SPECIAL OLED ISSUE

# Information DISPLAY

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SID

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## OLEDs Appear in Commercial Products

- OLED/POLED Overview
- OLED Failure Mechanisms
- Phosphorescent-Polymer OLEDs
- USDC's Display-Manufacturing Roadmap
- IDMC 2003/FPD Expo Taiwan Report

Information
DISPLAY

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*In 2003, for the first time, an active-matrix full-color OLED appeared in a consumer product. The 2.16-in. 521 × 218-pixel AM550L, developed by Kodak and Sanyo, was incorporated into Kodak's LS633 EasyShare digital still camera. In 2002, the first polymer OLED – an alphanumeric monochrome PolyLED by Philips – appeared in a commercial product. Along with the substantial number of OLED licensing agreements and OLED technical papers we have seen recently, these are important steps in the evolution of OLED displays.*


**OLEDs Appear in Commercial Products**

Eastman Kodak Co.



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- Touch Interfaces
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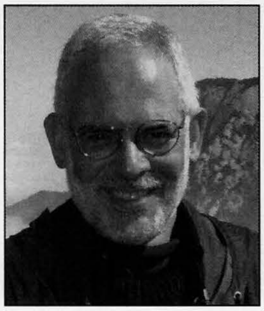

## Return to Chunghwa

We arranged it on the spur of the moment. I was talking to my old friend Hsing-Yao (Jim) Chen, a legendary designer of CRT electron guns at Chunghwa Picture Tubes (CPT), who now serves his company as an internal consultant. (At one time, and maybe still, every CPT CRT contained a Chen-designed gun.)

We were at IDMC '03 in Taipei, and I mentioned how interesting I found the CPT plasma displays being shown at SEMI's FPD Expo Taiwan 2003 across the street. "Would you like to see the factory?" Jim asked. Absolutely. "Let me see what I can I do." said Jim.

So, that Friday afternoon, Jim was driving me to the CPT plant in Taoyuan, a suburb of Taipei, in his Saturn (a rather unusual car in Taiwan, where Japanese and European vehicles dominate). We were welcomed by Senior Manager Yu-Shu (Jason) Wu, and PDP Plant Manager H. Y. Chen. I was later to have an extended conversation with Hsiang-Kuei Chung, Vice President of the Opto-Electronics Business Unit; and S. C. Chen, Vice President of the CRT Business Unit, courteously dropped by to say hello.

I had been here before. When I visited the Taoyuan plant nearly four years ago, a three-story portion of the facility was used for an impressive automated manufacturing line devoted to 14-, 15-, and 17-in. CDTs. That line has been moved to mainland China and the space is now given over to PDP manufacturing.

The several-month-old PDP plant – the first, Chung said proudly, to produce PDPs commercially in Taiwan – is producing 7000 46-in. WVGA panels per month. The panel and factory were developed with support from Mitsubishi, who was also CPT's technology partner for the original Taoyuan Gen 3 LCD plant that was completed about four years ago.

CPT builds the panels into TV/monitors, which are sold to consumers by other companies under their own brand names. (This makes CPT an "original design manufacturer," or ODM.) The plant's output is committed for two months into the future – that is, it will take the next two months of production to fill the orders currently on hand.

In a demo room with moderately subdued lighting, CPT's current and next-generation PDP monitors were on display, along with a variety of competing products. The program source was supplying slow-moving images, and the current 46-in. CPT product (PD46WVA) – with a luminance of 700 cd/m$^2$ and dark-room contrast ratio of 800:1 – held its own very well. But the next generation (PD46WVB), which will be available in August, looked a lot better.

Although the pixel format of 852 × 480 is unchanged in the PD46WVB, it uses a closed-cell structure – as opposed to the open-channel structure of the PD46WVA – and the luminance and contrast ratio jump to 1000 cd/m$^2$ and 1500:1, respectively. Although I have many opportunities to learn this lesson, it always strikes me anew when I see a side-by-side example of it: High contrast, especially when combined with good brightness and image definition, makes a strong subjective enhancement to the image, adding a sense of depth and vividness.

*continued on page 44*




# Information DISPLAY

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## Roll-to-Roll Manufacture of Displays

**by Sigurd Wagner**

The flat-panel-display revolution promises to develop along the lines of the printing revolution. Letterpress printing, which came as a purely technological advance designed to make the bible more affordable, produced a deep social shift in Europe by democratizing the exercise of religion. The ensuing alternation between advances in printing and further social development set a wheel in motion that still is turning after 500 years.

Flat-panel displays are set on a similar course. They are the exemplar of human–machine interfaces, and will be shaped to many uses, some of which will be revolutionary. They will grow to become a newspaper, book, music score, PDA, videophone, TV, download-your-design dress, road map, game, and camouflage. Thin as a coat of paint, they will be added to any surface and incorporated in any structure. They will be on machines, tablets, desks, walls, buildings, garments, and soft-drink bottles. Millions of users will buy them in supermarkets, at newsstands, in bookstores, at the mall, in home-improvement stores, and at gas stations. And these users will invent new uses.

Many of us can imagine display technologies that could become ubiquitous. But can displays become affordable at newsstand prices? A square meter of microprocessor costs close to $500,000 and a square meter of AMLCD costs $2500, but a square meter of *National Geographic Magazine* costs less than 25 cents. We must bring displays much closer to the *National Geographic*. While microelectronic chips are made affordable by miniaturization, displays cannot take this route but instead must be made inexpensive by large-area manufacturing. The 2-D paper-like structure of flat-panel displays suggests that we do this by going from batch production (Gutenberg's press) to roll-to-roll manufacture (offset lithography). What are the technological and manufacturing hurdles? How are we doing at overcoming them? How long will that take?

Keys to the additive printing of displays are the "inks," printable materials with highly differentiated functions: RGB light reflector, filter or emitter, semiconductor, insulator, and conductor. These inks must be printed in finely resolved patterns, in overlayers that are in register and chemically compatible. We may use various "printing" techniques: wet, dry, impact, non-impact, embossing, indentation, and photochemical.

It is likely that the printing of displays will begin in batches, then incorporate pre-press techniques, and eventually move to roll-to-roll production. As they become economical, advances in the printing of individual functions will be introduced step-by-step. The printing of color filters for AMLCDs is a case in point.

Many laboratories have started work on the additive printing of thin-film electronics and displays. The situation is reminiscent of the late 1950s, when the transistor had begun enabling new products like the portable radio, but transistor technology was far from settled. I foresee a similar development in the direct printing of displays. Early products made partly by printing will come out within a few years.

Given that bringing a true innovation to manufacture in optoelectronics or semiconductors takes an R&D investment of 10,000 person-years, and that the

*continued on page 43*



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# OLED-Display Technology

*OLEDs are exciting not only because of their excellent front-of-screen performance, but because their flexibility invites many approaches to materials and device design.*

## by Kathleen M. Vaeth

THE DEVELOPMENT of lightweight displays with sharp saturated images, lower power consumption, and more compact dimensions than the cathode-ray tube (CRT) has been a key factor in enabling the growth of many portable electronic devices. The improvements in image quality and physical dimensions which these new display technologies have made possible also have made them attractive for non-portable electronic-imaging applications such as desktop computers and televisions.

The liquid-crystal display (LCD) has been the dominant alternative to the CRT for the past 20 years, but a technology based on electroluminescent emission from thin solid films of organic materials has emerged as one of the most promising next-generation imaging technology. These organic light-emitting-diode (OLED) displays exhibit wide viewing angles and can be very light in weight because they do not require a backlight.

The response times of OLEDs are generally on the order of a few microseconds, which, when combined with the saturated colors and excellent contrast, make the technology ideal for high-resolution video-rate applications. Unlike inorganic electroluminescent materials, the emission color from OLED materials can easily be tuned through proper molecular design, and emission colors have been demonstrated across the entire visible spectrum. In addition, OLED materials are generally amorphous so they do not need to be matched to the substrate's crystal lattice. These properties, in combination with favorable mechanical properties, expand the types of substrates that can be used and raise the possibility of flexible full-color OLED displays.

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Low-information-content OLED displays fabricated by Pioneer, TDK, Nippon Seiki, RiTdisplay, SNMD, and Philips have already been commercialized. In October 1999, Eastman Kodak Co. and Sanyo prototyped a full-color higher-resolution OLED display. Since then, SK Display – a joint venture of Kodak and Sanyo – and eMagin Corp. have begun manufacturing higher-resolution OLED-display products.

### Early Developments

An OLED is an organic transducer that converts electrical current into visible light. The two types of emissive materials that can be used in this current-driven device are small organic molecules and polymers. Although both classes of materials are highly conjugated organics, they are usually integrated into OLEDs by very different methods.

In either system, electrons and holes are injected into the organic layer during OLED operation, and diffuse under the influence of an electric field until they meet to form a loosely bound excited electron–hole pair known as an exciton. This exciton can radiatively recombine to a lower energy state, giving off a photon characteristic of the band gap of the organic material in the device. The region where electron–hole recombination occurs in the device is known as the recombination zone; its thickness and location are determined by the materials and structure used for the device.

Early efforts in OLED development started in the mid-1960s with studies of charge injection and luminescence from single crystals of small organic molecules such as anthracene. These early devices exhibited reasonable quantum efficiencies, but they had high operating voltages and, consequently, poor power efficiencies.

The poor performance of these early devices can be attributed to three main factors. First, there was a disparity between the mobility of the electrons and holes – often of several orders of magnitude – which caused electron–hole recombination to occur near one of the electrodes, where non-radiative recombination pathways for the exciton are more probable. Second, the poor film-forming properties of the materials used at the time required investigators to use thicker films, which resulted in higher device operating voltages. Third, there was typically a mismatch in the energy levels between the organic material and the electrodes in these early devices, which led to high-injection barriers at the device electrical contacts and, again, higher device operating voltages.

The significant breakthrough in OLED technology that addressed all three of these issues and laid the groundwork for realization of full-color OLED displays came in 1987,



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when Ching Tang and Steve Van Slyke of Eastman Kodak Co. reported a new OLED structure based on small organic molecules that exhibited light output of 100 cd/m$^2$ at under 5 V and power conversion efficiencies of 0.46%. Tang and Van Slyke realized that charge movement in the device could be better controlled with a double-layered structure of small organic molecules, in which one organic layer is specifically designed to facilitate hole injection and transport and the other layer is designed to facilitate electron injection and transport as well as device emission.

This structure allowed efficient transport of electrons and holes into the device, even though each of the materials used transported one carrier type significantly better than the other. The bi-layered structure also promoted efficient exciton formation at the organic–organic interface inside the device, which reduced luminance quenching by the electrodes and produced higher light output at lower injection currents. The hole- and electron-transport molecules were also designed to form smooth amorphous or microcrystalline films, which permitted the creation of thin (less than 100 nm) pinhole-free layers. These thin layers resulted in devices with much lower operating voltages.

Finally, the cathode was chosen to be a low-work-function metal, which significantly reduced the barrier to electron injection into the organic material and further lowered the device operating voltage. This seminal report produced an explosive growth in research of new materials and device structures for small-molecule-OLED applications in both academia and industry. In 1989, a group at Cambridge University's Cavendish Laboratory discovered that conjugated semiconducting polymers with band gaps in the visible

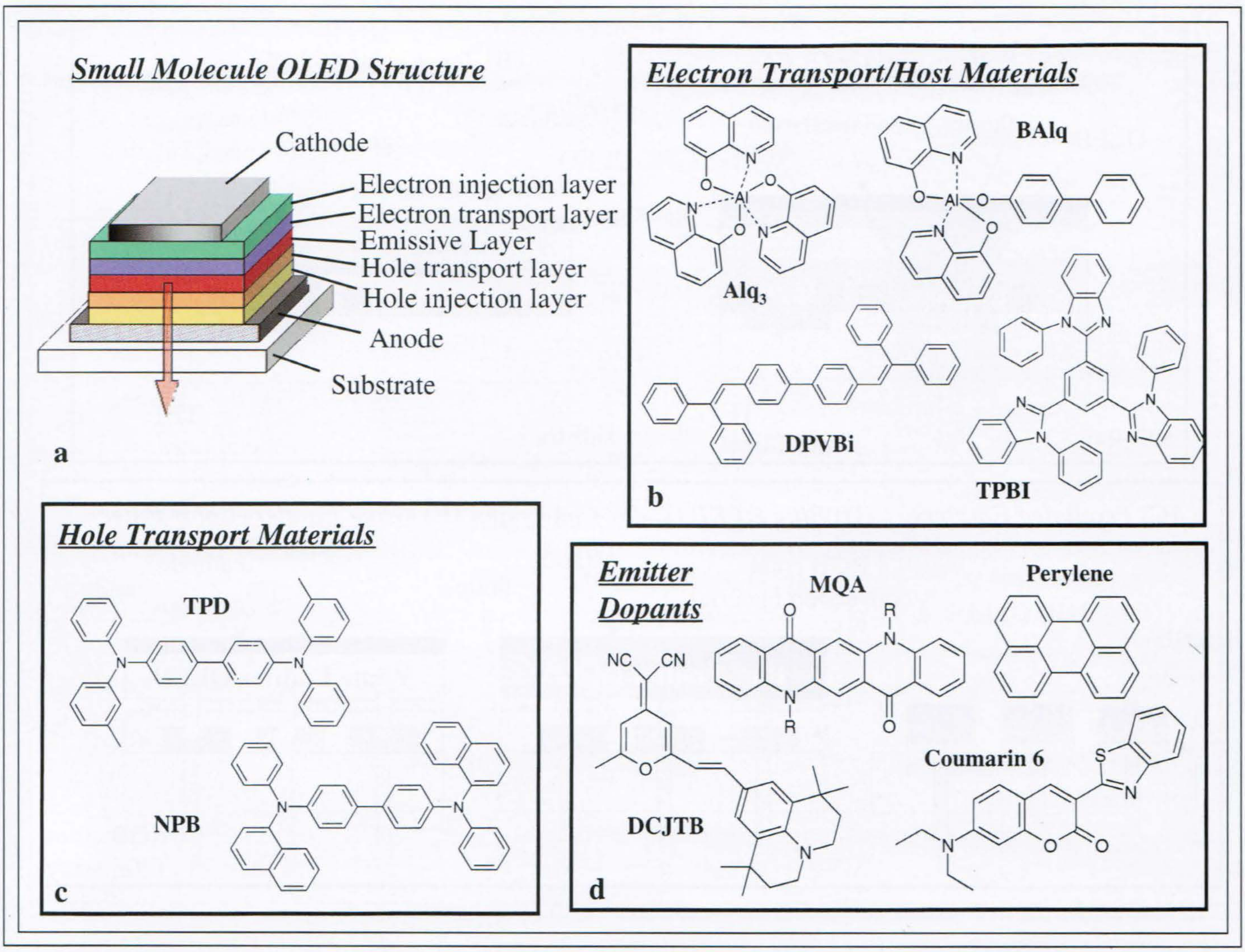


*Fig. 1: (a) A state-of-the-art small-molecule OLED has five distinct organic layers sandwiched between its metallic cathode and transparent anode. (b)–(d) The chemical structures of the hole-transport materials, electron-transport/host layer materials, and emissive-dopant materials have been carefully developed to optimize their individual functions.*

spectrum could also be used as the active element in OLEDs, which further broadened worldwide research in new classes of materials and device structures for OLED applications.

