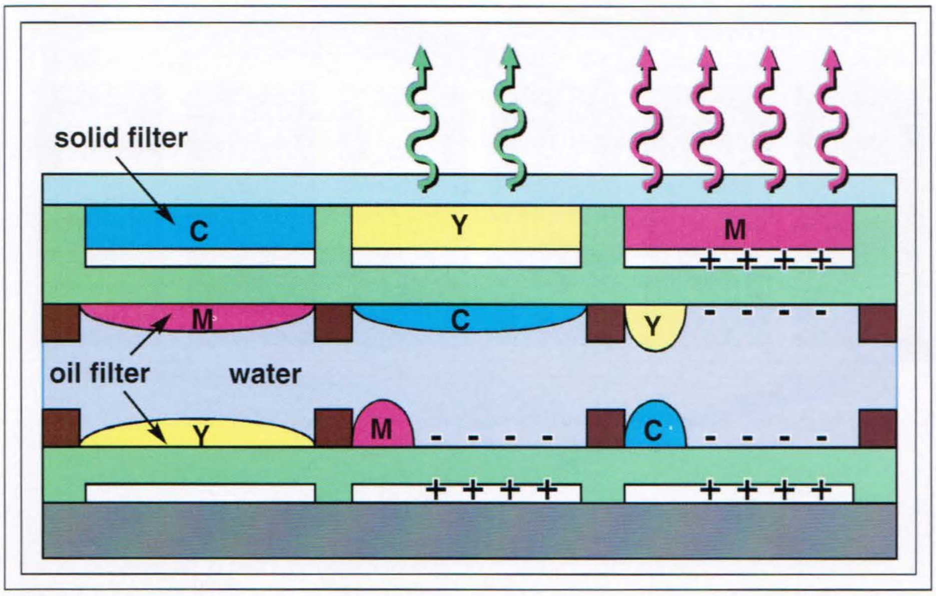


Fig. 5: Shown is a possible subpixel layout for reflective or transmissive CMY ELVs. One subpixel consisting of two differently colored oil layers can produce several colors. The center subpixel, for example, which has cyan and magenta oil layers and a solid-yellow filter, can produce black, green, red, and yellow, depending upon which of the two oil films is displaced.

called light-wave-coupling (LWC) displays [J. Heikenfeld and A. J. Steckl, *SID Intl. Symp. Digest Tech. Papers*, 470–473, (2004)]. LWC displays use a short-wavelength light source [a violet fluorescent lamp or light-emitting-diode (LED) array], which edge-pumps a light-storage plate (a planar waveguide). Violet light from the light-storage plate is selectively coupled to RGB organic fluorescent oils within electrowetting cells. These fluorescent oils emit bright light with saturated colors when excited by violet light. Because no electrical current need be passed through the organic fluorescent oils, their operational lifetime is far superior to the colored organic materials used in organic light-emitting diodes (OLEDs) and polymer LEDs (PLEDs). The result is a theoretical luminous efficiency of about 30 lm/W when 50% of the pixels are turned on in the display panel (Table 2).

This high luminous efficiency is partly due to the lossless optical coupling of ultraviolet/violet light from the light-storage plate to the fluorescent oils. Also, the fluorescent oils possess a quantum efficiency of greater than 90% in the conversion of violet light to saturated RGB light, thus eliminating the need for color filters.

Careful selection of the optical materials and cell geometry allows an LWC display to *recycle* unused light at a pixel even when it is turned off. Therefore, for low pixel usage, as in TV applications, the projected luminous-efficiency advantage of LWC displays can only increase (Table 2).

A demonstration of an LWC display in a signage application was given at SID 2004 (Fig. 7). As can be seen in the photo, LWC technology is also suitable for state-of-the-art transparent signage panels. Fluorescent LWC ELV panels possess the same structural simplicity as transmissive ELV panels, again offering the potential for very-low-cost manufacturing.

No Rewards without Challenges

ELV technology is presently in a very early stage of development for both reflective and emissive displays. Current efforts are heavily focused on creating convincing prototypes that populate high-efficiency ELVs over large array counts, and one goal of early prototypes is to further confirm record-breaking performance attributes.

However, much work still lies ahead in basic ELV-device development. For example,

Table 1: Comparison of Full-Color Reflective FPD Technologies

	LCD	Electrophoretic	ELV
Reflectivity	~10%	~15%	~40%
CR	50:1	10:1	15:1
Speed (msec)	10's	~300	~10
Color	RGB	RGB	CMY
Bistable	Some Are	Yes	No

Note. Data Sources: R. A. Hayes, *Philips Research Laboratories*, personal communication, and R. A. Hayes and B. J. Feenstra, *Nature* **425**, 383–385 (2003).

Table 2: Comparison of Transmissive/Emissive FPD Technologies

	LCD Transmissive	ELV Transmissive	ELV Fluorescent
Maximum efficiency* (lm/W)	~2 (RGB)	~10 (RGB) ~20 (CMY)	~30 (RGB)
Speed	video	video	video
CR	>500:1	100's:1	100's:1
Viewing angle	Polarizer	Transmissive	Emissive
Backlight	White diffuse	White diffuse	Violet waveguide

*Theoretical for 50% pixels "on," based on optical losses for a static image.

Note. Data Source. J. Heikenfeld and A. J. Steckl, *SID Intl. Symp. Digest Tech. Papers*, 470–473 (2004).

