OLED Displays Issue

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OLEDs – Never Too Rich or Too Thin

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- **Oxide-TFT Backplanes for AMOLED Displays**
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SEPTEMBER 2008
VOL. 24, NO. 9

COVER: It is an exciting time for the AMOLED industry as manufacturers ramp up their production lines and impressive product prototypes are shown at major consumer-electronics shows.

CREDIT: Cover design by Acapella Studios, Inc.

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Information Display

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editorial

OLED Development Follows the Familiar Pattern

In May 2005, Samsung stunned the display world when it first demonstrated a 40-in. prototype OLED TV. This breathtaking prototype used a white emitting layer with color filters and utilized amorphous-silicon (a-Si) TFTs in the active backplane – at a time when many others were working low-temperature polysilicon (LTPS). In an article in *Information Display* in February 2006, Kyuha Chung, Senior VP for OLED Development at Samsung, pointed out that a-Si TFTs posed some challenges that needed to be addressed before OLED TV could become a commercial success. These included relatively low electron mobility, wide variations in performance over temperature, and long-term degradation effects that lead to lower net current densities. And yet, a-si TFTs are the workhorse of the LCD-TV community: ease of fabrication on very large substrates, high uniformity across adjacent cells, and relatively inexpensive to produce. The problem lies in the fact that OLED cells, unlike liquid-crystal cells, require significant amounts of electrical current in order to generate bright light. OLEDs are analogous to earlier electroluminescent (EL) displays because they generate their own light, rather than modulating external light. In early 2006, much of the attention toward OLEDs understandably was focused on materials research: small molecule *vs.* large molecule; white emitters *vs.* RGB *vs.* blue with secondary phosphor; methods of material deposition and sealing; and organic contamination, emission efficiencies, and lifetimes. Relatively little attention was focused on backplane switches, although in that same February 2006 issue of *ID*, Amal Ghosh and Steven Van Slyke reported in their article that LTPS and a-Si backplanes were both being evaluated for AMOLED displays. They predicted that “LTPS will likely remain the technology of choice for small displays, where the high mobility enables integrated drivers on the display substrate, reducing module size. Whether a-Si is acceptable as an AMOLED backplane remains to be determined.” They were right in also noting that significant efforts were under way to fully explore multiple options.

Today, backplane technologies, including the switches, are clearly the focus of numerous development efforts and part of the required solution set before OLED TV can become a wide-range commercial success. Our Guest Editor this month, Julie Brown of Universal Display Corp., has done a stellar job in bringing us three interesting articles detailing the latest advances in backplane technology from LG Display, Samsung SDI, and Sony. Both Sony and Samsung report that poly-Si is no longer a long-term focus, and neither is traditional a-Si. Sony reports on a new process it has developed to produce “microcrystalline-silicon TFTs,” which has a mobility improvement up to 10 times that of a-Si while retaining a-Si’s good uniformity characteristics, according to the article. Samsung describes its development of amorphous indium-gallium-zinc-oxide (InGaZnO) TFTs, building on earlier work by LG and Cannon. With InGaZnO, Samsung achieves similar improvements of 10× or more over a-Si, and the process is compatible with existing vacuum deposition and masking steps. LG describes its work to fabricate a-Si TFTs on a stainless-steel flexible backplane. LG uses a-Si because it requires lower process temperatures than high-temperature poly-Si, but the article freely admits that because of the low mobility, very high luminous efficiency is required in its OLED materials. I have little doubt one of their next steps is going to focus on alternate TFTs on their flexible backplanes.

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iSuppli: Large-Sized LCD Market Set for September Recovery

El Segundo, Calif. – The large-sized LCD panel market — screens that measure 10 inches diagonal or larger — is due for a recovery in September after nearly three months of plummeting profitability and severe price plunges, according to market-research firm **iSuppli Corp.**

"The large-sized LCD panel market has been mired in a state of severe oversupply since the start of June, due to lower-than-expected panel demand and high inventory levels throughout the supply chain," said **Sweta Dash**, director of LCD and projection research at iSuppli. "Conditions have worsened in August, with poor economic circumstances causing prices to decline at an even faster pace than before. However, panel production cuts, combined with the clearance of inventory and a recovery in demand from televisions, desktop PC monitors and notebook PCs are expected to shift the supply/demand equation back to balance in September. This will lead to a recovery in pricing."

After rising by 6.9% in May, global large-sized LCD panel unit shipments declined by 9.6% sequentially in June. Prices dropped by 4% to 7% for mainstream notebook, monitor and TV panels from May to June and another 3% to 15% in July, and are expected to decrease by 4% to 20% for the entire month of August, according to iSuppli.

These latest price reductions mean that large-sized panel prices now are approaching the manufacturing-cost level, especially for some television and many monitor panels, iSuppli reported. However, panel suppliers and equipment makers moved quickly this year to adjust to weakening market conditions.

"Panel suppliers began to slash their utilization rates starting in July," Dash noted. "LCD-TV and desktop PC monitor manufacturers also are starting to cut their prices in order to reduce inventories and boost end-user demand. These developments, along with recovering demand from the notebook segment, will bring stabilization to large-sized LCD panel pricing in September. Some panel prices may even increase by 1% to 3% especially those which are reaching at or below the cost levels."

On the supply side, LCD makers ramped up production of TV panels in their Gen 7, 7.5 and 8 fabs, in the first half of the year, eschewing less-efficient Gen 6 fabs. Gen 8 fabs are capable of producing large-sized panels much more efficiently than Gen 6 factories, boosting productivity throughout the industry.

This increase in production helped spur declines in average LCD-TV panel prices throughout 2008 — these have fallen by as much as 15% to 20% from the start of 2008.

LCD monitor panel prices for desktop PCs have already fallen by 20% to 25% since May. Panel suppliers reported about one to two weeks of excess monitor module inventory in July. Channel participants and brand vendors also reported two to three weeks of extra inventory in July.

Branded vendors in Europe and parts of North America have started cutting prices to reduce inventories. Because of this, orders for finished monitors began to increase in August and are expected to rise again in September.

– Staff Reports

Unidym Extends Agreement with Samsung to Integrate Carbon Nanotubes into Displays

MENLO PARK, Calif. - **Unidym Inc.** announced August 12 that it has entered into a second joint development agreement with **Samsung Electronics Co. Ltd.** to extend their collaboration to integrate carbon nanotube materials as the transparent conductive layer in display devices.

According to a Unidym press release, next generation displays are expected to require a transparent electrode material that simplifies the deposition process and that is mechanically robust to meet necessary cost, flexibility and reliability targets. The company stated that carbon nanotubes simplify the transparent conductor deposition process because they can be wet processed utilizing printing techniques, or through roll-to-roll coating processes, in contrast to the current more difficult and time-consuming vacuum sputtering deposition process required by indium tin oxide (ITO) and indium zinc oxide (IZO). Additionally, in testing, ITO and IZO materials typically used in today's transparent electrodes have shown a doubling in sheet resistance after as few as 100 bending cycles around a 9.7mm mandrel, whereas Unidym's carbon-nanotube-based electrodes show minimal degradation under the same conditions. This increased mechanical robustness of nanotubes opens new possibilities for next generation display applications.

The initial agreement was signed in 2007, and one achievement from the first year of this collaboration was the world's first public demonstration of a working prototype of a carbon-nanotube-based active-matrix electrophoretic e-paper display (EPD) at the **SID's Display Week** in May 2008.

"We have made significant progress in the first year of our joint development agreement. The results of the collaboration have exceeded our expectations, and have been accomplished ahead of schedule," said **Dr. Paul Drzaic**, chief technical officer of Unidym and president of SID. "In this second year, we are looking to build upon these first year accomplishments, and extend the capabilities for carbon nanotubes as transparent conductors even further in various display applications."

— Staff Reports

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guest editorial

AMOLED Product Innovations Begin to Differentiate this Technology from the Pack

by Julie J. Brown

Since *Information Display* last published a special issue on OLED technology in February 2007, a lot has happened in this exciting new sector of the display industry. Samsung SDI has been expanding the product base of its AMOLED panels, which look wonderful. In addition, Samsung was recognized at the 2008 CES with a Best Buzz Award for its 31-in. AMOLED prototypes. Similarly, Sony impressed with its launch of an 11-in. AMOLED TV, which garnered a 2008 SID/*Information Display* Display of the Year Award, among its other accolades. Additionally, Chi-Mei Optoelctronics, LG Display, and others have also launched AMOLED products this year.

With all of this innovation in mind, I have been reflecting on the past 10 years in which I have been personally involved in OLED technology. I recall about 8 years ago, an expert in the flat-panel-display industry said to me, "You need to realize that LCDs took (over the) flat (sector) and so OLEDs need to do something different." I believe that OLED technology now has done something different with the new products that are moving into the consumers' hands and countertops. But, of course, I am engrossed in the technology and may be too close to be the best judge. So I have been conducting my own consumer research.

Two weeks ago, I hosted a group of high-school students spending their summer at Princeton University studying science and technology. When I showed them some of the AMOLED products, their response was very telling. I heard words like "wow," it looks so "intense and deep," and "the color is really different." This powerful, direct consumer feedback tells me that OLEDs have done something different – the screen looks better than an LCD to a teen-ager.

The impact of OLED technology, however, is not only the image quality but also the potential for saving power by using phosphorescent OLEDs (PHOLEDs) and addressing the world's great need for "green" products. Once they heard this, it was hard to tell which they were more impressed by: the AMOLED's picture quality or the environmental friendliness. I then asked them to imagine future AMOLED products that could be worn on the wrist or be flexible enough to be rolled up. At this point, I could see that these burgeoning scientists were fascinated by these concepts, which to them seemed more like science fiction than science. But as the articles in this issue of *Information Display* demonstrate, these innovations are all on the immediate horizon. The articles, from some of the biggest players in the AMOLED sector, provide a snapshot into how work on image quality and new OLED technologies are positioning OLEDs as a completely different, revolutionary FPD technology.

Tetsuo Urabe of Sony describes the company's work in manufacturing AMOLED panels with a vision for increasing display size beyond its first 11-in. AMOLED TV product. In order to achieve manufacturing scale, Sony has had to make critical decisions in panel design in order to achieve a manufacturable high-performance product design. Urabe discusses the technology choices Sony has made for manufacturability today and a prospective direction in the future to achieve ultimate low-power products along with manufacturing scale.

Then switching gears away from AMOLED displays on rigid substrates, we move into the future of flexible OLED displays. A number of companies are now working

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president's corner

A Good Display Is Hard to Define – Enter SID

What makes a good display? The electronic-display industry that SID supports is vitally interested in the answer to this question. In fact, this is not one question, but multiple questions, depending on who's asking. For the display researcher, the question might be, "What's the response time of this display?" For the display systems engineer designing a mobile-phone handset, the question might be, "What's the color gamut of this transflective display under daylight conditions?" For a consumer, the question is often, "What's the best deal for my next television?" For me, I've been wondering what the phrases "dynamic false contour" and "viewing freedom in 3-D displays" really mean.

Many of these questions do not seem to have quantitative answers, but many should, or already do. In some cases, the issue is simply finding a clear definition of a term. In other cases, one often finds that while it is possible to measure many aspects of an electronic display, there is no agreement on the exact measurement that should be used for a particular parameter. Perhaps, not surprisingly, one often finds that a particular group will define a measurement that shows off its display in the best light and highlights deficiencies in a competitive product.

One way to deal with these variations is to have broad agreement on a set of standards that can be relied on to provide a reliable way to define terms and make measurements. In this column, I'm proud to highlight some activities that SID is actively supporting in the world of electronic-display standards. While this effort is still very much in an intermediate stage, the outcome promises to serve all parts of the display industry by providing a set of reliable references on display performance.

The International Committee for Display Metrology (ICDM) is working to produce the ICDM Display Measurement Standard (DMS), a document for measurements of all types for displays. The goal is to produce a comprehensive use of procedures for use by the display industry. Today, many characteristics of displays are poorly defined, which leads to confusion at best and some serious misconceptions at worst. An industry as large and diverse as the electronic-display industry needs a set of accepted standards to enable a dispassionate comparison of different displays and their components.

The DMS is an ambitious effort and is targeted to contain several hundred of pages of display-metrology measurement instructions, technical discussions, tutorials, data tables, a glossary, a list of acronyms, and references. The principal goal is to provide a well-defined set of instructions on how to evaluate a display and quantitatively measure its characteristics. These instructions will be complete and clear, providing sufficient background so that the selection of criteria will make sense. Another goal is to put in place a common language that can be used by people evaluating displays, as well as by those who need to understand and evaluate those results.

Today, many display characteristics are measured in very different ways and produce very different results. These parameters are either poorly defined or are defined in such highly precise and technical language to be beyond the understanding of all but specialists in the field. A goal of the ICDM is to provide a reference guide that both simplifies and clarifies the choices available for characterizing a display. These references will serve both established and emerging display technologies, such as liquid-crystal displays, organic light-emitting-diode displays, and reflective "electronic paper" displays.

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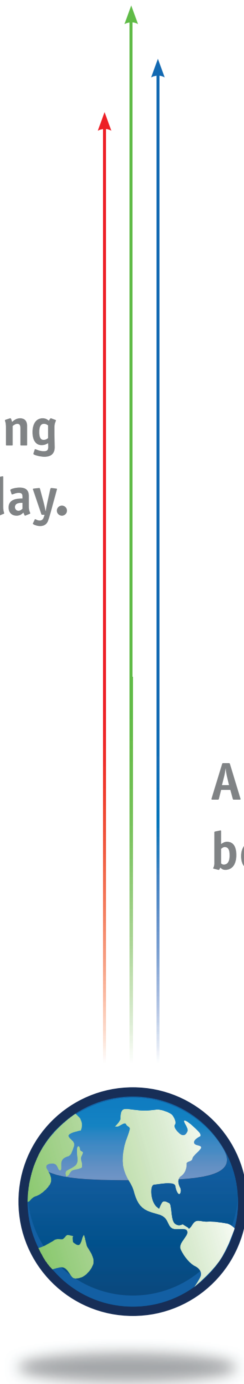

LED Backlights: Good for the Environment, but Can They Also Be Good Business?

by Sweta Dash

Much of the discussion surrounding the use of light-emitting diodes (LEDs) as backlights in flat-panel displays (FPDs) has centered on the technology's ability to be mercury-free and consume low amounts of power – making them a viable "green" alternative to the backlights being used today. But can LEDs also be used to drive higher sales or higher profit margins?

Liquid-crystal-display (LCD) panel suppliers are increasing efficiency, reducing power consumption, and reducing objectionable lamp materials. Up until now, LED-backlight-based LCD panels have mostly served the high-performance high end of the display market, in the process garnering higher profit margins that have also kept the adoption rate at a low level.

But as the cost difference between LED and cold-cathode fluorescent-lamp (CCFL) based backlights are going down, the efficiency of LED chips are increasing, giving it potential to reach the mainstream market. Because the panel price of LED-based LCDs will have some premium over CCFL-based products, which will allow higher revenue growth to suppliers, the competition will grow stronger in future years so that their advantage may decline. What this means in the short term is that LED backlights are not only green, but they may potentially bring more revenue to the LCD market in the near future for notebook applications.

High Adoption Rates

Notebook computers are expected to enjoy the highest LED adoption rate among the three major large-sized-LCD application markets. By 2012, we expect LED backlights for notebooks to reach a 90% adoption rate – that's up from a penetration rate of about 4.7% in the fourth quarter of 2007 and forecasted adoption rates of 18% by the fourth quarter of 2008 and 42% by the fourth quarter of 2009. This will be driven by their slim form factors, lower weight, and instant-on capability, as well as their lower power consumption and mercury-free attributes.

Therefore, notebook-PC OEMs and LCD-panel suppliers are aggressively going after this LED-backlight market in order to take advantage of the high-growth revenues predicted for LED backlights and to capitalize on the "green" movement occurring throughout the world.

TMD was the dominant supplier of LED-based notebook panels in 2007. But Samsung, LG Display, AUO, CPT, and CMO all introduced LED-based notebook panels in the second half of 2007. TMD has been an early adopter of LED backlights because the company mostly focuses on 10–13.3-in. panel sizes for notebook computers. By the end of 2007, more than 50% of its notebook panels have LED backlights. At SID's Display Week 2008, numerous vendors showed LED-based notebook panels in various sizes. For example, Samsung showed 12.1-, 13.3-, and 15.4-in. notebook panels with LED backlights at Display Week 2008.

Most of these panels use high-efficiency LED chips. In general, high-efficiency LED chips can cost 10% more, but are generally 20% brighter. Also, high-efficiency LEDs do not require higher currents which helps in thermal management, reducing the need for heat sinks. In terms of lifetime, LED-backlight-based notebooks are getting 70k hours.

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We are always interested in hearing from our readers. If you have an idea that would make for an interesting Business of Displays column or if you would like to submit your own column, please contact Mike Morgenthal at 212/460-9700 or email: mmorgenthal@pcm411.com.

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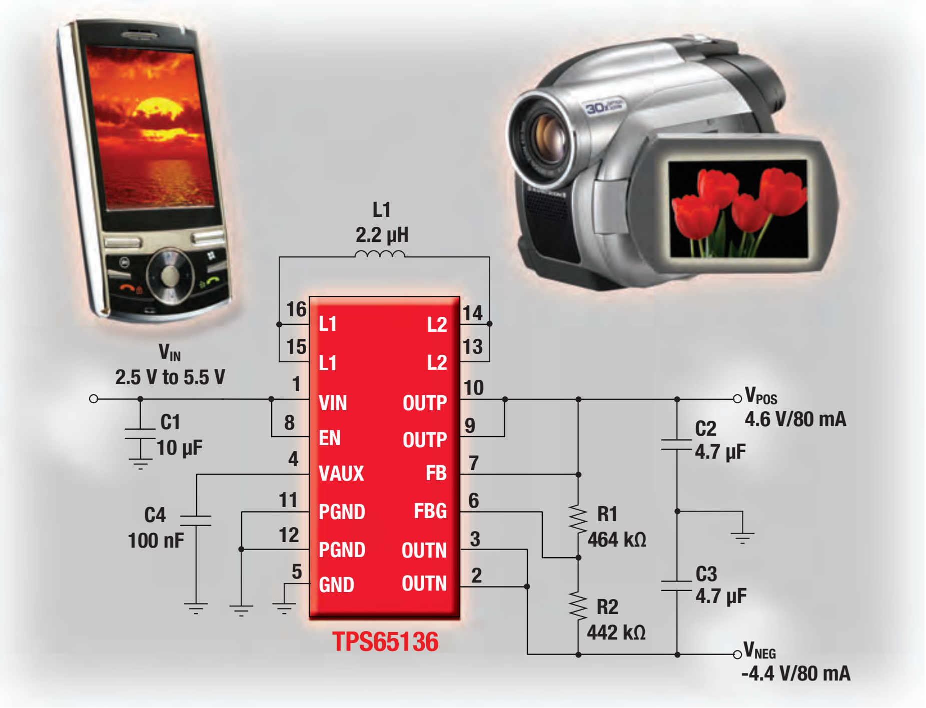

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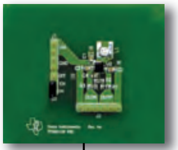
TPS65136	2.3 to 5.5	–6 to 4.6	0.7	70	16-pin QFN



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Gone are the days when the calibration of displays or projector systems can rely on the 'magic eyeball'. The correct adjustment and verification of RGB White Point, contrast, gamma, uniformity and screen gain, among others, requires accurate and repeatable measurement instrumentation. Along with built-in flexibility and ease of use, the proper tools can conduct the required tests in a timely manner and insure that the images being displayed, regardless of the technology, are the best possible.