### Small-Molecule OLEDs

The structure of a state-of-the-art small-molecule OLED is a multi-layered stack consisting of an organic hole-injection layer, a hole-transport layer, an emission layer, an electron-transport layer, and an electron-injection layer, as well as an inorganic anode and cathode, all fabricated on a transparent substrate such as glass [Fig. 1(a)]. One advantage of the multi-layered structure is that the various functions of carrier injection, carrier transport, and emission can be separated into the different layers of the device, and the properties of these layers can be optimized separately. This flexibility has significantly broadened the classes of organic materials useful for OLED applications [Figs. 1(b)–1(d)].

Hole-transport materials are typically based on benzidines and triarylamines, which were originally studied for photoconductor applications. Metal chelates, conjugated hydrocarbons, oxadiazoles, and imidazoles are typically used for the emissive, host, and electron-transport layers. The molecules are usually purified by train sublimation and are readily available in purities greater than 99%.

The layers in a small-molecule device are deposited by thermal evaporation in a vacuum chamber at pressures less than $10^{-6}$ torr and are 5–100 nm thick. In full-color displays, the red, green, and blue (RGB) subpixels are patterned on the substrate using high-precision shadow masking. Indium tin oxide (ITO) is typically used as the transparent anode, and low-work-function metals – such as magne-

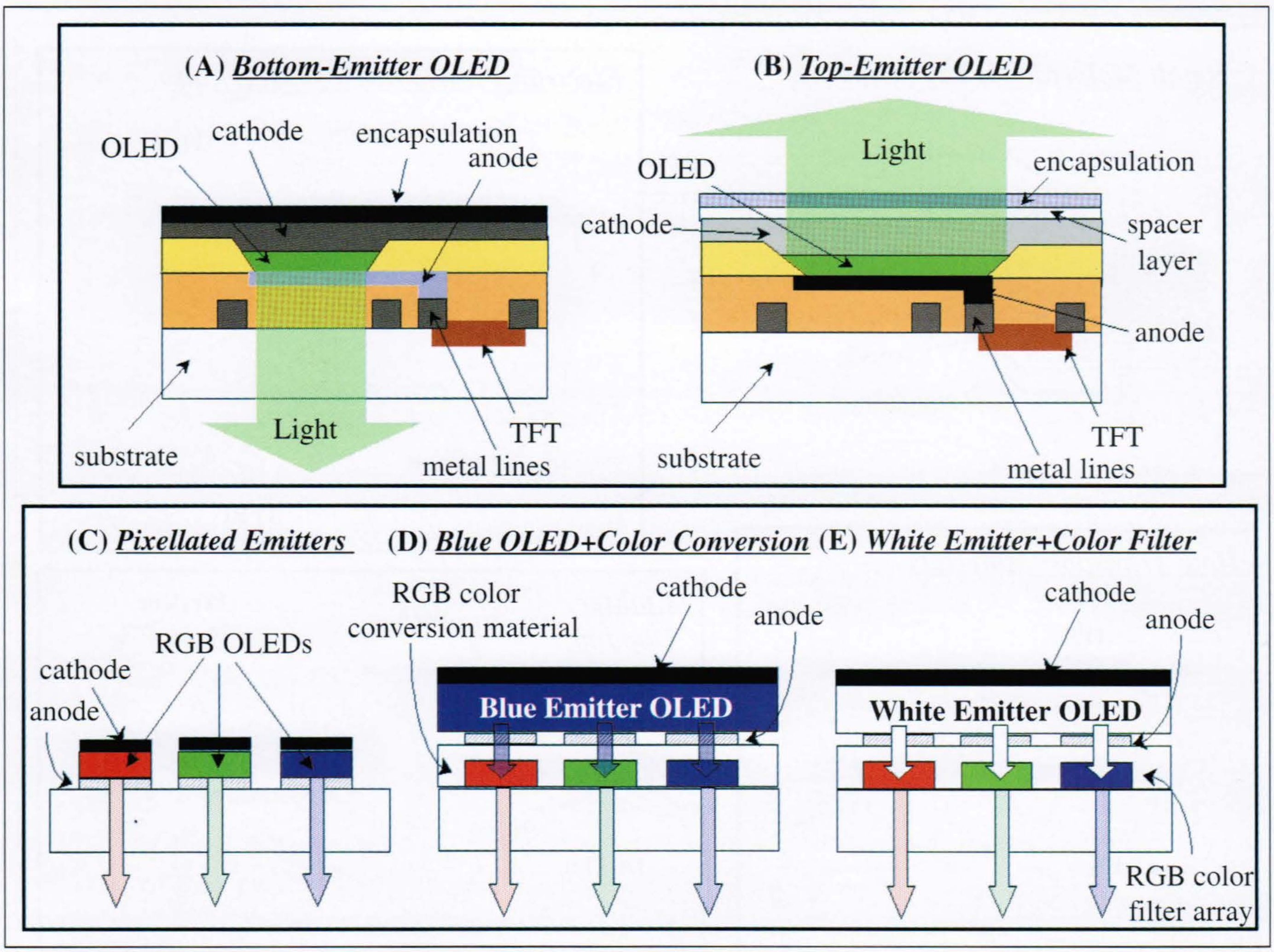


*Fig. 2: The most popular OLED structure has been the bottom-emitter OLED (a), but the top-emitter OLED (b) permits a larger aperture for the emission of light. Several ways of generating full color are available in OLEDs. RGB subpixels arrayed in a side-by-side pattern (c) are the most efficient but are susceptible to differential aging. A blue emitter with RGB color-conversion material (d) and a white emitter with a color-filter array (e) are less susceptible to differential aging but are less power efficient.*

sium:silver alloy or a thin layer of lithium fluoride salt backed by aluminum – are used for the cathode.

## Polymeric OLEDs

The typical structure of polymeric OLEDs differs in some ways from the typical small-molecule-OLED structure because polymeric-OLED materials are usually too large to evaporate and are typically integrated into the device by solution coating. The creation of a multi-layered organic structure by solvent processing requires that the solvent used to deposit a given layer be incompatible with the previously deposited organic layer. This can be difficult because the materials used for the hole, electron, and emissive layers of a polymeric OLED often have similar structures and solubilities.

Consequently, state-of-the-art polymeric OLEDs typically consist of a bi-layered organic structure, in which one of the layers is used for the injection and transport of holes, and the other is used for the injection and transport of electrons as well as emission. The organic layers are typically 5–200 nm thick.

The most commonly used material for the hole-injection-and-transport layer in polymeric OLEDs is a water-based dispersion of poly(ethylene dioxythiophene) and poly(styrene sulfonate) (PEDOT:PSS). The second device layer is an emissive co-polymer, usually based on polyfluorenes or polyphenylene vinylenes, with the composition tuned to optimize charge injection and transport as well as luminance efficiency. The RGB subpixels of a full-color polymeric-OLED display are typically deposited on a pre-patterned surface of the substrate by ink-jet printing. ITO is commonly used as the transparent anode, and metals such as barium, calcium/aluminum, or a thin layer of lithium fluoride salt backed by calcium/aluminum are used for the opaque cathode.

## Improving OLED Performance

The most active areas of research in both small-molecule and polymeric OLEDs have focused on improvement of the color purity, efficiency, and luminance stability of the devices. In most OLED systems, emission is based on fluorescence from an organic molecule [Fig. 1(d)] designed to have high luminescence efficiency, narrow emission spectra, and suitable color purity.

In order to avoid self-quenching of emission, the molecule is doped at a level of 0.5–2% by weight into a host organic molecule. During device operation, radiative excitons can form and recombine on the dopant directly, or be transferred from the host to dopant by a dipole–dipole interaction known as Förster energy transfer. Very effi-

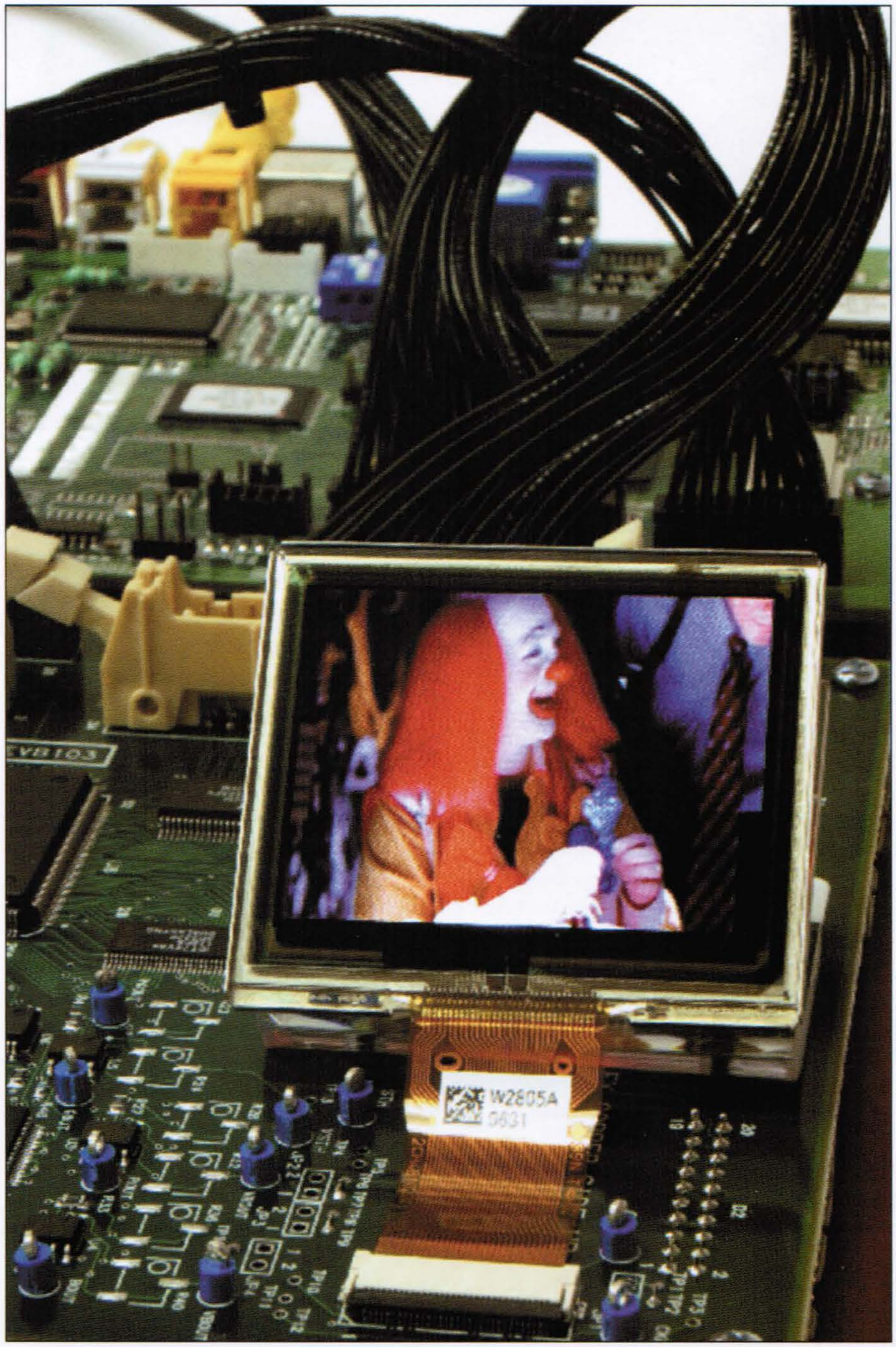


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***Fig. 3:*** *The award-winning AM550L active-matrix OLED display, jointly developed by Kodak and Sanyo, has a 521 × 218-pixel resolution and a diagonal of 2.16 in. It is 1.84 mm thick and weighs 8 grams.*


Eastman Kodak Co.

***Fig. 4:** Kodak and Sanyo have also developed this 14.7-in.-diagonal active-matrix OLED display prototype.*

cient luminescence is realized with this structure, in which the emission characteristics of the device are primarily determined by the dopant and the electrical properties of the emissive layer are primarily controlled by the host. A similar host–dopant approach is typically used for color tuning of polymeric-OLED emitters, either by incorporating the dopant emitter segment directly into the copolymer or by blending a small amount of an emissive molecule or polymer into a host polymer. The typical efficiencies and color coordinates for RGB OLED emitters are very suitable for full-color-display applications (Table 1).

One of the limitations of conventional fluorescent OLEDs based on either small molecules or polymers is that only singlet excitons provide a pathway for exciton transfer between the host and dopant for radiative electron–hole recombination, leaving triplet excitons, which can constitute up to 75% of the electron–hole pairs formed, to decay nonradiatively, *i.e.*, without producing light. This limitation can be overcome by using an appropriate phosphorescent dopant in combination with a suitably chosen fluorescent organic host. In this way, both singlet and triplet excitons formed in the host can potentially be harvested by the dopant and participate in device luminescence, resulting in significantly higher device efficiencies. Efficient luminescence with suitable color coordinates has been reported in such systems, particularly for the green part of the spectrum, where device efficiencies as high as 73 cd/A have been demonstrated.

### Luminance Stability

A great deal of progress has been made over the past decade in improving the long-term luminance stability of OLEDs (Table 2). The causes of luminance degradation in OLEDs are complex, but can generally be separated into two types: shelf and operational. In both small-molecule and polymeric OLEDs, poor shelf stability is mainly attributed to the formation of dark-spot defects. These arise from a deactivation of the cathode by reaction with water and oxygen, leading to a loss in device luminance over time [see the accompanying article, "Fighting OLED Degradation," by Gu Xu – *Editor*]. Dark spots can be controlled to a substantial degree through careful device fabrication and encapsulation, but permeation of water and oxygen becomes more critical when polymer and other non-glass substrates and encapsulants are used because these materials are relatively poor barriers to these contaminants.

**Table 1: Performance of RGB OLED Emitters**

| Emitter color | Electroluminescent efficiency @ 20 mA/cm$^2$ (cd/A) | CIEx | CIEy |
|---|---|---|---|
| Red | 3 | 0.63 | 0.37 |
| Green | 7 | 0.31 | 0.63 |
| Blue | 3 | 0.15 | 0.17 |
| White | 4 | 0.32 | 0.34 |

**Note.** Color coordinates and electroluminescent efficiency are listed for Kodak's red, green, blue, and white small-molecule OLED materials operating at 20 mA/cm$^2$.

Although the operational luminance stability of small-molecule and polymeric OLEDs is linked to a number of issues, including degradation of the organics and the organic–electrode interface, as well as to thermal instabilities, it typically scales with the amount of coulombic charge that passes through the device. Therefore, comparisons of the luminance stability of different OLEDs should be scaled to the operational time and current density to which the device is subjected.