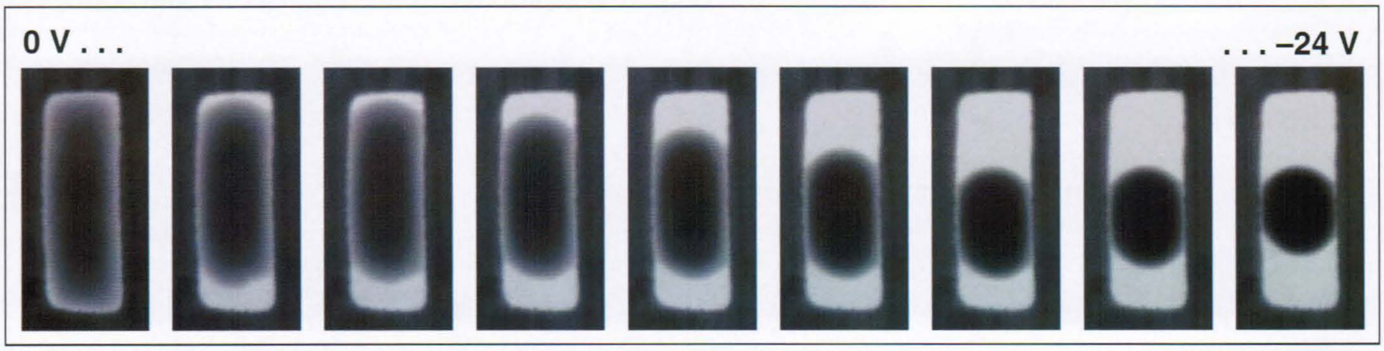


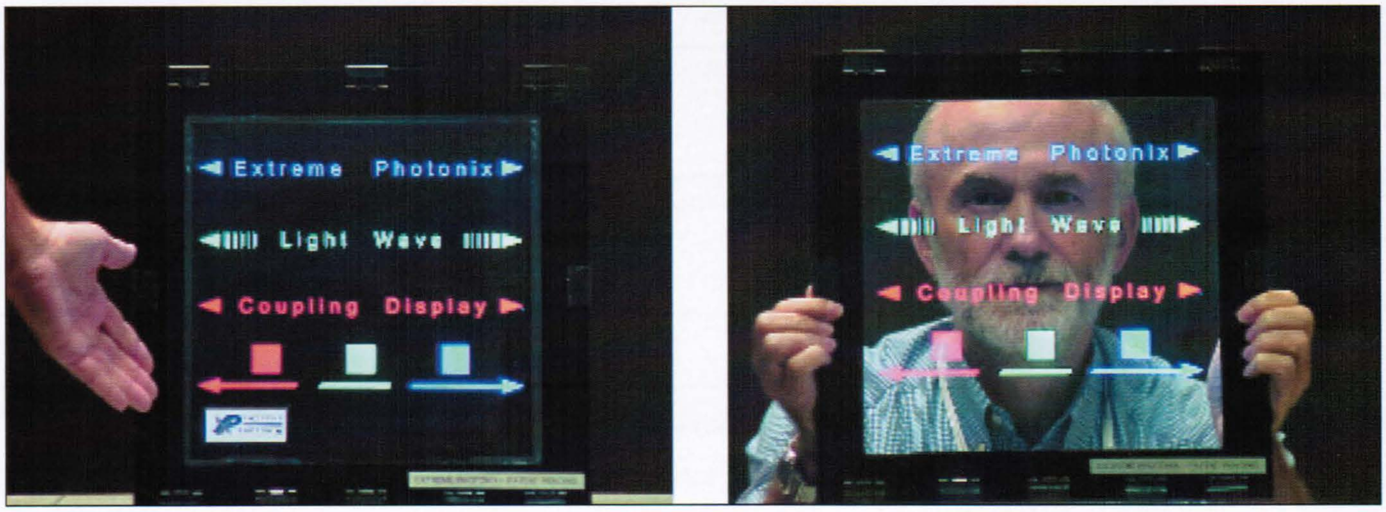
Fig. 6: ELV displays can also be transmissive. This backlit 1 × 3-mm ELV pixel is shown as it was progressively modulated from 0 to –24 V.

organic chemists will have to play a significant role in developing highly saturated black, CMY, and fluorescent dyes for doping into the low-viscosity oils used in ELV cells. Most dyes currently used, such as azo and anthraquinone dyes, have marginally satisfactory optical performance and limited solubility in hydrocarbon oils. In reflective and transmissive ELV displays, poor optical performance of the dyes results in reduced switching contrast. As new dyes are developed, the occasional problems of switching hysteresis and the inability to maintain a dc-switched response must be avoided.

Video-rate switching has already been demonstrated, which makes the development of field-sequential switching promising. Furthermore, with recent ELV R&D results demonstrating less than 10-V operation, ELV displays are now becoming increasingly compatible with passive- or active-matrix LCD on-board or on-glass driver circuits. However, it should be noted that first-generation open-cell ELV-pixel designs are not passive-matrix compatible and that the mating of ELVs to an active-matrix driver array awaits a first demonstration. Since ELV displays rely on liquids with physical momentum, boost-phase voltage-driving techniques might be necessary to allow ELVs to rapidly switch between numerous gray-level states. Repeatable gray-scale switching is currently a problem in first-generation ELV displays, but developers expect that second- and third-generation ELV displays employing specialized electrode patterns, improved cell geometries, and smaller cell or sub-cell dimensions will overcome this difficulty.

Temperature stability is also an issue, but if the same polar and non-polar liquid hosts are used in all ELV cells in a panel, the temperature-induced variance of switching characteristics should be no worse than the temperature variance experienced by LCDs. ELV-cell miniaturization and the use of liquids with nearly equal density should completely alleviate any remaining adverse effects from vibration or gravity. With respect to aging, the primary concern is degradation of the hydrophobic surfaces due to oxidation or contamination.