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The Outstanding Potential of OLED Displays for TV Applications

Despite all the buzz surrounding Sony's launch of the first commercial OLED TV in December 2007, the company is not resting on its laurels. This article details the company's approach to developing and manufacturing large-sized AMOLED TVs.

by Tetsuo Urabe

DURING THE PAST SEVERAL YEARS, organic-light-emitting-diode (OLED) technology has drawn increasing attention as the next-generation display platform (along with its potential as a source for general illumination). One of the main reasons is its "all solid state" nature, which provides myriad opportunity for further evolution in a variety of aspects.

The first stage of this evolution occurred in the 10–15 years since C. Tang's pioneering work on OLEDs at Kodak in 1988. Even in this initial stage, it is likely that OLED researchers recognized its great potential for display devices; however, it's passive-matrix drive limited OLEDs great potential. Consequently, in the second stage of OLED commercialization, which has taken place during the past 10 years, R&D activities have focused on active-matrix OLEDs. Great progress has been made in this decade, not only for the driving scheme including the design of the TFT pixel circuit, but also in the OLED device and materials. Sony has developed the "Super Top Emission" device structure, which enhances color gamut and efficiency, both of which are critical for TV-quality displays. Idemitsu and Sony jointly developed long-lifetime and highly efficient OLED materials sufficient for such displays. Further reduction on power consumption can be achieved by employing phosphorescent materials.

In this article, the advantage of OLED displays in terms of image quality is described – and it is this superior image quality that gives OLED displays the potential to become the premier displays for TV applications.

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Extraordinary Picture Quality

One of the great advantages of an emissive display such as an OLED display is that the dynamic range of the brightness can be controlled pixel by pixel. Figure 1 shows bright-

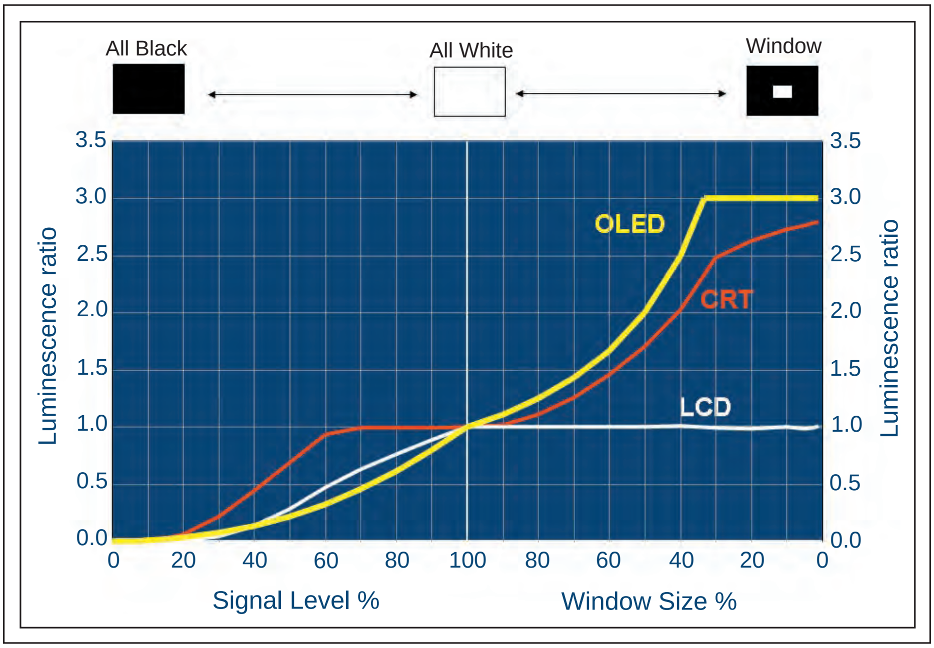

Fig. 1: A comparison of brightness vs. signal level and window size for OLEDs, LCDs , and CRTs.

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ness *vs.* signal level and window size. The maximum brightness of a liquid-crystal display (LCD) is basically equivalent to the fixed backlight brightness, which means that it is impossible to accurately display an image that contains an extremely bright local area. This is a very important feature for TV applications because the capability of strong peak luminance would improve the impact of images dramatically – for example, a scene of fireworks at night or strong reflection of sunlight from glass could be displayed much more realistically by an OLED display.

Extremely high contrast ratio is another advantage of OLED Displays. LCDs struggle to achieve "real black," since an LCD basically works as the shutter that modulates the polarization of transmitted light from the backlight unit – this makes it extremely difficult to curtail light leakage, which in turn limits the contrast ratio. Even a tiny amount of light leakage causes considerable image degradation for some scenes in TV pictures. Imagine a forest scene during a very cloudy day; the picture level of this TV signal is very low. Under this condition, color reproduction of the deep green color of the forest on an LCD screen is degraded by a very small amount of light leakage from blue and red subpixels. However, the same scene would be much richer in color when displayed on an OLED display, in which the off-state of each subpixel is completely black – the "off" state corresponds to a non-emissive state, which means there is no light leakage. Figure 2 shows the color gamut of an OLED display and an LCD plotted *vs.* picture level. A wide color gamut throughout all picture levels is extremely desirable for the display of TV images. Because an OLED display is an emissive display, similar to a CRT display, its light output can be easily managed, allowing for high contrast ratios over wide viewing angles.

Moving-picture quality, another critical factor for TV performance, is evaluated by moving-picture response time (MPRT). For active-matrix displays, the MPRT is limited by the hold-type driving scheme. Recently, LCDs have overcome this problem via a high frame-rate drive (120 Hz). OLED displays can take the same approach; however, there are other ways to solve this problem. The pixel circuit of an OLED display could be designed to turn off the emission at any time in the middle of a single frame, which reduces the motion blur originated in a hold-type driving scheme, though this would result in lower overall luminance.

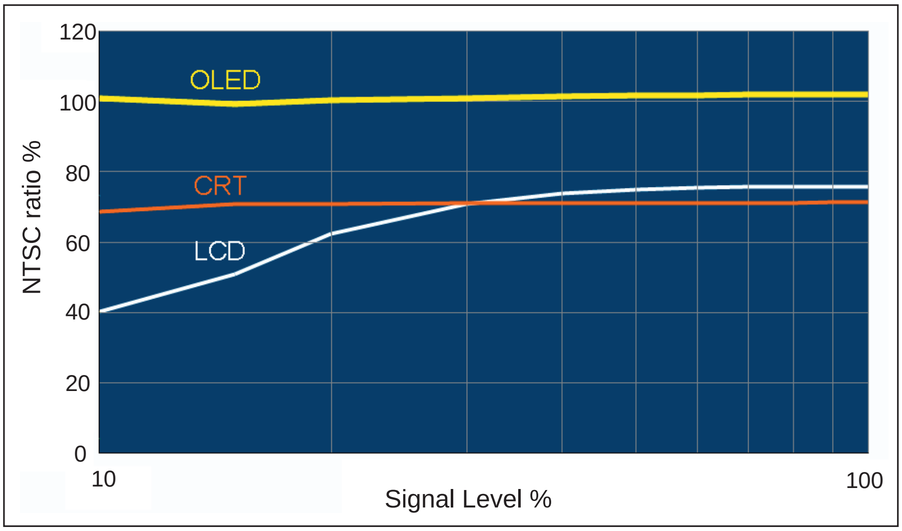


Fig. 2: *The color gamut of OLED displays, LCDs, and CRT displays plotted vs. picture level.*

OLED Process for Large-Screen Displays

Sony began to sell the world's first OLED TV, the XEL-1, in December 2007 (Fig. 3). The XEL-1's 11-in. screen size is relatively small, yet it still demonstrates the outstanding picture quality promised by OLED technology, to the point where Sony believes that the potential of OLED TV is now widely recognized. So, the next question is, how large can OLED TVs be?

The XEL-1 employs vacuum evaporation of small molecules by using a metal-mask process and low-temperature polysilicon (LTPS) TFTs for the backplane. It is well recognized these technologies cannot be

Fig. 3: *Sony's XEL-1 became the first commercially available OLED TV when it hit stores in December 2007.*

applied for large glass substrates; therefore, we have to develop the new technologies both for the OLED and TFT processes.

Various approaches have been proposed to achieve large-screen OLED displays. They are classified into three categories: (1) patterning by using RGB subpixels, (2) white emission plus the use of a color filter, and (3) blue emission plus color conversion. There has been vigorous debate over which type is best for large-screen-sized OLED displays.

When trying to decide which approach to take, Sony first had to determine the best way to industrialize OLED TV, for which there are really two options. The first option is to start the business with low-cost device and process technologies, followed by the improvement of performance (with the according price increases). The second is to start a business with high-performance device and process technologies (even at high costs), followed by reductions in cost. High-quality LCD and plasma TVs already permeate the market, so the next-generation TV must have superior image quality than existing flat-screen TVs. This has led Sony to the conclusion that we should choose a technology that gives us the best performance, including image quality.

A white-emission plus color-filter device has the simplest structure, so the production cost is estimated to be the lowest among these three options. Since the patterning process of the OLED layer is not required in this case, use of a metal mask is not necessary. However, power consumption is a real problem because more than two-thirds of the energy of the white emission from an OLED is absorbed by the color filter. Furthermore, this type of device gives rise to a severe tradeoff between color gamut and brightness. Adding a white subpixel (RGBW color filter) is a potentially smart way to compensate for the transmission loss caused by the RGB color filter. However, a polarizer and quarter-wavelength plate must be put on the panel to eliminate the reflection caused by the white subpixel, once again resulting in a power loss of more than 50%.

A blue-emission plus color-conversion device is better in terms of energy efficiency because basically there is no transmission loss *via* the color filter, providing that color conversion efficiency is 100%. For this purpose, color-conversion materials with high conversion efficiency and low-light-scattering characteristics need to be developed.

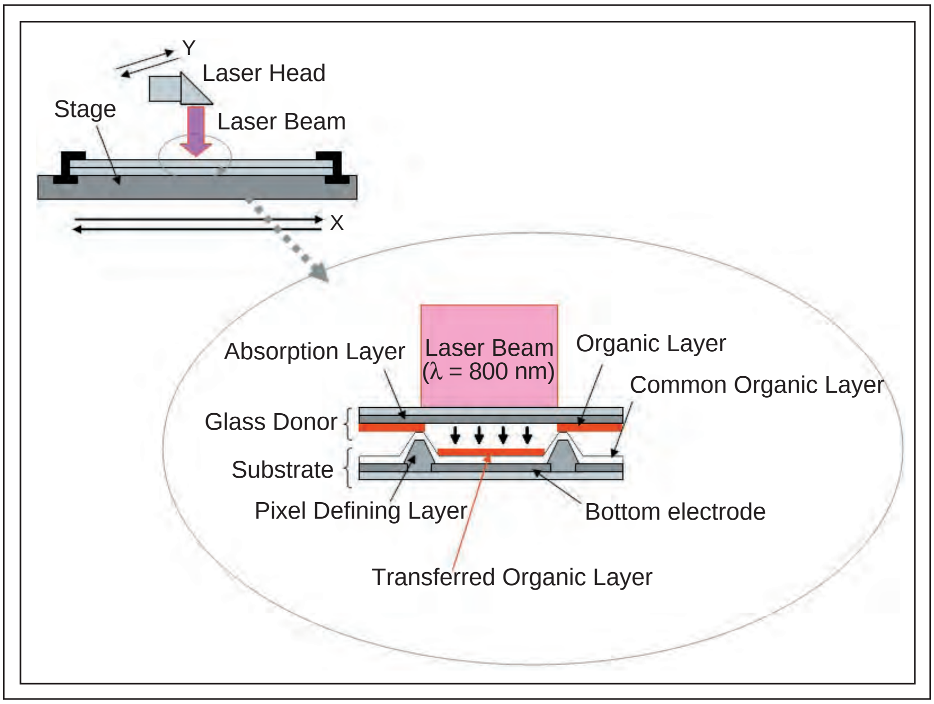


Fig. 4: *A cross-sectional view of Sony's newly developed laser transfer process named Laser Induced Pattern-wise Sublimation (LIPS).*

Based on these considerations, it is concluded that an RGB-patterned-type device should be the best choice for a TV display because of its excellent image quality. For example, the XEL-1 offers a color gamut of more than 100% NTSC, a contrast ratio of 1,000,000:1, *etc.* So the next question is, how do we get an RGB-patterned device without using a metal-mask process in order to be able to use large motherglass, such as Gen 6 or Gen 7? An attempt to employ a solution process has been actively undertaken in a variety of methods, including polymer materials and small molecules. This seemed very attractive, and we expected this process would be realized. However, we could not achieve long lifetime with pure blue using a solution process, and this is crucial for TV application.

The concept of Sony's approach is to keep the existing device structure and vacuum-evaporation process, which has been proven to yield good enough performance and lifetimes for TV applications, and omit the metal-mask process. Figure 4 shows the cross-sectional view of the newly developed laser-transfer process that we named Laser Induced Pattern-wise Sublimation (LIPS). In this case, only the emission layer is processed by LIPS, while the other layers (hole-transport layer, electron-transport layer, *etc.*) are formed by using a current vapor-evaporation process. It could be thought that the metal layer on donor glass is equivalent to the heat source of the conventional vacuum-evaporation process.

TFT Backplane for Large-Screen OLED Displays

Amorphous-silicon TFT (a-Si TFT) backplanes are now widely used for active-matrix LCDs, and the manufacturing infrastructure is now well established. It is desirable to make use of a-Si TFTs as the backplane for active-matrix OLED displays. However, the threshold-voltage shifts of a-Si TFTs caused by the bias stress voltage is a serious problem for OLED displays. Compensating for the threshold-voltage shift by using driving scheme has been investigated, but it is not yet good enough to apply to TV displays; accordingly, a new TFT with a small enough threshold-voltage shift has to be developed. LTPS, which is now widely used as the backplane for OLED displays, has a very high electron mobility and extremely small threshold-voltage shift. It turns out, though, that such a high electron mobility is not really required to

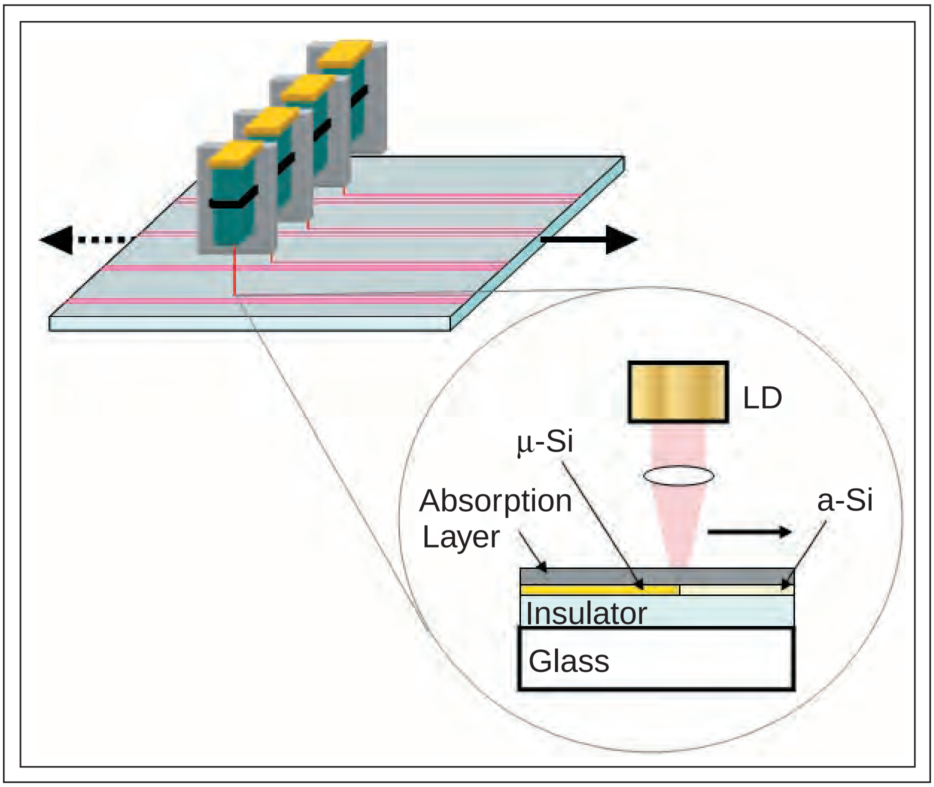


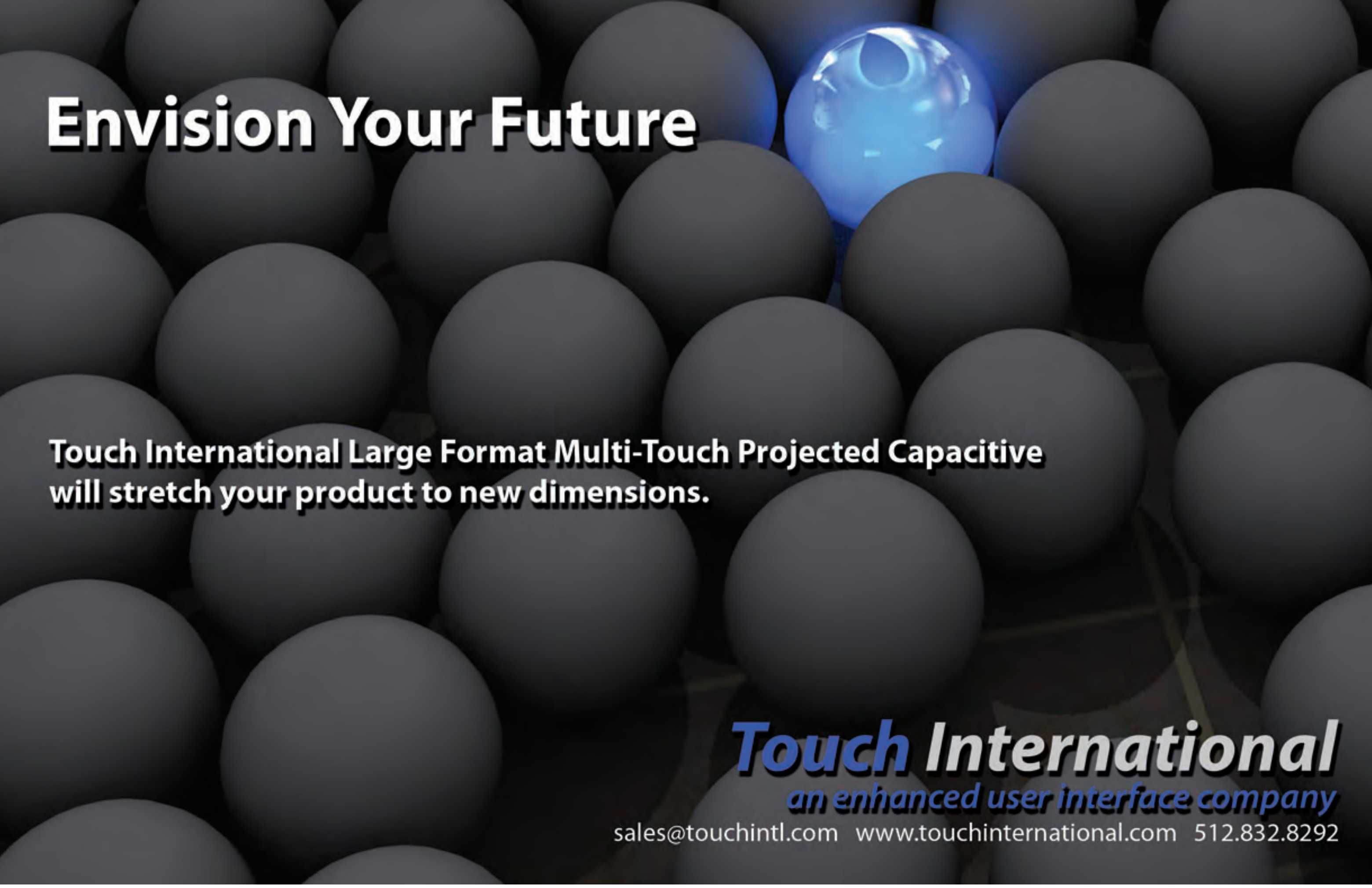
Fig. 5: A schematic of Sony's new thermal annealing process using a high-power diode laser, which it has named diode Laser Thermal Anneal (dLTA).