Most of the development work on OLED displays has been done with a device structure consisting of a transparent substrate, transparent anode, opaque cathode, and opaque encapsulating layer, with the emitted light escaping from the device through the substrate. This structure is popular because of its excellent transparency, and the water–oxygen-barrier properties of glass, the good hole-injection properties and transparency of the ITO anode, and the opacity of the low-work-function-metal cathodes.

**Table 2: Progress in Device Half-Life (hours) at 5 mA/cm$^2$**

| Year | Red | Green | Blue | White |
|---|---|---|---|---|
| 1988 | 2000 | 1000 | | |
| 1998 | 10,000 | 4000 | 3200 | 3200 |
| 2000 | 32,000 | 12,000 | 12,000 | 12,000 |
| 2002 | >40,000 | >40,000 | >10,000 | >20,000 |

**Note.** The time in hours to half of the initial luminance ($T_{50}$) are listed for Kodak's red, green, blue, and white small-molecule OLEDs operating at 5 mA/cm$^2$.

One disadvantage of this bottom-emitter structure is that the emission aperture must share the substrate with the device electronics, potentially limiting the pixel aperture [Fig. 2(a)]. This can be avoided by using a top-emitter structure, in which the light escapes from the device through the transparent cathode and encapsulation [Fig. 2(b)]. The top-emitter structure also permits larger pixel apertures, so the same integrated light output can be achieved at lower current densities. In 2001, Sony demonstrated a 13-in. full-color OLED prototype display with top-emitter technology.

### Full-Color OLED Displays

As the lifetime, efficiency, and color purity of OLED materials and devices have improved, the fabrication of full-color displays has become a reality. Several subpixel configurations have emerged for the RGB emitters, including side-by-side patterns, the color conversion of a blue emitter, and the use of a white emitter in combination with a color-filter array [Figs. 2(c)–2(e)].

Each layout represents a balance between manufacturing complexity and power requirements. The side-by-side pattern of RGB subpixels is the most power-efficient configuration because the emitted light escapes directly from the device. This has been the configuration of choice for most full-color OLED displays. The layout does require critical patterning of the active organic, and image color shifts can become an issue if there is a significant disparity between the luminance stabilities of the red, green, and blue emitters.

The color-conversion and color-filter-array approaches avoid patterning the active organic and minimize image color shift over the display's lifetime – provided that the electroluminescence spectrum of the blue or white emitter does not change during operation. However, these approaches do have light loss associated with the color-conversion materials or the color-filter arrays, which can increase the power requirements of the display. Further improvements in OLED efficiencies and lifetimes may make these configurations more attractive in the future.

The two main types of electronic drive schemes used in full-color displays are passive- and active-matrix addressing. Passive-matrix addressing is suitable for low-cost and lower-information-content displays. Each pixel in a passive-matrix display is defined by the overlap of crossed anode and cathode lines, and electrical current is passed through the pixel by applying a voltage to the corresponding row and column from external drivers attached to each of these lines. The resistivity of the electrode lines, particularly the anodes, limits the passive-matrix drive scheme to smaller display sizes.

Video input to the display is implemented by successively scanning through all of the rows in a certain frame time, typically 1/60 sec. Because each pixel is only on during a fraction of this scanning cycle, the display is typically driven at large peak current densities to obtain high luminances, which are then integrated over the frame time by the viewer to an average luminance. These high current densities can promote additional mechanisms of device instability. Products utilizing passive-matrix OLED displays include automobile stereos (Pioneer and TDK), handheld games (RiTdisplay), and cellular phones (Pioneer, RiTdisplay, and SNMD).

The active-matrix drive scheme, which is more suitable for larger displays requiring higher resolution and low power consumption, relies on an integrated backplane of transistors and capacitors for pixel switching. The backplane transistors are frequently based on low-temperature polysilicon (LTPS) because of this technology's higher carrier mobility and consequent capacity to deliver current to the device.

In active-matrix addressing, each pixel is turned on to the desired brightness by an individual circuit, and can stay on during the entire frame time. Therefore, there are no inherent limitations in size or resolution with an active-matrix drive scheme, making it suitable for the fabrication of high-information-content OLED displays.

In 2001, eMagin Corp. began manufacturing a 0.61-in. OLED microdisplay featuring an integrated active matrix and drivers fabricated on a silicon wafer. In 2002, Kodak introduced a 2.16-in. active-matrix display product, the AM550L Evaluation Kit (Fig. 3). The Society for Information Display and *Information Display* magazine granted Kodak the 2002 Display of the Year Gold Award for this product.

The considerable progress made in OLED color purity, efficiency, and lifetime has made fabrication of full-color displays a reality, and high-information-content products based on OLED technology are now entering the marketplace. Future trends in OLED developments include larger-area displays, suitable for television screens and computer monitors, and flexible displays. In 2002, Eastman Kodak Co. and Sanyo jointly prototyped a full-color 14.7-in.-diagonal display based on OLED technology (Fig. 4), and Toshiba prototyped a 17-in.-diagonal display based on polymeric-OLED technology. Several lower-information-content flexible displays based on small-molecule and polymeric-OLED technologies have also been demonstrated.

Because of their sharp images, saturated colors, video-rate response times, wide viewing angles, light weight, and thin profiles, OLEDs hold great promise for a wide range of applications in the future. ■



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# Fighting OLED Degradation

*New research sheds light on the two ways in which OLED displays go dark, but the complete solution remains elusive.*

by Gu Xu

IN RECENT YEARS, organic light-emitting diodes (OLEDs) have become the subject of intensive research in many universities and industrial laboratories worldwide. Many believe that they have the potential to unseat the existing dominant technologies – cathode-ray tubes (CRTs) and liquid-crystal displays (LCDs) – but there are important technical obstacles that must be overcome.

OLEDs offer many advantages over existing display technologies. They can be made into very thin, sheet-like flat-panel displays of large sizes, which would be desirable replacements for the bulky vacuum picture tubes in TVs and computer monitors. They are also suitable for large high-resolution displays, unlike inorganic-semiconductor LEDs that are limited to very small sizes. And their emissive qualities give them a wide viewing angle, unlike some LCDs, which still have a limited viewing angle and need to be illuminated.

Flat-panel displays have a fast-growing annual market of US$20–30 billion, and there are many new applications for display devices. If OLEDs could be developed into a commercially viable technology, the rewards could be enormous.

The biggest problem that stands in the way of this success is that OLEDs have a short lifetime. On average, they have a lifetime of only a few hundred to a few thousand hours. In comparison, a normal CRT can last for about 100,000 hours, or about 12 years of continuous operation, and most other display technologies can also operate for more than 50,000 hours. The short lifetime of OLEDs makes them impractical; even automobile applications require a lifetime of at least 10,000 hours.

In the laboratory, an OLED lifetime of over 100,000 hours has been claimed by using accelerated testing methods, but lack of understanding of the degradation mechanisms makes it difficult to accelerate the testing reliably. The ability to control – and ultimately to eliminate – the fast degradation remains the major challenge.

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### The Two Aging Problems

The typical OLED display degrades in two separate and distinct ways. The first is

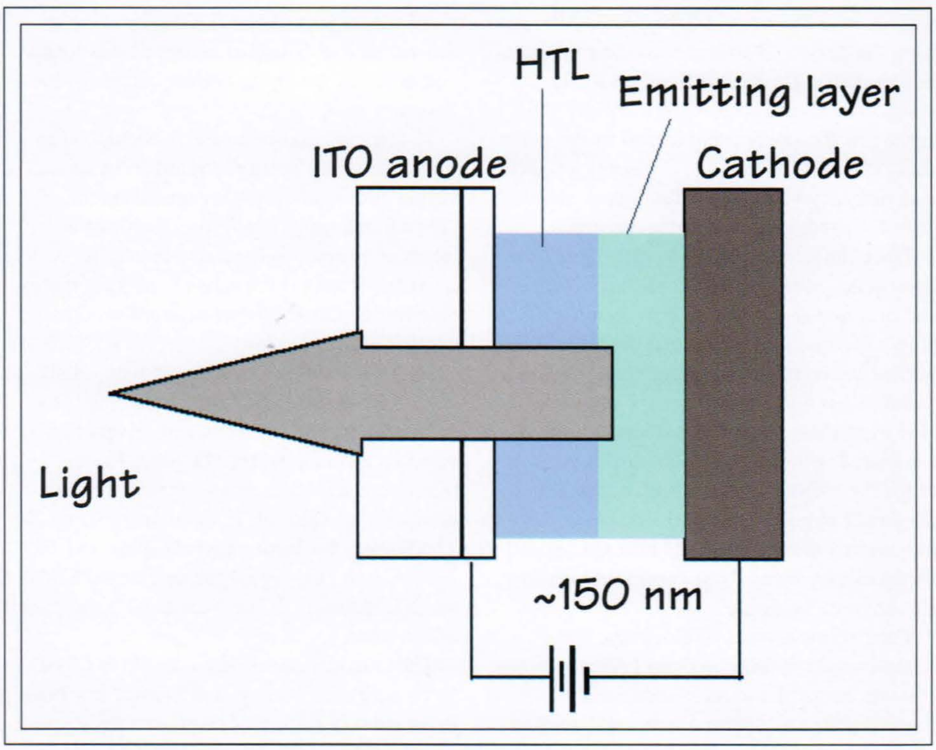


***Fig. 1:*** *This cross-sectional view of a typical OLED highlights its simple structure.*



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intrinsic degradation, a gradual decrease in luminance of the display phosphors that occurs during operation. One major problem today is that the blue phosphors employed in OLEDs age much more rapidly than the red and green phosphors, which creates problems in maintaining color balance and makes the overall lifetime of the display too short to be of practical use.

The other aging problem is known as dark-spot degradation, which is characterized by circular non-emissive areas that gradually cover a pixel. The growth of the dark spots contributes to the decay in the OLED luminance by reducing the operative area of the device. And, unlike intrinsic degradation that only occurs while the display is in use, dark spots can grow whether or not a device is in operation. As a result, dark-spot development also shortens the shelf life of an OLED display. Thus, the best reported lifetimes – up to 100,000 hours – achieved by accelerated testing may not be real because the process does not take into account the degradation of the shelf life. The acceleration serves only to increase the light emission, which is widely believed to speed up intrinsic degradation; Steve Van Slyke and colleagues developed the scaling rule in 1996: initial luminance × half-life = constant.

Until recently, little was known about these two different aging processes. In order to understand the origin of intrinsic degradation and dark-spot defects, one must first understand the structure and function of a typical OLED.

## OLED Structure

As first described by Ching Tang and Steve Van Slyke of Eastman Kodak Co. in 1987, an OLED based on small molecules has two organic thin-film layers sandwiched between metal electrodes. The anode is made of transparent indium tin oxide (ITO) and the cathode uses low-work-function metals such as calcium, magnesium, or lithium fluoride (LiF) plus aluminum (Fig. 1). One of the organic films, such as $Alq_3$ for green, serves as the electron-transport layer. The other film is the hole-transport layer (HTL) and usually uses NPB (N,N'-di(naphthalene-1-yl)-N,N'-diphenyl-benzidine) or TPD (N,N'-diphenyl-N,N'-bis(3-methyphenyl)-1,1'-diphenyl-4,4'-diamine).

OLEDs based on polymers have a similar structure, as described by Richard Friend and colleagues of Cambridge University in 1990. Ideally, the two electrodes will supply electrons and holes to meet in the juncture of the

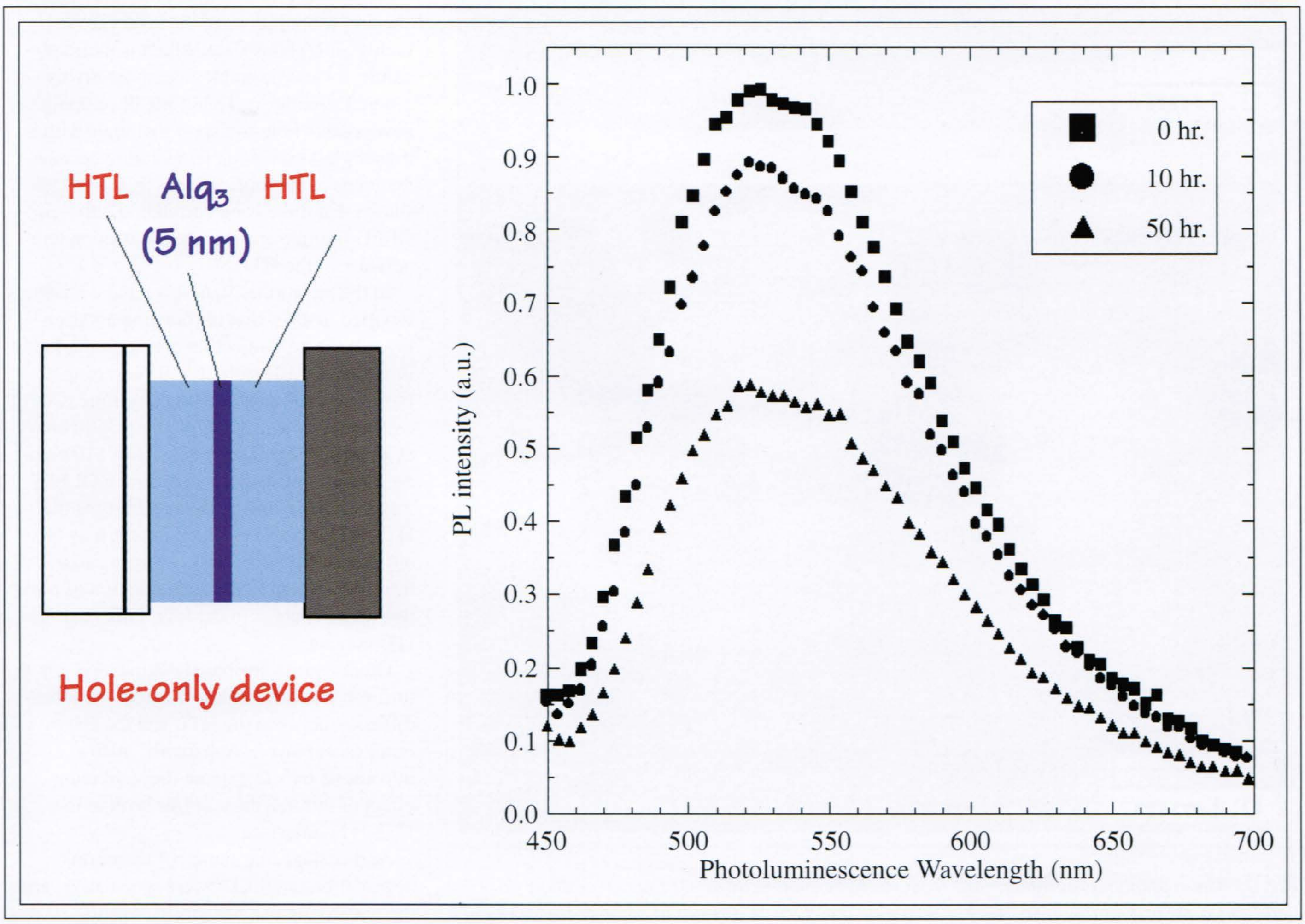


*Fig. 2: Over time, $Alq_3$ photoluminescence diminishes, demonstrating that it is unstable during prolonged current flow. (Courtesy of* Science.*)*

