

DISPLAY WEEK 2013 REVIEW AND SOLID-STATE LIGHTING ISSUE

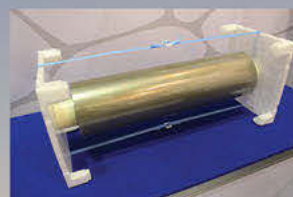
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SOCIETY FOR INFORMATION DISPLAY

# Information DISPLAY

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Sept./Oct. 2013  
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## Flexible Displays, New Materials, UHD, and More in Vancouver



**Plus**

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**ON THE COVER:** Top right: The 2013 I-Zone award for "Best Prototype at Display Week" is Shinoda Plasma's film-type display using plasma-array tubes. From lower right, clockwise: This year's four Best-in-Show winners are: Cima NanoTech's self-assembling nanoparticle mesh technology, E Ink's three-pigment e-paper, 3M's quantum-dot enhancement film, and Universal Display Corp.'s borderless flexible OLED lighting. Background image courtesy of the Vancouver Convention Centre.



Cover Design: Acapella Studios, Inc.

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- Interactive Digital Signage
- Digital Signage and ESLs in Europe
- The Metrics of Curved OLED TVs
- 4K x 2K: Manufacturing and Human Factor
- The Perils and Pitfalls of Venture Capitalism
- The Business of Displays in Europe

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## A Visionary Destination

by Stephen Atwood

The 50th annual Display Week event took place in Vancouver, BC, on the beautiful west coast of Canada. Despite a relatively long plane ride for many of us, the trip was well worth it. I arrived a couple of days early so I could get a taste of the local ambiance before the crush of activities ahead. Vancouver is a beautiful city with an endless array of activities. It is very walkable and features some of the

best natural scenery I have ever seen. One example is Stanley Park, which encompasses about 1000 acres of beaches, rainforest, and hiking trails. I spent most of a day there, following my own advice from last month about finding balance, and enjoyed some majestic views along with learning a lot about the local environment.

Needless to say, this was truly a visionary destination for Display Week 2013. If you were one of the lucky ones there then you know what I'm talking about. The exhibitions of new technology delivered on their promises as did the great paper presentations and seminars. There was a lot to see and do, and as I've observed every year, it's more than any one person can absorb. That's why we bring in a team of experts to cover it all for you. So, whether you were there or not, you'll certainly value the articles we've assembled in this annual Display Week review issue. Hopefully, they will whet your appetite for Display Week 2014 in San Diego, another postcard destination on the west coast of the U.S.

In our cover story this issue, Jenny Donelan reports on the winners of the SID Best in Show awards for 2013. Each year, the award winners are chosen from a select and highly competitive group of nominees in three categories. The process involves a dedicated group of industry experts who work incredibly hard to visit the exhibitors, learn about their latest products and technologies, and then select the very best in each category. Each of these recipients truly deserves the recognition they have received.

No matter where you work in the display industry, you cannot avoid interacting with touch technology. It's become an integral part of so many consumer products and a companion of countless display applications. This year, as our roving reporter and frequent contributing editor Geoff Walker discovered that the touch industry is moving toward a period of maturation, where almost every mainstream application uses touch in some way. In most cases, that technology is projected-capacitive. Now the industry is looking beyond touch to the next generation of interactive technologies, as we saw so vividly at the Touch-Gesture-Motion Market Focus conference also held at Display Week. Geoff covers it all in his article on touch technology.

Of course, LCD technology was dominant in practically every exhibit, as well as the subject of countless papers and seminar subjects. Despite being ubiquitous, the technology is still evolving rapidly in new directions such as ultra-high resolution, very large formats, sunlight readability, and extremely low power configurations. From 5-in. to over 110-in. screen sizes, our contributing editor Alfred Poor has it all covered for you in his report on LCDs.

Stereoscopic LCDs burst onto the market a few years ago as a strategy to hopefully boost the sales of new premium TVs. Although the strategy did not play out quite the way manufacturers had hoped, it did generate a new interest for innovation in all types of 3-D schemes including multi-plane projection, autostereoscopic, holography, and related technologies. Many of these were on display at Display Week and long-time

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## LG and Samsung Bring Large, Curved OLED TVs to Market

For those not inclined to head to the beach last summer, there was another option: stay inside and watch big, beautiful OLED TVs. In July, LG made its 55-in. curved OLED TV, first demonstrated at CES last January, available to the public. A few weeks later, Samsung introduced its own 55-in. curved unit.

The stay-at-home option would have required deep pockets: at least as of last summer, LG's TV was retailing for \$15,000 and Samsung's for \$9,000. Still, the commercial availability of these long-awaited TVs represents a breakthrough. The sets are now available through Best Buy in the U.S. *Information Display* contacted a Best Buy representative to find out what customer reaction has been thus far, but Best Buy had no comment. According to the Best Buy Web site, the LG unit must be ordered in stores and is only on display in about 20 stores nationwide. There are no customer reviews posted yet. (Note: At press time, the LG unit went on sale on Amazon for \$9,999 and the price was lowered to the same amount on Best Buy.)

*Consumer Reports* recently reviewed the Samsung unit and was uncharacteristically gushing about it, saying the test TV performed "brilliantly" and that the technology was a potential game changer. (*Consumer Reports* had not yet had the chance to review the LG unit.) Issues such as burn-in and lifetime still have to be tested and addressed, *CR* cautiously added.<sup>1</sup>

Many industry experts are scratching their heads as to why both Samsung and LG chose to introduce OLED TV commercially in curved rather than flat formats. The official word from the companies is that the curvature offers a more enhanced and immersive viewing experience. Time will tell whether the curve catches on with consumers.

In the meantime, the OLED TVs keep coming and keep getting bigger. At press time, LG had just unveiled a 77-in. UHD curved OLED TV at IFA 2013 in Berlin. The unit was a prototype.<sup>2</sup>

### References

<sup>1</sup><http://www.consumerreports.org/cro/samsungoled0813.htm>

<sup>2</sup><http://www.engadget.com/2013/09/06/lg-77-inch-curved-uhd-oled/>

## Microsoft Buys Nokia's Handset Business

In early September, Microsoft announced that it was buying Nokia's smartphone and cellular handset business for \$7.2 billion, with \$5 billion going toward Nokia's Devices & Services unit and the other \$2.2 billion to license Nokia's patents and mapping services. The Finnish firm Nokia is the maker of the Lumia line of smartphones, which run Microsoft's Windows Phone operating system.

Finland's flagship company began as a paper mill approximately 150 years ago and went on to enjoy success in many areas, including rubber, cable, and telecommunications. But Nokia has struggled with mobile-phone sales recently, even as its Lumia smartphone (winner of a 2013 SID Display Application of the Year Silver Award) was well received by both critics and consumers.

The acquisition appears to be designed to provide Microsoft with hardware traction in the mobile-devices market. Stephen Elop, a former Microsoft employee who became Nokia President and CEO and will now act as Nokia Executive Vice President of Devices & Services before returning, post-transition, to Microsoft as an executive VP,<sup>1</sup> spoke about the deal in a Microsoft press release. "Building on our successful partnership, we can now bring together the best of Microsoft's software engineering with the best of Nokia's product engineering, award-winning design, and global sales, marketing, and manufacturing.... With this combination of talented people, we have the opportunity to accelerate the current momentum and cutting-edge innovation of both our smart devices and mobile-phone products."

Going forward, according to a Nokia press release, the agreement stipulates that "Nokia continues to develop and sees significant value in, advanced technologies, its patent portfolio, and Nokia brand," and that the company will be "focusing on NSN, HERE, and Advanced Technologies post-transaction." The last three are divisions within Nokia.

### References

<sup>1</sup>[http://en.wikipedia.org/wiki/Stephen\\_Elop](http://en.wikipedia.org/wiki/Stephen_Elop)

## IFA 2013 Highlights

At press time, IFA 2013 was taking place in Berlin. In addition to the aforementioned 77-in. OLED TV from LG, the following

display-related products were announced:

- A 56-in. 4K OLED TV from Sony.
- The HP Envy Recline, a tablet/laptop hybrid with a 23- or 27-in. touch screen on a stand that can pivot down off the desk and over your lap.
- 4K UHD LCD TVs from Panasonic.
- 98- and 110-in. UHD LCD TVs from Samsung, plus an UHD OLED TV.
- Samsung's "Galaxy Gear" smart watch.

## Projected Touch

By now, most of us have been in the situation of wishing there was a touch interface that isn't there – on an iPod Classic, for example, or an ATM window that requires you to press the mechanical buttons to the side of the screen rather than the images on the screen. We seem to want it to be a touch-based world, and a new product from Seattle-based Ubi Interactive is designed to help us get there.

With a Kinect sensor, a computer running Windows 8, a projector, and the Ubi interactive software, you can have a touch screen on any surface. The user can interact with the display using simple gestures as if the projected image were a touch screen (Fig. 1).

The Ubi software analyzes the images captured by the sensor to detect the position of the user's hands or fingers in the 3-D space in front of the display. It can precisely determine when the user is in contact with the display and pass this on as a touch event to any touch-ready Windows 8 application. The software starts at \$149 for one touch point and ranges up to \$1499 for 20 touch points.



**Fig. 1:** Ubi's interactive software, when used with a Kinect sensor, a computer running Windows 8, and a projector, allows any surface to become a touch screen, as demonstrated at a recent architecture show at California Polytechnic State University. Photo courtesy Ubi Interactive.

# guest editorial



## OLED Lighting Edges Closer to Commercial Reality

by Sven Murano

OLED lighting entered the stage about a decade ago with significant enthusiasm behind it; however, one cannot fail to notice that recently more skepticism can be heard from market observers. Despite promising early design studies and small-sized production campaigns, OLED lighting is clearly struggling to generate significant sales volume. Even analysts – usually an over-optimistic group – have become rather careful with their predictions for the coming 2–3 years.

Does this mean OLED lighting will be stuck in its infancy? Is it already time to write obituaries for this once-promising technology? Certainly not!

There are some very good reasons to be optimistic about the current phase of OLED lighting and to see it as just a pause in the otherwise very dynamic development of this technology. What seems to be holding back OLED lighting at the moment is competition from inorganic LEDs. LED technology is impressing many with its high-performance levels and constantly decreasing costs. LEDs have garnered a lot of attention from lighting-market players who are still struggling with the adoption of the solid-state lighting wave and are looking for solutions that work now.

This issue of *Information Display* features two articles that outline how OLED lighting can develop toward commercial success in the coming years – both technology-wise and market-wise. Jörg Amelung from Tridonic gives us an overview of the technological features that OLEDs offer and the market segments in which this technology can benefit from these features, which include slim areas emitting diffuse light sources. The article also states which minimum performance requirements need to be fulfilled in order to ensure market entry and which integration difficulties need to be solved. The author also analyzes some devices that are available on the market today and offers examples of some first applications from different lighting companies.

The article from Panasonic's Kazuyuki Yamae focuses instead on the technological progress of OLED technology for lighting applications. His team at Panasonic has managed to achieve record-setting efficiency values for OLED lighting panels in recent years by maximizing the light-extraction efficiencies of the devices. He shows very nicely the fundamental optical problems that OLED developers must solve and describes a solution that was discovered at Panasonic's laboratories. Finally, he provides an outlook of how efficiency levels should develop in the coming years, in both R&D and commercial terms.

With both articles, you will have a good snapshot of the current state of OLED lighting technology, but none of the authors answers the question of when exactly OLED lighting will make the move into our offices and living rooms. My personal expectation is that the breakthrough is just around the corner. Steady improvements in technological foundations are being made in labs all over the world and all of the big players in Europe and Asia are just waiting for the right moment to ramp up their production. At the same time, several smaller start-up companies are pushing into the market in a search for their own niches, and this is keeping the bigger guys alert. Lighting designers have developed an initial understanding of this new thing to come, and luminaire makers are therefore beginning to implement OLEDs in their roadmaps.

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# I-Zone and Best-in-Show Winners

*The Society for Information Display honored five exhibiting companies at Display Week 2013, the 50th annual SID International Symposium, Seminar, and Exhibition, in Vancouver last May. These companies were Shinoda Plasma for best prototype in the Innovation Zone and Cima NanoTech, Universal Display Corp., E Ink, and 3M for Best-in-Show winners on the exhibit floor.*

by Jenny Donelan with Alfred Poor

ONE of the most exciting aspects of Display Week is all the innovations you will discover there. Some products are announced just prior to the show, but most attendees, including industry experts, do not really know what the most innovative and interesting exhibits will be until they see them on the show floor. Both the Innovation Zone (I-Zone) and the Best-in-Show awards were designed to highlight the kind of new and exciting technology that debuts at Display Week.