In manufacturing, one of the challenges is to develop methods for dosing oils in precise volumes measured in nanoliters. Picoliter



Extreme Photonix, LLC

Fig. 7: ELVs can also be used in emissive displays. This fluorescent LWC signage display demonstrator, consisting of printed fluorescent patterns, is capable of high-contrast or transparent operation.

ink-jet technology might be suitable, but it must be specialized for compatibility with oils that have much lower surface tension than that of the solvent or aqueous solutions presently employed in most ink-jet systems.

Because ELV structural and operational simplicity is currently unrivaled, the performance potential of ELVs is impossible to ignore. Once the remaining device issues are resolved and fully functional prototypes are developed – even if only a fraction of the full performance potential of ELVs is realized – commercialization should be able to proceed rapidly. The high efficiency and brightness of ELV displays point to possible market entrance in portable displays such as cellular telephones and PDAs. Because these products incorporate small displays, they represent an easy entry point from the perspective of manufacturing ramp-up. Increased market share is possible should high-volume manufacturing reduce ELV-manufacturing costs to the point at which ELV panels can attract consumers not only on the basis of better performance, but also lower price.

Now is the time for a broad effort to explore the potential of ELVs for displays. ■

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TFT-LCD Fabs: Is Bigger Always Better?

Manufacturers rush to build larger facilities, but the benefits may not always outweigh the costs and challenges. Are there practical limits to fab size?

by Sweta Dash

A NEW HUMAN GENERATION takes decades to mature, but in the hothouse environment of the large-sized TFT-LCD business, new generations of fabrication lines (fabs) are sprouting up at a furious pace. TFT-LCD panel makers – already investing billions of dollars in fifth-, sixth-, and seventh-generation fabs – are beginning to discuss the possibility of building eighth-, ninth-, and even tenth-generation manufacturing facilities.

To these companies, investments in progressively more-sophisticated fabs represent steppingstones to the future, enabling them to produce the ever-larger panel sizes required to serve the booming flat-panel-TV market. But as these suppliers undertake the vast investments required to stay on the large-sized TFT-LCD treadmill, questions are mounting about the headlong rush to build higher-generation fabs.

Just how long can the bigger-is-better approach persist? Is there an inherent limit to the expansion in the size of the motherglass beyond which the law of diminishing returns must assert itself?

Perhaps more profoundly, will the industry as a whole benefit from these higher-generation fabs – especially the seventh, eighth, and ninth generation and beyond – and does this rush to have the largest plant translate into greater market share for the individual manufacturers?

Complex questions such as these are impossible to answer with certainty, but one can find many clues in the past and present that point to how the future of LCD manufacturing may continue to evolve.

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Historical Background

The progress of the large-sized TFT-LCD industry has been characterized by periods of expansion, during which booming sales to a new application market increased the demand for larger glass sizes, which in turn led to soaring investments in new-generation facilities with larger manufacturing capacity (Fig. 1).

During the initial 5 years of large-sized TFT-LCD manufacturing, revenue rose from slightly more than $500 million in 1990 to $4.7 billion in 1995, driven exclusively by sales to the notebook-PC market. In the market's second phase, only 4 more years passed before revenue doubled, rising to $10.6 billion in 1999.

In another 4 years, large-sized TFT-LCD market revenue doubled again, reaching $22.3 billion in 2003; this time, growth was fueled

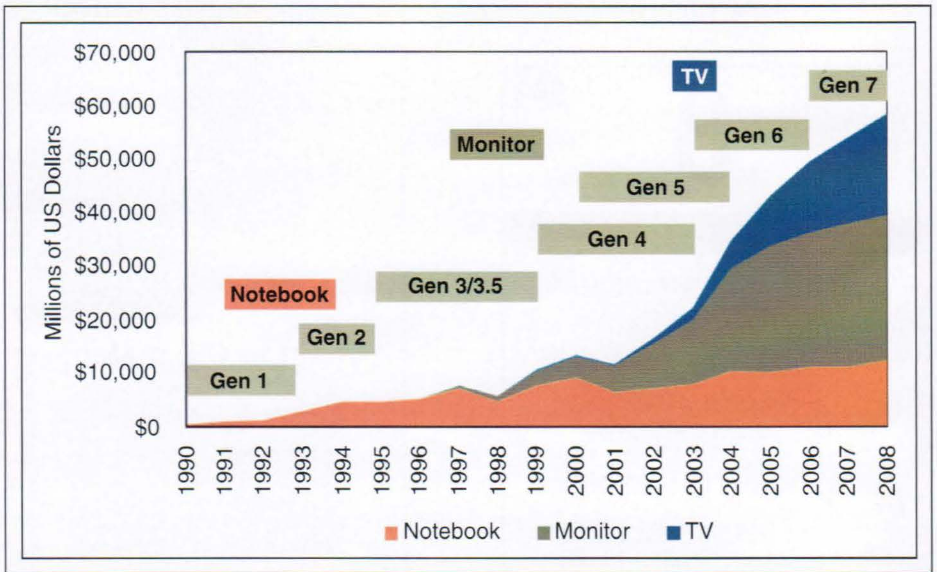

***Fig. 1:** The rapid growth of new display applications results in demand for increased TFT-LCD manufacturing capacity. (Data and graphic courtesy of iSuppli Corp. © 2004.)*