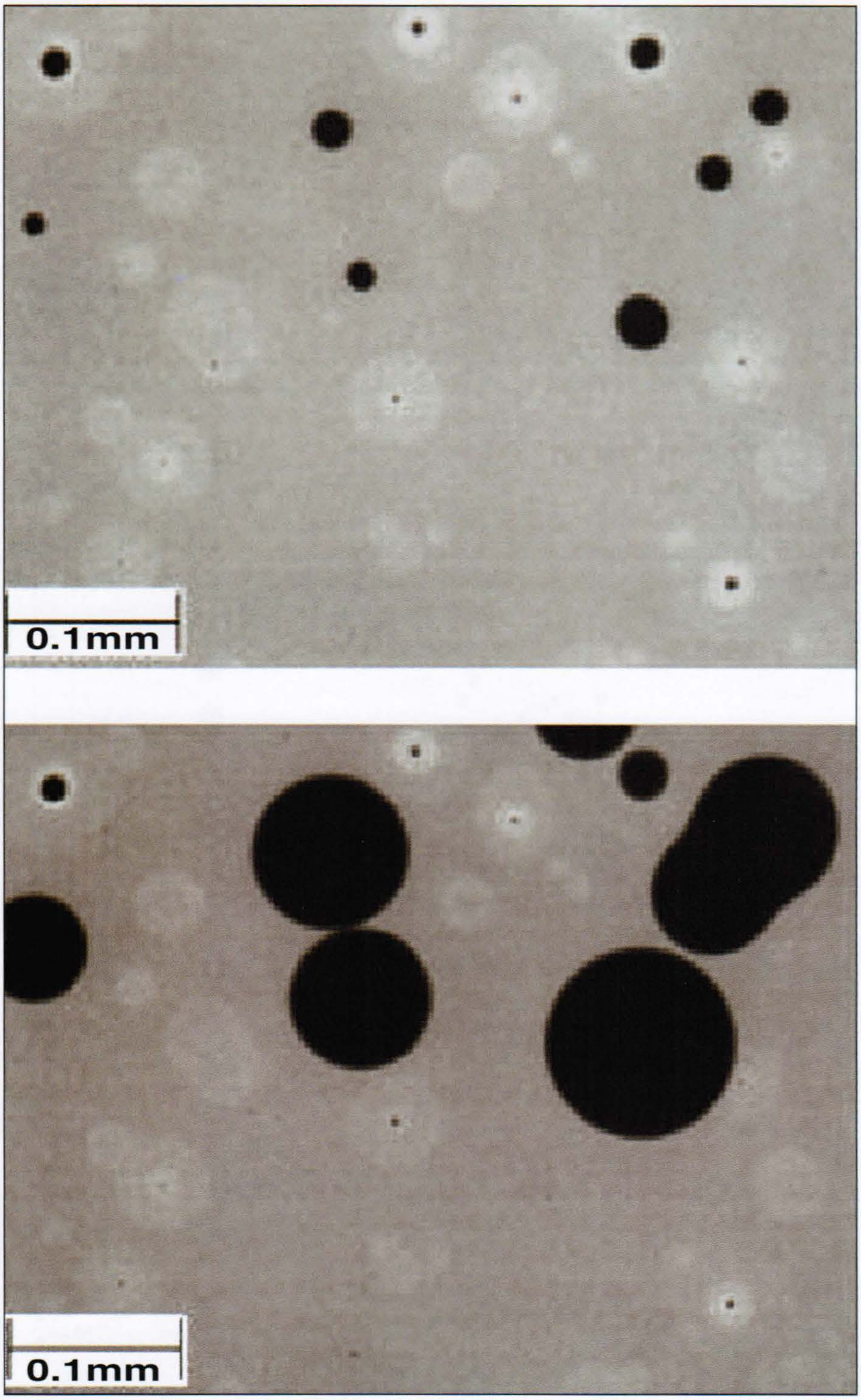


*Fig. 3: These photomicrographs made from the light emitted by an OLED device show dark and light spots originating from the $Alq_3$–cathode interface as a result of cathode replacement. The lower image shows the same device after being stored for 48 hours in ambient conditions. (Courtesy of* Applied Physics Letters.*)*

two organic layers, where the electron–hole recombination will take place to produce electroluminescence. The devices are fabricated by ITO patterning, vacuum deposition or spin coating of organic thin films, and evaporation of the metal electrode.

### Fading Light

Obviously, the most important step toward understanding the degradation is to identify the origins of the degradation processes. Studies of the intrinsic degradation in OLEDs are relatively few. One of the possible causes was the morphological instability of the organic layers, especially the HTL. This layer is usually made of organic materials from the diamine group, which is generally characterized by relatively low glass-transition temperatures, usually in the range of 60–120°C.

Organic layers in OLEDs are fabricated by vacuum evaporation, so the layers are in a highly amorphous state, which is thermodynamically less desirable than more highly ordered structures. Therefore, developing new organic hole-transport materials with a higher glass-transition temperature became the focus at the time. However, it was later shown that there is no correlation between OLED lifetime and the glass-transition temperature of the HTL.

In the meantime, Van Slyke and colleagues reported in 1996 that introducing a buffer layer at the hole-injection contact remarkably improved OLED stability. By inserting a buffer layer of copper phthalocyanine (CuPc), they achieved a lifetime of about 3500 hours at an initial luminance intensity of 510 cd/m$^2$. As a result, intrinsic degradation in OLEDs was then attributed to the instability at the ITO–HTL interface, which in turn may be attributed to the formation of deep carrier traps which lead to the accumulation of positive space charges in the HTL bulk near the ITO contact.

Other reports attributed degradation – both intrinsic and dark-spot formation – to interdiffusion between the HTL and the electroluminescent layer. Apparently, such a hypothesis fails to explain the stabilizing effect of introducing a buffer layer at the ITO–HTL interface.

At this stage, the causes of the intrinsic degradation in OLEDs were speculative, and the underlying mechanisms were still unknown by 1996. In addition, the effectiveness of the approaches used to achieve stable

OLEDs remained limited to certain OLED-material systems. Adding a buffer layer in these distyrylarylene-based blue-emitting devices had little or no effect. The OLED lifetimes could be increased only by doping the electroluminescent layer and not the HTL – as is usually the case in other OLEDs. Even then, the best lifetime was only 5000 hours at an initial luminance intensity of 100 cd/m$^2$.

Recent research has unveiled a better understanding of the intrinsic degradation; the injection of holes in $Alq_3$ is the main factor responsible for device degradation. This was verified by the fact that the photoluminescence quantum efficiency of $Alq_3$ layers – where holes are predominantly transported – decreases as a function of prolonged current flow. *In situ* measurements were carried out to monitor changes in the photoluminescence quantum efficiency of the $Alq_3$ layer. The results show a gradual decrease in the peak height of the PL spectra of $Alq_3$, revealing a continuous decrease in the photoluminescence efficiency of the $Alq_3$ during prolonged current flow (Fig. 2).

The decrease in the photoluminescence quantum efficiency of this layer points to degradation as a result of current flow. As the layer predominantly transports holes, the observed fluorescence decrease indicates that cationic $Alq_3$ species most probably promotes the formation of fluorescence quenchers.

These findings explain the different approaches to stabilizing OLEDs, such as doping of the HTL, introducing a CuPc buffer layer at the hole-injection contact, or using a mixed emitting layer of hole- and electron-transporting molecules. The findings also changed, to a certain extent, the usual design concept. Instead of trying to optimize hole or electron transport by introducing multiple layers of organic semiconductors, a more important step is to make sure that the electron and hole flows are balanced, so that the flow of holes into the electron-transport layer ($Alq_3$ in this case) is minimized.

### The Mystery of Dark Spots

On the dark-spot side, the story begins with several studies focused on dark-spot degradation phenomena. They seem to suggest that the dark spot is caused by various humidity-induced mechanisms which lead to (1) electrode destruction, (2) morphological changes in the electroluminescent layers, or (3) degradation at the electrode–organic-layer interface. Because ambient moisture plays a critical role in these mechanisms, dark-spot degradation is believed to be effectively controlled by encapsulating the OLEDs in a dry atmosphere.

In a recent study, the search for the exact origin of the dark spots was advanced by a simple strategy that has been known for some time: remove the cathode of a device and then quickly deposit a new cathode. This method reveals a surprising result. The dark spots that developed initially disappear after the cathode is replaced. However, a whole new series of dark spots begin to appear. The same procedure can be repeated, each accompanied by the disappearance of the existing dark spots and the creation of a new group.

This study provides a great deal of new knowledge about the dark spots. First, it shows that the original emissive material ($Alq_3$ or others) is still functional after repeated dark-spot development cycles. It also shows that neither the ITO anode nor the HTL appears to play a role in dark-spot formation. Most importantly, the dark spots must be generated at the organic-layer–cathode interface and created during cathode deposition. It was verified that dark-spot growth is not limited to $Alq_3$ molecules; other emissive organic molecules show the same behavior. Finally, it was found that after cathode replacement, brighter circles took the place of the old dark spots (Fig. 3).

Although a number of mechanisms for the formation of dark spots have been postulated, the causes underlying their initiation and nucleation sites remain unclear. Further examination of the metal–organic-layer interface is necessary in order to completely understand and to ultimately remove the dark spots.

### Long Live OLEDs

Both the intrinsic and dark-spot degradation problems must be thoroughly understood and resolved in ways that allow practical device fabrication, or OLED technology may never reach its full potential. The benefits of lightweight low-power bright emissive OLED displays are tantalizingly close at hand, but without further improvements they will not last long enough to be commercially viable in many otherwise attractive applications. ■

# Phosphorescent-Polymer OLEDs

*The first phosphorescent-POLED display demonstrates simple structures and high efficiency.*

by Shizuo Tokito, Mitsunori Suzuki, and Fumio Sato

ORGANIC light-emitting diodes (OLEDs) have stirred up interest in the display industry. Both small-molecule-OLED (SMOLED) and conjugated-polymer-OLED (POLED) technologies offer the potential for thin, lightweight, durable, and bright displays with excellent color, response time, and viewing angle.

Early demonstrations are encouraging. Several Japanese companies have developed a 14.7-in. full-color SMOLED display and a 17-in. full-color POLED display – the largest POLED screen demonstrated to date – which was fabricated using ink-jet printing.

POLEDs could be the basis for large-area fine-pixel displays because the polymer film can be prepared by using a solution process such as spin coating, screen printing, or ink-jet printing. The polymeric materials are also suitable for a flexible display using a plastic-film substrate because the materials are mechanically flexible.

### The Challenge of Efficiency

A number of hurdles must be surmounted before OLED displays can become commercially viable. One key challenge is efficiency. The quantum efficiency of POLED light emission is below 5% because the emission has been limited to the singlet state. The emission efficiency of SMOLEDs received an enormous boost by using a phosphorescent small-molecule material – an iridium complex – that emitted light from its triplet states. A green phosphorescent OLED demonstrated an external quantum efficiency of nearly 20%, which implies 100% internal quantum efficiency. Highly efficient red and blue emissions were also obtained from similar iridium complexes that had a suitable choice of ligands.

Unfortunately, these highly efficient phosphorescent SMOLEDs have complicated structures consisting of a hole-transporting layer (HTL), an emissive layer, a hole-blocking layer, and an electron-transporting layer (ETL). These layers require strictly controlled sequential depositions under high-vacuum conditions. If efficient OLED displays are to be produced at a competitive cost, the device structures and fabrication methods must be much simpler.

### Phosphorescent Polymers

One approach to the problem would be to use phosphorescent components in a POLED design. Previous attempts involved doping a phosphorescent small-molecule material into a hole-transporting polymer, resulting in good efficiencies for green. But this POLED's molecularly doped polymer system might be subject to problematic phase separation, resulting in non-uniform emission and decreased emission intensity.

Recently, we reported a new approach in which a phosphorescent polymer is chemically bonded to a hole-transporting-polymer

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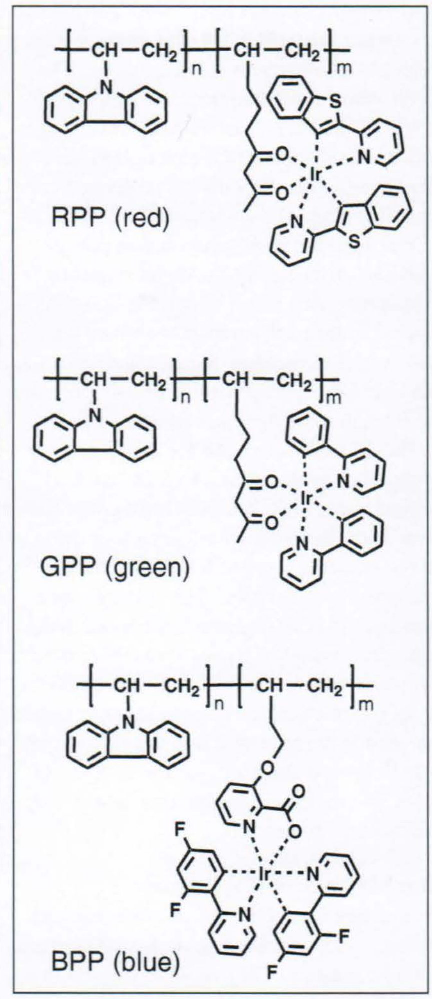


***Fig. 1:*** *Connecting an iridium complex to the vinyl-polymer backbone creates phosphorescent polymers.*



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backbone as the side group. The resulting fabrication process is much simpler than that for phosphorescent SMOLEDs, yet holds forth the promise of higher efficiency. J. J. Kim and his colleagues independently reported a similar approach, but they obtained a low quantum efficiency of 0.38% for the green emissive polymer.

We have created phosphorescent polymers that have a high molecular weight and exhibit higher quantum efficiencies in each of the three primary colors: red, green, and blue. We have also created white-light emission using blue and red phosphorescent polymers. And we have demonstrated a prototype 3.6-in. display based on a green phosphorescent polymer.

## Phosphorescent-POLED Structure

The basic structure of a phosphorescent polymer consists of a co-polymer of a charge-transporting unit and a phosphorescent unit. The ratio of the phosphorescent unit to the charge-transporting unit is very low in order to enhance the phosphorescence yield. The molecular structures of the red (RPP), green (GPP), and blue (BPP) phosphorescent polymers synthesized in this research show their similarities (Fig. 1). For the phosphorescent unit, the iridium complex is connected through an alkyl group with a vinyl-polymer backbone. For the charge-transporting unit, carbazole is directly bonded to the backbone.