The 19 exhibitors in the second-annual I-Zone were chosen to participate on the basis of their cutting-edge research and their ability to demonstrate a working prototype at the show. The presence of these companies, many of them start-ups or research arms of larger institutions, gave show-goers a look at display technologies of the future. Although every exhibitor in the I-Zone was chosen as part of a competitive process, the winner of the Best Prototype award, Shinoda Plasma, demonstrated the best of the best, according to the panel of experts who selected it.

### I-Zone Best Prototype

This year's winner of the I-Zone award for "Best Prototype at Display Week" was Shinoda Plasma Co., Ltd., for its film-type display using plasma tube arrays. The display

is actually made of tiny tubes of glass that are each plasma displays. The tubes are arranged horizontally. Although the tubes cannot bend, the carrier on which they are mounted is flexible, so the entire mat of tubes can be rolled parallel to their alignment, similar to a bamboo window shade (Fig. 1).



**Fig. 1:** Shinoda Plasma's Best Prototype winner resembles a home movie screen, but it is, in fact, a rollable plasma-based display. Photo courtesy Alfred Poor.

Information Display contributing editor Alfred Poor noted that although the module shown in the I-Zone had tubes that were 1 mm in diameter, a company representative indicated that smaller 0.5-mm tubes are in development. The tubes are filled with red, green, or blue phosphor and grouped side-by-side in threes to create white pixels. The screen in Vancouver weighed less than 2 kilos per square meter. This technology is currently available for large commercial display installations, but the company has plans for 100-in.-diagonal high-definition roll-up models to be used by consumers in the home. This article is based on an ID Display Week blog entry by contributing editor Alfred Poor.

### Best-in-Show Winners

Four companies – Cima Nanotech, Universal Display Corp., E Ink, and 3M – won Best-in-Show awards at Display Week 2013. These were selected by the Display Awards Committee based on the significance of their development and/or product, for their potential impact on the display industry and consumers of display products, and for their ability to generate excitement within not only the display industry but also the general public and the media. The awards were open to all exhibitors on the show floor during Display Week 2013 and were awarded to companies in small, medium, and large exhibit categories. "The selection of BIS award winners from among the many exciting new developments presented in the

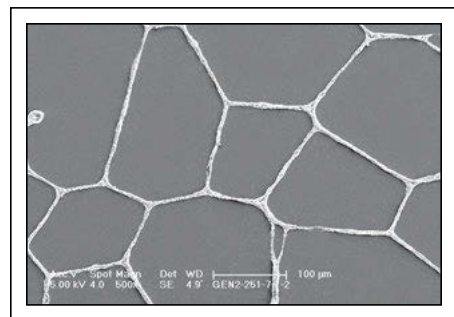
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exhibits during Display Week is a daunting and rewarding task that we all take very seriously,” says Robert Melcher, chairman of the 2013 awards committee.

**Cima NanoTech for its self-assembling silver nanoparticle mesh technology (small exhibit):** Cima NanoTech’s SANTE Technology is a nanoparticle dispersion that self-assembles into a random mesh-like structure when coated onto a substrate, enabling it to become a transparent conductor. Other key benefits are low surface resistance ( $< 25 \Omega/\square$ ) at high transparency (~88%) and flexibility. Unlike standard metal-mesh technology, the SANTE nanoparticle dispersion’s random network pattern on the surface of a film eliminates the need to orientate the film to a non-moiré position on a display screen.

Markets include EMI shielding, transparent heating, large-format multi-touch displays, OLED lighting, photovoltaic, electro-chromic, flexible displays, and many more. Cima NanoTech recently commercialized a SANTE product line for EMI shielding and transparent heating and a separate line for SANTE touch films (Fig. 2).

**Universal Display Corp. for its borderless flexible OLED lighting (small exhibit category):** UDC’s all-phosphorescent OLED lighting panel, built on a plastic substrate system, uses UDC’s proprietary single hybrid-layer UniversalBarrier encapsulation technology to meet the necessary packaging requirements for OLED displays and lighting. UDC’s encapsulation also provides complete perimeter coverage for nearly edgeless or “bezel-less” packaging, increasing the panel’s active area and creating many new product design possibilities (Fig. 3).



**Fig. 2:** This scanning electron microscope photo of SANTE shows the random mesh-like pattern formed by the nanoparticle dispersion.



**Fig. 3:** UDC’s OLED lighting panel is built on a flexible plastic substrate that is all but bezel-less.

**E Ink for its three-pigment electronic-paper display (medium exhibit category):**

E Ink Spectra is the first three-pigment electronic ink to be offered in mass production and was engineered specifically for electronic shelf labels (ESLs). Products using Spectra offer the same high-contrast, sunlight-read-



**Fig. 4:** E Ink’s Spectra adds a third color – red – to E Ink’s black and white electro-phoretic display technology.



**Fig. 5:** 3M’s new QDEF (quantum-dot enhancement film) enables more vivid, true-to-life color for LCDs.

able, low-power performance attributes of monochrome E-Ink-based display types – but now with the additional pop of red. The first generation of Spectra will feature black, white, and red pigments, and E Ink says it will release additional colors in the future (Fig. 4).

By using ESLs with E Ink’s technology, retailers have the ability to change pricing strategies as needed in real time. Spectra allows retailers to elevate the impact of their ESLs by adding color to logos and quickly directing consumers’ attention to important information, such as product sales and promotions.

**3M for its quantum-dot color enhancement film (large exhibit category):** 3M’s Quantum Dot Enhancement Film (QDEF) allows up to 50% more color than current levels in LCD devices. Prior to QDEF, LCDs typically were limited to displaying 35% or less of the visible color spectrum. Wider-color-gamut displays, as enabled by QDEF, will allow consumers to enjoy more visceral and truer-to-life color (Fig. 5).

Quantum dots emit light at very precise wavelengths. This means display makers can use them to create a highly optimized backlight that produces the exact wavelengths of red, green, and blue light needed by an LCD for optimal color and energy performance. Trillions of these quantum dots protected by barrier film fit inside an LCD backlight unit. The new film replaces one already found inside LCD backlights, which means the manufacturing process requires no new equipment or process changes for the LCD manufacturer.

3M teamed with Nanosys, Inc., to produce the 3M QDEF product specifically to deliver more color to devices such as smartphones, tablets, and televisions. ■

# Display Week 2013 Review: Touch Technology

*2013 was a year of evolution and maturation for touch technology, with projected-capacitive dominating the exhibit floor like never before. This article takes a close look at the state of p-cap at the Vancouver show, as well as at the “Touch-Gesture-Motion” Market Focus Conference at Display Week.*

by Geoff Walker

AS recently as only 2 years ago, there were 12 different touch technologies exhibited at Display Week<sup>1</sup>; this year, there were only four. Those were projected-capacitive (p-cap, both discrete and embedded, at 21 of the 23 exhibitors), analog and/or digital resistive (at 8 of the 23 exhibitors), electromagnetic resonance (EMR) digitizer at one exhibitor, and force-sensing at one exhibitor. That’s a big change! The main reason for the change is the expanded dominance of p-cap. According to DisplaySearch,<sup>2</sup> in 2013 p-cap will account for 81.4% of units and 92.3% of revenue shipped. Looking at the same data for all touch technologies by commercial (traditional “vertical markets”) vs. IT/CE (information technology/consumer electronics) products, 95.0% of units and 97.0% of revenue will be IT/CE. In other words, it’s all about p-cap, and commercial and industrial applications are becoming insignificant in the touch world.

Even with the reduced number of technologies shown, touch was still a big part of the Display Week 2013 exhibition. The 23 exhibitors mentioned in the above paragraph include those showing discrete touch modules, embedded touch, and controllers. In total, there were 63 touch-related exhibitors (35%

of 182 total) at Display Week 2013, as shown in Table 1 below. (Note that many of the materials exhibitors naturally serve both the display and touch markets.)

## Embedded Touch

At Display Week 2012,<sup>3</sup> embedded touch was big news with the announcement of the first high-volume shipments of hybrid in-cell/on-cell by Sony (now part of Japan Displays, Inc., or JDI). Not unexpectedly, JDI had the

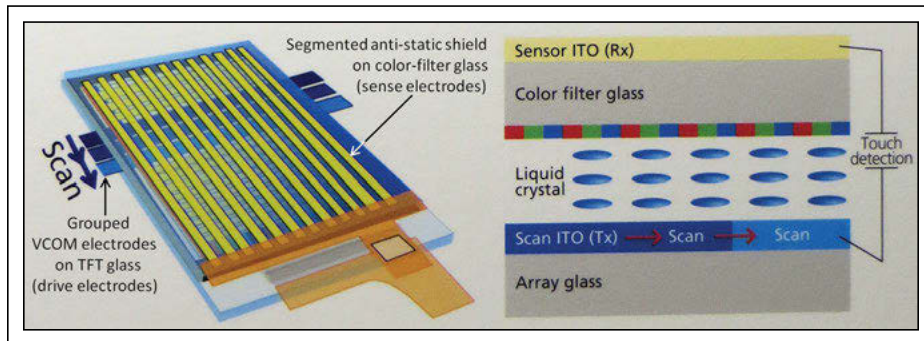
most extensive exhibition of embedded touch at Display Week 2013, with heavy promotion of its somewhat-misleading brand name “Pixel Eyes.” Figure 1 illustrates how Pixel Eyes is assembled, from both a physical construction and a layer perspective.

As an example of its latest innovation, JDI showed a 7-in. 2560 × 1600 (431 ppi) IPS-LCD with Pixel Eyes that was configured for use with a passive pen (only). At that pixel density, anything drawn on the screen

**Table 1:** There were 63 touch-related exhibitors at Display Week 2013; 23 (36%) showed touch modules, controllers, or embedded touch; 22 (35%) showed touch materials or related processes and technology; and 18 (29%) showed touch displays, integration, enhancements, or market research. In this analysis, each exhibiting company is counted only once, even though it could be in multiple categories.

Product Category	Exhibitors	Product Category	Exhibitors
Modules	15	Bonding	2
Enhancements	8	Glass processing	2
Adhesives	6	Market research	2
Metal & CNT films	5	EMR digitizer	1
Touch displays	5	Haptics	1
Controllers	3	Laser patterning	1
Embedded touch	3	Multi-touch self-capacitive	1
Glass	3	Pressure-sensing tiles	1
Integration	3	Passive styli	1

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**Fig. 1:** JDI's (formerly Sony's) "Pixel Eyes" hybrid in-cell/on-cell embedded touch is shown from both a physical construction (left) and a layer perspective (right). For a more detailed explanation of how it works, see Ref. 3. Source: Artwork by JDI; annotation on left by the author.

was rendered with exquisite sharpness. The entire display was only 1.78-mm thick, including the cover glass. JDI was also showing its version of OGS (one-glass solution), which it calls "Sensor on Cover Lens" (illustrated in Fig. 2).

LG Display (LGD) showed hybrid in-cell/on-cell embedded touch in a 7-in. LCD, where the drive electrodes were on the oxide-TFT glass (the same as JDI) but the sense electrodes were on a PET film laminated between the color-filter glass and the cover glass. LGD named this configuration "FIT", a creative modification of the current p-cap layer-construction abbreviation format. The signage shown with the display allowed an observer to calculate that 40 VCOM electrodes are grouped to form each of 32 drive electrodes. The signage also specified a minimum passive-stylus tip diameter of 2.5 mm, which is not quite as good

as the typical 1.8–2.0 mm currently being specified by the top touch-controller suppliers. Unfortunately, the touch performance of the display was very erratic. The booth staff suggested that the problem was too much electromagnetic interference (EMI) at the show. If so, I look forward to better demonstrations in the future when they work this out.

The third display manufacturer showing embedded touch was Innolux. In a change of strategy from last year's "we supply all forms of embedded touch" exhibit, Innolux this year showed only on-cell in many different displays, including a 4.5-in. 1280 × 720 (330 ppi) 2-D/3-D LCD. When questioned about this change, booth staff said that Innolux had decided to "keep LCD yields as high as possible" by building the complete cell, including glass thinning, and then adding the touch screen. This approach results in

lower-quality ITO, since high-temperature annealing cannot be done on a completed cell. Innolux explained that its business priority was to keep LCD cell yields at maximum, and therefore it had to accept some performance compromises in touch implementation. This positioning was emphasized (perhaps inadvertently) by Innolux in its 39-in. touch display made with ITO in a diamond pattern at 50 Ω/sq. The ITO in this display (shown in Fig. 3) was so visible that it almost seemed to be part of the image.