0362-0972/11/2004-032$1.00 + .00 © SID 2004

Table 1: The Number and Location of Fabs by Generation

Generation	Largest Side	Area	Output Example	Number and Location of Fabs
2nd	<470 nm	0.2 sq. m	2 @ 14 in.	13 in Japan (1 later moved to China), 3 in Korea, 1 in Taiwan; no more planned
3rd	470 mm and up	0.4 sq. m	4 @17 in.	7 in Japan, 5 in Korea, 7 in Taiwan; no more planned
4th	720 mm and up	0.6 sq. m	4 @ 21 in.	4 in Japan, 3 in Korea, 6 in Taiwan, 1 in Singapore; possibly one more in China
5th	920 mm and up	1.2–2.0 sq. m	6 @ 27 in.	4 in Korea, 6 in Taiwan (5 opertional), 2 in China (1 operational); more to come
6th	1.8 m and up	2.7 sq. m	6 @ 37 in.	1 in Japan, 1 coming on line in Korea, 4 being built in Taiwan; more to come
7th	2 m and up	>4.0 sq. m	6 @ 46 in.	2 being built in Korea, 3 planned in Taiwan; more to come

Source: iSuppli Corp., *Global LCD Supply/Demand 2Q 2004.*

by rising sales of flat-panel monitors. Analysts at iSuppli expect sales to more than double again in 3 years to an estimated $49.6 billion by 2006.

The growth of the LCD market has been driven more by supply/push forces than by demand/pull factors. Investments in higher-generation fabs may have been the most important reason for the growth because it impacted supply so directly. The evolution of production on larger substrates is directly tied to expansion of the large-sized TFT-LCD market.

During the initial 5 years of the market (1990–1995), TFT-LCD fabs evolved from the first to the second generation. During the period from 1996 to 2000, manufacturing shifted to third, 3.5-, and fourth-generation facilities. By 2005, the industry will have developed fifth-, sixth-, and seventh-generation fabs. Indeed, fifth- and sixth-generation fabs are already turning out panels (Table 1).

The TFT-LCD industry has greatly relied on immense capital investment to drive revenue growth. The move to larger glass sizes has enabled the manufacturers to simultaneously reduce manufacturing costs and to slash panel pricing, propelling growth across various applications. iSuppli's growth forecast that the large-sized TFT-LCD market will reach $60 billion in revenue in 2008 is based on the assumption of continuing investment in higher-generation fabs, which is expected to drop the cost of large-sized TFT-LCDs even further, fueling the growth of the LCD-TV market.

Not Always Smooth Sailing

The industry's growth in production capacity and sales revenues has been anything but steady. The market has been characterized by significant imbalances between supply and demand. These imbalances have resulted in strong revenue growth and high profitability during growth phases when supplies were tight. When the imbalances have swung to a glut of surplus product, however, the industry has suffered severe reductions in revenue, declines in profitability, and even losses.

This cyclical nature has made investing in the LCD business a high-risk venture at times and a high-return business at others. Each downturn – such as those in 1995, 1998, and 2001 – resulted in a slowing or decline in revenue, but it also enabled another new application market to develop as panel suppliers scurried after newer, larger markets in which to sell their wares (Fig. 2).

These periodic imbalances and intense cycles led to shifts in market share among manufacturers, spurring consolidation in the large-sized TFT-LCD market. Because of the staggering requirements for capital investment, those companies with access to the largest amount of capital have proven to be the survivors.

Suppliers who could not keep up with the constant increase in capital investment were forced to move away from center stage in the large-sized TFT-LCD market and focus instead on small-sized panels, for which capital requirements are much less demanding and the conversion of old fabs can produce higher volumes of displays for smaller devices such as mobile telephones.

The Bigger They Are . . .

The business history of large-sized TFT-LCDs has demonstrated a continuous shift to larger panel sizes within each application. Cost reductions from the higher-generation fabs have helped drive this movement.

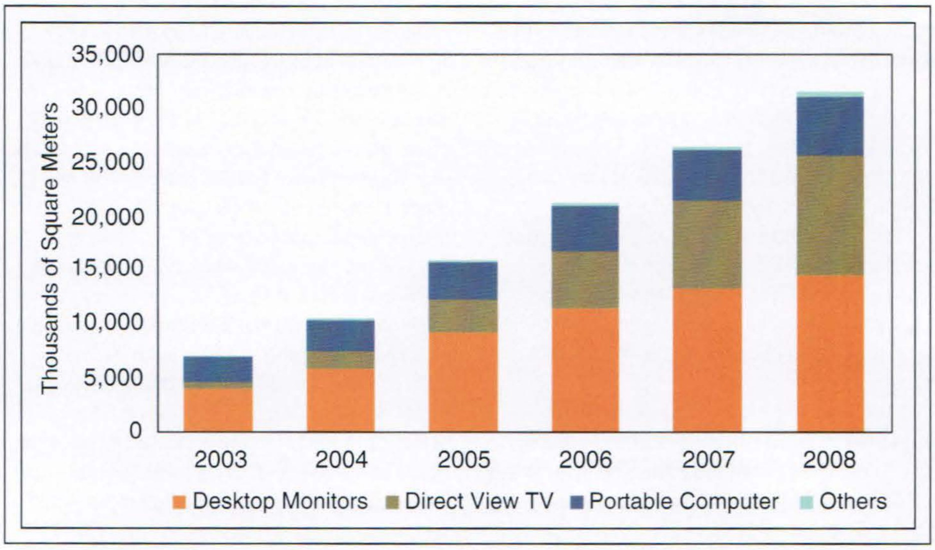

***Fig. 2:** As production capacity has increased, producing a surplus of panels, new markets have been established for large-sized TFT-LCD products. (Source: iSuppli Corp.,* LCD Market Tracker Q2 '04, *© 2004.)*