The concentration of iridium-complex units in the polymers can be easily controlled during the co-polymerization of a vinyl monomer with carbazole and a vinyl monomer having an iridium complex varying from 0.2 to 2 mol.%. The molecular weight of the polymers determined by gel permission chromatography (GPC) was around 13,000 grams/mole. These polymers are soluble in common organic solvents and can be formed into uniform films from the solution by spin coating.

The phosphorescent polymers show intense light emission in neat powders and organic solvent solutions under irradiation of UV light (wavelength of 364 nm). Measurements of transient photoluminescence decay are very useful in elucidating the light-generation mechanism in the material. The decay profiles of light intensity exhibited single exponential decays and relatively long lifetimes:

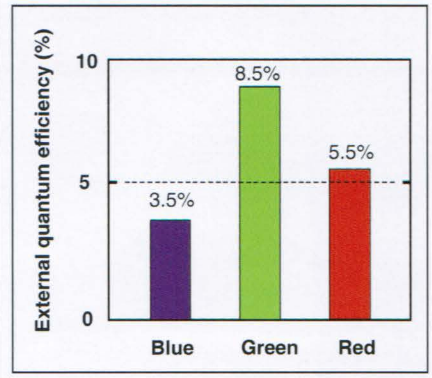


*Fig. 3: The measured external quantum efficiencies of red and green phosphorescent POLEDs are among the highest reported.*

1.1 μsec for BPP, 2.1 μsec for GPP, and 4.6 μsec for RPP. This indicates that the light generation in the phosphorescent polymers is from triplet states and that all the energy in the singlet state is transferred to the triplet states. Thus, light emission in these polymers is undoubtedly phosphorescence.

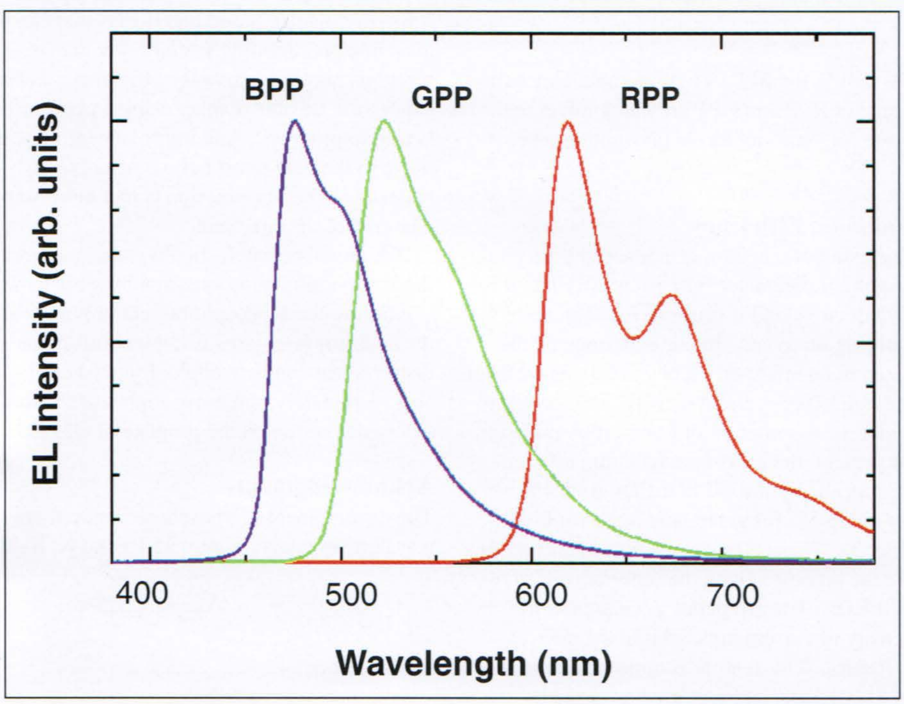


*Fig. 2: The electroluminescence spectra for three different phosphorescent POLEDs show blue-, green-, and red-light emissions.*

## POLED Fabrication

The POLEDs consist of a transparent anode, a conducting polymer layer, an emissive layer, and a metal cathode. Fabrication is carried out under nitrogen atmosphere. The conducting polymer layer (PEDOT:PSS, 50 nm) on the indium tin oxide (ITO) electrode is used for hole injection to the emissive layer. First, the conducting polymer layer is spin-coated on the ITO-coated glass substrate. Next, a 90-nm emitting layer consisting of phosphorescent polymer (70% by weight) and an electron-transporting material (30% by weight) is prepared from a dichloroethane solution by spin coating on the conducting polymer layer. In our study, the well-known oxadiazole derivative was used as the electron-transporting material. Finally, for the cathode, a bi-layered system of Ca (30 nm) and Al (100 nm) is formed by vacuum deposition. POLEDs that emit white light can be fabricated using two phosphorescent polymers (BPP and RPP) for the emissive layer. The devices are encapsulated using glass plates and UV epoxy resin.

## POLED Performance

The resultant POLEDs emit light if a voltage of 5–6 V is applied between the ITO and the


*Fig. 4: A prototype 3.6-in. green display using passive-matrix addressing achieved five levels of gray and fast response times.*

Al electrode. The electroluminescence (EL) spectra for three POLEDs have peak wavelengths of 475 nm for blue, 523 nm for green, and 620 nm for red phosphorescent polymers (Fig. 2). The color coordinates of the red and green are comparable to those of NTSC, but the blue emission is greenish blue and is not adequate.

These spectra are coincident with the photoluminescence spectrum of each polymer, which clearly indicates that the light emission is generated from the phosphorescent units in the polymers. An emission at around 430 nm – attributable to the carbazole moiety – is not observed in these POLEDs. One probable mechanism for the light generation is that excited carbazole units or excited electron-transporting molecules generated by the recombination of injected holes and electrons transfer energy to the iridium-complex units. Another is the recombination of holes and electrons directly on the iridium-complex units. The optimal concentration of the iridium-complex unit in the polymers is around 0.2 mol.% for RPP, 0.6 mol.% for GPP, and 1.0 mol.% for BPP. These optimal concentrations for RPP and GPP are much lower than those for small-molecule phosphorescent OLEDs.

## Emission Efficiency

The external quantum efficiency is a very important parameter for current-driving emissive devices, and it is useful for evaluating the emitting materials. In our experiments, the external quantum efficiency is calculated from the luminance, current density, and spectrum under the assumption of Lambertian emission. At present, the maximum quantum efficiencies for the optimized POLEDs are 5.4% for red, 8.5% for green, and 3.5% for blue (Fig. 3). These efficiencies for red and green are the highest among the reported values for POLEDs. The efficiency decreases as the density of current injected into the devices increases. This feature is quite similar to that of SMOLEDs, and it might be caused by triplet-triplet annihilation.

The POLED with a single emissive layer containing BPP and RPP emits both blue and red light, which is combined to create white light. In order to achieve white emission, the ratio of RPP to BPP is a key factor, which is related to the energy transfer and light generation in the emissive layer. The external quantum efficiency of the white emission is 4.5%, which is the highest among the reported values for POLEDs. The white POLED would be useful as a backlight for flat-panel displays and for lighting.

## Prototype Display

To evaluate the abilities of the phosphorescent polymers in a display, we fabricated a prototype 3.6-in. passive-matrix display with $70 \times 70$ lines using the GPP (Fig. 4). The conducting polymer and GPP layers were prepared by spin coating. The display showed sharp images with a fast response time. We measured a luminance of 100 cd/m$^2$, and, by controlling the applied voltage, created five gray levels. As mentioned above, the efficiency decreases with increasing current density. Therefore, the phosphorescent polymers should be suitable for active-matrix displays driven by thin-film transistors.

## The Next Steps

The ultimate goal of our research is a flexible full-color display based on OLEDs that can be used in a broadcasting system. We are currently trying to improve the efficiency. Fabrication of a flexible display using a plastic film is also in progress. And improvement must be made to the blue phosphorescent-polymer material so that its emission is in a more suitable part of the spectrum.

Additional research should yield answers to these remaining questions, and may open the way to use these phosphorescent polymers as the basis for large-area fine-pixel full-color displays that can be readily produced at low cost. Ultimately, these materials may be the key to delivering on the promise of OLEDs.

## Acknowledgments

The development of phosphorescent polymers was done in cooperation with Denko K. K. ■



Circle no. 10

# Reading the Roadmaps

*Rapidly evolving manufacturing techniques and novel technologies make forecasting the future of displays a challenge, but it is possible to locate some very informative mileposts.*

## by Norman Bardsley

THE flat-panel-display (FPD) industry is evolving at such a rapid pace that it is difficult to predict the speed or direction of future developments, even for liquid-crystal displays (LCDs), which are the dominant technology. Just a few years ago, it seemed that poly-silicon thin-film-transistor (poly-Si TFT) backplanes would rapidly replace their amorphous-silicon (a-Si) counterparts in most LCDs. This promised the integration of driver ICs on the glass of notebook PCs, as well as on smaller panels, and to enable the development of intelligent pixels and more adaptable addressing schemes. But the cost of external drivers has dropped more rapidly than that of poly-Si electronics, and the a-Si empire has grown ever wider. Almost all predictions regarding the size and resolution limits of a-Si LCDs have proved too conservative.

Lighting for LCDs is another area that has been affected by rapid technology evolution. The need for auxiliary lighting in reflective displays was initially met through front lights, but now almost all manufacturers have turned to transflective displays in which each pixel is divided into transmissive and reflective regions. The formidable challenge of achieving high contrast and vivid color in reflective-LCD panels is being met through a combination of new technology and judicious design compromises, mainly involving restrictions in viewing angle.

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Two valuable documents aimed at providing guidance on future trends for display users and suppliers to the industry – as well as display manufacturers – have been published in the past year. The Phase IV report of the Production Cost Saving Forum, organized by SEMI Japan, provides a 10-year roadmap for LCD technology. An English translation is now available from SEMI at www.semi.org.

A much broader perspective is given in the report from the United States Display Consortium (USDC) (www.usdc.org) entitled "The Global Flat Panel Display Industry 2003: An In-Depth Overview and Roadmap on FPD." Since this roadmap is written in English and aimed mostly at readers outside Asia, the emphasis is on FPD applications and the development of alternative technologies. Nevertheless, it includes a substantial chapter on LCD technology, both as a guide to display integrators and users and to encourage devel-

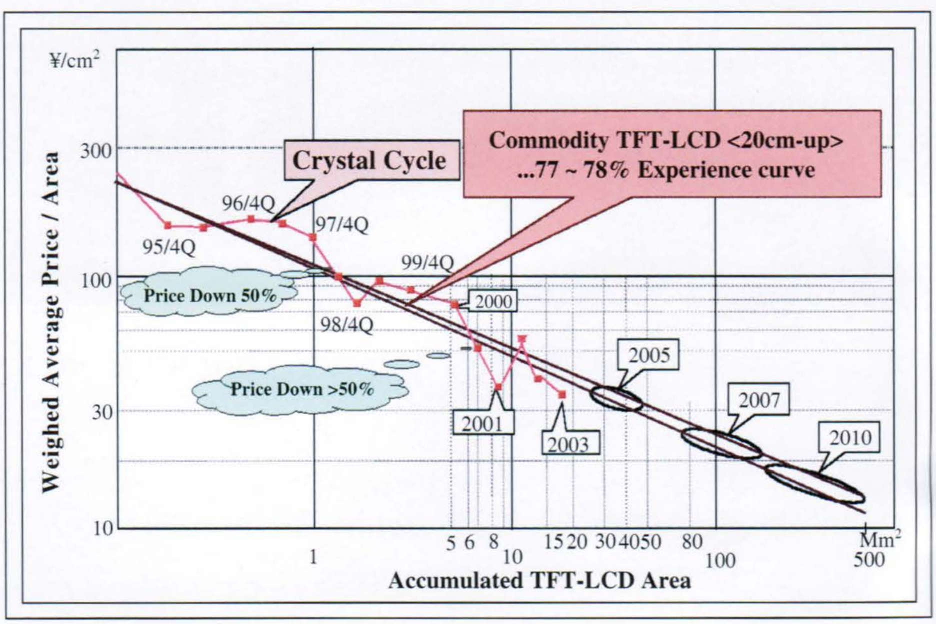


***Fig. 1:** Odawara's Law relates manufacturing experience to declines in costs, which are less volatile than short-term fluctuations in selling price. (Courtesy of Kozo Odawara.)*



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opers of competing technologies to set their goals high enough to exceed future progress in LCDs.

Before we can fully grasp or plan for the next phase (or next several phases) of LCD-technology development, it is important to examine its history and gain an understanding of how the industry arrived at its current status.

## Moore's Law for the FPD Arena

LCD manufacturing has evolved to the point where three FPD equivalents of Moore's Law have been identified and proposed by experts based in Japan. Each is based upon a 3-year period, which corresponds approximately to the cycle of FPD supply-and-demand fluctuations and to the development of new generations of manufacturing equipment.

Nishimura's Law predicts that the size of the substrates used grows by a factor of 1.8 every 3 years. This gives a doubling period of 3.6 years; in contrast, the size of IC wafers is only doubling every 7.5 years. The size predictions do seem to be on target; LCD substrates over 4 $m^2$ may well be in use by 2010.

Kitihara's Law describes the evolution of LCD panels in three parts. In each 3-year cycle, the average screen area grows by 44%, while the thickness and weight shrink by one-third, and the power consumption needed to provide a given functionality decreases by 44%. The fourth part of Kitihara's Law relates to information content, measured by the number of bits necessary to specify the image on the screen. This has been increasing fourfold each 3-year cycle, matching Moore's Law for ICs.

One final empirical relationship relates to panel prices. In a form of the generic learning curve, Odawara's Law states that for each doubling in the cumulative area of flat panels produced, costs are reduced by 22–23% (Fig. 1). The anticipated production of 100 million $m^2$ of AMLCDs by 2010 should lead to prices for large panels of about ¥23 per $cm^2$. At the present conversion rates, that is about $1.25 per square inch. Most U.S. analysts believe that this prediction is too conservative and that prices will drop below $1.00 per square inch for the most popular panels before the end of this decade. Of course, the high cost of electrical connections means that the price of small panels cannot be assessed on the basis of panel area alone. The cost of a full-color AMLCD cellular-phone display is expected to remain about six times higher than this formula would predict. This high price provides a market entry point for AMLCDs made with poly-Si TFTs and may do the same for newer technologies, such as OLEDs and electronic paper.