Fig. 6: Sony developed a 27-in. full-HD OLED TV prototype to test its new manufacturing technologies.

drive OLED displays. Microcrystalline-silicon TFTs, which have a considerably small shift in the threshold voltage and an electron mobility of 1–10 cm^2/V-sec, is considered to be a good choice. The question is, what kind of process is the most appropriate to obtain microcrystalline-silicon TFTs? It is quite obvious that an as-deposited process is desirable in terms of production cost. There are many ways to conduct the as-deposited process, but none of them are available for mass production at this time. As a practical method, we developed a thermal annealing process using a high-power diode laser and named it diode Laser Thermal Anneal (dLTA). One reason we chose diode lasers is that the output laser light is very stable and controllable. When compared with eximer lasers, which are commonly used for the LTPS process, the advantage of this technology is scalability. The design of the annealing equipment is described in Fig. 5. There should not be any limit in motherglass size. We could increase the number of laser heads to improve tact time. By using this technology, we obtained an electron mobility of 2–3 cm^2/V-sec and a threshold-voltage shift of ~2 V (after 100,000 hours under the bias conditions of I_{ds} = 10 μA, 50°C), which is good enough as the backplane TFT for active-matrix OLED displays.

Conclusion: A New Technology Prototype

In order to realize the feasibility of this new technology as described above, Sony has developed a 27-in. OLED-display prototype (Fig. 6) with full-HD resolution (1920 × 1080 RGB). Newly developed microcrystalline-silicon TFTs and LIPS yields a picture that is just as vivid as that for the XEL-1, which makes us confident enough to employ these new technologies for manufacturing displays on larger motherglass. The significance of the 27-in. prototype is to demonstrate the possibility of large-screen OLED TVs without sacrificing picture quality. We recognize that there must be myriad different approaches in addition to ours, and we welcome the attempts that will be made to find better ways to develop high-quality low-cost OLED manufacturing technology. Those challenges will certainly improve the technological level of OLED TV and stimulate the OLED industry. ■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A New Era of Oxide Thin-Film Transistors for Large-Sized AMOLED Displays

In order for large-sized AMOLED displays to achieve widespread adoption, manufacturers must find a way to mass produce them at affordable prices. However, scaling-up of production lines causes several technological challenges. This article delves into the critical issue of the TFT backplane, which is crucial for the success of AMOLEDs.

by Jae Kyeong Jeong, Hyun-Joong Chung, Yeon-Gon Mo, and Hye Dong Kim

AMONG existing display technologies, active-matrix organic light-emitting diodes (AMOLEDs) provide the best potential solution to achieve the "ultimate display" due to their fast motion-picture response time, vivid color, high contrast, and super-slim light-weight nature.[1,2] In 2007, Samsung SDI launched the first mass production of small-sized AMOLEDs for cell-phone and MP4 displays.

The display market is now burgeoning for mid- to large-sized applications, such as notebook PCs (NPCs), monitors, and televisions, which accounts for the majority of the flat-panel-display market. Samsung SDI's recent exhibition of 14- and 31-in. full-HD television prototypes[3] and Sony's commercialization of qFHD 11-in. TV (XEL-1) clearly show that the era of AMOLED TV is indeed nearby. Whereas the market is projected to reach 54 million units by 2011,[4] a number of hurdles in technology must be overcome for the mass production of mid–to–large-sized AMOLED panels.

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The biggest impediment to widespread adoption of AMOLED NPCs and TVs is finding a way to produce them in mass quantities at affordable prices. The best strategy for this purpose is to increase the motherglass size at least up to Gen 5.5 (1300 × 1500 mm), which corresponds to the most cost-effective backplane size for NPCs. However, the scaling-up of the production line causes several technological challenges. In this article, we focus on the current status and critical issue of the thin-film-transistor (TFT) backplane, which is one of the most crucial technologies for the success of AMOLEDs.

Amorphous-silicon (a-Si) TFT technology is well-established, a proven technology in the liquid-crystal-display (LCD) industry. This technology offers good scalability (up to Gen 8) and a low-cost process because it does not require the crystallization and ion-doping processes. In addition, its amorphous nature ensures excellent uniformity of device performance, including mobility and threshold voltage. However, the mobility of a-Si TFTs is quite low (~1 cm^2/V-sec), which may not be enough to drive large-sized high-resolution AMOLED displays. Furthermore, the device instability has been a concern for a long time. For example, the threshold voltage of an a-Si TFT seriously shifts under constant current stress due to either the charge trapping into the underlying gate dielectric or the weak bonding break-up of silicon and hydrogen in a-Si thin film, leading to image burnout or serious image sticking (*e.g.*, short lifetime) in AMOLED displays. This is why a-Si TFTs are rarely used as backplanes for AMOLED displays.

On the other hand, low-temperature polycrystalline-Si (LTPS) TFTs have high mobility and excellent stability, unlike that of a-Si TFTs. The key processes in fabricating LTPS TFTs are the crystallization methods that convert a-Si into polycrystalline-Si: non-laser crystallization and laser annealing. Among non-laser crystallization, the simplest method is solid-phase crystallization (SPC). But SPC requires annealing at 600ºC for tens of hours, which makes it unsuitable for use on large-area glass substrates. Other non-laser methods employ metal seeds for crystallization, which may result in a large current leakage in the channel area.

Among the laser methods available, excimer-laser annealing (ELA) has been the most widely used because of the resulting excellent crystallinity, fast crystallization speed, and high mobility. In addition, ELA is already been employed in mass-production, thus well-developed apparatuses are commercially available. However, ELA suffers from

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a narrow process window, as well as high initial investment and maintenance costs. Moreover, the limitations in laser-beam length and laser-beam instability are a major obstacle in the use of ELA on large-sized glass: the largest equipment available is applicable to Gen 4 (a motherglass size of 730 × 920 mm). Finally, all LTPS TFTs, including the ELA technique, suffer from non-uniformity issues because of the existence of grain boundaries, which require the use of a complicated compensation unit pixel circuit such as a 5 transistor + 2 capacitor pixel circuit, leading to a loss in device yield.

Therefore, an obvious question arises: Is there any new TFT that has both high mobility and excellent uniformity at the same time that is suitable for large-sized AMOLED displays? Amorphous-oxide TFTs can be an attractive alternative solution to this question. Amorphous-oxide semiconductors (AOS) provide unique properties that combine the advantages of a-Si and LTPS TFTs. For example, amorphous-oxide TFTs are free from the non-uniformity of mobility and threshold voltage, yet exhibit large carrier mobility (~10 cm^2/V-sec) and excellent subthreshold gate swing (down to 0.20 V/dec). Moreover, the channel layer can be fabricated by using a simple sputtering process. Therefore, large-sized fabrication can easily be implemented up to Gen 8 sizes without using expensive laser apparatus. The process is essentially the same as that for a-Si TFTs so that existing production lines can be used without significant changes. In addition, oxide TFTs can be deposited at room temperature, which in principle makes possible the mass production of AMOLEDs on flexible plastic substrates or cheap soda-lime glass. The technological comparisons among a-Si, poly-Si, and oxide TFT are summarized in Table 1.

A Brief History of Oxide TFTs

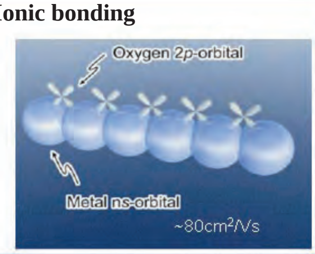
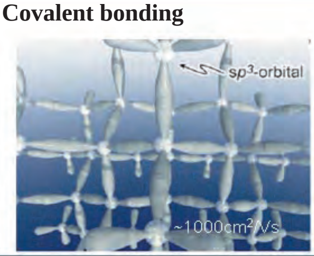
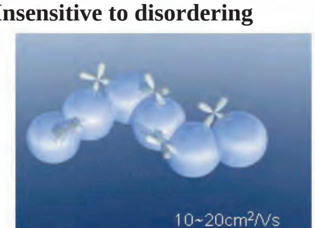
In 2003, the first paper describing high-performance transistors (mobility, ~80 cm^2/V-sec) by using single-crystalline InGaZnO material (from Professor Hideo Hosono's group) was reported in *Science*.[5] However, the high-temperature deposition (700°C) of InGaZnO using pulsed laser deposition (PLD) and annealing at 1400°C prohibited its practical usage as the channel layer of a TFT backplane for AMOLED displays. A subsequent paper in *Nature* in 2004 discussed the concept of amorphous InGaZnO in order to reduce the fabrication temperature (room temperature) by using a PLD technique.[6] These two papers created significant worldwide interest in AMOLED technology, both in industry and academia because of the potential for high mobility, excellent uniformity in device parameters, and good scalability to large substrate size.

Let's look at the origin of high mobility even in the amorphous state. Table 2 shows the orbital structure of the crystalline and amorphous state for indium gallium zinc oxide (IGZO) and solid silicon, respectively. The conduction band of IGZO material is closely related to the In 5s orbital, which has an isotropic property. Interestingly, the spherical symmetry of the 5s orbital makes the structural disordering no longer critical. So even though the phase is transformed into the amorphous state, the a-IGZO semiconductor still has good mobility (>10 cm^2/V-sec). This is drastically different than that for a silicon

Table 1: Comparison of TFT technologies including a-Si, poly-Si, and oxide TFTs

	a-Si TFT	poly-Si TFT	Oxide TFT
Generation	8G	4G	8G
Semiconductor	Amorphous Si	Polycrystalline Si	Amorphous IGZO
TFT uniformity	Good	Poor	Good
Channel mobility	1cm^2/Vs	~100 cm^2/Vs	10 ~ 40 cm^2/Vs
TFT for OLED	4~5	5~11	4~5
Pixel circuit	Complex (> 4T)	Complex (> 4T)	Simple (2T + 1C)
Cost/Yield	Low/high	High/low	Low/high
Stability (ΔV_{th}, 100 khr)	>5V	< 0.5V	NA
Circuit Integration	NO	YES	YES
Pixel TFT	NMOS	PMOS (CMOS)	NMOS

Table 2: The schematic orbital structure of the conduction-band minimum in a silicon semiconductor and in a ionic oxide semi-conductor.[6]

	InGaZnO	Si
Crystalline phase	• Ionic bonding 	• Covalent bonding 
Amorphous phase	• Insensitive to disordering 	• Sensitive to disordering 

H. Hosono et al., J. Non-Crystalline Solids 203, 334 (1996).

Items	Specification
Diagonal size	12.1 inch
No. of pixels	1280 × RGB × 768
Sub pixel pitch	69 × 207 μm^2
Resolution	123 ppi
Panel size	283 × 181 mm^2
Pixel element	2Tr 1Cap
Gray	256 gray
Scan driver	Integration
Color coordinate	White (0.31, 0.31) Red (0.67, 0.33) Green (0.29, 0.64) Blue (0.15, 0.11)

Fig. 1: *The panel image of a 12.1-in. WXGA AMOLED driven by oxide TFTs.*

semiconductor, in which the mobility drop is significant (from 1000 to 1 cm^2/V-sec) when the phase transforms from the crystalline state to the amorphous state.[6]

In 2006, Canon demonstrated that a high-performance transistor (mobility, > 10 cm^2/V-sec; gate swing, 0.2 V/decade) can be achieved by using RF sputtering with the capability of using large-area deposition rather than PLD.[7] Major panel makers such as LG and Samsung began performing R&D on oxide TFTs for AMOLEDs in 2006. The first AMOLED display was released by LG Electronics in 2007.[8] The fabricated InGaZnO transistor having a top-gate structure exhibited good device performance. This prototype of a full-color 3.5-in. QCIF+ AMOLED demonstrated the possibility of being used as a backplane for an OLED device.

This year at SID's Display Week 2008, Samsung SDI showcased a full-color 12.1-in. AMOLED prototype (Fig. 1) that used InGaZnO TFTs; this is the world's largest AMOLED panel among any oxide TFT-driven OLED display.[9] The WXGA high-resolution (1280 × RGB × 765) is compatible with TFT-LCDs that are currently commercially available for notebook PCs. In addition, even though a 2 transistor + 1 capacitor pixel circuit was implemented, a "random-mura-free" high-quality display was demonstrated, due to the excellent short-range uniformity of the threshold voltage of oxide TFTs.

Performance of Oxide TFT

Initially, an a-IGZO field-effect transistor fabricated on a flexible substrate had a mobility of 8.3 cm^2/V-sec and an $I_{on/off}$ ratio of 10^3.[6] Since 2004, the device performance of oxide TFTs has rapidly improved. The transistor performance reported in the literature includes field-effect mobilities between 1 and 53 cm^2/V-sec and $I_{on/off}$ ratios ranging from 10^4 to 10^8. However, most of the previously reported TFTs have rather large channel lengths and widths (>50 µm) because the shadow mask or lift-off techniques were mainly used to pattern the gate electrode, channel, and source/drain electrodes. Full array fabrication of oxide TFTs applicable for high-resolution AMOLED displays has been attempted by a few major companies, including Samsung SDI, LG, and Toppan, Inc.

Figure 2 shows the representative transfer curve of our IGZO TFT with W/L = 25/10 µm, which was taken from a full-array-panel device rather than the individual test device without a suitable passivation layer. We adopted a bottom-gate structure with an etch stop layer. The high field-effect mobility of 17 cm^2/V-sec, an excellent gate swing of 0.28 V/decade, and a good $I_{on/off}$ ratio of 10^9 was achieved; these are state-of-the-art characteristics for any oxide TFT. We believe that these specifications of oxide TFTs are good enough to drive high-resolution and large-area AMOLED panels.

The most difficult aspect of fabricating high-quality AMOLED displays is the presence of "mura" caused by TFT non-uniformities. These non-uniformities are caused by localized differences in TFT properties, which ultimately result in the variation in current levels supplied to the individual subpixels throughout the display. Therefore, another important figure of merit is the short- and long-range uniformity of device performance. The short-range uniformity of oxide TFTs is surprising – the representative standard deviations of threshold voltage is less than 0.01 V.

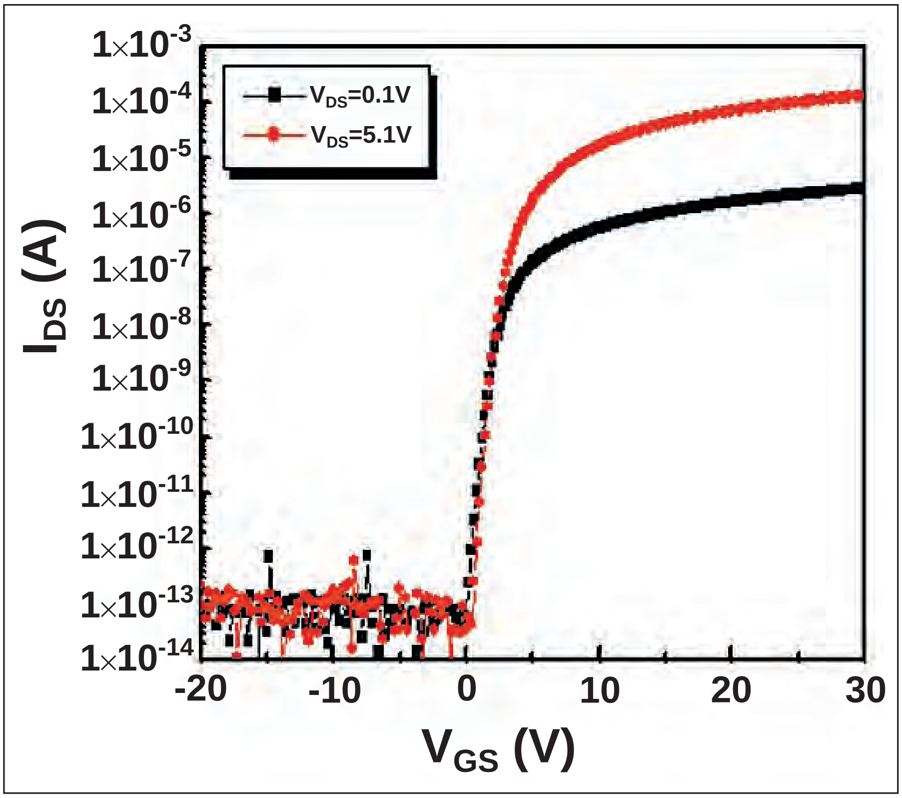


Fig. 2: *The representative transfer characteristics of IGZO TFT.*

The simple calculation predicts the non-uniformity in luminance to be less than 2%. This result suggests that an ultra-simple pixel circuit such as a 2 transistor + 1 capacitor pixel circuit can be used for the design of AMOLED displays, which will have a very positive impact on the device yield and cost.