In another change of strategy from last year's exhibit, Innolux did not make any use of its "Touch On Display (TOD)" brand. While the company confirmed that the brand *does* cover all forms of embedded touch (in-cell, hybrid in-cell/on-cell, and on-cell), booth staff said that Innolux is only using the brand "with customers."

### Projected Capacitive

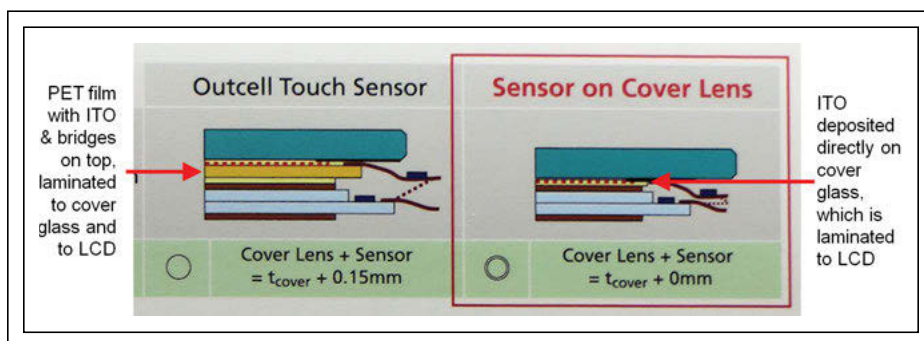
Showing off its expertise in high-performance large-format p-cap, 3M Touch showed a prototype of its latest 55-in. touch-display table. It truly was a prototype; underneath the table was a standard laptop strapped to a standard NEC LCD.

AMTouch USA (part of AMT-Taiwan) showed a 21.5-in. p-cap touch display with surprisingly good performance. In part, this performance is due to AMTouch doing its own controller firmware so it can provide better support to commercial customers. AMTouch is not the only supplier using this strategy; another on the exhibit floor was UICO. In UICO's case, the primary reason for doing its own controller firmware is to optimize for industrial-application conditions such as water and gloves. A supplier (also on the exhibit floor) taking the opposite strategy is Ocular; instead of doing its own firmware, Ocular partners very closely with Atmel to optimize for industrial-application conditions.

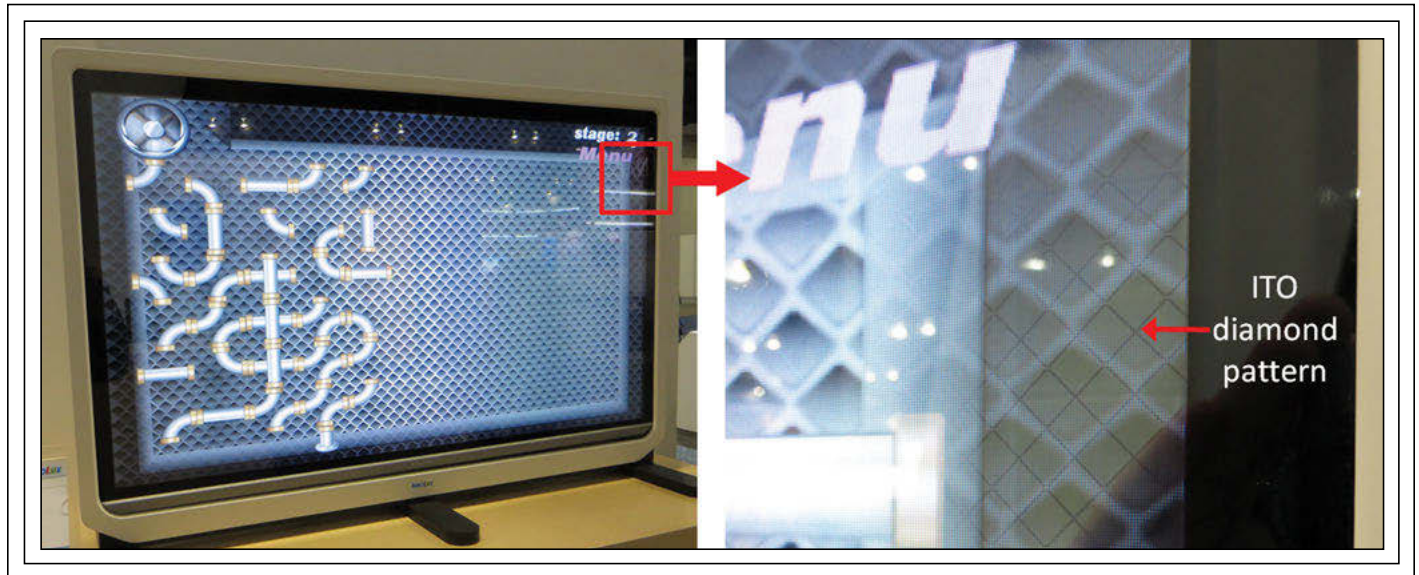
While visiting the Panjit (Mildex Optical) booth, this author was able to take a picture of the wide variety of sensors being shown. Figure 4 shows a stack of seven Panjit p-cap touch screens. This is actually a good example of the large quantity of touch-screen hardware that is available for close inspection on the exhibit floor.

### Other Touch Technologies

As noted in the introduction to this article, the only other technology shown in any quantity



**Fig. 2:** JDI's version of OGS (one-glass solution), called "Sensor on Cover Lens," is compared with conventional discrete ("outcell") touch-sensor construction. Note that the total thickness reduction gained through OGS is only 150 μm. Source: Artwork by JDI; annotation by the author.



**Fig. 3:** Innolux's 39-in. touch display was made with ITO in a diamond pattern at  $50 \Omega/\text{sq}$ . The right-hand photo is a close-up of the area outlined in red in the left-hand photo. The ITO is so visible it almost seems like part of the image. Source: Author photo.

on the exhibit floor was analog and/or digital resistive. Of the eight exhibitors, the best in the author's opinion was Fujitsu. The reason is that it was best able to clearly communicate its differentiation in terms of features as follows:

- 4-, 5-, 7-wire and "gesture-touch" types
- Pinch, rotate, flick, and swipe gestures
- 10-finger multi-touch via digital resistive
- Film-glass and film-film-plastic construction
- Very low activation force ("Feather Touch")
- Drivers for Windows, Linux, and Android
- USB, serial, I2C, and SPI interfaces
- Gorilla glass and plastic substrates
- Anti-glare or clear finish

Instead of saying (in effect) "we sell resistive touch; everybody knows what that is," the company painstakingly identified its advantages and engaged visitors with demos that fit the audience such as digital resistive for military applications.

There actually was one additional touch technology on the exhibit floor, but it wasn't identified as such. Bi-Source (BSI), a touch-display maker, used a 72-in. touch display with traditional infrared as an attention-getter for its booth. The author is fairly sure that it was the *only* IR touch screen on the entire floor.

### Other Interesting Bits

Touch is so well-integrated into Display Week that you really have to walk the entire show in order to see everything that's touch-related. Exhibits of particular interest included Fogale, Cima NanoTech, Canatu, and Samsung Display. Fogale, based in France and exhibiting in the Innovation Zone, was showing "multi-touch/multi-touchless self-capacitive." In these times of pervasive mutual-capacitive p-cap, self-capacitive is not something that's seen frequently. Fogale's technology uses an "active guard" to totally eliminate all parasitic capacitance, allowing measurement of  $0.0001 \text{ pF}$  between an electrode and the target (this is  $100\times$  better than what's possible with current technologies). This active-guard approach isolates a sense electrode (or an entire circuit) from ground, thus eliminating the effect of the parasitic capacitance between the sense electrode and ground. It works by applying a sinusoidal signal to the sense electrode; this allows measurement of the current flowing through the parasitic capacitance between a sense electrode and ground. An exactly equal signal is applied to a guard electrode that surrounds the sense electrode. Because the sense and guard electrodes are at the same potential, the leakage current from the sense electrode to ground is reduced to essentially zero, thus eliminating the effect of the parasitic capacitance.

Fogale is initially focusing its technology on smartphones and tablets; it supports five touches on a 5-in. screen and 10 touches on a 10-in. screen. When the user's hand is hovering above the screen, Fogale supports recognition of individual fingertips at up to 5 cm, and the whole hand at up to 8–10 cm. Accuracy and linearity are better than 1 mm. Figure 5 shows a block diagram of Fogale's controller with a red dotted line around the portions that are isolated by the active guard. Note that the leakage capacitance shown in the drawing is in terms of attofarads ( $1 \times 10^{-18}$  farads).

Cima NanoTech is a relatively new entrant in the ITO-replacement materials market; it was showing a "self-assembling silver mesh." Cima's material starts as an opaque liquid that's coated on film using industry-standard equipment; 30 sec later the liquid dries into a random-pattern silver mesh with  $5\text{-}\mu\text{m}$  conductors and  $150\text{--}300\text{-}\mu\text{m}$  open spaces – very similar to the characteristics of printed metal-mesh material. This product received a Best-in-Show award at Display Week.

Canatu, based in Finland and exhibiting in the Innovation Zone, was showing a new form of carbon nanotubes (CNTs) called Carbon NanoBuds. These are yet another new transparent conductor (*i.e.*, ITO-replacement) material consisting of carbon nanotubes with a buckyball (fullerene) attached. Canatu claims that the addition of buckyballs to some CNTs

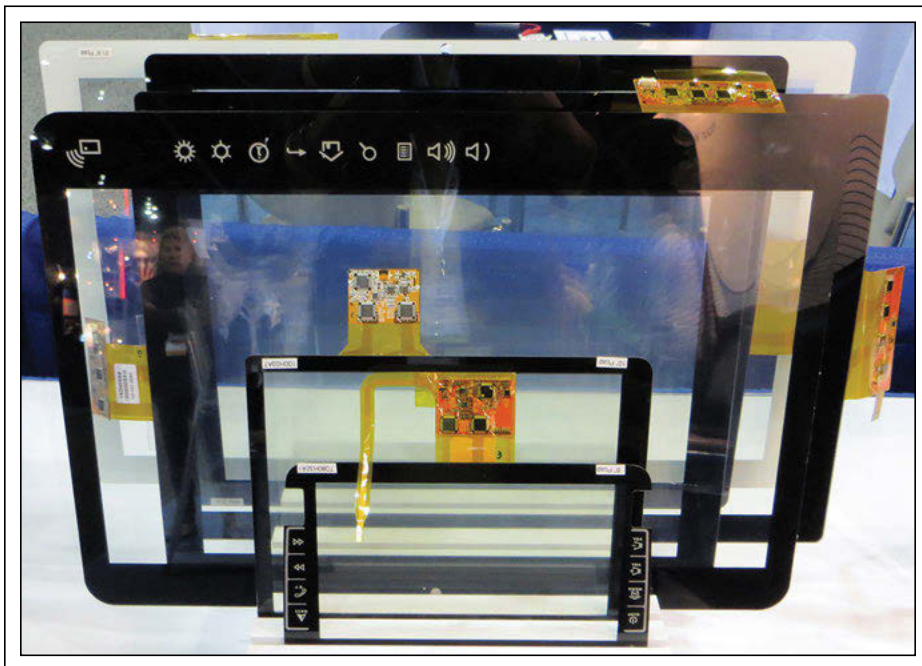
makes the material much more able to combine with other materials due to some buckyballs having only five carbon atoms rather than CNT's six-atom structure. In the author's opinion, Canatu's real breakthrough is its "NanoBud Reactor," which takes transparent film and carbon gases as inputs and outputs a patterned touch sensor made with relatively uniform length and relatively pure CNTs. Solving the problems of length and purity in a single manufacturing process is something that the rest of the CNT industry has not been able to accomplish yet.

Finally, among many other things, Samsung Display showed a 23-in. "metal-wired touch" display with a plastic cover lens. The touch module was constructed of poly-methyl methacrylate (PMMA) with an OCA-attached film-sensor (made of either metal mesh or silver nanowire; it wasn't clear which). The PMMA cover glass was particularly nice, with anti-glare, a very good touch feel, and 5H hardness. Unfortunately, the touch performance (rated for 10 touches) was not as good as it could be; the system tended to drop touch points when 10 touches were moving at high speed. It may have just been over specified, since the system performed acceptably with two or three touches at moderate speed.

### Summary of Observations from the Exhibit Floor

The following are the author's observations after studying the exhibits:

- In previous years, the number of touch module-makers exhibiting usually exceeded the number of touch-materials makers; in 2013, they were roughly equal.
- At least for Display Week, p-cap has knocked out almost all other touch technologies except resistive.
- Embedded touch in all forms (in-cell, hybrid in-cell/on-cell, and on-cell) is growing.
- ITO replacements, especially metal mesh, are growing.
- Enhancements such as top-surface coatings, filters, and bonding are very important in commercial applications.
- In general, Display Week touch exhibitors tend to appeal more to commercial users than consumer users.
- Even though p-cap is overwhelmingly dominant, innovation in touch continues.