## The Battle for the Big Screen

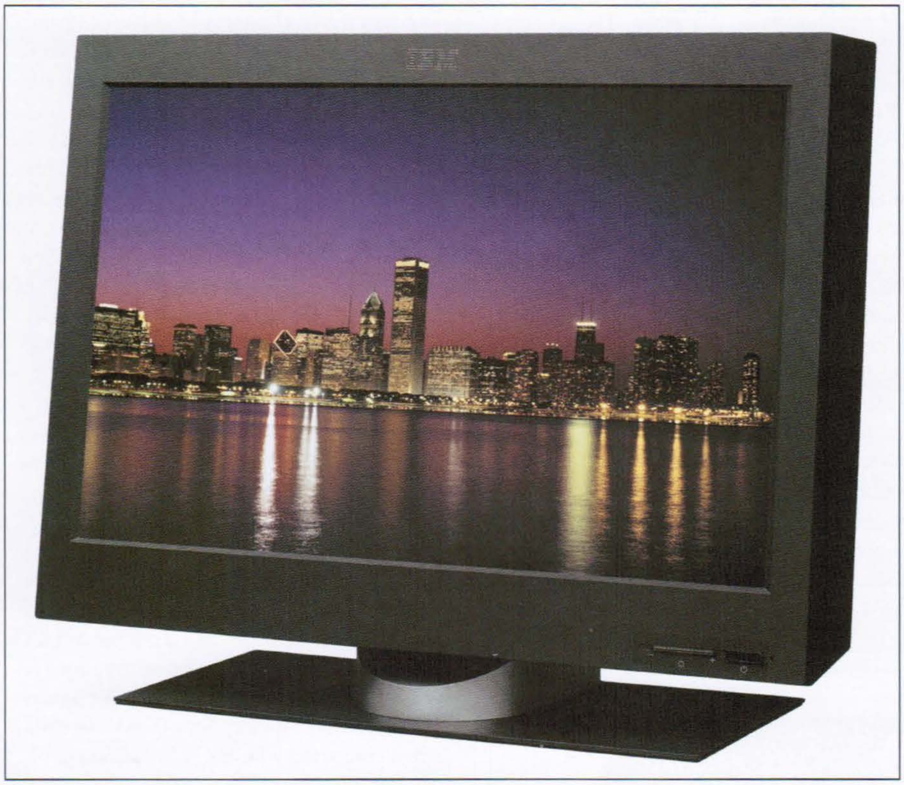
AMLCD technology is also vulnerable to attack in the battle for the large-screen-TV and home-theater markets. Traditional LCDs – as used in notebooks and desktop monitors – are deficient in response speed, color saturation, and image quality for off-axis viewing when compared with the "old-fashioned" cathode-ray tube (CRT). Alternative technologies, such as emissive flat panels and DLP-based projectors, are potentially more suitable for these applications. But LCD manufacturers are eager to capture this market, and progress is being made on all fronts.

Faster materials, thinner gaps, modes such as optical compensated bend (OCB), and flashing backlights are just some of the new approaches that have driven response times of prototype displays to well below 5 msec. Light-emitting-diode (LED) backlights with matched color filters lead to color gamuts well beyond those specified by the U.S. and European standards agencies: NTSC, sRGB, and EBU. Modes such as in-plane switching (IPS) provide off-axis viewing that is adequate for many applications.

The rapid progress being made in LCD response time and LED backlights raises the possibility that the color filter can be eliminated through the use of field-sequential color. This approach has already been successful in projection systems that use digital micromirror devices (DMDs). The removal of the color filter would lead to much higher efficiency and wider color range while eliminating one of the most expensive components in current LCD panels.


Sanyo-Kodak

*Fig. 2: The Sanyo-Kodak prototype 14.7-in. OLED panel shows the vivid images and thin profile that are possible with this technology.*




IBM

*Fig. 3: The IBM T221 with 9.2 Mpixels (3840 × 2400) arose from a contract with the U.S. Department of Energy (unauthorized use not permitted).*

So far, the only large-area emissive FPD technology that has been successful in the market is the plasma-display panel (PDP). Most initial sales were to commercial organizations to display information in settings such as trade shows, reception areas, and public thoroughfares. If this success is to be repeated in the consumer market, the manufacturing cost and channel mark-ups must be reduced substantially. Technical improvements are also needed, including increased contrast under bright ambient lighting conditions and longer display lifetime.

The status of DMD-based projectors is similar to that of PDPs. This technology relies on an array of moving mirrors to modulate the light from a compact light bulb, and it has gained market dominance for both ultra-portable and large-venue projection systems. The major challenge to manufacturers of projection systems for the home is again cost. Substantial reductions are necessary in the cost of the lamp, the optical components, and the screen, as well as in the light modulator itself.

Systems built using liquid-crystal–on–silicon (LCoS) light valves also have strong potential in this market; prototype LCoS rear-view projection systems now boast excellent image quality. These systems also require significant cost reductions if they are to become competitive in consumer products.

## The Potential of Future Technologies

What about innovative FPD technologies, such as organic light-emitting diodes (OLEDs) and electronic paper? Is the discovery of carbon nanotubes or other new cathode structures going to lead to a revival in field-emission displays (FEDs)? These questions cannot be answered by simple empirical laws. There is certainly no shortage of academic papers or patents for any of these approaches, but neither papers nor patents assure profits.

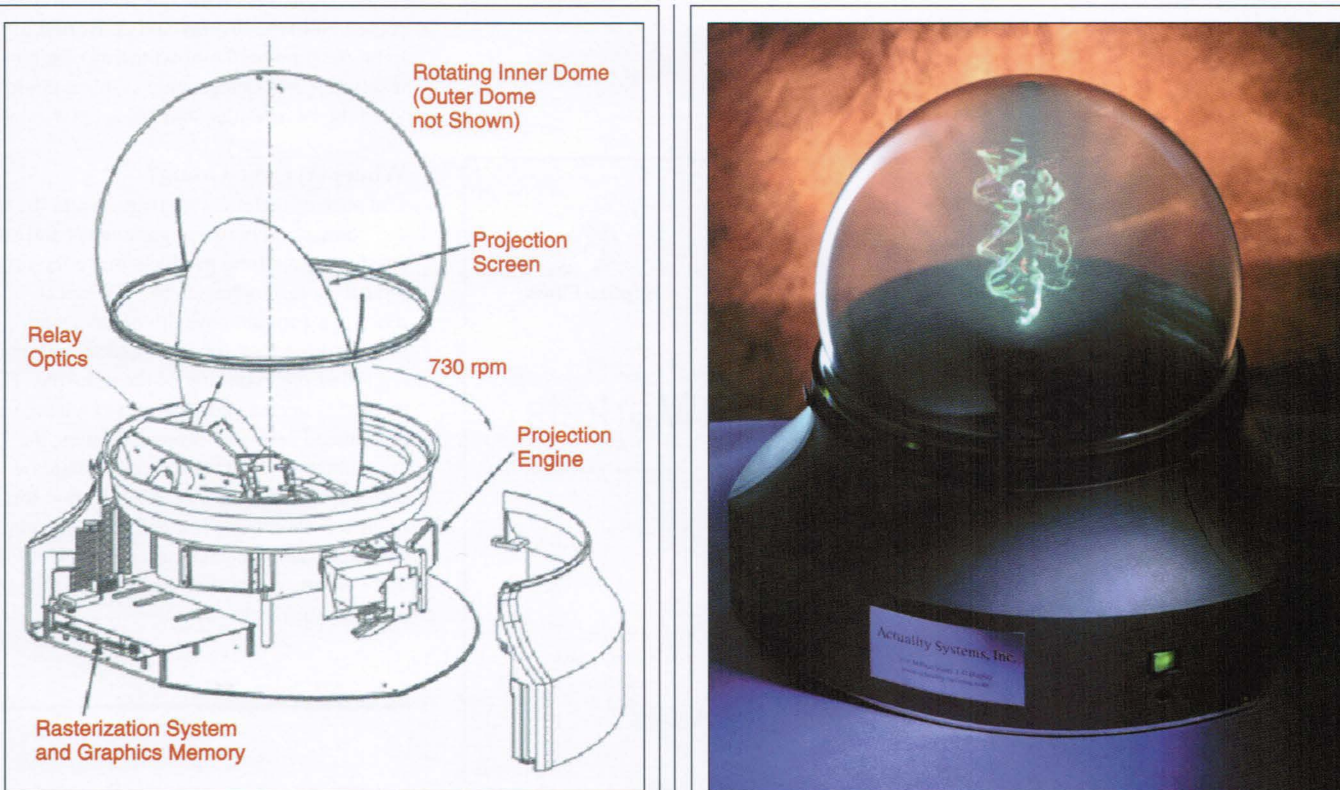
New processing techniques essential to the development of OLEDs, electronic paper, and FEDs offer exciting possibilities. Bridging the gap between microelectronic techniques and traditional printing methods could open the way to create a broad range of new products on flexible substrates as well as on glass or silicon. Substantial progress has already been achieved in ink-jet printing and laser-induced transfer processes. The success of high-precision versions of mechanical stamping suggests that even the simplest and oldest technologies should not be discarded.

Of the new display designs, OLEDs appear to provide the ideal display technology for the 21st century. They are all-solid-state, extremely thin, respond almost instantaneously, and – thanks to their emissive design – provide a wide range of viewing angles. Reports indicate that progress is being made to solve the well-publicized deficiencies of short lifetime and poor blue saturation. The fact that all major Asian manufacturers of LCDs have active OLED programs is evidence that the technology poses a very real threat to the LCD's dominance of the FPD market. The superb quality of these companies' prototype panels shows that OLED technology development will likely prove far more than an academic exercise.

Still, important hurdles remain, especially in the area of manufacturing processes. For example, consider the implications of the structure of Sanyo-Kodak's recent 14.7-in. OLED prototype (Fig. 2). The images produced by this display are excellent, but the light comes from a white organic source, and the colors are separated using filters. This suggests that the patterning technology the company has developed for multi-colored OLED emitters cannot be scaled at this time, even to 15-in. panels.

The simplicity of the original OLED concept is further compromised by the need to add contrast-enhancement films, such as circular polarizers, to reduce the reflection of ambient light. If OLEDs require both polarizers and color filters, it will be difficult to achieve a substantial savings in materials costs. Add that to the higher cost of electronics and the lower yields that will be almost inevitable in the early stages of production, and it becomes increasingly difficult for OLED displays to effectively challenge LCDs.

The USDC report offers no simple prediction regarding the commercial success of OLEDs or other alternative technologies. Instead, it provides a thorough analysis of the two major challenges associated with moving from the laboratory to profitable products: matching the undoubted advantages of these




Actuality Systems, Inc.

*Fig. 4: This true 3-D display forms images by projecting onto a spinning screen.*

technologies to specific market opportunities and developing manufacturing processes and equipment with efficiency and costs close to those of LCDs over the next 3–5 years. If the manufacturing challenges can be overcome, OLEDs could provide the ideal route for current manufacturers of poly-Si LCDs to produce large panels for entertainment applications with viable performance and price points.

Desktop-LCD-monitor pricing leads even Asian manufacturers to be concerned about the danger of FPDs becoming commodity items. Through its High Resolution Working Group, the USDC has been encouraging the development of high-performance displays suitable for demanding applications in both the government and commercial sectors. The success of the 9.2-Mpixel display from IBM (Fig. 3) demonstrates that government interest can still lead to valuable display products.

## New Frontiers: Flexible and 3-D Displays

Some developers are looking at more dramatic ways to provide product differentiation, such as through flexible displays or three-dimensional (3-D) imaging. New sources of support may soon be available for U.S. companies that wish to pursue these opportunities. The U.S. Army will likely launch a major new program this year to fund the development of display technologies and manufacturing processes suited to flexible substrates, while the U.S. Air Force is directing its display efforts towards higher information content and 3-D.

Manufacturing on flexible substrates is key to the success of the several proposed electronic-paper approaches. Since these are less sensitive than OLEDs to oxygen and water, the high porosity of most plastics is of less concern. However, the production of the necessary electronic backplanes presents a major challenge, especially for technologies that require active-matrix switching. A major initiative seems to be warranted to test and integrate low-temperature processes for the deposition and patterning of insulators and conductors, as well as semiconductor devices.

Despite several decades of research, no form factor for 3-D displays has been found that is acceptable to a wide spectrum of users. The basic requirement is rapid response, so that the signals for both eyes can be delivered within the 15 msec of integration time of the human vision system. Stereoscopic systems that require the viewer to wear eyeglasses are easiest to produce, but are limited by this requirement.

Autostereoscopic systems direct one of two images to the appropriate eye without requiring glasses, but users must view the display from specific locations unless head-tracking systems are implemented. The most intriguing approach is through true 3-D systems, in which a volumetric image is created, with voxels (volume pixels) replacing pixels. It is difficult to achieve high resolution with a fixed 3-D array of emitters; light blockage and emission are essential if the correct image is to be presented in all directions.

Spinning-disc systems (Fig. 4) lead to higher spatial resolution, but place much greater demands on the rate at which data is presented to the display and converted to light. Commercial embodiments of high-resolution 3-D holographic systems could yield the best results, and are eagerly awaited.

### Where Are We Going?

The pace of technical innovation and the tenuous connection between great ideas and successful commercial products make the display industry a fascinating field. Technical roadmaps provide a wealth of information for those willing to make independent judgments regarding the evolution of the industry. For those that need a shorter route to wisdom or guaranteed investment opportunities, the development of 3-D and flexible displays – coupled with wireless communication through brain waves – may eventually provide electronic crystal balls and tarot cards. Until then, there is little doubt that the industry will continue to surprise us. ■

# IDMC Meets Taipei: Love at First Sight

*IDMC came to Taipei for the first time, producing newsworthy keynote addresses, technical conflicts, reports of new technology and manufacturing techniques – and record attendance.*

by Ken Werner

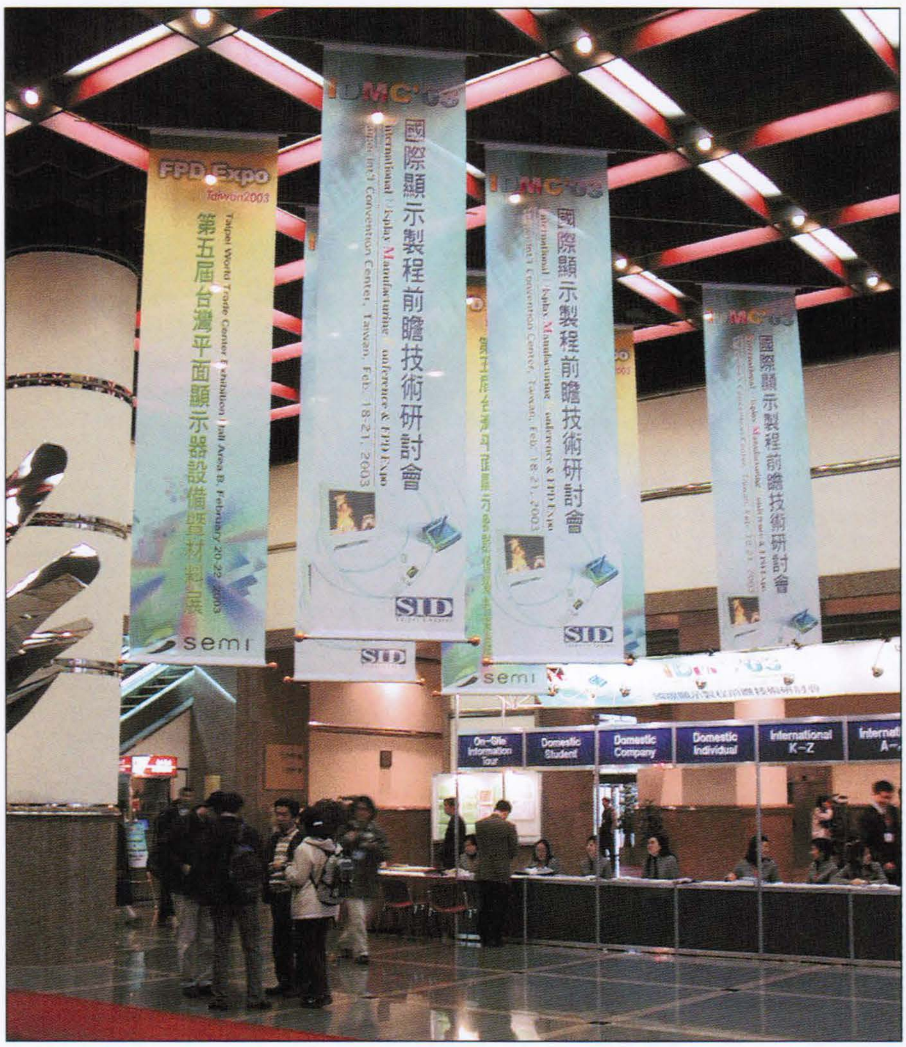
THE International Display Manufacturing Conference (IDMC) was held in Taipei for the first time from February 18 to 21, 2003. It drew a record registration of approximately 800, said Conference Executive Chair Han-Ping D. Shieh (National Chiao Tung University, Taiwan).