Issues and Outlook

In order to impact the TV market, AMOLED TVs must be competitively priced with identically sized AMLCD and PDP TVs. Moreover, the following specification should be met: a lifetime > 100,000 hours, a color gamut > 90%, a peak luminance > 400 nits, a contrast ratio > 100,000:1, and no image burn-in (> 500 hours).

The first issues that must be resolved include the attainment of a TFT threshold voltage change of less than 0.2 V for the lifetime of the display; the elimination of fine mura; and a brightness uniformity of more than 80%. In particular, the instability of the threshold voltage should be improved by the proper choice of passivation material and careful optimization of robust IGZO compositions. Of course, a new oxide semiconductor and compatible gate dielectric should be developed in parallel, which allows for better stability than the combination of IGZO semiconductor and a SiNx dielectric. In addition, to be cost competitive, AMOLEDs must maintain a production yield similar to that of AMLCDs, and the TFT backplane should be produced by using a process consisting of four or five photo-masking steps.

Secondly, OLED patterning technology capable of large-area motherglass size (greater than Gen 5) and high resolution (> 200 ppi) also must be developed. To date, the fine-metal shadow mask (FMM) has been the only commercialized patterning method used in the color primaries of OLEDs. However, an FMM has an intrinsic limit of mechanical bending (~ Gen 4) when the size is increased. To circumvent the problem, a sequential pattern formation can be implemented, but the method has weaknesses in uniformity and tact time. Ink-jet printing of soluble OLED material,[5] color filters on white OLEDs,[6] and laser-induced thermal transfer are strong candidates to replace FMM.

Finally, encapsulation is another important issue for large-sized displays. Encapsulation is necessary in order to prevent the degradation of OLEDs caused by the attack of the oxygen and moisture in the atmosphere. Because HDTVs require at least 50,000 hours of lifetime, the development of a simple but reliable encapsulation method is unquestionably important.

Resolving the aforementioned issues will guarantee the era of AMOLED adoption for use in notebook PCs and HDTVs.

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Tyco Electronics Introduces the Elo TouchSystems 1900L and 2200L Touchmonitors

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Technological Considerations for Manufacturing Flexible Active-Matrix OLED Displays

AMOLEDs hold great promise for use in flexible displays. LG Display has showcased a full-color 4-in. flexible AMOLED prototype on an 80-µm-thick stainless-steel foil substrate, achieving a curvature of 5-cm bending radius. This article discusses the challenges ahead, including transporting the flexible backplane substrate and obtaining reliable TFT characteristics in order to achieve brightness and uniformity suitable to commercialize this technology.

by Juhn S. Yoo, Nackbong Choi, Yong-Chul Kim, In-Hwan Kim, Seung-Chan Byun, Sang-Hoon Jung, Jong-Moo Kim, Soo-Young Yoon, Chang-Dong Kim, In-Byeong Kang, and In-Jae Chung

THE display market of the future demands ubiquitous devices that are more portable, fashionable, and environmentally friendly.[1] Display manufacturers need to advance their technologies to build lighter, slimmer, more rugged devices that consume low amounts of power while at the same time improve the picture quality. The emerging technology of flexible active-matrix displays is being developed in order to fulfill these needs. Currently, there are active research projects in reflective-type flexible liquid-crystal displays (LCDs),[2] flexible electrophoretic displays (EPDs),[3] and emissive-type flexible organic-light-emitting-diode (OLED) displays.[4] Today, EPD technology is considered the most desirable flexible-display technology because of its simple fabrication process and very low power consumption. An active-matrix OLED (AMOLED), on the other hand, is an emissive-type display device that promises better picture quality – including brightness, color, contrast ratio, viewing angle, and response time – compared to active-matrix liquid-crystal displays (AMLCDs). An OLED is a thin-film solid-state device, which makes it easier to apply to flexible displays because of its relatively simple fabrication process and reduced distortion according to the geometric form of display. However, in general, AMOLED displays have yet to overcome numerous technological obstacles for mass production.[5] When imple-

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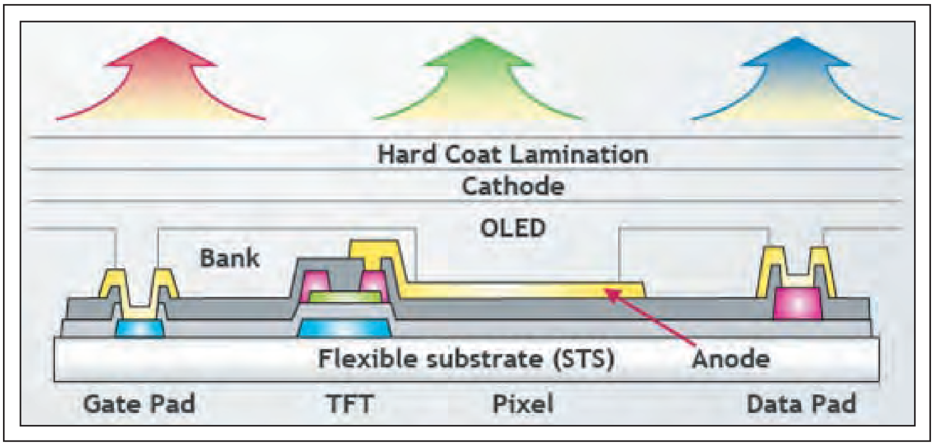

Fig. 1: *A cross-sectional schematic of the developed flexible AMOLED display. A low-temperature a-Si TFT array and top-emission OLED is integrated on a thin stainless-steel substrate. The display device is encapsulated with thin-film passivation and hard-coat lamination.*

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menting AMOLEDs into flexible displays, even more technological issues need to be considered.[6]

This article examines the technological considerations for transferring flexible AMOLED display manufacturing to existing AMLCD product lines based on LG Display's recent development of a 4-in. prototype using amorphous-silicon thin-film transistors (a-Si TFTs) on stainless-steel foil. The structure and fabrication process of the flexible backplane, issues concerning TFT performance, and suggestions on process improvements will be discussed. The structure and design of the display panel is also presented, as are the issues of our OLED driving circuits and possible solutions.

Flexible Backplane Fabrication

Compared to plastic substrates, metal foil has excellent dimensional stability under relatively high process temperature. Until the thermal instability issue of plastic substrates is resolved, stainless-steel substrates remain the most promising candidate for the manufacture of flexible displays.

Our first consideration for using stainless-steel foil is that it is opaque, meaning it is limited to either reflective or emissive display devices. Therefore, we designed the TFT backplane to be compatible with a top-emission OLED structure, of which the cross-sectional schematic is shown in Fig. 1. Our second consideration is the method of transporting the substrates to prevent sagging while being transferred in and out of the manufacturing equipment. Our third consideration is the surface-planarization method to reduce the roughness of the steel plate, where protrusions and dents can cause line-open defects in the display array. Our fourth consideration is the insulation of the conductive substrate from the TFT array, where capacitive coupling causes signal line delay and crosstalk. Our fifth and most important consideration is the material and process integration needed to build a reliable TFT.

We fabricated a back-channel etch-structure a-Si TFT array using a typical five-mask process. In order to prevent substrate sagging, we fixed a set of metal foils to a glass carrier with adhesive. We developed a set of epoxy adhesive films to endure thermal stress as high as 200°C without failure. The stainless-steel foil was mechanically and chemically polished to reduce the surface roughness and minimize the height and depth of protrusions and dents. In order to further planarize the metal surface, a multi-barrier structure was prepared by coating 3-μm-thick polymer resin and depositing 0.4-μm-thick plasma-enhanced chemical-vapor-deposition (PECVD) silicon nitride. Figure 2 shows the structure of the prepared substrate and Fig. 3 compares the atomic-force microscopy (AFM) images of bare stainless steel and the planarized substrate surface. The thick insulating layer not only reduces the capacitive coupling between the conducting substrate and the TFT array, but also protects the metal foil from chemical attack. The RMS value of the substrate surface roughness decreased from 1000 to 50 Å.[7] The characteristics of fabricated a-Si TFT are shown in Fig. 4.

Despite the comparable characteristics of the a-Si TFT on a flexible substrate to a glass counterpart, the threshold-voltage shift under bias temperature stress is drastic, as shown in Fig. 5. The process temperature of the PECVD deposition of the gate insulator and active layers is limited to 150°C, thus preventing debonding of the adhesive film. The temporal variation of threshold voltage creates image sticking, as shown in Fig. 6, where a ghost image of the previous picture is observed. Therefore, it is not encouraging to use the bonding–debonding method for transporting the flexible substrate. One way to increase the process temperature by removing the thermally unstable bonding process is to adopt the method used in the glass-thinning process.

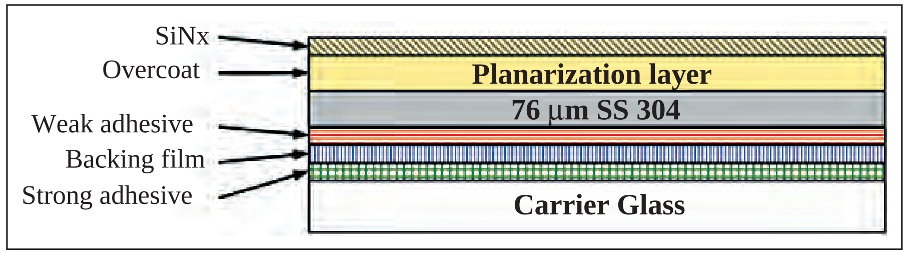
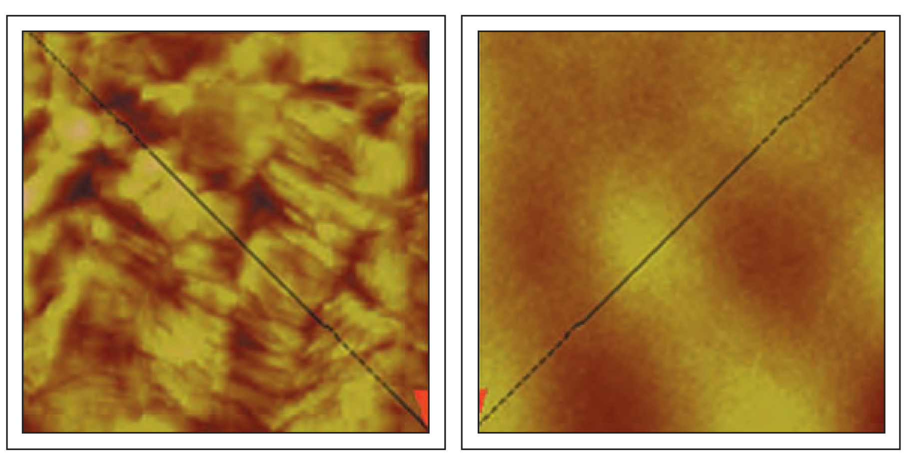


Fig. 2: *A cross-sectional schematic of the thin metal substrate bonded on a glass carrier and coated with planarization layers.*

Top-Emission OLED

Considering the opaqueness of the metal substrate, a conventional bottom-emission OLED structure is not applicable. Hence, a



(a) Bare stainless steel (RMS ~1000 Å) (b) Planarized substrate (RMS ~50 Å)

Fig. 3: *Images of (a) AFM surface-roughness measurement of bare stainless steel and (b) the planarized substrate.*

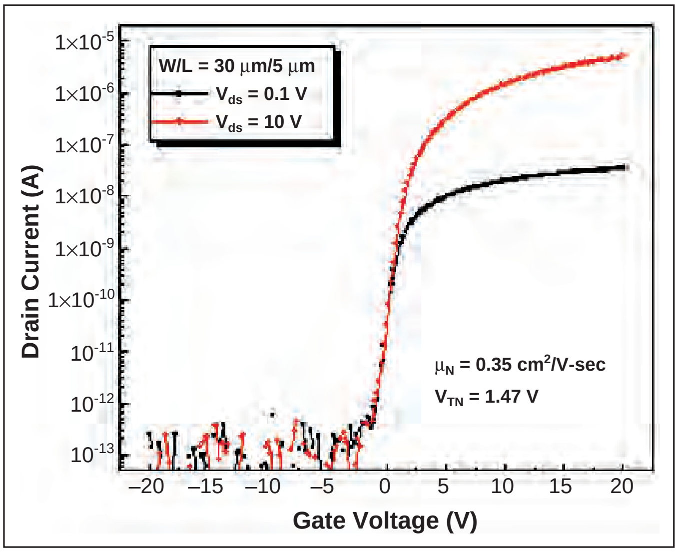


Fig. 4: Measured transfer characteristics of the a-Si TFT with channel dimensions of W/L = 30 μm/5 μm fabricated on metal foil at a maximum process temperature of 150°C. Field-effect mobility and threshold voltage are 0.35 cm^2/V-sec and 1.47 V, respectively, of which the values are comparable to a typical a-Si TFT on glass.

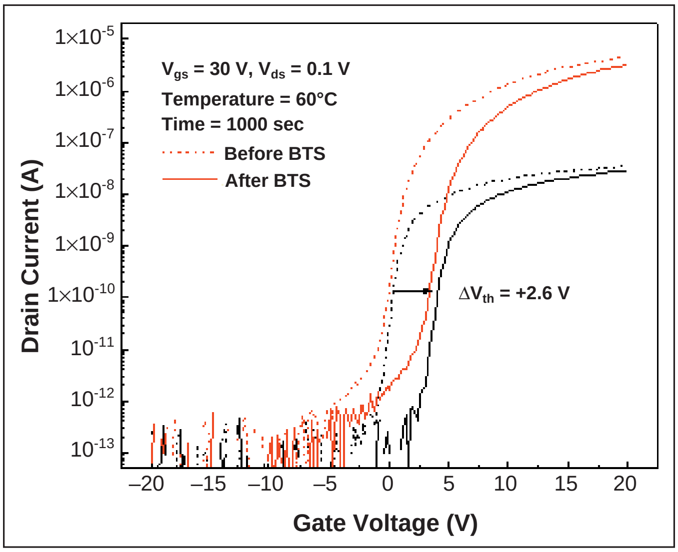
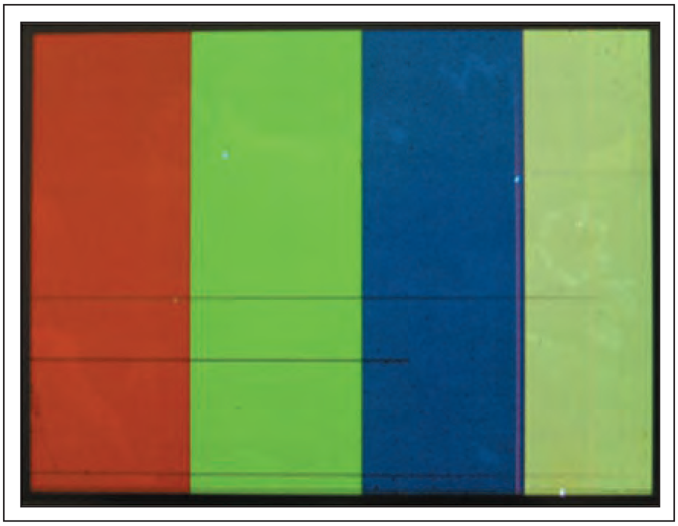


Fig. 5: Measured transfer characteristics of the fabricated a-Si TFT before and after bias temperature stress applied for 1000 sec under 60ºC with V_{gs} = 30 V and V_{ds} = 0.1 V. The threshold voltage shifted 2.6 V.

top-emission OLED structure was integrated on the flexible TFT backplane. Considering the process-temperature limitation, a-Si TFTs are our preferred choice over polycrystalline-silicon TFTs, of which the typical maximum process temperature is more than 350°C. Because a-Si TFTs have very low transconductance, a highly efficient electro-optical characteristic of the OLED is required. We employed a top-emission OLED structure with a highly efficient phosphorescent emissive layer and highly transparent cathode material. To secure the stability of the OLED under bending stress, organic-bank and thin-film passivation structures are recommended.

(a)



(b)

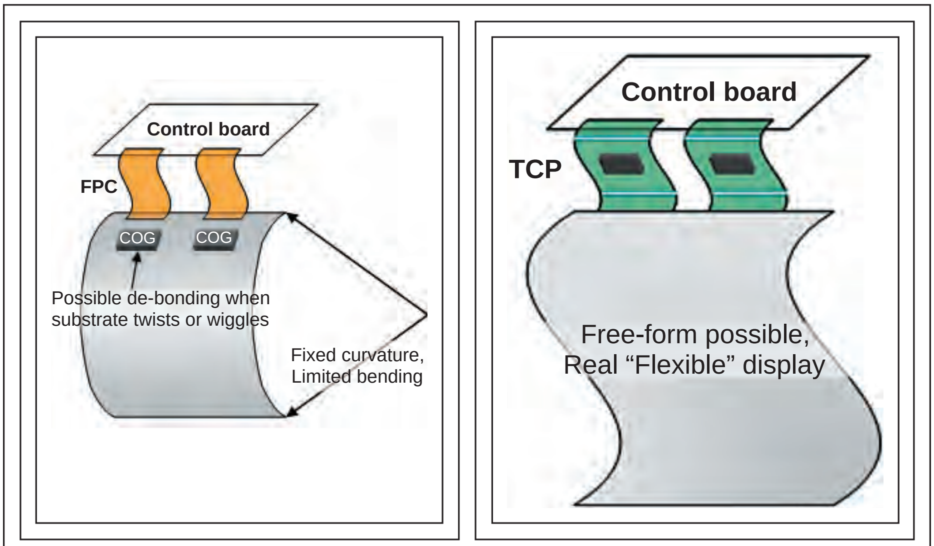
Fig. 6: Photographs of sequentially displayed images. Initial image of (a) the "flower" and (b) the consecutive images of the "RGBW stripe" where a ghost or residual image of the flower is observed. This image-sticking effect is mainly caused by the threshold-voltage shift of the pixel driving TFT.

We employed acrylic resin for the bank layer and multiple layers of organic and inorganic films for passivation structures. The OLED frontplane was finally encapsulated by a hard-coat lamination to protect from moisture permeation and scratching. In order to further enhance the luminous efficiency of the top-emission OLED, development of a reflective anode combined with a well-designed micro-cavity structure is also considered requisite.