*Fig. 4: This stack includes seven Panjit (Mildex Optical) p-cap touch screens. Source: Author photo.*

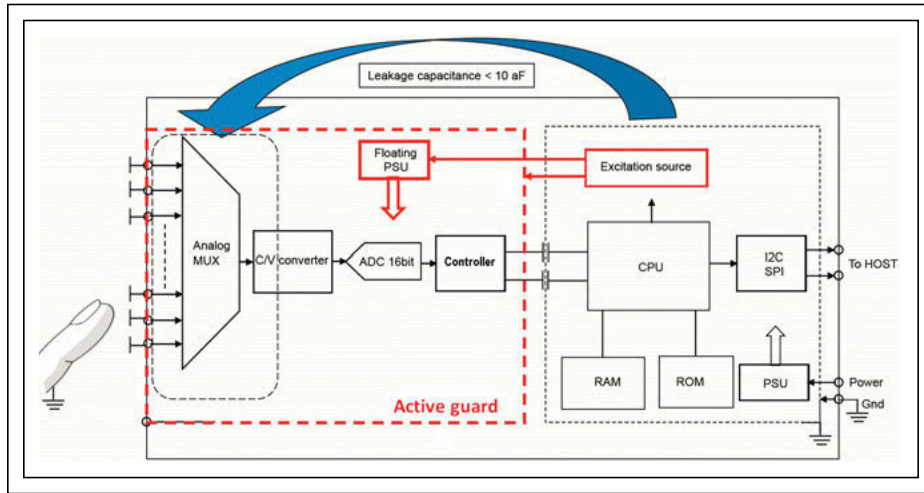
### Market Focus Conference

Wednesday's all-day "Touch-Gesture-Motion" (TGM) Market Focus conference (produced by IHS in cooperation with SID) consisted of 23 presentations focused on next-generation touch-, gesture-, and motion-based technologies applicable to the display industry. In the author's experience, presentations at business/technology conferences such as this can be classified into three groups: market or technology forecasts, product or company pitches, and truly thought-provoking presentations that transcend either of the first two. The first category is straightforward, usually consisting of talks by analysts and technologists (including the author). The challenge for all speakers at business/technology conferences is to land in the third category; the realities of marketing and business typically force many (or most) speakers into the second category.

At this TGM conference, there were four presentations that the author found truly thought-provoking; they were by York University, Sensor Platforms, Elliptic Labs, and Qualcomm. Wolfgang Stuerzlinger, a professor at York University in Toronto, Canada, presented "Is 'Iron Man 2' Right? Re-Investigating 3D User Interfaces."<sup>4</sup> Beginning with a video clip from the movie

*Iron Man 2*, showing superhero Tony Stark commanding a "floating-in-the-air" 3-D user-interface (UI), Wolfgang's presentation argued that while floating objects look cool in movies, they do not exist in reality and are therefore a poor basis for a 3-D UI. Wolfgang also showed results from several studies that measured the throughput achieved with a variety of 2-D and 3-D pointing and touch methods, with the general conclusion that as the distance from the target increases and/or as 3-D viewing is added, throughput goes down. In other words, it is tough to beat the good old mouse, even for manipulating 3-D objects! During his presentation, Wolfgang noted that in his opinion, the "*Iron Man*" trilogy should be required viewing for students of 3-D UIs (along with, of course, *Minority Report*) – primarily as examples of what not to do!

Kevin Shaw, CTO of Sensor Platforms, presented "Context Awareness Using Sensors." Kevin defined context as "a framework that provides understanding of an event." Context is transitory, multivariate, and personal; it is not a gesture or a picture; and it must work for everyone all the time. Kevin used a number of common activities to illustrate the value of context; these included answering the phone, going to a meeting, reaching for toothpaste,



**Fig. 5:** A block diagram of Fogale's "multi-touch/multi-touchless self-capacitive" controller shows the components that are shielded with an "active guard" surrounded by a red dotted line. Source: Excerpted from Fogale's Exhibitor Forum presentation.

driving home, visiting your doctor, teaching a class, and monitoring the driving behavior of your teenage daughter. He then used the analogy of human senses and the brain to make the point that mobile devices equipped with (a) a variety of hard and soft sensors (he showed a list of 16), (b) sophisticated algorithms, and (c) always-on sensing (*i.e.*, continuous measurement) can become *context platforms* that enable a new class of smart mobile apps. In closing, Kevin showed the power consumption of 10 common sensors that ranged from 5  $\mu$ A to 75 mA, making the point that designing for low power is the pre-eminent challenge in achieving his vision of "context platforms."

Tobias Dahl, the founder and CTO of Elliptic Labs, presented "Touchless Ultrasound Gestures – from Physics to Use Cases." Tobias's presentation explained in detail how ultrasound can be used as a rich gesture-recognition platform technology. Tobias started with the physics of ultrasound: (a) the relatively slow speed of sound allows accurate determination of relative motion even with low bandwidth and only a few sensors and (b) the wide field of view created by diffraction allows sensing movements far away and up close, with a 180° field of view. Next, describing features derived from the physics, Tobias explained that it is easy to create a depth filter using ultrasound because ultrasound derives (x,y) position from multiple-range (z) measurements, while stereoscopic

optics derives z from multiple correlated (x,y) positions. Finally, Tobias described nine categories of gestures that can be used with mobile devices, and five uses cases – including how ultrasonic-sensed gestures could be used to play *Angry Birds*.

Francis MacDougall, Senior Director of Gesture Technology at Qualcomm, presented "Touch-Free Gestures for Next-Gen UX." Francis's presentation focused on the emerging use of gestures in mainstream consumer-electronics devices. He used, as an example, the Samsung Galaxy S4, analyzing the functionality of its five "air gestures," as well as the use-case for hover in five applications. Francis pointed out that hover is now available in touch controllers from Cypress and Synaptics and that hover is a standard part of Android, implemented seamlessly with other touch-screen event handling. Next, Francis summarized the common near- and far-field gestures in use today and described a method of adding gestures to existing applications through the use of a "gesture layer." After summarizing some current and soon-to-be available hardware, Francis closed with three pieces of advice to device-makers: (a) focus on using gestures to enable user experiences that go beyond touch by speeding up specific tasks, (b) rapid UI feedback for all touch-free interactions is essential, and (c) expect higher-fidelity gestures using emerging technologies (such as ultrasound) in the next 12 months.

The astute reader may say, "Wait a minute! The last three of those presentations sounded suspiciously like product pitches!" True, *every* presentation by a commercial enterprise other than market or technology forecasts are basically product or company pitches at heart. What separates the wheat from the chaff is if after a presentation I feel more knowledgeable (educated), I'm excited about future possibilities, and I find myself thinking hard about how what I just heard fits into my view of the world.

### Touch in Depth and Breadth

Once again, there was an amazing amount of touch technology at Display Week 2013. This is especially clear when one considers the additional touch resources at Display Week beyond the exhibits, including the 13 Symposium touch papers, the Sunday Short Course on touch, the two Monday Seminars on touch, the six Exhibitor's Forum touch presentations on Tuesday, the 23 presentations at Wednesday's Market Focus "Touch-Gesture-Motion" conference, and, finally, the seven Touch and Interactivity posters presented in Thursday's Poster Session. It is these additional resources that differentiate Display Week from any other touch conference worldwide. While Asian touch exhibitions such as Touch Taiwan<sup>5</sup> (in Taipei) or C-Touch<sup>6</sup> (in Shenzhen) may have more exhibits by touch module and material suppliers, no other conference has Display Week's depth and breadth of presentations on touch. If you are involved in the touch industry, you just can't afford to miss Display Week 2014 in San Diego. Start planning for it now.

### References

- <sup>1</sup><http://informationdisplay.org/IDArchive/2011/JulyAugust/TouchTechnology.aspx>
- <sup>2</sup>DisplaySearch, "Quarterly Touch Panel Market Analysis Report" Q2-2013.
- <sup>3</sup><http://informationdisplay.org/IDArchive/2012/September/DisplayWeek2012ReviewTouchTechnology.aspx>
- <sup>4</sup>An earlier version of Professor Stuerzlinger's presentation can be viewed as a 27-minute TEDx video at <http://www.youtube.com/watch?v=3Q3Pft-xA0Y>.
- <sup>5</sup><http://www.touchtaiwan.com/en/>
- <sup>6</sup>[http://www.chinaexhibition.com/Official\\_Site/11-3311-C-TOUCH\\_2013\\_Shenzhen\\_-\\_The\\_11th\\_China\\_\(Shenzhen\)\\_International\\_Touchscreen\\_Exhibition.html](http://www.chinaexhibition.com/Official_Site/11-3311-C-TOUCH_2013_Shenzhen_-_The_11th_China_(Shenzhen)_International_Touchscreen_Exhibition.html) ■

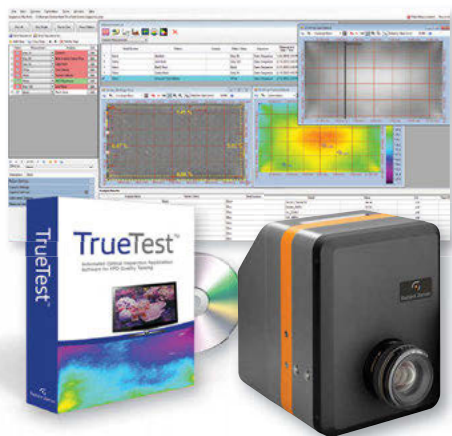


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# Display Week 2013 Review: LCDs

*LCDs dominate the display market despite challenges.*

by Alfred Poor

**H**ERE'S A MYSTERY: liquid-crystal displays (LCDs) dominate just about every information-display application worldwide these days. Yet, to paraphrase Winston Churchill's famous quote about democracy, LCDs are the worst form of display technology except for all the others that have been tried.

Consider the following: It is a fussy technology that requires a complex switching backplane. It is not a solid-state solution; it actually requires that some components physically change their location and orientation in order to work. And it is dreadfully inefficient in that a typical active-matrix LCD consumes 95% or more of the transmitted light, even when it's showing a pure-white image. As a result, you have to use very bright backlights, which, in turn, require complex light recovery and management components to make efficient use of this energy.

Yet, despite of all this, LCD technology remains without question the dominant electronic-display technology in the world. Nowhere was this more evident than at SID's Display Week 2013 in Vancouver, British Columbia, Canada, last May. From the Exhibit Hall to the Symposium, it was clear at every turn that LCD technology have an enormous lead over all other display technologies,

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and this situation is not likely to change soon. It is true that cathode-ray tubes (CRTs) once held a similar lead that seemed insurmountable, but current competing technologies are not gaining much traction, while LCDs continue to improve. Organic light-emitting-diode (OLED) displays are starting to build out from their beachhead in the mobile-device market, but they remain a small factor in the overall numbers. Reflective and bistable displays continue to evolve and have had some success in niche segments, but show little sign of competing in any significant way in broader markets. The fact remains that LCD technology continues to improve – and costs continue to fall – faster than the levels achieved by competing technologies. This makes it difficult for any alternative to mount a serious challenge.

LCD industry revenues are forecast to grow even as the unit prices of the products continue their steady decline. As was pointed out by Sweta Dash from IHS at the Display Week Business Conference, LCDs will generate more than \$120 billion in market value this year, a figure that will climb to more than \$150 billion by 2017 (Fig. 1).

## More Pixels

While there were many interesting improvements in LCD technology in evidence at Display Week 2013, one clearly stands out from the rest. The trend toward “4K” resolution displays is gaining momentum, which was evident just about everywhere you turned at Display Week.