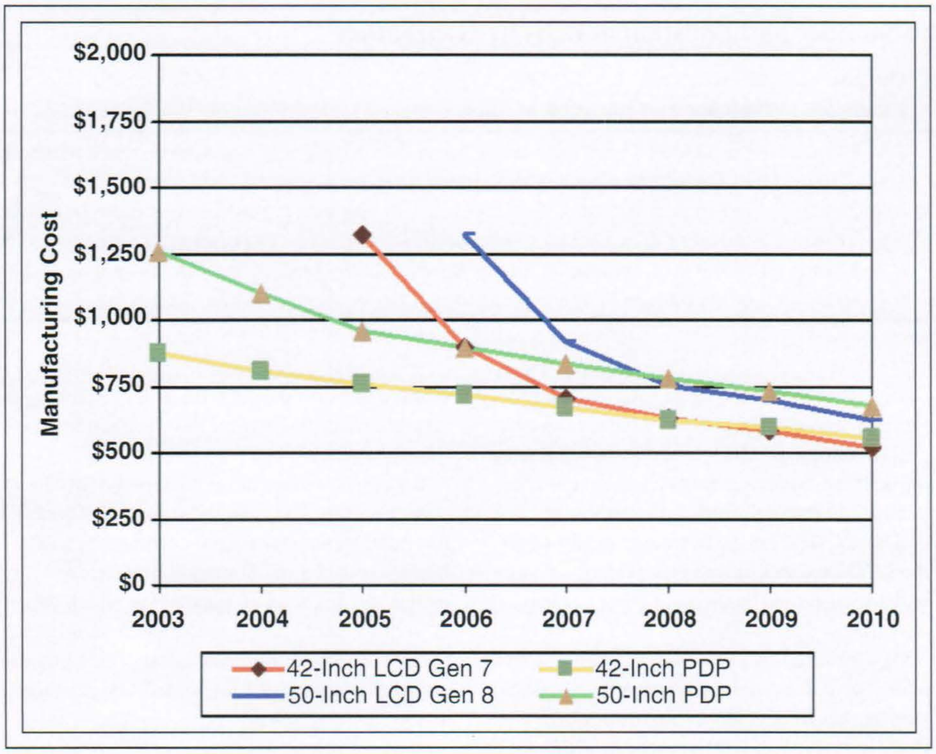

Fig. 3: *The potential TFT-LCD manufacturing cost could drop below that of plasma displays of the same size by utilizing higher-generation fabs employing larger substrates. (Source: iSuppli Corp.,* Flat Panel Display Cost Model 2004, *© 2004.)*

The first-generation fabs in the early 1990s made 8.4-in. panels efficiently, while the third- and fourth-generation fabs principally made 12- and 14-in. products. During the same period, the notebook-PC market shifted from 10.4-in. panels to 15-in. sizes or larger.

The dominant size in the desktop-computer-monitor market is now is migrating from 15- to 17-in. panels. This is the result of the move toward fifth-generation fabs, which can make 17-in. panels efficiently.

The TV market now has an urgent need to shift to larger TFT-LCD sizes in order to compete with CRTs larger than 30 in. and plasma displays and microdisplay-based rear-projection products in the 40–50-in. range.

Large-sized TFT-LCD shipments are expected to increase to 300 million units in 2008, rising at a compound annual growth rate (CAGR) of 23% from 97 million units in 2003. The viewable-area growth is expected to be even greater; the total viewable area of all large-sized panels will rise from 7.2 million square meters in 2003 to 31.6 million square meters in 2008, a CAGR of 31%.

In 2003, about 57% of the large-sized TFT-LCD area was dedicated to monitors, 34% to notebooks, and only 8% to TVs. However, in 2005, 46% of the area is expected to be dedicated to monitors, only 17% to notebooks, and 35% to the TV market. As customer acceptance and screen sizes increase, the TV market has the potential to claim an even higher percentage of sales. The unit penetration of LCD technology in the TV market amounted to less than 3% in 2003 and is expected to pass 5% in 2004. More than 90% of the global TV market is now served by direct-view CRTs.

By 2008, the global TV market is expected to surpass 200 million units, with more than 90% in sizes less than 40 in. on the diagonal. In 2008, approximately 14 million televisions, or 7% of the market, are expected to be in the range of 40–49 in. Only 4 million units – just 2% of the market – are expected to be in the 50–59-in. range, while a mere 1.6 million units are expected to be 60 in. and larger.

Thus, most industry experts believe that sixth-generation fabs – those using 1500 × 1800- or 1850-mm substrates that can be cut into eight 32-in. units or six 37-in. units – should be sufficient to serve 90% of the TV market. Using this reasoning, there would be no rationale to use substrates larger than those of the sixth-generation fabs.

However, there are competing plasma display and microdisplay-based rear-projection products that also focus on the high-priced and high-quality large-sized-TV market, including products in the 40–50-in. range. If TFT-LCD prices can be reduced sufficiently, they should be able to compete effectively with plasma displays because LCDs offer advantages including a slimmer form factor, lower weight, and lower power consumption.

The entire market for such large panels may appear to be small now, but it can be expanded substantially in the near future; all it takes is an end-product price low enough to be attractive to consumers.

Seventh-generation fabs – using 1870 × 2200-mm substrates – are calculated to be efficient at making 40- or 46-in. panels, but not as efficient at the 50- or 52-in. sizes because only three panels per substrate can be achieved. In order to produce 50-in. panels most efficiently, some suppliers believe that it is essential to go to eighth-generation fabs, despite the fact that the market may now appear to be minuscule. And forecasts for the 60-in.-and-above sizes indicate that for such a small market, a sound financial case cannot be made for fabs larger than eighth generation. Still, some discussions have occurred within the industry concerning ninth- and tenth-generation fabs. Eighty-inch plasma and rear-projection TVs are already available, yet these sets make up only a tiny segment of the overall market.