Panel Design

Even if the substrate of the display panel is flexible, it would be difficult to curve the display module with a low-enough bending radius if rigid driver electronics are attached. It would be preferable to have just one or two flexible connectors tabbed on the panel, but this would also require a chip-on-glass (COG) type drive IC. As illustrated in Fig. 7, this module configuration is applicable for a curved display with a fixed bending radius, but not for real-flexible or rugged display applications because the rigid drive IC could easily de-bond when twisting or wiggling the substrate. We used a tape-carrier package (TCP) type source drive IC assembled on one side of the panel.

It is also highly imperative to integrate the gate driver circuit on the panel using a-Si TFTs to reduce the number of IC components, thus increasing the flexibility of the display module. As a result, we were able to operate the display in curvature with a bending radius of less than 5 cm along the vertical axis. In order to increase the flexibility along the horizontal axis of the panel, the control printed-circuit board (PCB) made of rigid plastic should be replaced with a flexible printed circuit (FPC). Bending demonstrations of our recently developed 4-in. flexible AMOLED display module with three drive ICs, one integrated gate driver, and one control PCB, along with the previously developed display module with six drive ICs and three control PCBs, are shown in Fig. 8.



(a) COG-type display module (b) TCP-type display module

Fig. 7: Schematic diagram of the suggested flexible-display-module configuration using TCP-type drive ICs (b). A COG-type module (a) is more compact but limited in flexibility, whereas a TCP-type module is more rugged due to better flexibility.

Conclusion

Preparing the metal-foil substrate for manu-


(a) Flexible display module with six ICs and three PCBs (b) Flexible display module with three ICs and one PCB

Fig. 8: Bending demonstration of the 4-in. flexible AMOLED panels displayed in curvature. (a) The previously developed display panel is limited in bending because it is surrounded by three control PCBs. (b) The bending radius of our recently developed display panel is less than 5 cm due to gate-driver integration and one control PCB assembly on one side of the panel.

facturing flexible AMOLED displays is a demanding process, which involves coating of a thick planarization layer to reduce the surface roughness and capacitive coupling between the conductive substrate and TFTs. Due to the process temperature limitation of a carrier glass bonding method for substrate transport, the reliability of a-Si TFTs fabricated below 150°C exhibits rather poor device stability under bias temperature stress. To increase the process temperature and thus achieve sufficiently reliable TFT backplanes, new planarization and transporting methods for stainless-steel substrates is under development. We employed a highly efficient top-emission OLED structure with a phosphorescent emissive layer integrated with organic-bank and multilayer thin-film encapsulation to secure flexibility. The development of a reflective anode and microcavity structure is considered a key technology in enhancing the luminous efficiency of the display. To realize a truly flexible or rugged display module, it is essential to have a flexible interface of driver electronics assembled on one side of the panel. It is also imperative to reduce the number of drive-IC components by integration of gate drivers using TFT devices and replacing the rigid plastic control PCBs with flexible printed circuits.

We have demonstrated 4-in. flexible AMOLED displays in curvature having a bending radius of less than 5 cm along one axis. In order to manufacture reliable flexible AMOLED displays with good picture quality, device process and OLED-driving technologies need to be improved in terms of the above-mentioned considerations.

Acknowledgment

This work is a joint development project with Universal Display Corp.

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The Evolution of Projection Displays. Part II: From Mechanical Scanners to Microdisplays

The development of projection-display systems has encompassed numerous technologies through the decades. CRTs have always played a crucial role, but other critical technologies such as the Eidophor oil-film light valve, Hughes light amplifier, liquid-crystal devices in various forms, diffraction gratings, mechanical scanners, and digital micromirrors have all played an important role in the evolution of this technology. The second installment of this two-part series explores the innovations of the modern era of projection technology, from the 1990s to the present day, exploring how the development of LCOS, DLP, and LCD technologies threatened the dominance of light valves and CRTs. Part I of this series was published in the May 2008 issue of Information Display*, which can be accessed at www.information display.org.*

by Matthew S. Brennesholtz

FOR MUCH of the 20th century, the key technologies enabling projection-display systems were cathode-ray-tube (CRT) systems and light valves. However, beginning in the early 1990s, myriad new display technologies began to mature, and several of these – such as microelectromechanical systems (MEMS), liquid-crystal on silicon (LCOS), and liquid-crystal displays (LCDs) have had a tremendous impact on projection displays.

DLP Projection

Microelectromechanical systems (MEMS) devices have been proposed for television applications for many years. In 1970, RCA Laboratories[27] developed and demonstrated a MEMS system that used a dark-field Schlieren optical system and electron-beam addressing similar to the Eidophor or Talaria. An array of stretched-metal membranes were substituted for the oil film.

The MEMS efforts at Texas Instruments (TI) date back to 1977. Early efforts with light control, by analog motion of the mirrors,[28] were replaced by the digital off-on mirror effect used by TI today. By 1987, TI had demonstrated its first digital mirrors, and their development into a display product was aided by a $10.8 million ARPA grant in 1989.[29] The first Digital Micromirror Device (DMD) product was released in 1990, an airline ticket printer with an 840-dots × 1-row DMD.

The first full demonstration of a color-sequential static image on a two-dimensional DMD microdisplay was in May 1992, and an improved 768-dot × 576-row DMD was demonstrated in 1993. By 1994, DMD generated enough interest for the SID Symposium in San Jose to dedicate an entire session (Session 30 with three papers) to it. In the same time frame, TI began to work with consumer-electronics companies[30] to develop commercial products based on the DMD.

The first commercial projection DMD product was released in 1996,[31] a portable front projector with a single VGA DMD. At this time, the system was given its current name, "Digital Light Processing" (DLP), to cover the entire system, not just the DMD chip itself. This single-chip system was followed by two-chip consumer-home-theater front projectors and three-chip professional front projectors.

Although most previous projection systems, from John Logie Baird through CRTs to oil-film and LCLVs, used analog modulation of the light in the image to produce gray scale, the DLP was only capable of producing black and white, with no gray scale in between. DLP systems produce gray scale by using time-division binary multiplexing where the fraction of the time each mirror is in the "white" state compared to the "black" state

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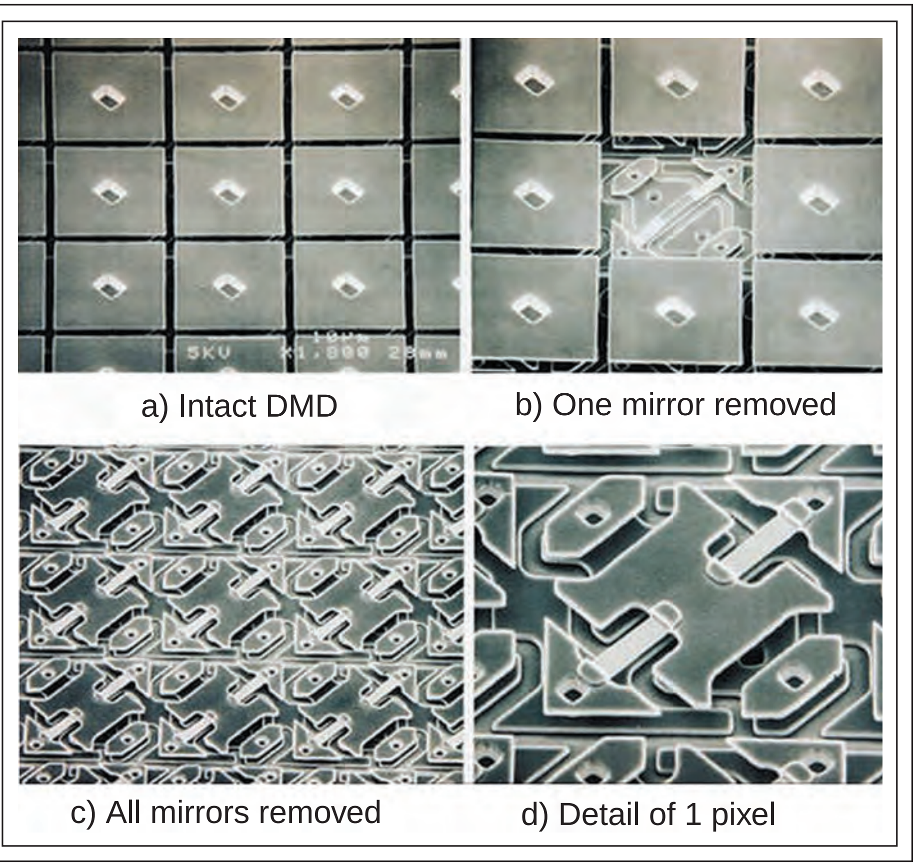
determines the gray level perceived by the viewer. This switching occurs fast enough so the human eye would perceive this as a continuous gray scale. In single-chip systems, it was necessary to produce gray scale for each of the three colors sufficiently fast enough so the eye would also merge the colors into a full-color image. The DLP, especially the early models, were only marginally fast enough to produce good gray scale in color-sequential systems. TI has developed increasingly sophisticated dithering algorithms and DSP chips to augment the native ability of the DMD to produce these gray scales.[32]

Figure 13 shows electron-microscope images of a DMD imager in 2004. Since then, the square holes in the center of each pixel have been reduced in size to improve both contrast and efficiency.

In three-DMD projectors, this gray-scale issue disappears, and the DLP projector is capable of producing very high quality images. In 1999, a DLP projector similar to the one shown in Fig. 14 was used to demonstrate electronic cinema by showing "Star Wars Episode 1" in theaters with paying customers. Most of the electronic-cinema projectors sold today are based on DLP technology, which is now also used in a wide range of projection systems from pocket projectors to electronic cinema – DLP projectors account for about one-half of all microdisplay-based projection-system sales.



Texas Instruments

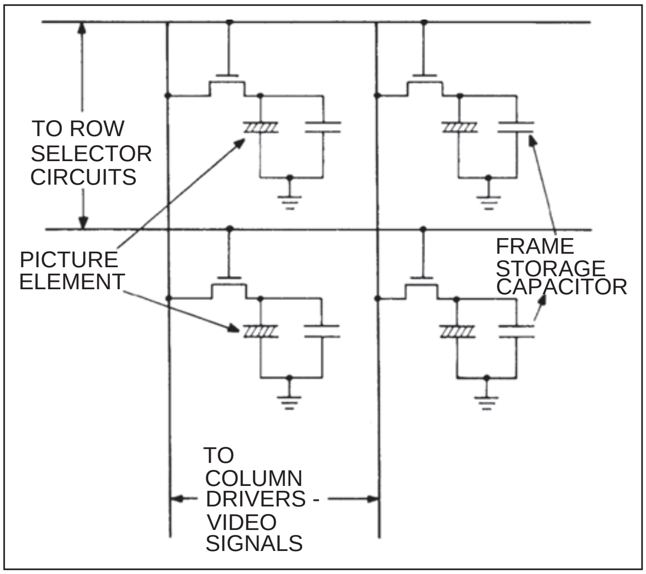
***Fig. 13:** Electron microscope image of pixels in a DMD device.*

Liquid-Crystal Projection Systems

After an abortive start in the 1930s and 1940s, serious work on thin-film transistors began in the early 1960s. There was considerable research into active-matrix systems for direct-view and projection applications from the 1960s through the 1980s. By 1976, for example, Westinghouse had achieved a 6 × 6-in. 20-line/in. LCD, and Hughes had achieved a 1-in.-square 100-line/in. active-matrix LCD on crystalline silicon.[33] According to Brody, "The materials used in forming the thin-film circuits are normally metals, such as Al, Au, Cr, Mo, and In; insulators, such as Al_2O_3 and SiO_2; and semiconductors, such as CdSe, CdS, Te (Westinghouse), and PbS (Aero-jet). No obviously superior combination has at yet emerged." At this point, Brody does not even mention silicon as an option! The basic circuit used in some of these early LCDs,[34] shown in Fig. 15, was the design that continues into modern 3LCD panels or large-screen LCD-TV displays. Silicon-on-sapphire (SOS), the predecessor of modern high-temperature polysilicon (HTPS) used in most current 3LCD panels, was developed in this same time frame.[35]

The first LCD projector that can be considered "modern" was introduced by Seiko-Epson in 1986.[36] This projector had several design features that would be recognized by a modern 3LCD projection engineer, including a 32-mm-diagonal (1.3-in.) polysilicon-TFT transmissive microdisplay with drivers integrated on the same substrate, a twisted-nematic LC effect, a three-panel unequal path architecture, and a crossed-dichroic color-combining cube similar to the modern one shown in Fig. 16. It had a resolution of 320 ×

***Fig. 14:** DLP projector used in the 1999 digital-cinema tests mounted on a Christie xenon-lamp lighthouse originally designed for a film projector.*



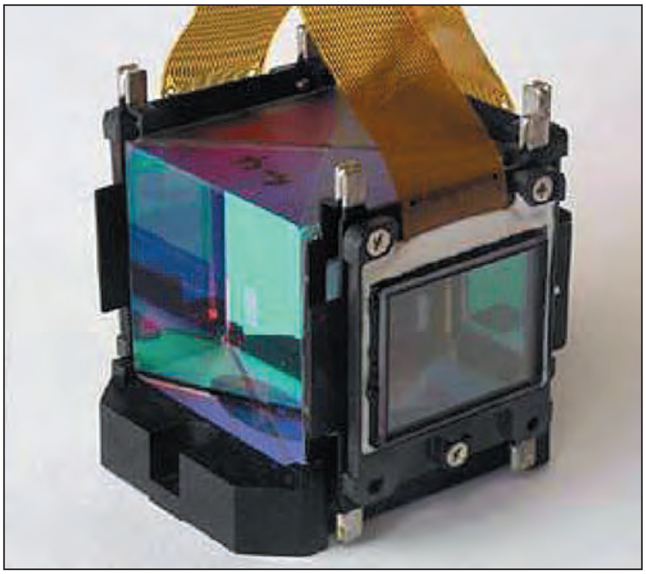


Fig. 15: 1974 circuit configuration used to achieve frame storage in liquid-crystal matrix displays.

Fig. 16: Modern crossed dichroic 3LCD prism with LCD microdisplays attached. The projection lens would attach to the fourth face.

220 pixels, a 70-lm output from a 300-W halogen lamp, and a contrast of 20:1 – poor performance by modern standards, meaning it certainly represented no threat to the established oil-film projector vendors, or even the CRT vendors. Nevertheless, it set the stage for improved projectors to come.

The uncertainty over the optimum active-matrix technology continued. For example, at the SID Symposium in 1991, papers covering 10 technologies suitable for use as transmissive LC light valves in projection systems were presented:

- a-Si TFTs (Mitsubishi, paper 4.2; Sanyo Electric, papers 20.1 and 20.2; NEC, paper 20.3).
- Ferroelectric matrix (Seiko Epson, paper 4.3).
- Metal-insulator-metal (MIM) diodes (Citizen Watch Co., paper 12.2).
- SiN thin-film diodes (NEC, 12.4).
- SiN bilateral diode matrix (Seiko Instruments, 12.5).
- a-Si double-diode plus reset (Philips Components, paper 12.8).
- CdS TFTs (University of Stuttgart, paper 20.5).
- Passive-matrix STN-LCDs (Citizen Watch, paper 20.6).
- Polysilicon TFTs (Xerox Palo Alto, paper 27.2. This paper discusses both HTPS and LTPS).
- Unified-structure field-induction drain poly-Si TFT (NTT, paper 27.3).

That year, Session 13 was dedicated to "Projection Light Valves," with H. Wayne Olmstead as chair and Akihiro Mochizuki as co-chair. The session introduction stated: "Market demand for large-screen projection displays continues to drive a huge investment in basic R&D for various types of light-valve projection systems. The old adage that 'necessity is the mother of invention' is exemplified in the field of light-valve research. A large number of unique techniques and very creative solutions to light-valve problems have been reported over the years here at SID. This year, there were a record number of papers covering this broad topic. The papers on light-valve projectors were grouped into two sessions. Systems that use 'direct active-matrix' were in Session 20: 'LC Projection Television,' and all other novel approaches were covered in this session."

Barco Blows Oil-Film Projectors Away

The year 1992 was a key year in projection systems, especially in terms of professional applications. It marked the introduction of the BarcoData 5000 projector,[37] popularly known as the "Light Cannon." This was the first LCD projector with performance comparable to a light-valve projector and doomed the Talaria and Eidophor. General Electric was so concerned about the effect of the Barco projector on its Talaria business that it bused about one-third of its employees to Infocomm in Philadelphia for the day so they could see the new competition. The JVC ILA also was threatened, but the underlying technology still survives in the D-ILA and other LCoS designs. The basic specifications for the BarcoData 5000 are listed in Table 1.

At $47,500, the BarcoData 5000 was expensive, but not as expensive as a Talaria projector with equivalent lumens. A Talaria projector with about 1250 lm would cost at least $79,980. In addition to the lower price, the BarcoData projector was significantly easier to use. For example, it required 2 minutes to warm-up compared to the 30 minutes to an hour required by oil-film projectors.

Following the Barco Light Cannon, there was a flood of data-projector introductions featuring varying technologies, including primarily LCD, DMD, and LCoS technologies. Extreme cost sensitivity in the consumer

Table 1: Specifications for the BarcoData 5000 projector introduced in 1992.

Property	Value
Model	BarcoData 5000
Pixel count	756 × 556
Panel	5.8-in. LCD with active-matrix diode addressing[42]
Lamp	575-W metal halide
Output	1250 lm
Contrast	50:1 checkerboard 200:1 sequential
Price	$47,500

Fig. 17: The InFocus LitePro 550LS from 1998. This VGA projector used a 400-W halogen bulb, produced 130–155 lum, and was intended to replace an overhead projector.

market meant that most non-CRT projection systems first penetrated the professional market. "Microdisplay" cannot always be used to describe some of these professional projectors. The BarcoData 5000 and other products in the same series had three 5.8-in. panels. Even larger panels were used, such as the panel in the InFocus LitePro 550 shown in Fig. 17, which had a single 8.4-in.-diagonal panel.

There were three key developments in the years following the introduction of the Light Cannon, allowing the growth of the consumer and professional projector markets:

- Development of the DMD by TI, as already discussed.
- Introduction of the UHP lamp by Philips.
- Introduction of the flat integrator/PCS combination by Epson.

UHP Lamp

The Philips UHP lamp,[38] first publicly discussed in 1995, revolutionized lamp technology for projection systems. All previous lamp technologies had serious flaws: incandescent lamps had very low efficiency, poor colorimetry, and very poor life; xenon lamps had low efficiency and short life; and metal-halide lamps normally had long arcs.

Metal-halide lamps actually represent an entire family of technologies. By adjusting the composition of the fill material, the color of the lamp could be changed to nearly any target color and spectrum. In general, however, the lamps had long arcs, color uniformity problems, and lifetime problems. They were, or could be, very efficient, with efficacies of 100 lm/W or more, and output spectra suitable for projection applications. The arc length and uniformity problems of these lamps were minimized when they were coupled to relatively large, high-étendue LC panels, such as the a-Si panels then available.