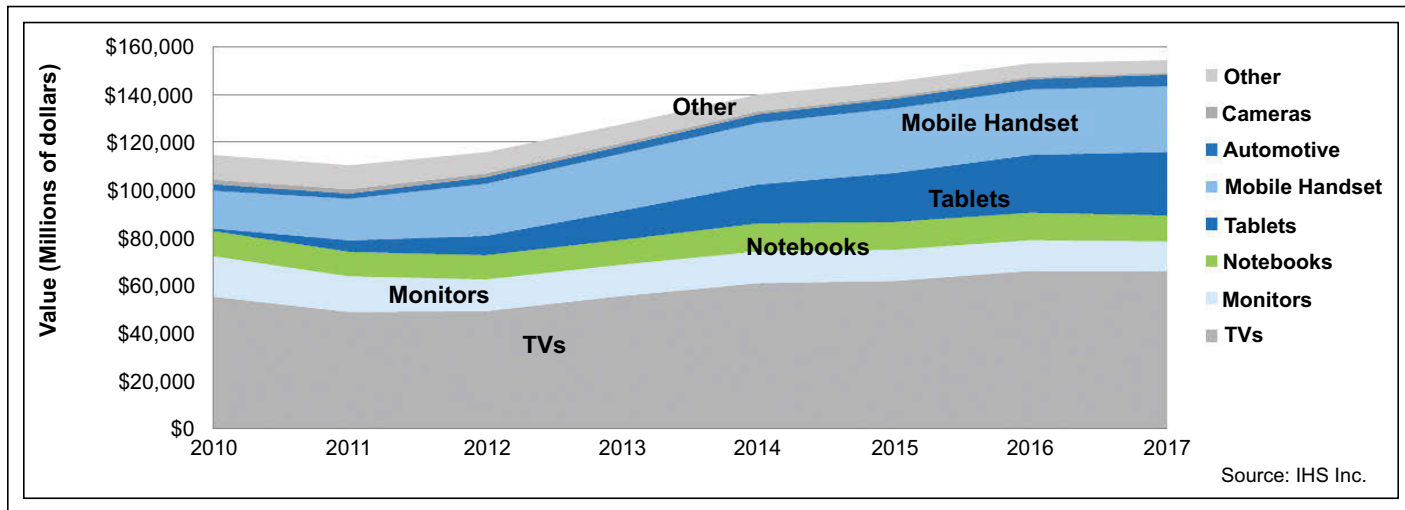
For example, Mike Lucas, Senior VP of Sony's Home Entertainment and Sound Group, addressed the Business Conference

with a presentation on “4K: The Resolution Revolution.” Citing nearly 75% penetration of HDTVs in the U.S. and a move to larger set sizes, he made the case for increasing resolution on TVs to 4K resolution (four times the pixels of HDTV). More than 15,000 digital cinemas already have projectors with 4K resolution, more than 100 feature films have been released in 4K, services including Netflix are developing prototype streaming services for 4K content, and Sony has a 4K media player that can download new content from the Internet. Clearly, many manufacturers are hoping that 4K will revive flagging interest in new televisions and help shorten the replacement cycle for consumers.

A 4K LCD was the recipient of one of the SID Display Industry Awards this year. The 110-in. LCD TV from Shenzhen China Star Optoelectronics Technology (CSOT) won the Silver Award in the Display of the Year category. This model also supports 3-D TV using active-shutter glasses, incorporates multi-touch technology, and has a dynamic backlight to boost contrast performance.

Other 4K LCDs were on display in the Exhibit Hall. Samsung showed its giant 85-in. prototype (Fig. 2) and LG showed its nearly as enormous 84-in. screen (Fig. 3).

New technologies are also bringing these high-resolution images to smaller screens. For example, the metal-oxide IGZO backplanes have higher electron mobility than the standard amorphous-silicon (a-Si) backplanes, which makes it possible to create smaller transistors for the active-matrix backplanes. Sharp was showing a 31.5-in. LCD panel that offers 4K resolution using an IGZO backplane (Fig. 4).



**Fig. 1:** According to IHS, LCD worldwide revenues are forecast to continue to rise in the near future, despite stagnating television sales and declining unit prices in general. (Source: IHS)

### Smaller Pixels

In fact, the fabrication of smaller and smaller pixels is another area where LCD technology has been advancing. With the ever-growing consumer interest in smartphones and tablets, manufacturers are seeking to increase resolution as a differentiating feature. Smaller pixels mean that a panel has more pixels per inch. In order to create an active-matrix display, each pixel must have at least one transistor switch. These switches have to be small enough to let some light through (the aperture ratio), so the development of backplanes that support smaller semiconductor devices is a primary driver for higher resolutions. There were many examples of displays with small pixel structures throughout the exhibit hall. For example, Samsung showed a new 13.3-in. LCD panel with an amazing  $3200 \times 1800$ -pixel resolution, which works out to 276 pixels per inch (ppi).

That pales by comparison to the one that Innolux was demonstrating. Its full HD ( $1920 \times 1080$ -pixel resolution) panel was only 5 in. on the diagonal. Using low-temperature polysilicon (LTPS) TFTs for the backplane, the panel was able to display 444 ppi. This is all the more impressive because each pixel was composed of four subpixels – red, green, blue, and white – and the display also had a panel border of just 0.5 mm.

### Smarter Pixels

LCD pixels are not just getting smaller, they are getting smarter, too. Sharp showed its

Memory LCD panels that have one bit of memory embedded in each pixel of the monochrome (black and white) displays (Fig. 5). This makes it possible to greatly reduce the power consumption required to

maintain an image compared with conventional LCD designs. Some models are designed to run on 3-V dc power supplies, making them compatible with standard “button” batteries.



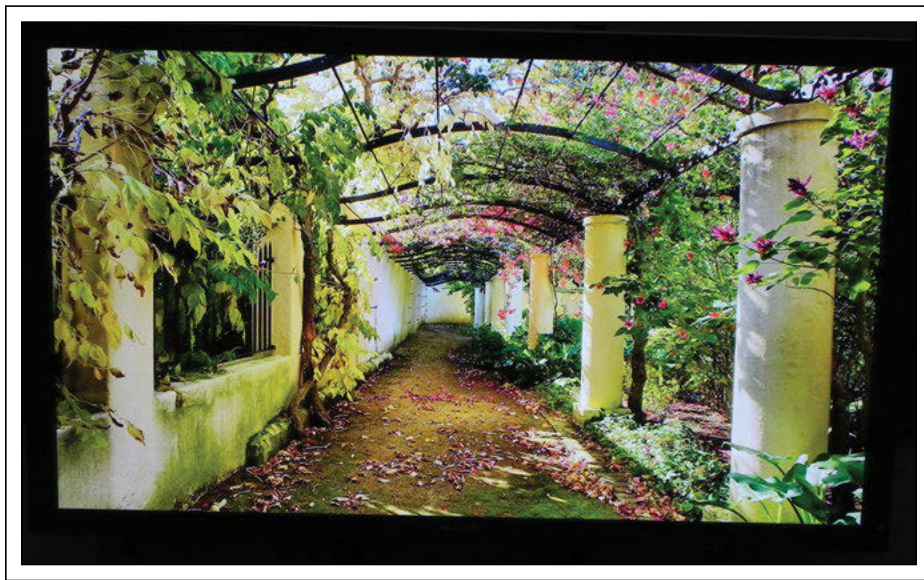
**Fig. 2:** Samsung was one of the major display makers showing products that raised the bar for LCDs, including this 85-in. 4K panel. (Photo credit: Alfred Poor)



**Fig. 3:** LG also is helping to bring the “big screen” to living rooms worldwide with its 84-in. 4K LCD panel. (Photo credit: Alfred Poor)

Pixels are getting smarter in other ways as well. Working in partnership with Nanosys,

3M announced its new Quantum Dot Enhancement Film (QDEF). The quantum



**Fig. 4:** Sharp’s 31.5-in. LCD panel relies on an IGZO metal-oxide backplane to deliver 4K resolution. (Photo credit: Alfred Poor)

dots can convert light of one wavelength to another, and they can be tuned to produce a very narrow range of wavelengths, which results in precise colors. In turn, this greatly increases the color gamut that LCD panels can display. The film takes the place of another film already used in LCD backlights, which means that no production changes are required to use this material with existing panels. (3M won a Display Week 2013 Best-in-Show award for this product.) Quantum dots are also used by the Color IQ material made by QD Vision. This is used in select models of Sony’s BRAVIA LCD-TV product line and helps increase the color gamut of the display. Color IQ received the Gold Award for the SID Component of the Year, which was presented at Display Week 2013.

### Many Kinds of Pixels

These examples just scratch the surface of the LCD products shown at Display Week 2013. Some had unusual shapes or configurations. For example, Kyocera showed a 2.5-in. round LCD with a  $240 \times 240$ -pixel resolution. Japan Display Inc. (JDI) had a rectangular LCD panel designed for use in an automotive instrument cluster. This panel had a hole in the middle that would accept the shaft of a conventional mechanical indicator. The result is that automobile engineers can design gauges that can provide different displays using a physical pointer. JDI also had a mockup of a car’s dashboard using curved and circular LCDs (Fig. 6).

Other automotive panels were also in evidence, such as Kyocera’s rearview-mirror display, which is already in production.

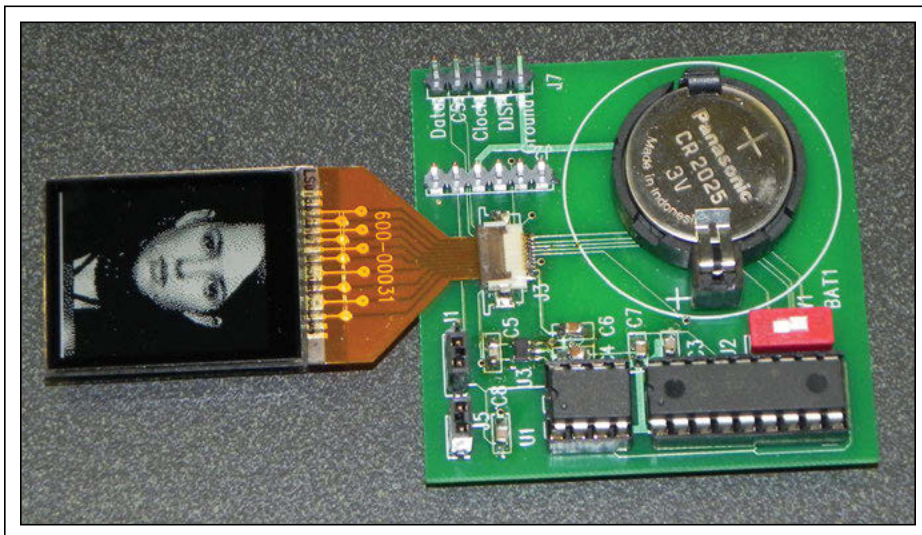
An area of specialization to note is high-brightness displays, which include sunlight-readable modules for use everywhere, from avionics to bank ATMs. LG had a panel intended for digital-signage applications that boasted a luminance of 2000 nits (candelas/square meter). MacroDisplay, Inc., demonstrated a novel approach to sunlight-readable displays by using its directional light-guiding film (DLGF). This allows an LCD panel to employ both a backlight and a bright ambient light as an illumination source, so that the same panel can be used in daylight and indoor settings. BrightView Technologies offers a variety of high-brightness solutions and was showing a choice of cold-cathode fluorescent (CCFL) and light-emitting-diode (LED) backlights. The company also provides dimmable

panels, so the same display that is suitable for high levels of ambient light can also be dimmed for nighttime viewing. Mitsubishi Electric Corp. and Santek were among other LCD-panel providers offering high-brightness products.

In addition to all these, there was a nearly endless assortment of panels for industrial applications and other uses. One interesting development is that nearly all the LCD panels offered now use LED backlights instead of CCFLs. Many of the manufacturers and vendors provide support for their clients who want to switch from CCFLs to LEDs for the panels used in their products. Endicott Research Group (ERG) specializes in this area and was showing a number of power-conversion products and drivers for LCD backlights at Display Week. Renesas Electronics America showed a wide variety of panels from NLT Technologies, primarily focused on value-added solutions for lower-volume applications. This company is affiliated with Tianma Microelectronics, which showed a range of high-volume solutions. These included panels with integrated projected-capacitive (p-cap) touch, displays for outdoor viewing that use transmissive or reflective technology, and panels for specific purposes such as medical applications.