IDMC '03, organized by the SID Taipei Chapter, was sponsored by a dozen industrial, governmental, academic, trade, and professional organizations, and was clearly seen as a showcase for Taiwan's burgeoning display industry. IDMC was successful in its first two outings in Seoul, Korea, but drew about twice as many attendees this year in Taipei. The close coupling of IDMC '03 (held at the Taipei International Convention Center) with SEMI's FPD Expo Taiwan (held across the street at the Taipei World Trade Center Exhibition Hall) was hailed by organizers as contributing to the record attendance at both events (see the text box, "Collaboration Helps Boost Visitor Numbers at SEMI FPD Expo Taiwan").

### Keynote Address: Plan for a Revolution

The technical program began with a keynote session that attracted the local as well as business and trade press. In the first keynote, K. Y. Lee – the much-honored Chairman and CEO of Taiwan's AU Optronics Corp. – modestly presented what sounded at first like a simple tactical move.

*Ken Werner is the editor of* Information Display *magazine.*




Ken Werner

*IDMC '03 registration is in progress here in the main lobby of the Taipei International Convention Center.*



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*During his presentation, Katsumi Kondo of Hitachi, Ltd., showed this slide comparing the off-angle color fidelity of S-IPS LCD technology* vs. *the "other" wide-viewing-angle mode. The battle between S-IPS and MVA for the hearts of television manufacturers and the eyeballs of their customers is just beginning.*

Ken Werner

Lee noted that AU Optonics is looking for system partners and also pursuing several approaches to improve the historically low ROI and ROE of LCD panel makers. Among these are working to increase the participation of Taiwanese companies in the "display value chain," *i.e.*, encourage local sources of component and materials supply, and also to increase vertical integration and collaboration in display manufacturing. At AU Optronics, this includes the in-house fabrication of matrix color filters and the increased production of smart panels, which brings the FPD manufacturer closer to brand-name merchandisers.

In "Development and Prospective of Information Technology and Image Display

Taiwanese companies have the ability to manufacture flat-panel TVs very efficiently, said Lee, but do not have brand names that are internationally recognized in the world of consumer electronics (CE), nor do they have the extensive marketing, sales, and distribution infrastructures necessary for big-time success in the CE world. The Japanese CE giants, on the other hand, have all of this but increasingly can not afford to manufacture their products in Japan. What could be more logical than a Taiwan–Japan alliance, especially when the competing, vertically integrated Korean giants have great capabilities in both manufacturing and CE marketing and sales.

But no matter how off-handedly it was presented, such an alliance would be neither modest nor merely tactical. If successful, it would constitute a strategic restructuring of the Asian CE business, a point that was clearly appreciated by at least some listeners, including Hoi-Sing Kwok of the Hong Kong University of Science & Technology (HKUST).

*IDMC's lively poster session was integrated into the FPD Expo Taiwan exhibition held by SEMI.*

Ken Werner

# Collaboration Helps Boost Visitor Numbers at SEMI FPD Expo Taiwan

by Craig Addison

Not all the crowds at the Taipei World Trade Center Exhibition Hall were there to attend the SEMI FPD Expo 2003, which was held February 20–22 in conjunction with the International Display Manufacturing Conference (IDMC '03). Hundreds of thousands of teenagers and 20–30-year-olds converged for the Taipei Games Show, which started a day after the FPD expo.

Still, the crowded aisles at the flat-panel-display expo were testament to a highly successful event, thanks in part to the collaboration between SEMI and the Society for Information Display Taipei Chapter.

It was the first time that SID staged the annual IDMC in Taiwan, following a two-year stint in Korea. It was also the first time SID collaborated on a large scale with SEMI, the global industry association for the semiconductor and flat-panel-display industries.

It was generally agreed that the sum of the individual parts exceeded the whole. On the expo side, the cooperation significantly boosted both exhibitor and visitor numbers. "There's a big difference compared to last year," said Johnny Su, Country Manager for the Taiwan branch of AKT America, Inc., one of the largest exhibitors at the expo. "There are many more visitors this time, and in terms of scale it is also bigger."

That impression was confirmed by the official numbers. Booths totaled 250, up almost 50% from the 2002 SEMI FPD Expo in Taiwan. Visitors this year exceeded 8000, a hefty 62% increase compared with 4930 in 2002.

*Craig Addison is an editor and writer with the SEMI public relations group. Prior to joining SEMI in May 2002, he spent 10 years in Hong Kong, including 4 years as editor-in-chief of* Electronic Business Asia.

SEMI

*Chi Mei Optoelectronics's exhibit of LCD-TV panels, ranging from a 20.1-in. model to a 30-in. model, drew large crowds.*

"It has been one of the most productive experiences we have had working with other associations on a large-scale event," said George C. T. Lin, President of SEMI Southeast Asia. "This is a very rewarding relationship, one we would like to expand going forward."

At the opening ceremony of the expo, Stanley Myers, President and CEO of SEMI, cited DisplaySearch data to illustrate the strong growth in the FPD sector. "While most of the high-tech world has been in the doldrums, in 2002 the flat-panel-display market grew its revenues by 31% to almost $29 billion," he said. Furthermore, the size of the market is expected to double, to about $62 billion, within 3–4 years. "That is a very significant growth path, and one that other sectors of the high-tech industry would be envious of," Myers said.

As would be expected, the largest single contingent among the 148 exhibiting companies – or almost 47% – were from Taiwan. More than 20% of participating companies came from Japan, while Korean companies, which were represented in a separate Korean pavilion, accounted for just over 16% of the total. U.S.-based firms made up almost 11% of the exhibitors, while European companies accounted for the remainder.


Ken Werner

*As part of its large exhibit, AU Optronics proudly exhibited a Gen 5 substrate measuring 1100 × 1250 mm. The company said this was Taiwan's first Gen 5 TFT-LCD motherglass when it was produced in December 2002.*

The majority of the companies exhibiting at the expo were manufacturers or suppliers of equipment, components, and materials used to produce flat-panel displays. Some of the largest booths were occupied by major equipment companies such as AKT, Inc., Aixtron AG, and Nikon Corp. In keeping with the "vertical" nature of the show, several of Taiwan's flat-panel makers were also present, including AU Optronics, Chi Mei Optoelectronics, Chunghwa Picture Tubes, HannStar Display, Picvue Electronics, and Toppoly Optoelectronics.

Chi Mei Optoelectronics's exhibit of LCD-TV panels, ranging from a 20.1-in. model to a 30-in. model, drew large crowds. Indeed, on the day before the opening of the show an executive from Chi Mei told delegates at the SEMI FPD market briefing that unit shipments of LCDs for TVs will reach 4.2 million this year and were forecast to increase to about 17 million by 2006.

AU Optronics, ranked as the world's No. 3 TFT-LCD maker, mounted an impressive display of motherglass substrates ranging from Generation 1 (36 2.45-in. panels) to Generation 5 (12 17-in. panels). The Gen 5 substrate, at 1100 × 1250 mm, was Taiwan's first Gen 5 TFT-LCD motherglass when it was produced in December 2002, AU Optronics said.

While exhibitors were delighted with the attendance figures, it was hard not to be envious of the much larger crowds attending the Taipei Game Show in the adjacent exhibit hall. But games and toys accounted for only 3% of FPD revenues in 2002, according to DisplaySearch. The irony wasn't lost on one exhibitor. "Considering the size of the FPD industry in terms of revenue and its influence, I think it needs to be bigger than the game show next door," joked I. D. Kang, AKT's Vice-President of global sales and marketing. ■


SEMI

*The Unaxis and Kromax booths at FPD Expo Taiwan.*

in Taiwan," the second of three keynote addresses, Yen Shiang Shih, Vice Minister of the Ministry of Economic Affairs, presented extensive statistical information on the status and growth of the Taiwanese IT industry, with emphasis on display growth and the development of Gen 5 manufacturing, and the global market for display-centric products. He noted that while the figures for the investment by Taiwanese companies are impressive, they are always understated because they exclude at least part of the large investment these companies have made in mainland China over the last 15 years. Estimates for this investment, he said, go as high as US$200 billion, but nobody knows for sure because for years much of this money had to be invested indirectly. One popular route, Shih said with a smile, was through the U.S. Virgin Islands.

Shih strongly supported Lee's point about increasing Taiwanese content in FPDs manufactured here. In particular, he said, one could expect more investment in glass substrates, color filters, and polarizers. Shih projected that Taiwan's share of the TFT-LCD market would grow to 35%, and said that in the future, the Taiwanese industry would have to produce content as well as hardware.

The final keynote address – presented by Ching Tang of Eastman Kodak Co., co-inventor of the organic light-emitting-diode (OLED) display – was "OLED Perspective." Tang reviewed the technical development of OLEDs, and concluded that although the efficiency of OLEDs is often said to be inferior to that of LCDs, in real-world applications OLEDs will be at least competitive, and sometimes superior. "OLEDs can compete in all applications," Tang said, although he acknowledged that this is most difficult in Windows™ applications, which typically have white backgrounds and, therefore, large numbers of lit pixels.


Ken Werner

*SEMI's FPD Expo Taiwan, held across the street at the Taipei World Trade Center Exhibition Hall, was closely coupled with IDMC '03.*

## Technical Program

Approximately 200 technical papers were delivered at IDMC '03. This is just a sampling. The organizers cleverly began the Active Matrix session by inviting papers from representatives of two of the antagonists in the increasingly intense LCD-TV technology war. In "Recent Developments in MVA-LCDs," Kenji Okamoto (Fujitsu Display Technologies Corp., Japan) said that an MVA (multi-domain vertically aligned) LCD has the response time, contrast, and wide viewing angle needed for LCD TV. But the extra processes needed to make the protrusions that create the multiple domains involve added expense. He presented a new structure in which the protuberances on the TFT plate are replaced by shallow wells. The easy-to-make wells create a fringing field that establishes the multiple domains.

On the color-matrix plate, overlapping the color areas of the matrix inexpensively replaces the traditional chromium black matrix. Protuberances are still needed on this plate, so Fujitsu has made a virtue of necessity and added a second set of larger protuberances that act as spacers and eliminate the need for a separate application of spacer balls.

Okamoto also described Fujitsu's drop-filling process, in which drops of LC material are applied to one plate. The second plate is then placed on the first (think of making a peanut-butter sandwich). The process has one-third the TAT time of conventional filling and there is no LC waste.

With a new driving scheme, "MVA Premium" technology reduces the old MVA's average gray-to-gray response time from 29.3 to 11.6 msec, Okamoto said.

Then, Katsumi Kondo (Hitachi, Ltd., Japan) presented "Recent Progress of the IPS TFT-LCDs." The current version of in-plane-switching (IPS) LCDs – the technology that first allowed the words "LCD" and "wide-angle" to be used in the same breath – is Super IPS (S-IPS). With a simple change in electrode configuration, S-IPS induces a multi-domain structure in the liquid crystal while still retaining in-plane switching.

For fast response time, S-IPS combines changes in LC materials with an overdrive addressing method. A blinking backlight could be added if an even faster response time is needed. Kondo said that early assumptions that a blinking backlight would compromise luminance and efficiency are incorrect. If the lamp is driven at higher peak current, the average luminance can stay the same and efficiency can actually increase.

Kondo presented photos that showed impressive off-axis stability of skin colors compared to the clearly inferior – and coyly identified – "other WVA mode." Okamoto presented RGB data implying that MVA Premium had better off-axis performance than S-IPS.

Ken Werner

*A day of workshops preceded IDMC's mainstream technical program. Gregory Crawford (Brown University, U.S.A.) concluded his well-attended LCD workshop by having the attendees make single-pixel LCDs.*

In the Q&A session, *Information Display* asked Kondo if he could explain this apparently conflicting data. Kondo said that the Fujitsu paper was comparing dark colors, while he was comparing lighter ones. He said he believed they would both agree on the data. What was not said, but strongly implied, was that the flesh-tone comparison was the more meaningful one for LCD TV.

In "Display Visibility in Dynamic Lighting Environments," Lou Silverstein (VCD Sciences, U.S.A.) discussed the visibility issues that arise when lighting is not constant, as when a driver's point of regard changes from a brightly lit roadway to the shaded instrument display inside his car. They have developed a device-independent time-to-visibility (TTV) model for predicting the time it takes for a user to adapt to the new conditions and be able to see the information presented on a display. The TTV model has been used to help Toppoly Optoelectronics optimize a transflective display that requires as little backlight use as possible.

Jacob Lin and Thomas Cho (Picvue Electronics, Taiwan) outlined Picvue's development of several types of bistable displays. Among these are a surface-stabilized cholesteric-texture (SSCT) display and a bistable nematic display (with BiNem™ technology licensed from Nemoptics). The SSCT technology is being used in a monochrome e-book display, and in a 1 × 2-m tiled array as a color outdoor advertising billboard.

R. C. Liang and Scott Tseng (SiPix Imaging, U.S.A.) described the application of SiPix's Microcup® roll-to-roll manufacturing technology to a monodispersed liquid-crystal display. (The company's primary application for Microcup technology is electrophoretic displays, which it first presented at IDW '02 in Hiroshima in early December, but it also sees applications in the PDLC arena.)