The fill material in a UHP lamp is nearly pure mercury, which gives the lamp a characteristic mercury emission spectrum. Unfortunately, this mercury emission spectrum is short of red, so most UHP-based projectors have a relatively poor red primary color. This is considered by most projector manufacturers to be a minor problem compared to the short arc, long life, high efficiency, and other advantages provided by the UHP lamp.

In general, high-performance projectors such as the Eidophor and Talaria used xenon lamps before the UHP was available. The Barco Light Cannon was introduced with a metal-halide lamp. Incandescent lamps, because of their very poor performance, were only used in certain low-performance low-cost projectors, at least after the introduction of the UHP.

Epson introduced the integrator and flat polarization system[39] combination in 1997. These were the final design features that, when added to the features Seiko-Epson introduced in 1986, define the modern 3LCD projector engine. This design was used in projector model ELP-3500, which also used 1.3-in. TFT-LCD VGA panels and a 100-W UHP lamp to produce 650 lm. Although this does not seem like much in 2007, in 1997 it competed against projectors like the InFocus LitePro that produced 130 lm from a 400-W lamp. The use of the polarization conversion system largely eliminated the light throughput advantage of systems such as the DLP system that needed only unpolarized light compared to systems such as the LCD and LCoS systems where polarized light was required.

Future of Projection Systems

Sales growth of consumer rear-projection systems has currently slowed to a standstill, due to price competition from LCD and plasma systems. In the larger sizes (52 in. and above), rear projection continues to hold its own, although most marketing forecasts show even the larger-sized rear-projection TV sales declining by 2011. Front projection for consumer home theater continues to grow, as do professional projection applications.

Two new technologies are on the horizon that threaten the dominance of the UHP and similar lamps in projection systems. First, high-brightness LEDs are beginning to

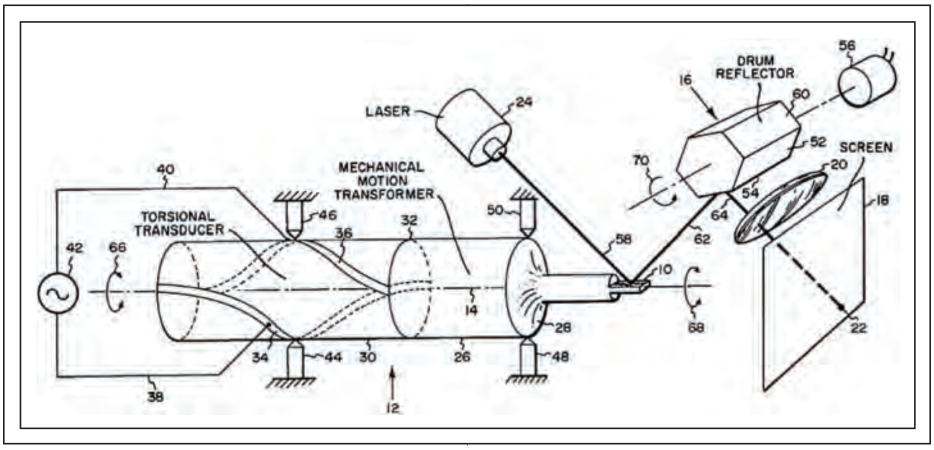


Fig. 18: Laser projector scanner design patented by Texas Instruments in 1969.

replace UHP-type lamps in certain low-brightness applications, including consumer rear projection and a new category commonly called the "Pocket Projector." The two main advantages of LEDs over UHP lamps are colorimetry and lifetime. LEDs also have very simple drive circuits and can be used in applications where even a 50-W UHP-type lamp produces too much light. On the other hand, the brightness of most LEDs in lm/mm^2-sr[40] is much lower than a UHP lamp. This generally prevents the use of LEDs in higher-output projection systems. Recently, Luminous Technologies has developed very-high-light-output R, G, and B LED devices using proprietary light-collecting and thermal-management techniques. This product, trademarked "Phlatlight," has seen initial commercial adoption as a light source in some large-screen DLP TVs.

The second technology is really a new category of projectors, often called "Pico-Projectors," which can be designed with LED illumination, although laser illumination is also common. These projectors are currently in the R&D phase and commercial models are expected in late 2008 and early 2009. These tiny projectors are designed either to be integrated inside a cell phone or be stand-alone projectors about the size of a cell phone. It is not currently certain exactly what these projectors will be used for when they are introduced but they will certainly have a major impact on the marketplace.

Laser Projection Systems

Lasers do not have the same étendue limitations as lamps or LEDs and can have luminance output values 10^5 times or more higher than UHP-type lamps. This would enable very high brightness systems to be built with very small microdisplays, or no microdisplay at all.

Lasers have been proposed for projection systems almost since they were first developed in 1960. For example, a 1969 patent[41] from Texas Instruments related to laser projectors contained a reference to a still earlier 1966 internal TI memo on the subject.[42] To anyone who has examined Scophony drawings from 25 years earlier, this design shown in Fig. 18 will seem remarkably familiar. The main problem with lasers has been, and continues to be, their cost. Several companies, most noticeably Novalux,[43] are working on low-cost high-powered lasers for projection systems. For a full-color system, of course, it is necessary to have at least three lasers: red, green, and blue.

In general, laser projector designs fall into one of three types:

1. Flying spot scanners where a single mirror, or a pair of mirrors, does the scanning – Fig. 18 is one example. A modern single mirror MEMs device from Microvision is shown in Fig. 19. For scale, the mirror in this system is 1-mm square.
2. Scanned one-dimensional linear arrays, such as the system shown in Fig. 20.
3. Microdisplay-based systems with a two-dimensional pixel array where the laser is used mostly as a light source in a conventional projection system.

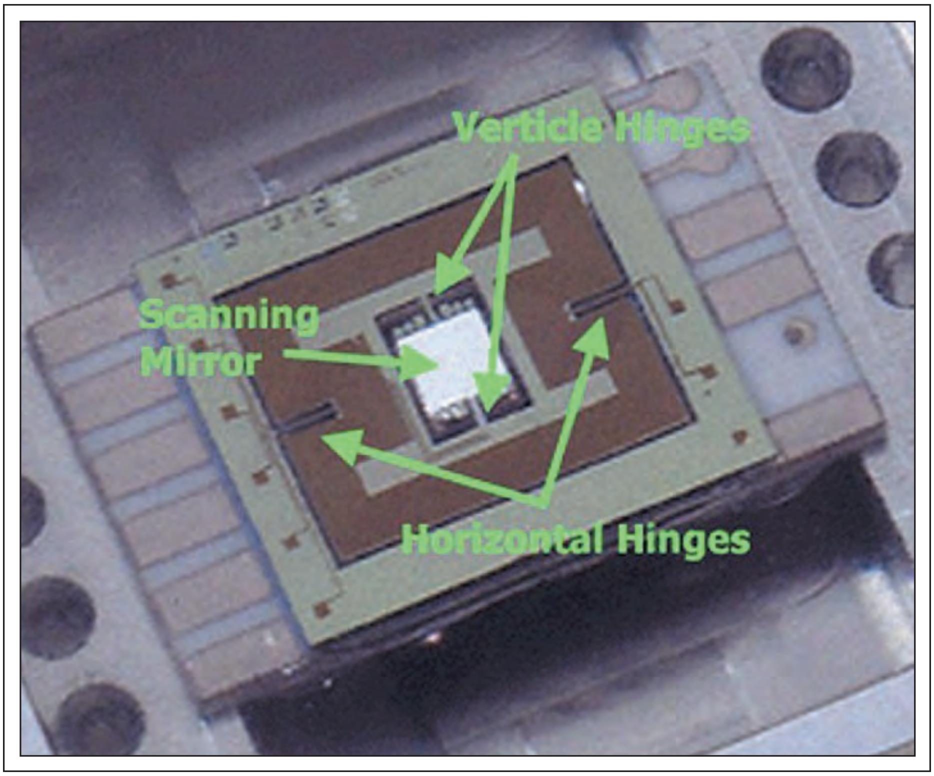


Fig. 19: Microvision scanner with a single mirror mounted on horizontal and vertical hinges.

In flying-spot scanner systems such as the ones shown in Figs. 18 and 19, the laser beam is scanned in a raster pattern, or a variation on a raster such as a Lissajou figure. As the beam is scanned, it is modulated at the video rate in a technique familiar to anyone who knows CRT systems. This is repeated at a high enough speed (60-Hz frame rate or higher) so the eye merges the images into full-motion video. For a full-color system, each laser must be modulated separately and the three modulated beams are normally combined into a single white beam. The resolution of this type of system, like the Scophony, is limited by either the horizontal scan rate or the maximum rate at which the light source can be modulated. With modern electronics, the mechanical scanning of the high-speed mirror is more commonly the limit.

In a linear array system, the high-speed scanning is done by a linear array,[44] such as the one shown in Fig. 20. The low-speed scanning at the field rate is still done by a moving mirror. Systems of this type can have extremely high resolution. For example, the Evans & Sutherland laser projector (ESLP) has a resolution of 4K × 5K, the highest-resolution image the author is aware of made by a non-tiled projection system.[45] The NHK 8K projector,[46] with a resolution of 8192 × 4320 (34 Mpixels), has nominally higher resolution, but this is achieved by tiling displays inside the projector and subpixel rendering. It has, in fact, fewer real pixels than the ESLP.

The linear array works much like the oil-film light valves used by the Talaria or Eidophor. The array, which is a MEMS system like the DLP projector or the Microvision scanner, has alternating fixed and moving microscopic ribbons. The array is typically used in a schlieren optical system similar to the ones shown in Figs 21 and 22. When the moving ribbons are in the "up" position, the GLV presents a flat mirror to the laser beam. Specular reflection takes the light back to the schlieren mirror and the source. When the moving ribbons are in the "down" position, the alternate high and low ribbons form a diffraction grating, changing the angle of the light. The light now misses the schlieren mirror, enters the projection lens, and ultimately winds up at the screen. Since they are based on diffraction, which is wavelength-dependent, most linear-array systems use three linear arrays, one each for red, green, and blue.

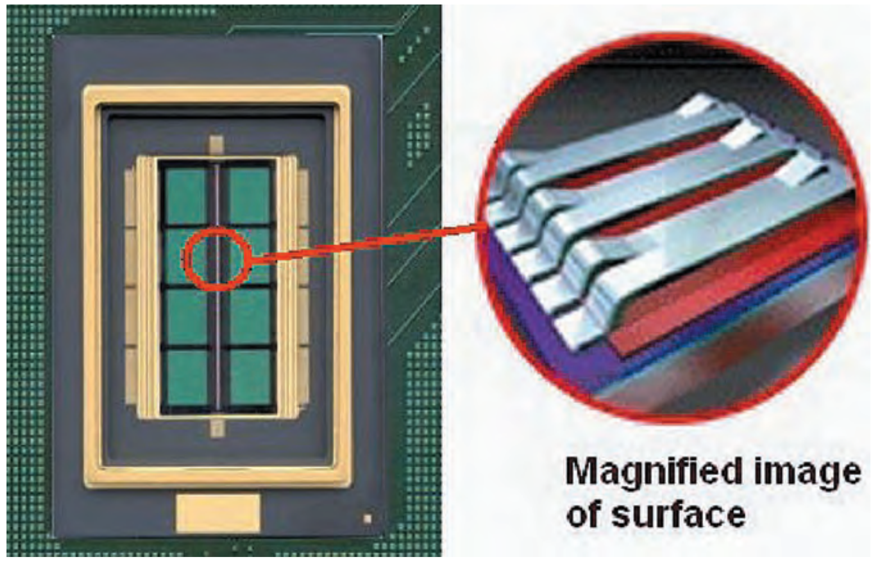


Fig. 20: GLV linear array from Evans & Sutherland. Sony calls a similar array the GxL. Kodak has independently developed another linear array, called GEMS.

Laser illumination of microdisplay projection systems provide several major advantages over illumination by UHP or other types of lamps. These include:

1. The very low étendue of the laser beam allows use of smaller lower-cost microdisplays.
2. The low divergence angle of the laser allows the use of low-cost high-$f/\#$ projection lenses.
3. Lasers can be modulated at the field rate, eliminating the need for a color wheel in color-sequential systems and increasing energy efficiency.

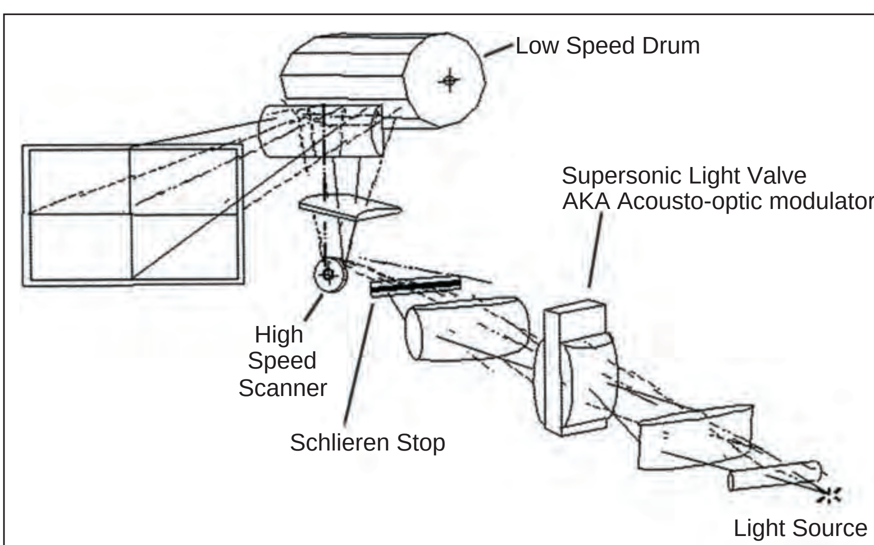


Fig. 21: Layout of Scophony mechanical scanning projection system. Note the use of cylindrical lenses because spherical lenses of sufficient size would have been too expensive.

4. Lasers provide very large color gamuts, larger even than LEDs.

Due to these advantages, laser advocates believe the future of projection systems is tied closely to lasers. But currently, lasers have two major problems that must be overcome:

1. ***Cost:*** Current commercially available lasers as of this writing are far too expensive for use in mass-market projectors. Development of laser designs specifically for display applications should end this problem soon.
2. ***Safety:*** Lasers are both a perceived and actual safety problem. The issues are much more serious for front-projection systems with 200 lm or more than they are for RPTV, so lasers may be used in rear projection before front projection.

Conclusion

The projection business continues to be an industry full of vitality, with a variety of new projection systems ranging from ones capable of resting in the palm of your hand to complex, multi-projector systems with total pixel counts up to 100 Mpixels. A wide variety of components needed for these advanced systems are also under development, including new microdisplays and scanners, new light sources such as lamps, LEDs and lasers, and the more mundane but essential components such as lenses, polarizers, and filters. This development is spread across the world, with new technologies coming from Europe, North America, and Asia.

As Charles Bensinger said about CRT projectors[47]:

"Big-screen TV is here to stay, and home VCRs give it a real reason to exist. The next step forward will be solid-state liquid-crystal or CCD-type one-piece wall screens that will be bright and sharp and not need the bulky tubes and optics used by conventional TV projection systems. We should see these devices in about 5 years, but in the meantime, we can have a lot of fun with the big-screen TVs."

Unfortunately, for Bensinger's power of prognostication, he wrote that in 1979. Today, 29 years later, big-screen projection systems are still with us, even for the consumer. On the other hand, he was talking about what would be considered today small systems, ones up to about 48 in. on the diagonal, and in this market category, LCD and plasma TVs have largely replaced rear-projection TV. As was true in 1936, in 1979, and in 1991, the consumer and other end users in 2008 seem to have an insatiable demand for larger and larger television screens, so even with the pressure from LCD and plasma displays, I do not expect to see consumer projection systems vanish in my lifetime.

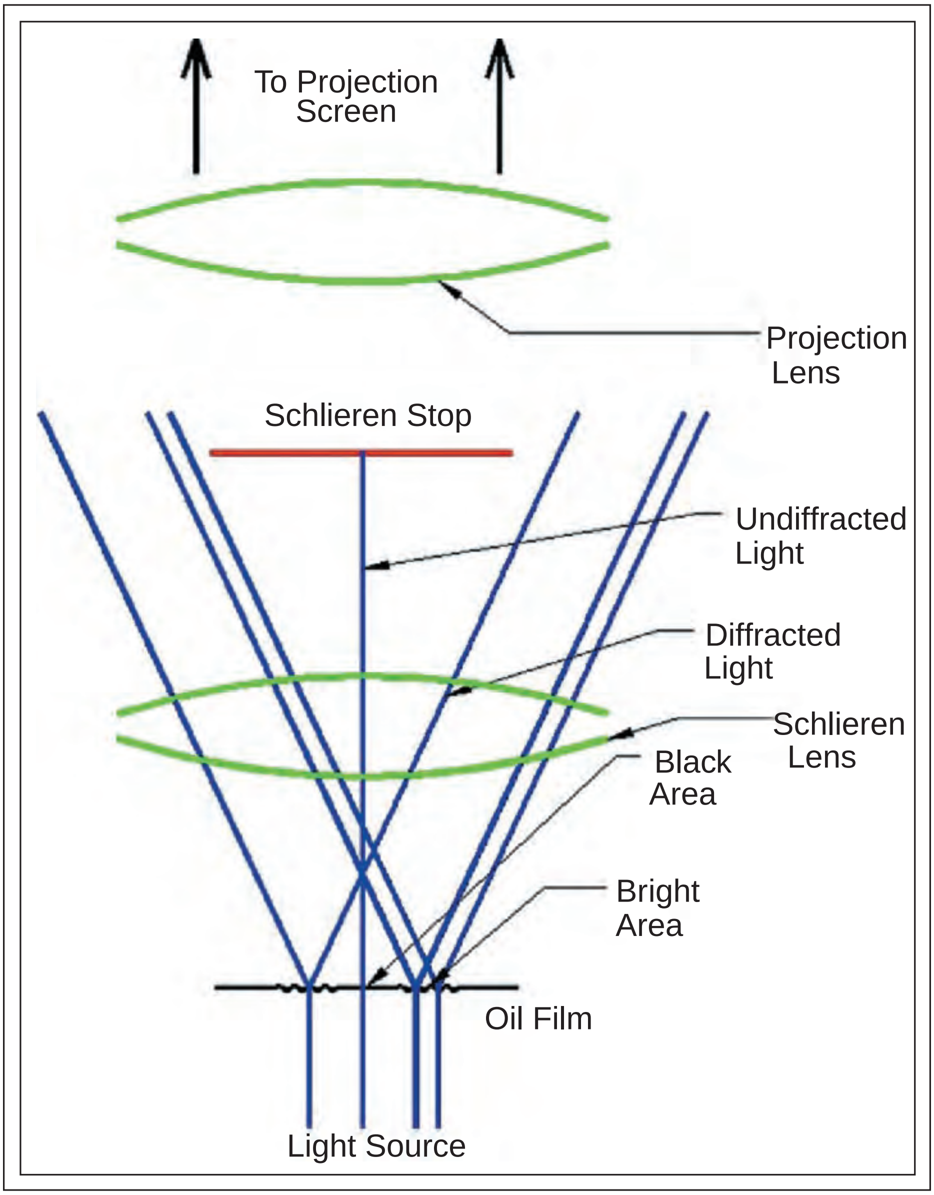


Fig. 22: Principle of operation of an oil-film dark-field schlieren optical system.