### Moving Forward

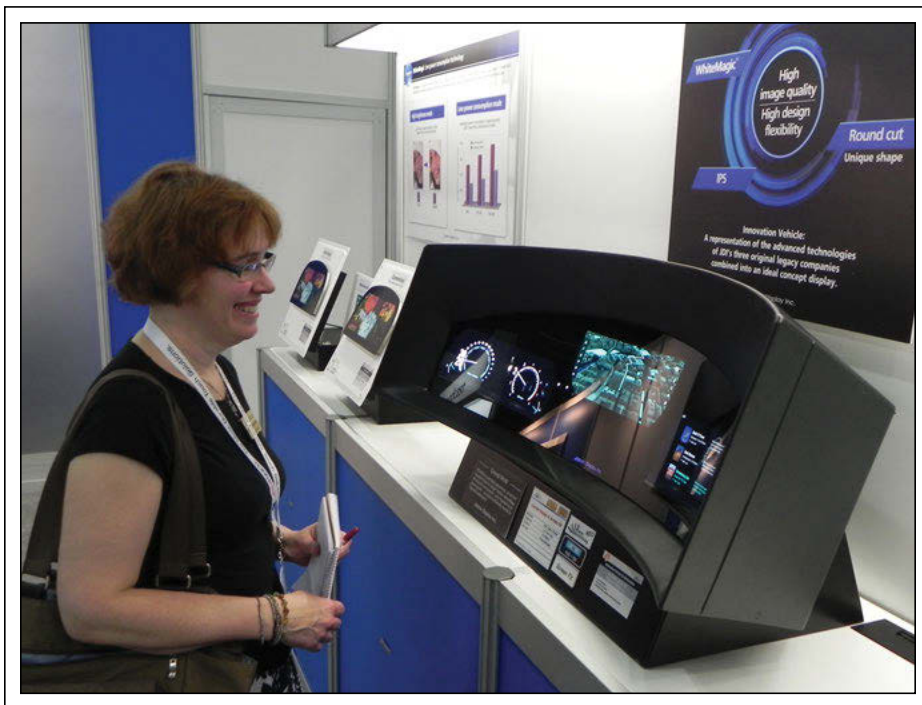
If the Symposium is any measure of overall interest in improving LCD technology, the field continues to advance. Only the subject of 3-D displays had more sessions devoted to it than liquid crystals and related topics. If you added the sessions on TFT and metal-oxide semiconductor research, LCD topics outnumbered them all. Perhaps the most intriguing session of all was Session 5, which presented three different views of the competition between LCD and OLED technology for displays, especially in the mobile-device market. The strong indication is that OLED technology is not likely to mount a serious challenge to LCD dominance, at least for the short term. Industry-analyst David Barnes of BizWitz gave a compelling analysis that predicts that no matter which technology wins out, it is the consumer who will likely gain all the benefit of the competition. Yasuhiro Ukai from the Ukai Display Device Institute took the position that LCD dominance is likely to continue, although there is room for improvement in manufacturing efficiency. And Joun



*Fig. 5: This tiny LCD panel from Sharp includes memory for each pixel, which greatly lowers power consumption. (Photo credit: Alfred Poor)*

Ho Lee and colleagues from LG Display presented a comparison of LCD and OLED performance in mobile displays, showing that LCDs have some specific advantages for resolution, contrast ratio, and color.

The LCD industry is an industry with an apparently insurmountable lead in many market segments. Part of the reason for this status, despite the technology's aforementioned shortcomings, is that the researchers



*Fig. 6: This curved automotive dashboard from JDI demonstrates the many ways that LCDs can be adapted to bring new functionality to existing applications. (Photo credit: Alfred Poor)*



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and the companies behind LCDs are not complacent. Competing technologies keep stepping up to challenge LCDs in one segment or another and before they can do so, LCD technology raises the bar. Think of OLED technology's edge in terms of color, contrast, and panel thickness and how every year, LCDs improve so as to lessen that edge on all three counts. Display Week 2013 clearly demonstrated that liquid-crystal technology continues to provide the best value for many applications by combining excellent performance with low cost, and that everyone involved in the industry continues to invest time and money to make these displays more versatile and powerful than ever. ■

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# Display Week 2013 Review: 3-D

*The 3-D technology on the show floor this year was represented primarily by small, glasses-free displays with improved image quality.*

by Ken Werner

THE topic of 3-D did not have a promising start at SID's Display Week 2013. In his keynote address, Bill Buxton of Microsoft Research said, "3-D [television] was a demonstrably bad idea before it even started." He was referring to the industry's hope that 3-D could enable a new generation of high-margin products that would induce customers to replace the largely commoditized 2-D LCD and plasma TVs they had already bought. Said Buxton: "It didn't work out that way."

It is widely accepted that 3-D TV is all but dead in the North American market, and three weeks after Buxton made his comment, ESPN put a large additional nail in the coffin by announcing it would discontinue its ESPN 3-D sports channel by the end of this year.

### Large-Screen 3-D Largely Absent

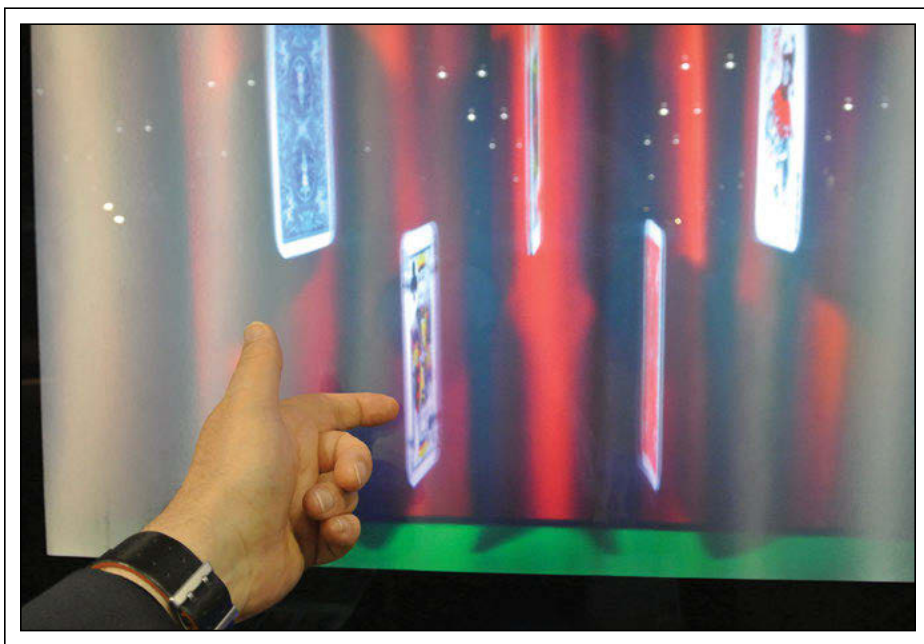
One area in which you might think medium- and large-screen 3-D could work is digital signage for advertising. Of course, the 3-D would have to be autostereoscopic, that is, glasses-free. And for several years, large autostereoscopic (AS) 3-D demonstration displays could be seen at Display Week and elsewhere. But there was no AS 3-D signage at the Digital Display Expo in late February

and very little at InfoComm in Orlando, which followed Display Week by 3 weeks.

The Display Week exhibition did not deviate from this pattern. I saw only a modest number of large 3-D screens on the show floor. Two of these were LG Display's 55-in. AMOLEDs, in both the flat and curved versions. Only the curved version was showing 3-D content when I was at the booth, and both versions used passive glasses.

Another 3-D example was from a more surprising source. Fraunhofer's Heinrich Hertz

Institute (HHI) was showing a moderately large (TV-sized) sample autostereoscopic display with "viewpoint adaptation." Although AS 3-D displays often have several viewing zones for different angles of view, they are all best viewed from a specific distance predetermined by the display's design. HHI uses an Adobe After Effects plug-in suite to generate multiple sets of views from the standard stereoscopic inputs. These multiview images are compatible with many existing AS 3-D displays, according to HHI Research Associ-



**Fig. 1:** The author's finger points to imagery in Holografika's HoloVizio light-field display. (Photo: Ken Werner.)

**Ken Werner** is Principal of Nutmeg Consultants, specializing in the display industry, display manufacturing, display technology, and display applications. He serves as Director of Marketing for Tannas Electronic Displays and is a regular contributor to HDTVexpert.com and Insight Media's Display Daily. He can be reached at [kwerner@nutmegconsultants.com](mailto:kwerner@nutmegconsultants.com).

ate Bernd Duckstein. For the demo at Display Week, there were three fixed viewing distances that Duckstein selected manually, but it is possible to automate the process by detecting the viewer's distance from the display.

Although the large 3-D displays at this year's show were not the highlights, there was an assortment of small-to-medium-sized AS 3-D screens, some of which were interesting.

The most compelling 3-D display at Display Week was shown at the I-Zone, the area designated for committee-reviewed tabletop exhibits for prototypes and innovative demonstrations. Space is free to the chosen exhibitors, thanks to the sponsorship of E Ink and the efforts of the volunteers on the selection committee.

The device in question was the HoloVizio Model 80WLT light-field display made by Holografika Kft. in Budapest, Hungary (Fig. 1).

The display consisted of 80 projection engines, each producing a 720p image, according to Holografika CTO Peter Tamas Kovacs, but the image on the exhibit floor appeared to have considerably less resolution than 720 lines. Kovacs said that may have been the result of misalignment produced by jostling in transit.

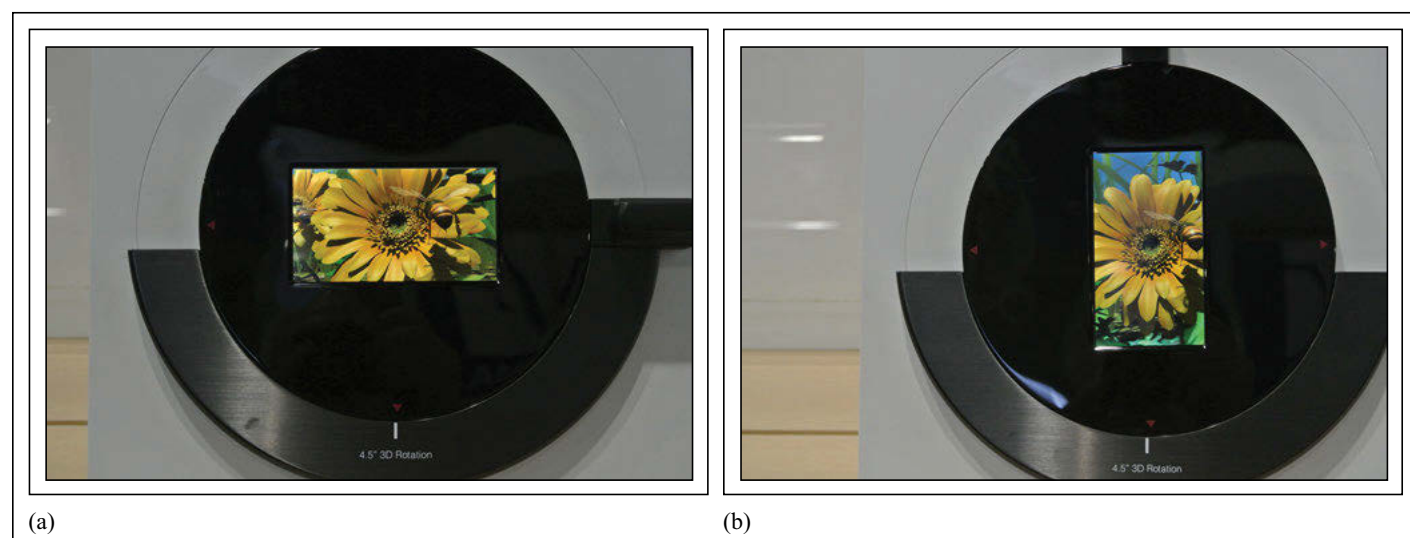
The display was driven by four GPUs contained in two computers that sat inside the display's large pedestal and which were connected to the display with 20 dual-DVI



*Fig. 2: NLT's autostereoscopic 7.2-in. 2-D/3-D prototype exhibited very low cross-talk thanks to its glass lenticular lens. (Photo: Ken Werner.)*

cables. Ideally, said Kovacs, each of the 80 projection engines would show an independently captured image, but a studio session with 80 video cameras is clearly not realistic. So, the company uses four cameras and synthesizes the 80 separate views from them.

The result of this heavy-duty video processing is a 3-D display with a field of view of 180° and continuous motion parallax that permits the viewer to “look behind” elements of the image. The 3-D image is viewable from any position in front of the display; there



*Fig. 3: Innolux 4.5-in. 2-D/3-D autostereoscopic display was able to show 3-D images in both (a) landscape and (b) portrait orientations. (Photo: Ken Werner.)*

## 3-D review

are no dead zones. The 80WLT is available for €60,000 by special order. Expect your unit to be shipped 3 months after it is ordered, said Kovacs.

Although the HoloVizio unit is undoubtedly interesting, you will not be seeing very many of them given the price and production rate. So, it is perhaps fortunate that the bulk of the 3-D displays on the exhibit floor were small AS 3-D LCDs. Most were unsurprising, but left-right crosstalk is improving on average, and some of the displays were based on native-FHD ( $1920 \times 1080$ ) displays, which does a lot for the image quality of the AS image if the other engineering details are taken care of properly.