In "Development of a DLP™ Common Engine Platform," Julius Horvath (Texas Instruments, U.S.A.) and Lai-Chang Ling (Opto-Electronics & Systems Laboratories, Industrial Technology Research Institute, Taiwan) describe the collaboration of their institutions to build a common projection-engine platform that would permit the standardization of some components and allow several manufacturers to use the same engine design, with substantial engine-cost reductions. The completed engine was targeted at a 12° 0.7-in. XGA DDR DMD system using TI's SCR light-recovery technology, and was designed to be compatible with field-sequential systems using a 0.7-in. XGA or 0.55-in. SVGA DDR panel. The reference system has an output of 1700 ANSI lumens, a contrast ratio of 700:1, and a uniformity of greater than 85%. The estimated weight of a production projector using the engine is 5.5 lbs.

Members of the SID Asia Region Board of Directors considered IDMC '03 to be a great success. They and executives of SEMI called the cooperation between the two organizations a successful model that should be quickly replicated. ■

## my turn

*continued from page 4*

roll-to-roll manufacture of displays needs a series of true innovations, I foresee the need for a worldwide investment in R&D of 100,000 person-years. The cost of this investment is comparable to the value of one year's production of flat-panel displays. If it is made a national priority, high-volume roll-to-roll printing of displays could arrive within 10–20 years. If this cost seems high and the time seems far away, it is worth remembering that after 500 years Germany still is the leading manufacturer of printing presses. ■

***Sigurd Wagner*** *is Professor of Electrical Engineering in the Department of Electrical Engineering at Princeton University, B-442 E-Quad, Olden St., Princeton, NJ 08544; telephone 609/258-4631, fax 609/258-6279, e-mail: wagner@princeton.edu. Much of his research is related to laying the groundwork for the direct printing of electronic circuits.*

17 03

AUGUST

*The 8th Asian Symposium on Information Display (ASID '03)*

*NANJING, JIANGSU, CHINA*
*AUGUST 17–20, 2003*

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*The 23rd International Display Research Conference (IDRC 2003)*

*PHOENIX, ARIZONA*
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• An international conference on display research and development aspects of:
• Display Materials (liquid crystals, small-molecule and polymer OLEDs, phosphors, optical compensation films, flexible substrates, etc.) • Display modeling, Design and Processing • Display Systems and Human Interfaces

## SID news

### Committee Announces First Two SID Senior Members

The SID Senior Member Grade Committee is pleased to announce that the following SID members are newly elevated to SID Senior Member status:

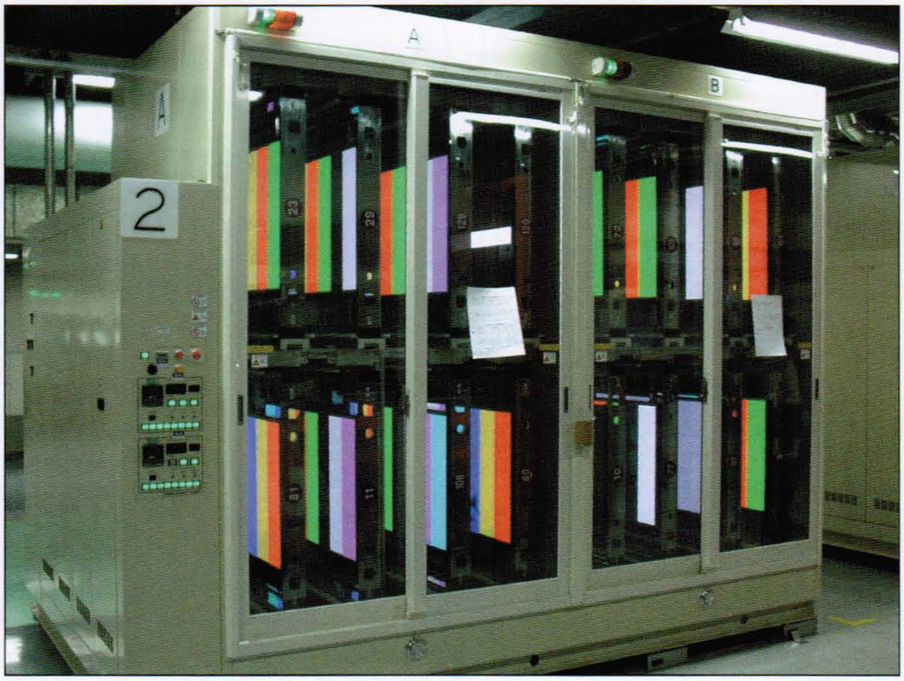
***Dr. Aris K. Silzars*** (Northlight Displays), Americas Region
***Dr. Ravi P. Rao*** (Plasmaco, Inc.), Americas Region

Senior Members are those individuals who are recognized to have made significant technical contributions to the advancement of displays and who have demonstrated active participation in the display community and in SID.

**Shigeo Mikoshiba, Chair**
**Senior Member Grade Committee** ■

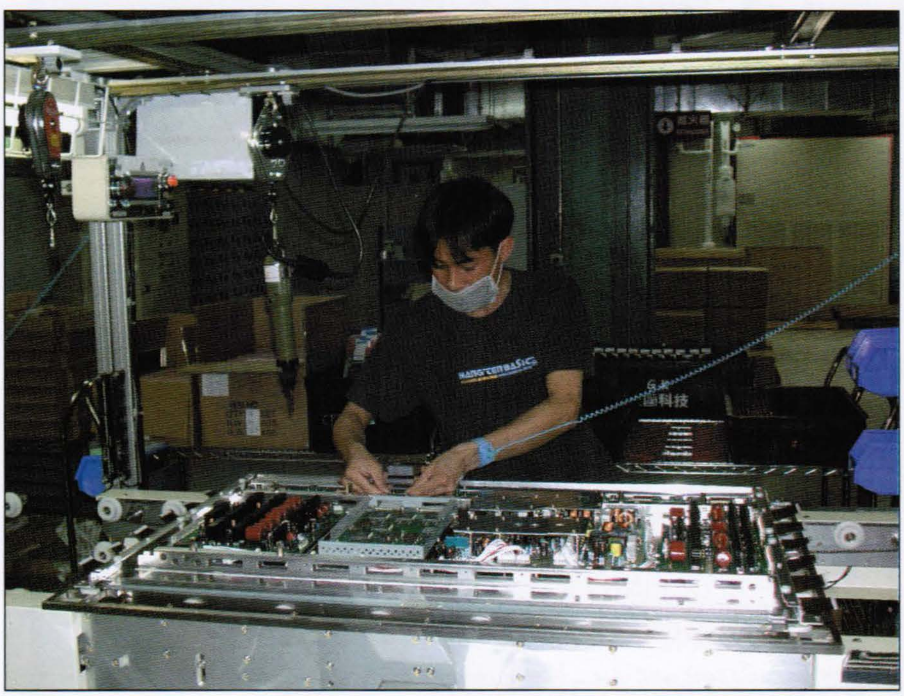
For those of you who wish to be considered for the Senior Member grade, please click "Senior Member Grade" which can be found under "NEW TO THE SITE" on the SID home page, www.sid.org. Also, please see *Information Display* **18**, No. 11, 30 (2002).

*continued from page 2*



Ken Werner

*Shown are Chunghwa Picture Tubes' 46-in. PDPs going through post-assembly testing for 5 hours at elevated temperature.*



Ken Werner

*The final assembly of electronics boards in a PDP module is performed at Chunghwa Picture Tubes.*

A 46-in. WXGA TV/monitor will be available in Q3 '03, with an estimated MSRP in the U.S. of $4000–5000 through CPT's OEM customers.

Chung expressed great optimism about the PDP's future in the developing competition between PDPs and TFT-LCDs for the large-screen direct-view home-TV market. There is lots of room for more electronics integration in the PDP, he said (with Jim Chen translating), while the LCD is far more mature. LTPS could change that, he added, but LTPS is proceeding slowly.

The cost models for PDPs and TFT-LCDs are very different. A lot of the cost of TFT-LCDs is in the front end, while PDPs have much less of their cost in the front end and a lot more in the electronics. Jason Wu commented that CPT's PDP plant cost only US$160 million, while new-generation TFT-LCD plants cost US$1 billion – and going up.

The only negative factor Chung sees for PDPs is that much less money is being spent on PDP development than on that for TFT-LCDs. "On the other hand," he said with an infectious laugh, "the Gen 5 LCD guys are killing each other!"

I left CPT with an invitation from Mr. Chung and his colleagues to return for an update on their PDP activities – and not to wait four years this time. I'll do my best. There's a lot to be learned at CPT.

– KIW

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

## backlight

*continued from page 48*

frustrating, for example, as dealing with a telephone company? And how copious are the offerings? Will they satisfy a reader (like me) with diverse and sometimes esoteric reading habits? Or would I be limited to the latest best-selling fare, most of which I have no interest in reading? Did the e-book experience, in short, satisfy you or make you long for the charm of paper?

Speaking (as I was some paragraphs back) about the hang-on-the-wall TV, I recently encountered a stunning example on a trip as I was walking through the airport in Detroit, Michigan. What I'm used to in airport waiting areas are ceiling-hung CRTs at a few select locations with screens too small to see well unless you are sitting very close and willing to adopt a neck-wrenching posture. This particular screen, on the other hand, was a humongous thing – probably 15 ft. wide and 10 ft. high – well placed high up on a wall at the end of a large waiting area and presenting an excellent picture that was visible from virtually all points. Moreover, speakers with good quality and volume were dispersed on the side walls throughout the waiting area – and reasonable audio is even less common in airports than good video. All in all, it was an excellent installation, although an annoyance for those who might prefer to read rather than watch TV. The big screen, painstakingly and expensively constructed of many smaller display modules, made me think again about big flexible displays of the future, quickly unrolled and mounted like a billboard sign.

While we are in the travel-discussion mode, I cannot resist the opportunity to say a few discouraging words about the infotainment displays on airplanes themselves. On my recent trip through Detroit, I encountered the three common solutions in coach: ceiling-hung CRTs, LCDs mounted under the overhead luggage compartment, and a ceiling-hung projector feeding a single screen at the front of the cabin. Talk about neck wrenching! All three alternatives are reasonably viewable by only a fraction of the passengers. Did I watch a movie? Nope. Read a book instead. ■

***David Lieberman** is a veteran display journalist living in Massachusetts.*

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**Symposium, Seminar, and Exhibition**
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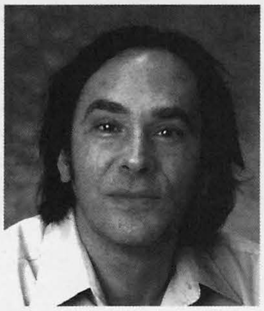
# backlight



## Displays on the Road

**by David Lieberman**

About to go on vacation, I have almost finished packing and it is time to start thinking about what books to bring with me. This coming trip, like every other trip, poses a significant challenge in getting the reading selection just right: not too many books, not too few, the right formats for all the coming reading situations – and not a single book that I'm going to regret adding to the weight of my suitcase and possibly consider dropping into the pool.

Lately, I have been giving considerable thought to the electronic alternative. What if I only had to bring one "book" on any trip that would give me access to many different selections? How nice that would be! And a number of companies within and beyond the display industry are working toward that vision, including E-Ink Corp. of Cambridge, Massachusetts, an MIT Media Labs spin-out that sells electrophoretic displays.

"The culminating dream of E-Ink," according to a company document, "is to create an electronic book with real pages that can be leafed through, thumbed over, and read on the beach. Moreover, these pages will typeset themselves with the latest newspaper headlines or a best-selling novel at the user's command."

Quite a vision! But, of course, the display pages of this future e-book are going to have to be flexible if we are going to be able to leaf through them. There has been considerable interest lately in the flexible-display concept, with both the United States Display Consortium (USDC) and Intertech Corp. holding conferences on flexible displays earlier this year. The fulfillment of the e-book-on-the-beach vision, though, seems to be more than just a few years away.

The challenges for the flexible display are many, lying in such areas as substrates, conductive coatings, barrier layers, seals, enhancement layers, display media, and electronics, to name only the most obvious; and considerable challenges lie in coping with the interactions among these items and in developing all the pieces of manufacturing equipment required to pull them together into viable products.

In these, the early years of the 21st century, we now have some very nice hang-on-the-wall TVs available, but it took somewhere around 25 years for that great display vision to traverse the challenging technical path from visionary concept to concrete realization. I am fairly certain that it will not take a quarter-century for developers to deliver excellent roll-up, fold-up, and leaf-through displays for us all to wonder at and enjoy, but those of us with 5-year expectations are probably destined to be disappointed.

Meanwhile, I wonder whether I ought to consider buying an e-book now, although today's models will only provide me with a single page at a time and there will be no leafing through, no folding up and stuffing into my jacket pocket, and no rolling up for sticking into my pants pocket. Might be nice, though. I would be interested in hearing from any of you who have already taken the e-book plunge. What has your experience been so far? How affordable are these things? Are they easy to use and, above all, are they easy on the eye under various lighting conditions? And that's just the beginning.

Are the subscription services something you would recommend? Is the whole experience as pleasant and efficient as dealing with my local librarian, or is it as

*continued on page 45*

# calendar

**The 8th Asian Symposium on Information Display (ASID '03).** Contact: Southeast University, Electronic Engineering Dept., Nanjing, Jiangsu, 210018 China, telephone/fax +86-25-3363222, URL: www.asid03.seu.edu.cn.
**August 17–20, 2003 Nanjing, China**

**The 12th International Symposium on Advanced Display Technologies & Flowers, 2003.** Contact: SID HQ, 408/977-1013, fax -1531, e-mail: office@sid.org.
**August 25–27, 2003 Moscow, Russia**

**The 23rd International Display Research Conference (IDRC '03).** Contact: Ralph Nadell, PCM, 212/460-8090 x203, fax -5460, e-mail: Rnadell@pcm411.com.
**September 15–18, 2003 Phoenix, AZ**

**The 10th Annual Symposium on Vehicle Displays.** Contact: Mark Goldfarb, PCM, 212/460-5460 x202, e-mail: mgoldfarb@pcm411.com.
**October 13 and 14, 2003 Detroit, MI**

**The 3rd SID/MAC OLED Research & Technology Conference.** Contact: Mark Goldfarb, PCM, 212/460-5460 x202, e-mail: mgoldfarb@pcm411.com.
**October 24, 2003 New Brunswick, New Jersey**

**The 11th Color Imaging Conference: Color Science, Engineering, Systems & Applications.** Sponsored by IS&T and SID. Contact: SID HQ, 408/977-1013 fax -1531. e-mail: office@sid.org, www.sid.org.
**November 4–7, 2003 Scottsdalde, AZ**

**The 10th International Display Workshops (IDW '03).** Contact: SID HQ, 408/977-1013, fax -1531, e-mail: office@sid.org.
**December 3–5, 2003 Fukuoka, Japan**

**SID 2004 International Symposium, Seminar & Exhibition.** Contact: Mark Goldfarb, PCM, 212/460-8090 x202, fax -5460, e-mail: mgoldfarb@pcm411.com.
**May 23–28, 2004 Seattle, WA ■**