Some observers question whether it will really be possible for LCD-TV panels – with their higher capital and materials costs – to ever compete with plasma displays, even if the efficiencies promised by seventh- and eighth-generation fabs are achieved. Certainly, when comparing the current prices of plasma and LCD TVs in the 40- and 50-in. range, consumers can see that plasma TVs retain a decisive cost advantage in the near term.

At least in theory, the efficiency of seventh- and eighth-generation TFT-LCD fabs could reduce costs sufficiently to be competitive with those of plasma displays in the future. Yield rates greatly affect the cost structure of both TFT-LCDs and plasma-display production, and TFT-LCDs have a better potential for significantly lower costs by improving yield rates (Fig. 3).

Microdisplay-based front-projector screen sizes generally range from 60 to 100 in. Front projectors are now available at retail prices less than $1000. By 2008, these prices will fall close to $500, giving consumers viable options to gain large-screen viewing experiences at much lower prices.

Generation Cost Gap

Fifth-generation fabs using 1100 × 1250-mm substrates provide a 15% reduction in the manufacturing cost of 30-in. TFT-LCDs compared to that of fourth-generation fabs using 880 × 680-mm substrates. Seventh-generation fabs using 1870 × 2200-mm substrates provide a further cost reduction of 32% compared to that of fifth-generation fabs. A seventh-generation fab can produce 12 units of 30- or 32-in. panels per motherglass, whereas a fifth-generation fab can produce only three units of 30-in. panels from a single substrate (Fig. 4).

The cost of a 42-in. plasma panel is projected to be $758 in 2005 and $553 in 2010. The cost of a 50-in. plasma panel is forecast to be $956 in 2005 and $681 in 2010.

TFT-LCD suppliers must reduce their panel costs to some point closer to plasma-display prices in order to effectively gain market share. This can only be done with the help of higher-generation fabs, such as seventh-, eighth-, or even higher-generation facilities.

Growth in Emerging and New Applications

Are there any other market applications that require 60-in.-and-larger TFT-LCDs? Public-information applications in airports, railway stations, or indoor shopping malls have been served mainly by plasma displays. But where signage must display static information continuously, plasma panels have suffered from "burn-in," especially first-generation plasma products. This has created an opportunity for 30–40-in. TFT-LCDs.

Because public-information applications are less price-sensitive than the consumer-TV market, they are the early adopters of 40- and 42-in. TFT-LCDs. These markets are also served by rear-projection video-wall technologies and by plasma displays in sizes ranging from 50 to 70 in. Although they can provide an excellent opportunity for large-sized TFT-LCDs, these markets are quite small compared to the consumer-TV market.

Why Invest in a Next-Generation Fab?

The most important reasons for building a next-generation fab are to reduce manufacturing costs and increase the production of larger-sized panels by accelerating throughput.

Factory size definitely affects unit costs. Higher-generation fabs also spur technological innovation, which is driven by the necessity to increase the efficiency of large-sized-panel production.

Older fabs used seven- or five-mask technologies, but the newer fifth-and-higher-generation fabs use four-mask technology. This reduces the time required and the overall costs, thereby boosting efficiency. Other examples of improved processing are one-drop filling (ODF) and color-filter slit-coating technologies.

The ODF method reduces the time required to fill the panel with liquid-crystal material. As substrates become larger, slit coating has also become essential for color filters. Due to the growth in substrate size, costs have spiraled upwards for the conventional spin-coating method because of greater resist wastage and higher levels of power consumption. The slit-coating method can apply an even coating of resist without spinning, and is being adopted by most fifth-generation fabs, thereby reducing wastage and cutting costs.

Vertical Integration of Infrastructure

As substrate sizes have increased, transportation has emerged as a serious issue; not only are transportation costs higher, but the risk of damage to materials while in transit is also greater. This is true of both glass and color filters and drives the trend toward vertical integration.

Glass, color-filter, and module factories must be located nearby – or even integrated into the TFT-LCD fabs – to reduce costs and increase efficiency. Furthermore, because color filters are one of the essential components and account for a significant percentage of the cost of the TFT-LCD production process, many panel suppliers have developed in-house color-filter capabilities. Moreover, as substrate sizes become larger and more capital investment is required on the component side, it is increasingly difficult for component production to keep pace with investments in panel production because component suppliers tend to be smaller companies. This has already created significant problems; component shortages impacted TFT-LCD manufacturing in the first half of 2004. TFT-LCD suppliers are now investing in essential components such as glass, either as a joint venture or as a partner, in order to ensure sufficient supply.

Expansion Plans

By the end of 2004, a total of 11 fifth-generation fabs will be in operation, and at least seven of them will be running at full capacity. Sharp Corp. will be operating its sixth-genera-