### Small AS 3-D Displays at the Show

NLT Technologies, formerly NEC LCD Technologies, was demonstrating its multiview AS 3-D H $\times$ DP displays in which the horizontal subpixel density is  $\times$  times that of the vertical subpixel density. In addition, each of the red, green, and blue subpixels is arranged in rows instead of the conventional columns. The arrangement, an extension of the company's Horizontally Double-Density Pixels (HDDP) arrangement, can display both 3-D and 2-D images simultaneously by simply changing the input data. And, says NLT, it displays

"perfect 2-D images" without 3-D/2-D switching and delivers multiple views without reducing the display's native resolution.

NLT showed a 7.2-in. HDDP 2-D/3-D prototype with viewing angles of 80/80 horizontally and 80/60 vertically, a contrast ratio of 600:1, and a luminance of 370 nits (Fig. 2).

In addition, the display incorporated glass lenticular lenses instead of polymer. The result, explained NLT's Engineering Manager Bob Dunhouse, is less left-right cross-talk because glass is more dimensionally stable under prolonged heating by the backlight than is polymer. The claim was supported by a side-by-side comparison and an analysis that showed that the Qualified Binocular Viewing Space (QBVS) of a display with the glass lens is twice that of conventional displays.

Innolux showed a 4.5-in. 2-D/3-D display with  $1280 \times 720$  pixels in 2-D and  $640 \times 720$  in 3-D. Luminance in 2-D was 450 nits and 225 nits in 3-D. The interesting thing about the display was that it could show a 3-D image in both landscape [Fig. 3(a)] and portrait [Fig. 3(b)] modes simply by being rotated 90°. The display used a 2-D/3-D switchable barrier.

Next on the Innolux counter was a similar display with eye tracking. The angular range over which the 3-D eye tracking operated was

rather limited, but an icon in the corner indicated when the image left the active range and had automatically defaulted to 2-D.

Japan Display, Inc. (JDI) showed an automotive display in which an LC parallax barrier was switched by tracking the viewer's head position, so the viewer's (presumably the driver's) head was always in the display's sweet spot. The display was 12.2 in. on the diagonal with a native  $1920 \times 720$  pixels; the 3-D resolution was  $960 \times 720$  (Fig. 4).

Tianma Microelectronics showed a WVGA parallax-barrier 3-D module that produced 350 nits in 2-D and 180 nits in 3-D with a contrast ratio of 800.

So, there was quite a bit of 3-D at Display Week after all if you looked at the industrial purveyors of smaller displays. And these purveyors are learning how to make displays with less cross-talk and more forgiving 3-D sweet spots. It is clear that eye tracking is the way to go for larger (but not large), single-user AS 3-D displays, but is it needed for a hand-held display in which the user can readily – even unconsciously – adjust the angle of view with a slight rotation of his or her hand? Consumers will make that decision for themselves – if head-tracking AS 3-D displays get enough design wins to give consumers the chance. ■



**Fig. 4:** JDI's 12.2-in. autostereoscopic automotive display utilized head tracking to keep the driver's eyes in the display's sweet spot. (Photo: Ken Werner.)

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# Display Week 2013 Review: OLEDs

*TVs were not the only OLED-based products of interest at Display Week.*

by Sven Murano and Anke Lemke

**A**MID the beautiful scenery of Vancouver, British Columbia, Canada, Display Week 2013 offered a great deal to visitors looking for the latest in OLED technology. Even before the exhibit opened, discussions about OLEDs and, in particular, OLED TVs were featured during the Business Conference on Monday and also in the keynote speech given by Samsung Display President & CEO, Dr. Kinam Kim. In his talk, Kim described how Samsung sees the display market of the future being dominated by OLEDs. He considers it the key display technology for coming display generations.

Dr. Kim also painted an enticing future of add-on features that OLEDs could enable for displays to come, ranging from the close-at-hand, such as transparency and flexibility, to the more visionary, such as displays with embedded gas sensors or piezo-elements that enable haptic feedback through the display surface.

Some of those visionary developments were on display on the exhibit floor in the form of demonstrators or products. The Futaba Corp. booth probably had the most interesting and futuristic OLED demos. What Futaba was showing were a number of transparent and flexible models, including a flexible OLED wristwatch with integrated touch functionality (Fig. 1). In addition to these

demos, Futaba also showed its first transparent OLED display product, which is used for the Lenovo S800 smartphone.

Even though the displays at the Futaba booth were based on a passive-matrix approach, they all showed the potential of OLEDs very nicely. Futaba appears to be focused mainly on automotive applications, which explains the company's strong interest in flexibility. This aligned nicely with an observation by Samsung's Dr. Kim, who stated in his keynote speech: "There are no flat surfaces inside a car."

Samsung emphasized its product portfolio of mobile devices at Display Week, showing new versions of its OLED-based Galaxy S4 smartphones. Among the technical aspects

that the company highlighted were the excellent color space and low energy consumption of OLEDs. With regard to the latter, Samsung showed OLEDs and LCDs in direct comparison, claiming that 47% less energy is consumed by OLEDs in the so-called ALPM (AMOLED low-power mode). Even though this power-consumption comparison could conceivably be questioned by the LCD camp, the dynamic power consumption of OLEDs in contrast to the virtually constant consumption of LCDs in all driving situations was very apparent.

Samsung also showed its new pixel-arrangement scheme, which it calls the OLED diamond (Fig. 2). This new type of PenTile display (with twice as many green pixels as



*Fig. 1: Futaba showed a futuristic watch with a curved OLED display.*

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red and blue ones) is supposed to deliver even better image quality than the earlier striped-pixel PenTile display layout used in its Galaxy S3 model smartphone.

### TV Progress

LG Display showed its 55-in. OLED TV set, which has been commercially available for quite some time on the Korean market. In addition, it also showcased a curved 55-in. AMOLED TV, which is now available for sale in the U.S. as well as Korea (Fig. 3).

With those two items, LG Display certainly highlighted its commitment to OLED-TV technology. Until recently, it was the only company with a commercially available large-screen OLED TV. (At press time, Samsung Display had just introduced a curved 55-in. OLED TV for sale in the U.S. as well as Korea.) LG Display also showed a 5-in. HD flexible OLED screen on a plastic foil substrate (Fig. 4). Besides the obvious freedom of being able to shape the display in ways beyond the usual planar restrictions of glass, LG Display also emphasized the ruggedness of such panels.

Early visitors to the booth of LG Display at Display Week could try their luck with a hammer and a non-working dummy panel so as to experience the shock resistance of the plastic device themselves. However, shortly after the opening of the show, the dummy panel mysteriously vanished from the booth.

A major topic at both the technical symposium and business conference was the question of how OLED TV can be best produced. A common understanding throughout the talks was that eventually printing processes could be a workable solution for structuring and fabricating OLED TVs. However, it was also understood that such processes still need at least a few more years of development in order to become mature enough for manufacturing.

Therefore, for the time being, vacuum evaporation of the OLED structures seems to be the only feasible method of production. With regard to this technology, the principle line of debate spins around two very different methods of producing the color subpixel array. On one side is the method favored by LG Display, which deposits a four-subpixel array made up of a combination of fluorescent-blue- and phosphorescent-yellow-emitting materials in a white-emitting OLED structure. (LG Display calls this “WOLED”



*Fig. 2: Samsung demonstrated the brightness of an LCD (left) vs. an OLED (right) display using its new “OLED Diamond” pixel scheme.*

technology.) Each subpixel is then filtered with red, green, blue, or white filters, making up a four-subpixel matrix referred to as the “RGBW” approach.

Samsung Display meanwhile currently favors an approach in which the red, green, and blue pixels are separate native color emitters without the need for any filter overlay. The displays made by this method have only RGB subpixels (no fourth white emitter); however, in the case of Samsung Display implementing the PenTile approach, there is a higher ppi number for green than for R and B. These subpixels are fabricated by an evaporation step through a shadow mask, in which the RGB emitters are deposited through separate shadow masks next to each other. This structure is commonly referred to in the OLED community as an RGB side-by-side arrangement.

One new player in this field entered the ring during the symposium – the Taiwanese company AU Optonics Corp. (AUO) – which reported results from a 65-in. AMOLED TV

that was also produced with shadow masks in an RGB arrangement. AUO did not, however, commit to production of devices with that method during the conference.

The other big question that remains to be answered is which backplane technology will serve the future AMOLED TV market best. Some presenters recommended oxide TFTs as a possible solution. The products by LG Display are based on this approach. On the other hand, Samsung Display stated that it prefers polycrystalline silicon at this time for its OLED-TV development. An idea of the currently running dispute over which technology is most effective could be obtained at the keynote sessions, in which Dr. Kim of Samsung Display advocated the polysilicon approach and John F. Wager of Oregon State University made a clear commitment to oxide TFTs as the most promising approach. A discussion of the details of this debate would go beyond the scope of this article, but it will be very interesting to watch how this technological competition evolves.

## OLED technology review



*Fig. 3: LG Display showed curved OLED TVs at Display Week.*

In any case, AMOLED-TV development will be strongly influenced by steadily increasing competition with LCDs, which are setting new standards in terms of resolution

and color gamut. Clearly, it can be seen that the next generation of OLED-TV products will have to answer the challenge of  $4K \times 2K$  resolution and higher brightness, which



*Fig. 4: LG Display showed a flexible OLED display on plastic foil substrate.*

require improved backplanes, manufacturing, and OLED pixel technologies.

### Microdisplays and Lighting

Returning to the exhibition floor, microdisplays based on the current wave of interest generated by Google glass were of note. Products and demonstrators of this technology could be seen in the eMagine booth and also in the I-Zone exhibit from SA Photonics, Inc. The news that Google glass will use an OLED microdisplay produced by Samsung Display was announced on the last day of the exhibition.

Finally, a few words about OLED lighting. There were limited demos during the exhibition at UDC's and Novald's booth. Impressive improvements were, however, reported at the symposium during the last sessions on Friday morning. Panasonic reported a new record, with a device achieving 114 lm/W in the laboratory, using the company's proprietary light-outcoupling technology. Hitachi described progress in flexible lighting devices made from solution processing, and LG Chem reported on its 80-lm/W product, which will be launched later this year. Also, in terms of light extractions, some updates were given by the glass-manufacturing companies AGC and Saint-Gobain, which both reported on light-scattering substrates for enhanced light outcoupling for OLED lighting. In practical terms for comparing the efficiencies of LED and CCFL lighting products to the aforementioned OLED example, LEDs are passing the 200-lm/W limit in the lab, and commercial products are at around 150 lm/W. CCFLs are at around 80–100 lm/W, with little room for improvement.

Finally, it should be mentioned that for OLED electrode materials, several interesting contributions have been made. Cambrios reported on its "Bottom-Emitting Large-Area Stacked White OLED with Silver Nanowire Network as Transparent Anode," which detailed the benefits of the company's ClearOhm silver nanowire material as an alternative to ITO for OLED solid-state lighting. ClearOhm transparent electrodes enable efficiencies of more than 40 lm/W, improve angle dependence of color, and can enable metal-grid-free large-area OLED lighting tiles, such as the 100-cm<sup>2</sup> (10 cm × 10 cm) OLED tile that Cambrios created recently in collaboration with Novald.

IBM showed some progress on making OLEDs on graphene electrodes, reaching up

to 60% quantum efficiency for a green OLEDs using a laboratory outcoupling regime. The American start-up company nVerPix presented some OLED pixels on carbon-nanotube electrodes.

If and when these new electrode materials will be seen in OLED applications, such as lighting and display tiles, remains uncertain, but certainly the promises toward low cost and flexibility are exciting.

In summary, Display Week 2013 showed an overall positive momentum for OLEDs. In particular, the commitment of the two major players from Korea to OLED TV is reassuring for the industry. Even though several engineering problems still remain to be solved in terms of OLED manufacturing and lifetime, there can be little doubt that, in the long run, OLEDs will develop into a major display technology, especially with its promise for devices with additional functionalities such as transparency and flexibility. ■

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# Display Week 2013 Review: e-Paper

*A new product line from E Ink Corp. topped the surprises at this year's show.*

by Jason C. Heikenfeld

**M**ANY OF US expect Display Week to provide one of the best annual measures of the momentum and status of advances in display technology, and Display Week 2013 lived up to that expectation yet again as a “can’t miss event.” The first measure of interest in reflective displays came at the e-Paper seminar I gave on the day before the symposium and exhibit. The presentation was unfortunately the very last seminar of the day, in a large room, and it was therefore pleasing to see a sizable attendance for the second year in a row. Clearly, there is strong industry desire to understand what is available in e-Paper today and what the future holds. Many of us working in this area continue to field a barrage of inquiries for “zero-power,” sunlight-legible, super-lightweight, or flexible displays, all of which e-Paper is uniquely positioned to satisfy. Our response tends to be: “We are working on it, stay tuned!” So the demand for the next generation of e-Paper products remains robust, and the remaining question is what progress is being made to satisfy that demand.