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Edited by Aris Silzars

Liquid-crystal photoaligning by azo dyes *(Invited Paper)*

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Haruyoshi Takatsu
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Abstract — Liquid-crystal (LC) photoalignment using azo dyes is described. It will be shown that this photoaligning method can provide a highly uniform alignment with a controllable pretilt angle and strong anchoring energy of the LC cell, as well as a high thermal and UV stability. The application of LC photoalignment to the fabrication of various types of liquid-crystal displays, such as VAN-LCDs, FLCDs, TN-LCDs, and microdisplays, on glass and plastic substrates is also discussed. Azo-dye photoaligned super-thin polarizers and phase retarders are considered as new optical elements in LCD production, in particular for transflective displays.

A novel photoaligned TN-LCD cell was fabricated by one-step illumination with oblique non-polarized UV light of an empty cell with azo-dye layers coated on indium tin oxide (ITO) substrates. If the incident angle was sufficiently large (>75°), the p-polarization of the light was more pronounced for the bottom azo-dye layer in comparison with that for the upper one. Thus, the photoalignment of the azo-dye layer on the bottom substrate became perpendicular to that of the upper one, and LC directors on the top and bottom substrates also oriented perpendicularly.

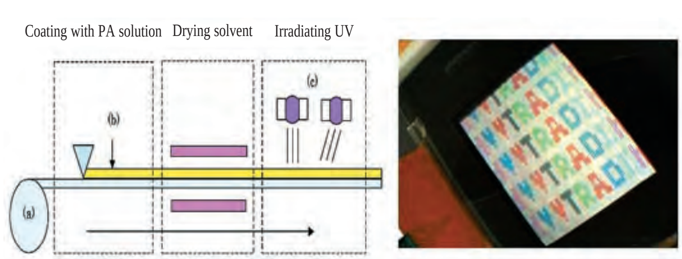

FIGURE 10 — A plastic full-color TN-LCD was produced using photo-aligned polymerized azo-dye film SDA2.

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Plasma-beam alignment of passive liquid crystals *(Invited Paper)*

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Sepas Satayesh
Mireille Reijme

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Abstract — A plasma-beam process, developed for the alignment of liquid crystal (LC) in electro-optic applications, has been successfully applied to align "non-standard" LC, such as crystalline materials with LC phases at elevated temperatures and reactive mesogenes. In addition to the high alignment quality of the materials, there is no need for an intermediate layer between the substrate and the LC layer. Furthermore, the construction of our source simplifies the alignment procedure of large-area rigid substrates and the roll-to-roll processing of flexible films. This method opens new horizons for optical retarders and polarizers, as well as anisotropic semiconducting films for organic electronics.

The exposure geometry preferably used is shown in Fig. 2. By rotation of the source, the incident angle of the plasma beam can be varied. The incident angle typically used was about 70°. The substrates were treated in a cycling (there and back) translation regime or in a roll-to-roll translation manner by mounting a corresponding moving system in the vacuum chamber. The translation speed was about 2 mm/sec. The substrates were treated entirely or partially. In the latter case, masks of different configurations were used.

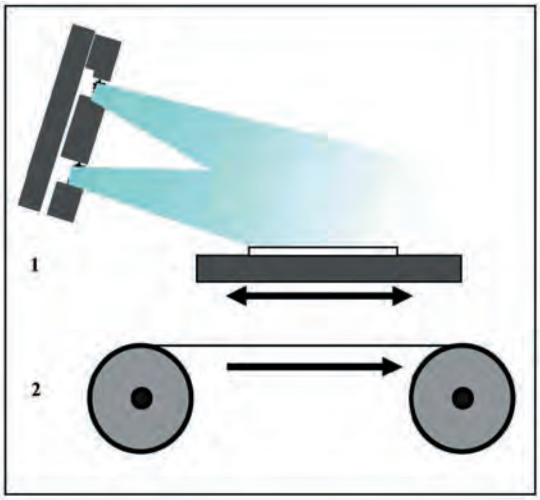

FIGURE 2 — Plasma-beam exposure geometry. 1 – Cycling translation regime (mainly used for rigid substrates); 2 – roll-to-roll translation regime (used for flexible plastic strips).

Nano-structured liquid-crystal alignment layers *(Invited Paper)*

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Abstract — The alignment of liquid crystal by nano-structured surfaces is investigated. It is shown that reliable pretilt angles of any value between 0° and 90° can be produced with these surfaces. The physics and properties of such alignment layers are studied using a variety of techniques. The anchoring energy and temperature stability of the alignment are also measured. Dependence on various processing conditions is also characterized. It is shown that these nano-structured alignment layers are useful for the production of high pretilt angles needed for a variety of applications.

The pretilt angles are measured using a 5-μm-cell-gap homogeneously aligned (anti-parallel) test cell in a conventional crystal rotation setup. Figure 6 shows a set of 5-μm electrically controlled birefringence (ECB) cells. The top row cells are anti-parallel rubbed and are ECB cells. The bottom row cells are parallel rubbed. For the parallel-rubbed cells, an interesting transition from splay alignment to bend alignment occurs at around 45°. This is to be expected and is the basis of the no-bias bend cell for fast LCD applications.

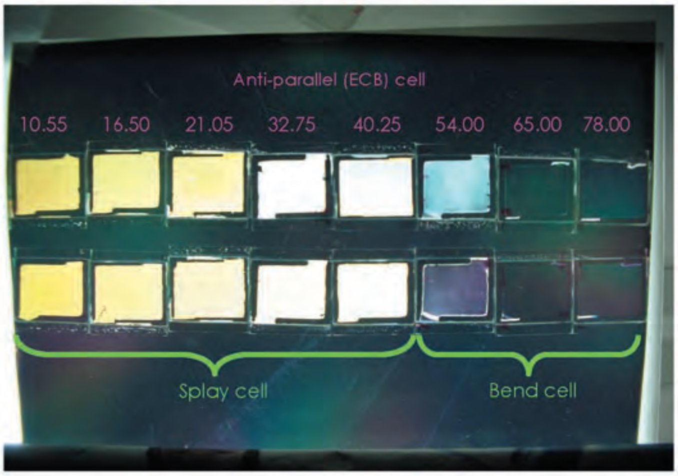

FIGURE 6 — Test cells at various pretilt angles. The top row cells are anti-parallel rubbed and the bottom row cells are parallel rubbed.

Tuning the alignment of liquid crystals by means of nano-structured surfaces *(Invited Paper)*

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Abstract — The solid-surface/liquid-crystal interactions, defining the field-free alignment of the liquid crystal in conventional liquid-crystal displays, are playing a vital role in their optical appearance and performance. Nano-scale changes in the solid-surface structure induced by light have been recently shown to affect the anchoring strength and the easy-axis direction. Fine tuning of the anchoring strength is also demonstrated by nano-structuring of the Langmuir–Blodgett monolayer employed as liquid-crystal alignment layers promoting homeotropic orientation. On the basis of nano-engineering of the surface alignment properties, two novel alignment concepts have been introduced: electrically commanded surfaces (ECS) and high-performance alignment layers (HiPAL). Nano-structured polymers related to these concepts have been designed, synthesized, and used as materials for alignment layers in LCDs. ECS materials belong to the category of active alignment materials designed to mediate switching of the liquid crystal, whereas the HiPAL materials make possible the control of the molecular tilt angle in a broad range, from 0° to 90°, and they seem to enable the control of the anchoring strength as well. The nano-structured alignment materials are strong candidates for implementation in a new generation of advanced liquid-crystal displays and devices.

The photo-induced changes that take place at the LC/solid-surface interface on a molecular (nano) scale level result in changes of the anchoring strength, which, in turn, affect the switching characteristics of the photosensitive nematic represented by U_F, τ_{rise}, and τ_{fall}. When the surface density of *cis*-isomers exceeds a certain critical value, a spontaneous anchoring transition from the initial planar to homeotropic alignment of the bulk liquid-crystal molecules takes place due to the bent form of the *cis*-isomeric molecules [Fig. 1(b)]. The light-induced alignment transition demonstrates clearly that the alignment of the liquid crystal is very sensitive to the nano-scale changes of the structure of the alignment surface. Hence, the nano-engineering of the alignment surface seems to be a powerful approach for an efficient tailoring of the LCDs characteristics.

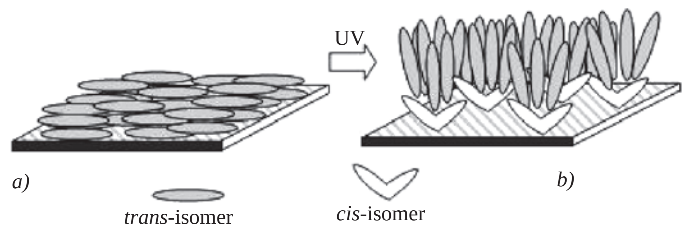

FIGURE 1 — Schematic presentation of light-induced transition from planar to homeotropic alignment of a photosensitive nematic upon exposure to UV light. (a) Before illumination with UV light all liquid-crystal molecules in the cell are in *trans*-form and the liquid-crystal material possess a planar alignment (for simplicity, only one of the liquid-crystal cell substrates is shown). Illumination with UV light results in generation of cis-isomers which are selectively adsorbed onto the surface of the confining substrates due to their higher polarity compared to one of the *trans*-isomers. This, in turn, results in a homeotropic alignment of the liquid-crystal bulk.

New properties and applications of rewritable azo-dye photoalignment

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Abstract — The rewritable azo-dye photoalignment (ORW) of liquid crystals (LCs) for application in optical rewritable electronic paper has been investigated. It was observed that a periodic change in the azimuthal aligning direction with polarized UV light (365 nm) brings about homeotropic alignment, while utilization of visible light (450 nm) does not affect the LC tilt angle. The wavelength dependence of the ORW photoalignment result and the behavior of the photoinduced anisotropy was explored. The dark amplification of film anisotropy after exposure was observed, which is believed to be the relaxation process related to hydrogen bonding in azo-dye film. New material, CD1, for azo-dye rotation photoalignment that possesses a high azimuthal anchoring energy (about 2×10^{-4} J/m^2) was found.

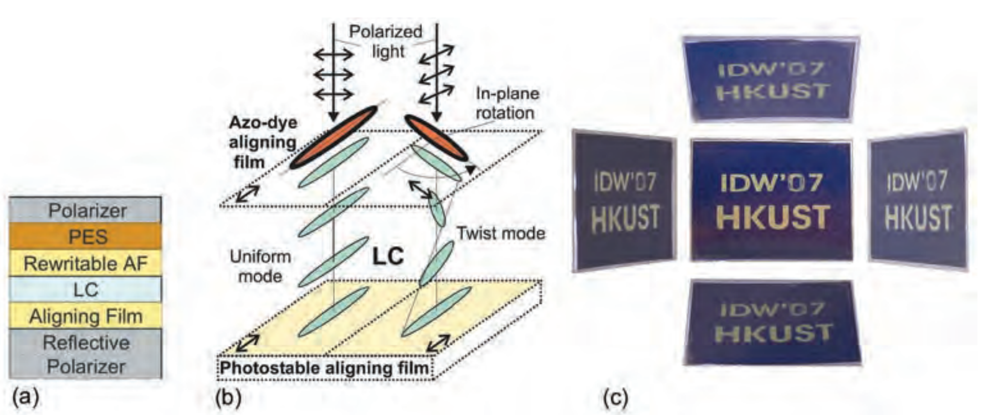

FIGURE 1 — Optical rewritable electronic paper: (a) structure design; (b) operation principle; (c) prototype on plastic.

O films with adjustable tilt of optical axis for LCD compensation

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Abstract — A method of preparation of positive O films with the tilt angle of the optic axis continuously controlled in the range 0–90° is proposed. It is based on the use of reactive mesogens and alignment materials that provide a wide range of pretilt angles. The method developed allows for further improvement in the viewing-angle characteristics of LCDs with O compensation films.

Optimization of LCDs with integrated O compensators, from the viewpoint of contrast angular dependence, gray-level stability, and color shift, requires the technology of O films, providing a continuous variation of O film parameters, such as thickness, birefringence, and optic-axis profile. The present paper offers such technology. An approach developed for conventional liquid crystals, which provides a continuous change in the LC pretilt angle from 0° to 90°, is used. This variation is attained by using a mixture of two polyimides designed for planar and homeotropic alignment (polyimides p-PI and h-PI, respectively). The p-PI/h-PI layers are backed and unidirectionally rubbed to impart alignment function.

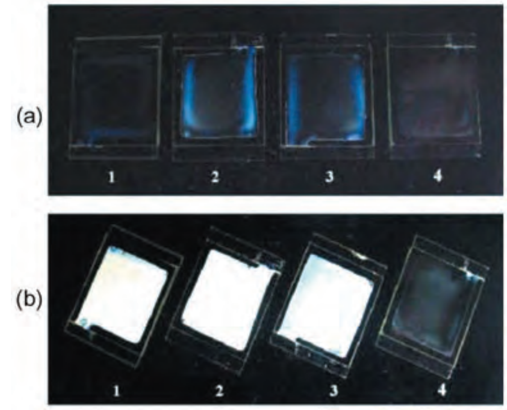

FIGURE 1 — The cells filled with RM UCL-011 viewed between a pair of crossed polarizers: (a) the in-plane projection of the optical axis is parallel to the polarization direction of incident light; (b) the in-plane projection of the optical axis is rotated with regard to the polarization direction of incidence light. The tilt angle of the optic axis is 3, 33, 56, and 89° in the cells 1, 2, 3, and 4, respectively.

Factors affecting the dynamics of a π-cell *(Invited Paper)*

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Abstract — The basic factors related to the dynamics of a π-cell device are reviewed. Specifically, the director dynamics are studied for the case of a periodic drive voltage that is sometimes referred to as "impulse drive." It is found for this type of drive waveform the desired bend state is more stable against the twisting effect of transverse electric fields found in AMLCD devices. This effect causes the reduction in light transmission due to "impulse drive" to be smaller in π-cell devices than is expected to be found in other AMLCD modes.

To consider the effect of impulse drive on the twisting of the director field, two factors need to be considered. One is the transverse field that can result from "fringing fields" generated by adjacent pixels of different voltages or from gate electrodes near a pixel. It could be expected that these transverse fields will cause the director to twist and thereby affect VC, Fig. 2(b). Another is the effect of flow in the device, as the in-plane flow induced by the impulse drive could possibly stabilize the director in the bend state against the destabilizing affect of the fringing fields.

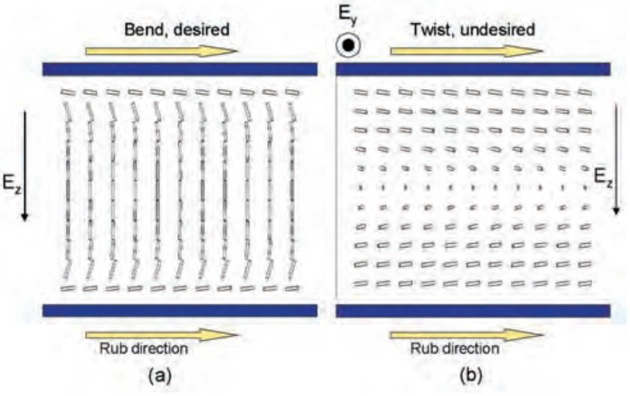

FIGURE 2 — The director configuration of π-cells. E_z is the applied field, E_y is the transverse field induced by the neighboring pixel: (a) desired state, since the cell should be operated in the bend state; (b) undesired state, due to the transverse field. The twist state is triggered at the lower applied voltage.

Defect-free deformed-helix ferroelectric liquid-crystal mode in a vertically aligned configuration *(Invited Paper)*

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Eunje Jang
Yong-Woon Lim
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Seoul National University

Abstract — A novel deformed-helix ferroelectric liquid-crystal (DHFLC) mode in a vertically aligned (VA) configuration is described. In this configuration, several unique features of display performance such as uniform alignment, fast response, and analog gray-scale capability are obtained. Particularly, this VA-DHFLC mode allows for the defect-free uniform alignment of both the FLC molecules and the smectic layers over a large area without employing additional processes such as rubbing or electric-field treatment that are generally required for planar FLC modes. Based on the VA-DHFLC mode, a transflective display having a single-gap geometry with in-plane electrodes on two substrates in the transmissive regions and on one substrate in the reflective regions is described.

Figure 4 shows the operational principle of our transflective VA-DHFLC cell in a single-gap geometry. It is composed of two crossed polarizers, the upper and the lower quarter-wave plates (QWPs) and the DHFLC layer. The small (black) and curved (gray) arrows in the FLC layer denote the dipole moments of the FLC molecules and the electric-field directions, respectively. The R region has in-plane electrodes only on the top substrate while the T region has in-plane electrodes on both the top and bottom substrates. The thickness of our transflective VA-DHFLC cell was maintained using a glass spacer 6.5 µm thick.

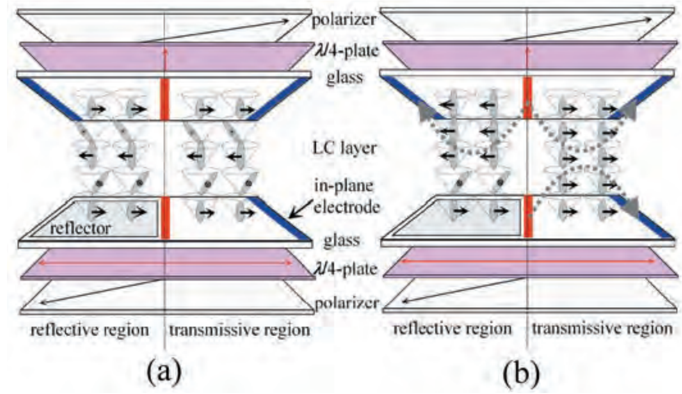

FIGURE 4 — The operational principle of our transflective VA-DHFLC cell in a single-gap geometry with in-plane electrodes on two substrates in the T regions and on one substrate in the R regions: (a) under no applied electric field (a dark state) and (b) under an applied electric field (a bright state).