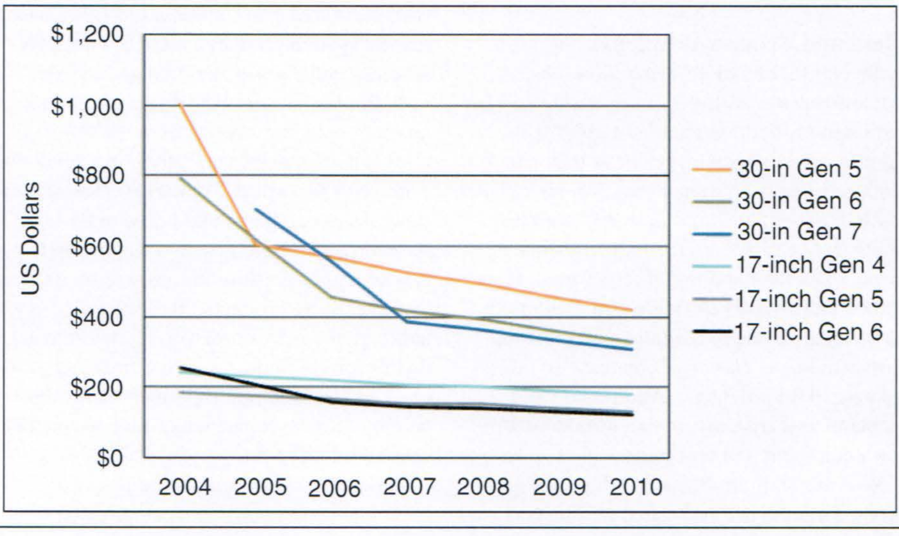

Fig. 4: *Newer fabs using larger substrates are able to produce large-sized panels more efficiently, and thus reduce costs. (Source: iSuppli Corp.,* Flat Panel Display Cost Model 2004, *© 2004.)*

tion fab at full production, while Chunghwa Picture Tubes (CPT) and AU Optronics Corp. of Taiwan plan to start mass production in their sixth-generation fabs by mid-2005. S-LCD Corp. (a joint venture of Samsung and Sony) intends to begin operating its seventh-generation fabs in the first half of 2005. However, the general slowing of the market combined with substantial reductions in prices in the third quarter of 2004 may result in some delays to these expansion plans.

Even when suppliers convince themselves to move ahead with seventh-, eighth-, or higher-generation fabs, various financial and technological challenges can arise that will make the plans very difficult to implement.

Higher Fixed Costs

Capital spending was high among TFT-LCD suppliers throughout 2003, which they planned to continue in 2004 and 2005. A typical sixth-generation fab will cost approximately \$1.9–2 billion to establish, while a seventh-generation fab may cost from \$2.5 to \$3 billion. Each generation is likely to require at least a 20–30% increase in equipment costs.

The cyclical nature of the large-sized TFT-LCD market makes it a high-risk investment arena in which return on investment may be uncertain. This is especially true in the short term due to supply-and-demand fluctuations, low prices, and various production problems that need to be solved. Also, survival and leadership in this market require a continuous infusion of significant capital investment.

Yield and Process Problems

In the eighth- and ninth-generation fabs, motherglass measuring 2–3 m per side will be extremely difficult to handle. Equipment manufacturers apparently believe they can produce process equipment for 3-m sizes, but beyond that dimension it is simply not clear whether they can serve the industry's needs. In any case, the handling of larger glass sizes will be increasingly difficult, and yield problems can arise due to chipping and breaking. Furthermore, as glass sizes increase so does the potential for defects. Additional yield problems can arise due to the introduction of new equipment and processes.

New methods are being developed to handle the larger glass sizes, such as transport *via* a non-contact means, floating the glass on a cushion of air, or by using a conveyor. Some suppliers are discussing single-end or in-line load/unload processes.

Transport of the extremely large manufacturing equipment and materials is also very difficult. A single seventh- or 7.5-generation fab-line machine could weigh 100–200 tons. Shipping those machines, delivering them, and lining them up in a conventional clean room could be monumental tasks.

Equipment manufacturers are devising creative modular designs to increase productivity and overcome transportation limitations. Also, as the fab size gets larger, the law of diminishing returns may come into play, as materials costs become a higher percentage of the unit cost.

How Far Can It Go?

Suppliers have been considering many glass sizes beyond the current seventh generation's 1870 × 2200-mm substrates, including raising the size to 2120 × 2450 mm or 2160 × 2400 mm for 7.5-generation fabs. The eighth-generation glass sizes that are being discussed are 2300 × 2700, 2300 × 2600, and 2200 × 2600 mm.

The ninth-generation TFT-LCD fabs could even use glass sized up to 2600 × 3100 mm, which is more than 8 square meters or 80 square feet of glass per sheet. From a financial and process point of view, there are no good reasons to move to larger glass sizes because 90% of the TV market and 100% of the notebook and monitor markets can be handled efficiently by fab-line sizes up to the sixth generation. But in order to compete with plasma displays and microdisplay-based rear-projection products, there is a need for seventh- and eight-generation glass sizes.

Both plasma and microdisplay-based rear-projection displays compete in the 40–50-in. market even though currently it is a small percentage of the world TV market. The 40- and 42-in. sizes can be handled efficiently in seventh-generation fabs, and advancing to 7.5- or eighth-generation fabs will be required to make 50-in. products. Beyond that, although there are some very high-end market niches for 70–80-in. sizes, the financial, process, and transportation problems may discourage further expansion of higher-generation TFT-LCD fabs.

In the end, success in the large-sized TFT-LCD market depends on a complicated set of variables. As suppliers contemplate newer-generation fabs, their strategies must account for all these factors, and see beyond just the "bigger is better" approach. ■

backlight

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LETI and Motorola, Inc., in turn, discussed their work with CNT FEDs made by chemical-vapor deposition (CVD). (It was the microtip-FED work done at LETI that spawned an international FED alliance in the 1990s, led by the now-defunct PixTech, Inc.) Researchers from Kyung Hee University in Korea described their CNT FED work using plasma-enhanced CVD (PECVD). And a team from Brown University and Sandia National Laboratories discussed their work on carbon nanofibers and nanotubes based on lyotropic liquid-crystal material.

According to Motorola and LETI, their CNT FEDs are very close to meeting all the requirements for large low-cost TVs. They have built a 32 × 96-pixel prototype delivering over 3000 nits of luminance and degrading by only about 40 nits after 7500 hours of operation.