Transflective ferroelectric liquid-crystal display with a single-cell gap

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Abstract — A ferroelectric liquid-crystal (FLC) display was optimized as a transflective liquid-crystal display (LCD). In this configuration, the single-cell-gap approach was considered. The optimized configuration exhibits a high contrast ratio, wide viewing angles, and achromatic (black/white) switching in both the transmissive and reflective modes. Because no double-cell-gap structure, no subpixel separation, and no patterning polarizers and retarders are included in the configuration, the configuration is easy to fabricate and also possess a perfect dark state. This configuration is also suitable for bistable applications.

The structure of a transflective FLCD is shown in Fig 1. It is composed of two polarizers, a retardation film, a transflective film, and an FLC cell. The transflective film is used as a reflector in the sunlight or a bright place and as transmitter at night or in a dark place. An anti-reflection layer is inserted at the top of the configuration in order to reduce the surface reflectance. The FLC cell is prepared by using the photoaligned method.

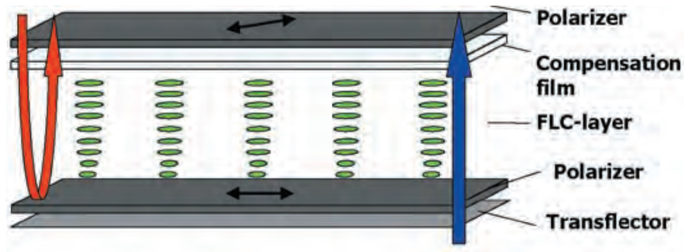

FIGURE 1 — The structure of a transflective FLCD.

Fast electro-optical response at low temperature for metal nanoparticle embedded STN-LCDs *(Invited Paper)*

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Abstract — STN-LCDs embedded with special metal nanoparticles of Ag/Pd are shown to be useful for a direct-multiplexed dot-matrix STN-LCD with 320 × 240 pixels and show a fast response time by 3–5 times compared to those without nanoparticles. This phenomenon is shown to be attributed to the reduction of rotational viscosity by 70% at room temperature and by 30% at a low temperature (–20°C). The alteration of elastic constants by doping nanoparticles could be also essential.

The fabrication and characteristics of direct-multiplexed dot-matrix STN-LCDs showing fast electro-optical response, particularly at low temperatures, *e.g.*, –30°C, that is needed in current LCDs, particularly in automotive applications, mobile phones, and personal LCTVs, is reported. Our solution to this requirement is to dope metal nanoparticles into the LCD host media using specially synthesized metal nano-particles that are particularly useful for dot-matrix LCDs.

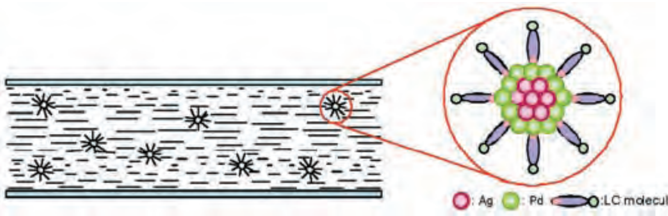

FIGURE 1 — Conceptual scheme of STN-LCD doped with metal nanoparticles.

Diffraction on birefringent elements with sine surface microrelief

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Vadim M. Novikovich
Peter L. Denisenko

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Abstract — Light diffraction on optically anisotropic substrates using sine surface microrelief has been calculated by using the OAGSM method. The influence of the microrelief depth and material birefringence on the diffraction intensity on the order of 0–3 is reviewed and discussed. The results are compared with the results of the calculation for a rectangular microrelief. The microrelief depth and material birefringence allows the realization of different polarization states of the light beam transmitted or reflected by the substrate. The approach can be used to control the light-beam propagation for different applications including LCD backlights.

Figure 1 illustrates the calculation parameters. A substrate has a solid part with thickness *H* and a microrelief part. The periodical sinusoidal or rectangular microrelief is characterized by the period Λ and depth *h* (both Λ and *h* are normalized to the light-beam wavelength λ). The material of the substrate is a uniaxial medium (a polymer or a liquid crystal) with the largest refraction index ($n_e = n_2$) in the direction of the grooves. For comparison, the case of the isotropic material ($n_1 = n_2 = n_3 = 1.50$) was also considered too.

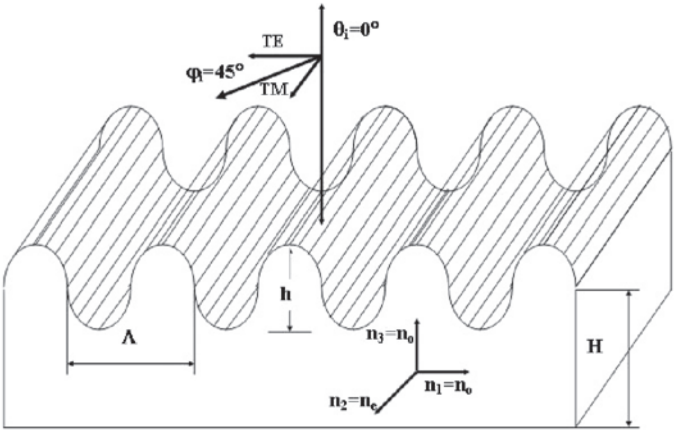

FIGURE 1 — Geometrical dimensions of a microreliefed substrate (*H* – thickness, Λ – microrelief period, *h* – microrelief height); its optical axis and *TM* wave are parallel to the grooves; *TE* wave is perpendicular to the grooves.

Measurement of human visual perception for Mura with some features

Chun-Chih Chen
Sheue-Ling Hwang
Chao-Hua Wen

Acer, Inc.

Abstract — The defects of flat-panel liquid-crystal display are usually not uniform, and the defects are called "Mura." There are many factors that cause the Mura phenomenon. At present, the human eyes define the seriousness of Mura, and different operators define the same Mura phenomenon with different meanings. For this reason, there have been many conflicts between the suppliers of flat-panel liquid-crystal display and customers. In order to solve the conflicts between the suppliers and customers, some researchers proposed a regression equation for the luminance contrast threshold and the size of Mura. In addition to the effect of Mura size on luminance contrast threshold, this study investigated the relationship between other factors and luminance contrast threshold. An analysis of the results show that Mura size, polarity of Mura, Mura position, and different color backgrounds significantly affect the visual contrast threshold. However, polarity did not significantly affect visual contrast threshold. In this study, it was found that Mura size was more important than the other factors for visual contrast threshold. The results of this study is expected to be referenced for inspection by the LCD industry.

Multiple comparisons of Mura size showed that there were significant differences among each level of Mura size. However, there was no significant difference between 2.84° and 5.13°. In other words, when the visual angle fell to the range from 2.84° to 5.13°, the difference of visual contrast threshold was not significant. As illustrated in Fig. 6, there were some interactions among these three variables, but the results of analysis of variances showed that these interactions did not significantly affect visual contrast threshold.

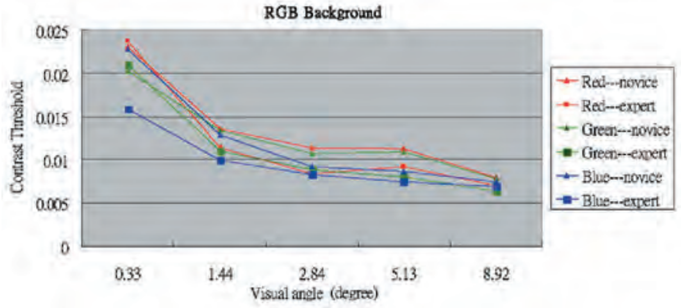

FIGURE 6 — Average visual contrast thresholds of novices and experts under different color backgrounds and Mura sizes.

editorial

continued from page 2

I'm focusing on this component of the stories because I think it represents a major theme in the natural evolution of new display technologies. Whether it is OLED, FED, plasma, LCOS, or any other similar technology, the roadmap usually starts with the supposition that an existing supporting platform of manufacturing processes and underlying technologies can be leveraged to attain commercial success as rapidly as possible. It's an appealing story and, more often that not, is true at least in part. Liquid-crystal–on–silicon (LCOS) developers touted the fact that they could utilize trailing-edge semiconductor fabrication lines and processes to achieve a very short time to market. In fact, they could, except for an almost endless array of seemingly minor details that resulted in long delays and very expensive process modifications.

As development progresses, the depth and scope of the resulting efforts grows way beyond the original fundamental technology involved. Numerous side projects crop up to solve secondary process and technology problems that emerge along the way. In the end, the total scope of the effort looks much greater than what was originally considered. I don't know if Samsung, LG, or Sony specifically anticipated the need for a new TFT technology when they began commercializing OLED TVs, but I'm sure a lot more money and time has been spent on oxide TFTs than ever would have been without OLED technology. I can also imagine that out in the world somewhere, there could be a totally unrelated application of InGaZnO that would otherwise never be possible without this effort.

In the end, that's the good news. The cycle of technological development produces ever greater opportunities that come with ever greater challenges and surprises at the same time. What appears as a setback to one endeavor can end up creating the crucial enabler for a totally different endeavor. The universe is funny that way.

We welcome back Matt Brennesholtz from Insight Media with the second part of his historical perspective on the evolution of projection technology which takes the story from 1992 to the present, offering a number of insights into the various innovations that rose up so rapidly in the last 20 years to build the rich landscape of products we see today. Part I can be found online in the May 2008 issue of *ID* at www.informationdisplay.org.

Stephen P. Atwood

president's corner

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The ICDM is a committee that is part of SID, under the umbrella of the Definitions and Standards Committee. A more detailed description of the ICDM and the goals of the MDS appeared in the February 2008 issue of *Information Display*, though significant progress towards the DMS has occurred since that time. (This article is available in the archives section of www.informationdisplay.org.) Currently, the committee consists of about 130 people in the display industry, including some of the most preeminent experts in display metrology and evaluation, as well as representatives from most of the major manufacturers in the display industry.

The ICDM has a Web site that can be accessed at www.icdm-sid.org/. It also has a wiki under development at http://wiki.sidmembers.org/index.php?title=ICDM . The wiki is particularly interesting because it allows the greater SID community to add their expertise and know-how to the mix. If you would like to contribute to the effort, one way is to check out the wiki!

The ICDM is a great example of SID's ability to attract volunteers who are passionate about displays, donating their time and expertise for a worthy effort to promote the industry. So, a big salute to them, and please keep an eye out for the results of their efforts. Just don't expect an answer to the question, "What's the best deal for my next TV?" The ICDM deals primarily in display physics and not consumer psychology – maybe SID needs a parallel effort here with marketing professionals!

Paul Drzaic
President
Society for Information Display

guest editorial

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on the vision for ultra-thin lightweight displays on flexible-substrate systems. For example, 2 years ago, both Samsung SDI and the team of LG Display and Universal Display Corp. reported full-color AMOLED displays built on thin stainless-steel substrates. Now that impressive prototypes have been demonstrated for a number of years, the next challenge is to figure out how to mass-produce such products. A vision for manufacturing flexible AMOLED displays by fashioning AMOLED flexible-display fabrication to fit into existing AMLCD lines is presented in the article from Juhn S. Yoo and his colleagues at LG Display.

Finally, we consider the work ongoing in developing non-Si backplane technology, namely, oxide TFTs. This is an area that has been attracting a great deal of R&D focus. The article by Jae Kyeong Jeong and his colleagues from Samsung SDI poses the question, "Is there any new TFT with the high mobility and excellent uniformity at the same time, which is suitable for the large-sized AMOLED displays?" They then make the case that oxide TFTs could possibly be this technology.

While these articles detail some exciting work in the OLED sector, they truly represent just the tip of the iceberg. This is an exciting time to be working on OLED technology, and I urge you to stay tuned for more exciting developments that are just around the corner. ■

***Julie J. Brown** is Vice President and Chief Technology Officer at Universal Display Corp., 375 Phillips Blvd, Ewing, NJ 08618; telephone 609/671-0980, fax -0995, e-mail: jjbrown@universaldisplay.com*

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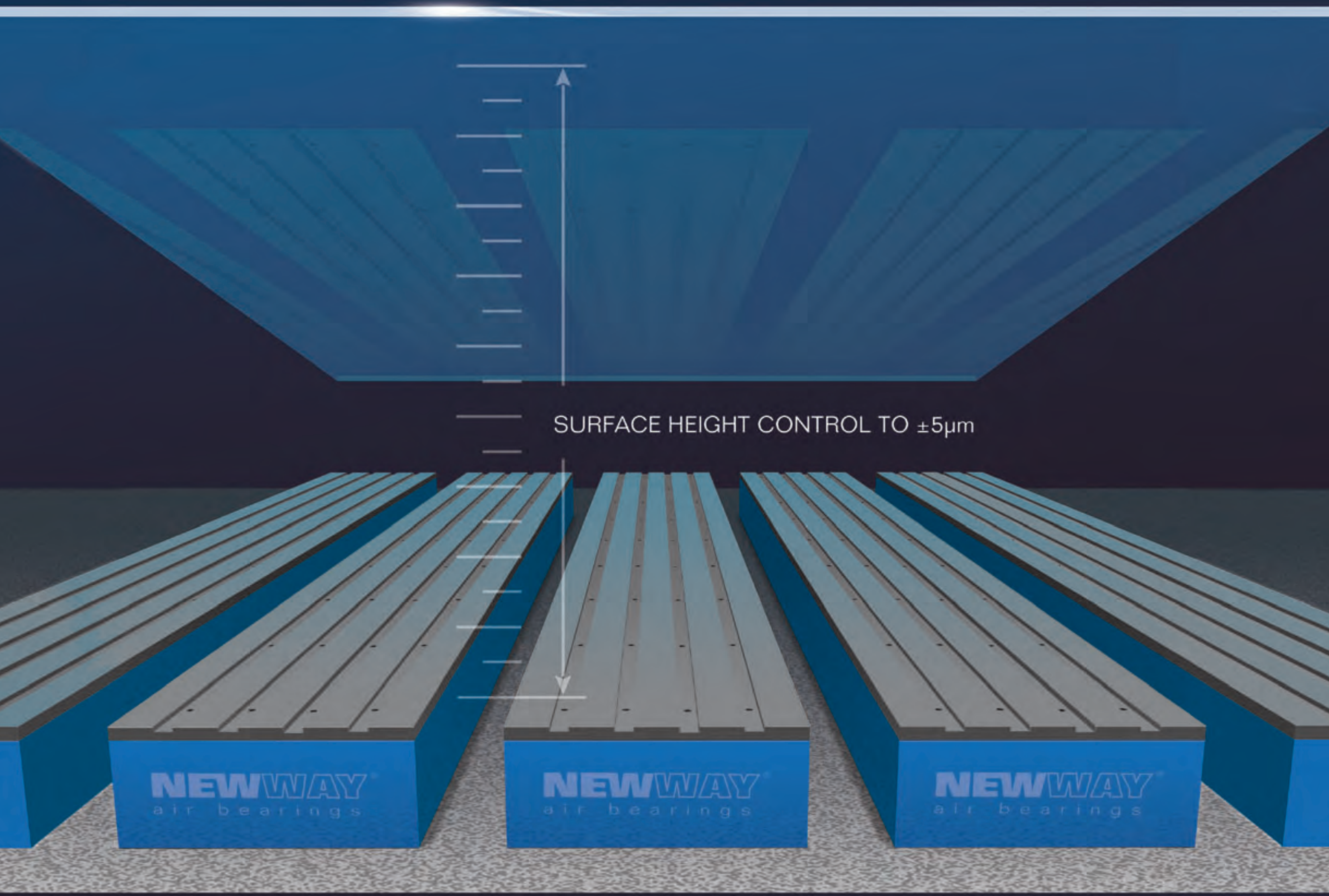

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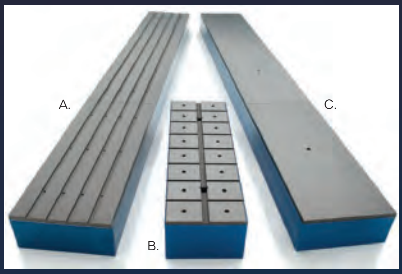

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Despite the higher adoption rates of LED backlights, the yield rate of LED panels is still quite low. The LED penetration rate will be hampered by high costs. Panel makers have planned to increase the thickness of LED light-guide designs and use VESA-like technology to boost the yield rate and reduce the mechanical requirements.

White LEDs: The Low-Cost Answer?

The white-LED-backlight notebook-panel price gap *vis-à-vis* CCFL backlights will narrow to within $10 in the future, iSuppli believes. In general, branded-notebook vendors are requesting thinner light-guide plates for LED backlight units to be used in ultra-thin panels. But the lower production-yield rates for these thinner light guides are affecting the overall LED penetration rate for notebooks. CCFL light guides require a thickness of 2.0–2.2 mm, but for LEDs the requirements are 0.7–0.9 mm for ultra-thin notebooks, making it difficult to produce these in volume. Panel suppliers are asking that the thickness be increased to 1 mm, which will help to increase the yield rate. The current yield rate is estimated to be only 60%, but the adoption of thicker light guides could increase it to 75%. LEDs used in notebook backlighting currently have a brightness of more than 1800 mcd, and some LED suppliers have boosted the brightness to more than 2000 mcd in 2008.

The Japan Institute of Material Science has developed a prototype of a white LED composed of red and green phosphors and a blue LED chip. Used for an LCD-panel backlight, the white LED can have a 99% color gamut, which is considerably higher than the current level of 72% color gamut of a conventional LED.

In terms of price positioning, RGB LED backlights are still much more expensive than CCFL-backlit notebook panels, with $50–$80 price premiums, while white LEDs are targeted to be less than $25 higher than CCFLs in 2008. A 13.3-in. white-LED-based notebook panel uses 20% less power and is 40% thinner and 20% lighter than conventional products. Apple's new MacBook Air notebook weighs only 3 pounds, with a maximum thickness of only 0.76 in.; it features a 13.3-in. LED-backlight-based LCD panel. Samsung recently introduced a new 15.4-in. LED-backlit panel that features 10 times (10,000:1) the contrast ratio of a typical notebook PC display.

Conclusion

The opportunity is ripe for manufacturers and LCD-panel makers to take advantage of not only helping the environment, but making a profit along the way. LED backlighting presents vendors across the value chain with a way to revolutionize the FPD market without taking much of a hit in regards to sales and revenues. iSuppli expects that the notebook market will be the first market to utilize LEDs in a majority of its products, but as the technology becomes more ubiquitous, it is expected that we will see products adopt this technology across the board. ■

Sweta Dash *is Director of LCD and Projection Research for iSuppli Corp. For media inquiries on this article, please contact Jonathan Cassell, Editorial Director and Manager, Public Relations, at jcassell@isuppli.com. For non-media inquiries, please contact analystinquiry@isuppli.com.*

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