Yet another CNT-FED report was provided by researchers from Southeast University in the Peoples Republic of China. They discussed a novel under-gate CNT-FED structure which they said achieves "large emission area, notable emission uniformity, and high luminance efficacy."

How fast might some of these second-generation FEDs make it to market? What might their first applications be? And how wide could their market window be before one of the established FPD technologies responds?

"The FED is the much-touted contender that so far has lost all its fights," said Tom Holzel, Principal at Velocity Associates, "and yet it keeps showing promise that someday, maybe, it will win a victory. If some contender does not win a round or two in the next two to three years," said Holzel, "FEDs will go down for the count." ■

David Lieberman *is a veteran display journalist residing in Massachusetts. He is the co-author of* **Flexible Displays and Electronics: A Techno-Economic Assessment and Forecast** *published by Intertech Corp. (www.intertechusa.com). He can be reached at davidlieberm@earthlink.net.*

editorial

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and Paukshto discuss replacing expensive polarizing films in LCDs with a self-assembling in-cell polarizing material. And in his Guest Column, Michael Kane somewhat surprisingly identifies cost savings as one of the most important reasons to pursue organic-TFT backplanes.

One or more of the articles in this issue of *Information Display*, as well as others, may find themselves translated into simplified Chinese and published in the Chinese publication *Advanced Display* under a newly formalized agreement between that publication and SID. *Advanced Display*, edited by Jingwu Wen, has the support of the Beijing Chapter of SID. We look forward to implementing this cooperative relationship and to broadening even further the reach of the articles that are published in *Information Display*.

— KIW

We welcome your comments and suggestions. You can reach me by e-mail at kwerner@nutmegconsultants.com, fax at 203/855-9769, or phone at 203/853-7069. The contents of upcoming issues of ID *are available on the SID Web site (http:// www.sid.org).*

guest column

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material, which may be curved or flat, glass or plastic. In the meantime, expect to see OTFT displays introduced with little fanfare, as a hardly noticeable alternative TFT technology whose differentiating feature is low cost. ■

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Second-Generation FEDs

by David Lieberman

The technical literature is filled with light-manipulating phenomena that have been revisited by researchers, decade after decade, as they applied the technologies of their day to historical problems. The technical sessions held last May at the SID 2004 International Symposium, in fact, were rife with FPD technologies waiting to take their place on stage.

For example, the failure of field-emission displays (FEDs) to find a market in the 1990s does not mean that they have been abandoned. We are in the era of so-called second-generation FEDs, most of them based on carbon-nanotube (CNT) emitters. Taiwan, Japan, Korea, China, the U.S., and France were all represented by CNT papers presented at SID 2004, many of them describing the results of cooperative efforts between industry and academia or government.

However, the basic cathode (or emitter) technology of the 1990s – the microtip or Spindt cathode – has not been discredited. At SID 2004, Futaba reported on the results of its three-year effort to improve the luminance and lifetime of Spindt tips. Its prototype 11.3-in. full-color VGA-format microtip FED display had an average luminance of 350 nits and a lifetime of about 6000 hours. What is new in the Futaba microstructure is a higher anode voltage, a wider gap, and a new technology that makes spacers invisible. The spacers, according to Futaba, consisted of 50-μm-diameter 0.6-mm-long glass fibers which are placed "between vertical dots on the black matrix."

The researchers at Futaba have also reduced the hole diameter of its emitters from 1.3 to 0.9 μm, effectively doubling the possible number of emitters per pixel. Work will continue, they explained, on a new anode structure for higher anode voltage, focus properties improvement, and deflection of electron beam affected by spacers to improve the picture quality.

Elsewhere, CNTs are the cathodes of choice, but not all of the research efforts are the same. At the Symposium, a team from Mie University, the National Institute of Advanced Industrial Science and Technology of Japan, and Noritake Co., Ltd., discussed a prototype 48 × 480-pixel 48 × 480-mm message display based on CNTs. (Noritake has been reporting on its CNT FED work since 1998.) The architecture of this display includes ceramic walls that serve the same function as the barrier ribs in PDPs, *i.e.*, to separate red, green, and blue subpixels to prevent color crosstalk. The CNTs in the display have been irradiated by an excimer laser, the researchers said, "to improve emission uniformity and lower driving voltage."

Mitsubishi, reporting on a simple stacking method for making CNT FEDs, also makes use of laser irradiation to treat its CNTs. The ability to stack layers to create a triode structure relies on "an extremely smooth CNT layer," which the company achieves through a "newly developed dispersing agent."

Variant ways of making a CNT FED were well represented at the conference. A team from Taiwan's TECO Nanotech Co., Ltd., and the Lan-Yan Institute of Technology, for example, discussed a fast, low-cost spray-coating method which they said also easily scales up for large sizes. The result of the process, they said, is CNTs with "good electron-emission properties."

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calendar

11th International Display Workshops (IDW '04). Contact: Niigata Visitors & Convention Bureau, e-mail: nvcb@nvcb.or.jp.
December 8–10, 2004 Niigata, Japan

International Display Manufacturing Conference & Exhibition (IDMC '05). Contact: www.di.nctu.edu.tw/IDMC05.
February 21–24, 2005 Taipei, Taiwan

SID International Symposium, Seminar & Exhibition (SID '05). Contact: SID HQ, 408/977-1013, fax -1531, e-mail: office@sid.org.
May 22–27, 2005 Boston, Massachusetts ■

The 25th International Display Research Conference (EuroDisplay 2005). Contact: Mark Goldfarb, PCM, 212/460-8090 x202, e-mail: mgoldfarb@pcm411.com
Sept. 19–22, 2005 Edinburgh, Scotland ■

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