E Ink Corp. remains the dominant player in the field, surrounded by a diverse set of technologies and small companies vying to grab its market share through improved performance or to enable new applications unmet by E Ink Corp.’s electrophoretic imaging film. Unlike in recent years at the show, it was not the insurgent technologies or companies that caused the greatest excitement in Vancouver;

it was E Ink Corp. itself. The big news occurred on Tuesday in the form of a new product line from E Ink Corp. that was not incremental and not an R&D demo that would never turn into a product.

The press release read: “E Ink Corp. Launches Spectra, the World’s First True Three-Pigment Electronic-Paper Display.” This is significant for two reasons. First, it shows a major investment and advance toward capturing market share in the electronic-shelf label and signage market. The market right now is dominated by simple and dim reflective liquid-crystal displays (LCDs), with at best poor color that is relegated to only subsections of the display. Now, with E Ink Corp.’s Spectra, any part of the display can provide a deep black, a brighter and more paper-like white, or a red color to highlight sales or promotions (Fig. 1).

The second reason for excitement steps us back to last year’s breakthrough reported by Fuji-Xerox on full-color electrophoretic displays based on cyan/magenta/yellow switchable particles. Many of us wondered whether more than two particles (black and white) could ever be commercialized. The answer is now yes, and it should be interesting to see just how far this type of technology can continue to advance for signage. Don’t expect it to lead to color eReaders anytime soon, though, because each time you add another colored particle, the switching speed slows dramatically. The Spectra demos shown provided only 1-bit gray scale. Nonetheless, it is great to see a significantly new and visibly compelling product from E Ink Corp. Credit should be given also to the researchers formerly at SiPix Corp. (which was acquired by AUO and then by E Ink Corp.) who origi-



**Fig. 1:** E Ink Corp.’s Spectra, a new commercial product, adds a third color – red. At left is a schematic showing how the new product works. In the middle are examples of three-color labels that could be used as shelf labels in stores, and at right is a shot of a Spectra display alongside the author’s paper business card (conveniently in red, black, and white) for comparison.

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nally developed the technology that underpins this new E Ink Corp. product.

The fluid in E Ink has a level of “stickiness” to it, such that it takes a bit of a threshold of electric field to get colored particles moving such that more weakly charged particles will move more slowly. The displays first switch between black and white colors, as normal, and in the process move the red particles to the back where they are invisible. Then, a weaker second electric field is applied to move the red particles to the front in select regions, and, voila, now you have color without the losses of side-by-side color-filter systems such as RGBW (red, green, blue, and white). Simply put, the demonstrated units at the E Ink Corp. booth looked great. How long then until additional colored particles can be added? Despite Fuji-Xerox’s 2012 demonstration of full-color single pixels, the general suspicion is that full-color operation is still fairly far away from commercialization.

Other players showing e-Paper in the exhibit hall included Sharp, Opalux, and Qualcomm, each displaying familiar looking e-Paper demonstrators. The Qualcomm booth had two smartphones with the company’s “next generation” mirasol technology. These displays looked really, really good and completely superior to the performance of the commercially available Kobo eReader that uses mirasol. If e-Paper modules like this can be manufactured economically, it would be tough for any other technology to compete with its visual performance in bright ambient light. However, the prototypes were, in fact, static images, meant to convey the expected performance of a “multiposition” mirror that uses optical interference to generate any pure color within a single subpixel (except white, which still significantly limits the maximum possible white state). These static-image prototypes are just thin-film interference stacks, and I recall seeing similarly beautiful static images shown a decade ago by Iridigm (acquired by Qualcomm in 2004). Given the manufacturing challenges Qualcomm had faced for just the two-position mirrors, multiposition mirrors are likely to raise even more difficult challenges (Fig. 2).

Also in the exhibit was the Japan Display, Inc. (JDI), reflective-display prototype, which I was able to see up close for the first time. The color looks excellent for a reflective LCD (Fig. 3). It employs a gain reflector. I was very skeptical of gain reflectors until recently,

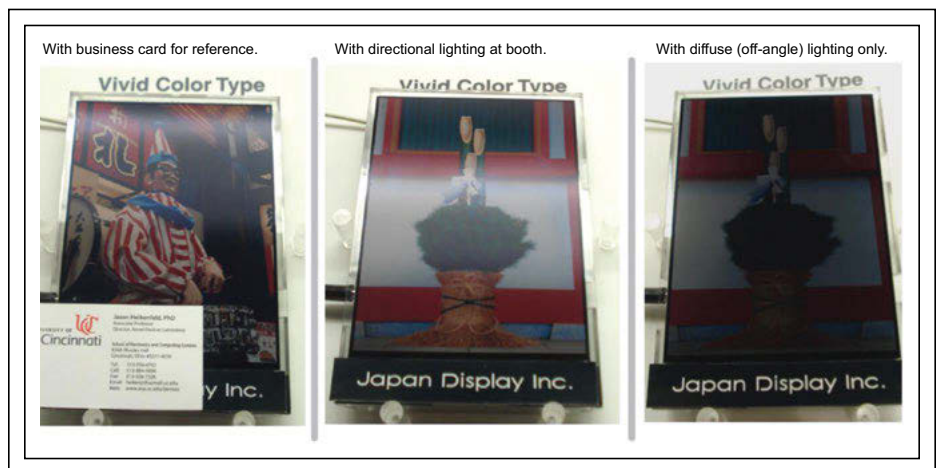


**Fig. 2:** Wouldn't it be great if e-Paper displays looked like this? This “static” non-switchable demonstrator from Qualcomm shows the excellent potential performance of a multi-position mirror; next to a white business card for brightness comparison.

when through some of my own company’s (Gamma Dynamics) developments I saw that, if properly implemented, gain reflectors can look diffuse over a wide viewing cone and in diffuse or off-axis lighting. This is the case, however, only if the reflector is properly engineered and has adequate amplitude. Gain reflectors, when they work best, leverage the fact that for a personal device such as an eReader, you can orient the panel toward yourself. This allows the reflector to then do at least one of two things: (1) reduce light loss

due to total-internal reflection (TIR) at the front glass and (2) amplify the light falling within the typical viewing cone of the user.

In the case of the color reflective LCD from JDI, the designers chose to use a highly directional (and conventional) gain reflector that does not make efficient use of off-axis (diffuse) illumination. This was evident if you blocked the directional light source above the demo and permitted only diffusion illumination. So this embodiment would require a bright ambient light source located just behind



**Fig. 3:** At left, the JDI color reflective LCD appears next to a business card for color reference. The middle image shows the LCD with directional lighting at the booth, and the image at right appears with the author’s portfolio blocking the light so the panel receives off-angle light only.

your head or shoulders to make a compelling eReader or tablet display. However, such displays could be valuable in a fixed orientation and lighting environment, which, for example, signage or electronic shelf labels can provide. Also to its credit, in its proceedings paper, JDI does show diagrams and openly communicates the lighting and measurement orientations used in its characterization of performance.

The e-Paper symposium talks were all on Tuesday this year, with a few other related papers and posters scattered throughout the remainder of the week. In the first talk of the day, Seiko-Epson reported on a binary (1-bit, only black/white) eReader based on E Ink that allowed fast scrolling, page turning, and pen input. I tried the pen input at the author-interview session and it was nearly flawless with seemingly immediate response. The talk showed how high resolution (300 ppi) can help spatially dither gray-scale images with fast 1-bit E-Ink switching. Most importantly, the talk provided human-perception tests that show that simple black/white operation might be better for dedicated reading and office documents – applications for which the faster page turning, scrolling, and pen-input might bring real value to the user. It has been known for some time that E Ink can provide fast switching if you are willing to give up some or all gray scale, and, for video demos, sacrifice display contrast.

During the second e-Paper session, my Ph.D. student Matthew Hagedon delivered an invited talk on “Progress in Electrofluidic Imaging Film.” The data presented supports an argument that this is the only known technology with a roadmap that can provide high resolution, video speed, and SNAP (newsprint) quality color. Unfortunately, as I am intimately aware, the technology development is early stage, only about 18 months old, and active-matrix-driven modules are just now in development. One promising demonstration for the electrofluidic imaging film, though, was basic proof of concept for passive-matrix addressing. Passive-matrix addressing is highly desirable for applications such as signage and electronic shelf labels, where low cost is critical. Passive-matrix addressing is something that E Ink currently cannot provide.

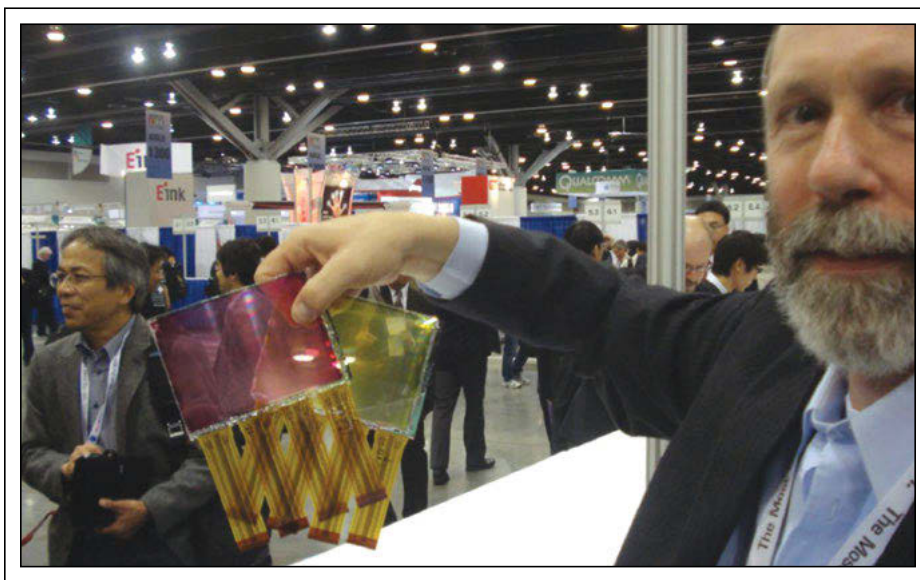
In the second e-Paper session, IRX Innovations (Henzen *et al.*) presented some much more sophisticated active-matrix-driven electro-osmotic display technology (Fig. 4). This approach is unique in terms of particle movement, but not enough information was presented to provide a deep understanding of the underlying physics. The early prototype results were modest (3:1 contrast, slow switching of several seconds) but the team from IRX maintains that the upside potential includes a maximum white state near 70% in

stacked CMY (cyan, magenta, yellow) operation and near-video speeds. The electro-osmotic approach is novel in many ways and will be worth following closely as IRX continues to develop the technology.

Another talk of note was given by Norihisa Kobayashi from Chiba University. Prof. Kobayashi was part of the early electrochromic material development that led to Ricoh’s recent demonstration of a strikingly beautiful color active-matrix electrochromic display. This year, he presented a single electrochromic cell that could switch between a clear state, a black state, and also a mirror reflector state. Although this is early-stage work, and the maximum number of switching cycles is unknown, I can imagine many interesting applications ranging from switchable mirrors, to privacy windows, to light- and thermal-management technology.

The last note of interest came not at Display Week 2013, but right before the conference, with the revelation that Amazon had just purchased Liquavista from Samsung. The history of this company began with Philips, from which it was spun off in 2006. Then it was purchased by Samsung, then Amazon. Time will tell what this all means. It has been clear for some time, especially with its investment in Lab 126, that Amazon takes the hardware side of displays quite seriously. The speculation is, of course, that this could lead to a next-generation color-video reflective eReader or tablet product from Amazon.

With Display Week 2013 now behind us, progress clearly continues on all fronts. Without doubt, e-Paper is a real and growing segment of the display industry. What is less clear is how much longer it will take to satisfy consumer and corporate demands for the next generation of e-Paper technology. OLEDs and LCDs will continue to battle it out in coming years, but neither will supplant many of the e-Paper applications. With the huge shift to LCD tablets already enacted, e-Paper is left to control much of its future destiny and that will depend on its ability to provide bright whites, more saturated color, and access to broader media content such as seamless web browsing and at least crude animation/video. Looking forward to 2014! ■



**Fig. 4:** Alex Henzen of IRX Innovations displays active-matrix magenta and yellow modules built on electro-osmotic technology.

# Raising Capital for Technology Ventures

*Investors come in different packages. It's important to know the various types, along with their pluses and minuses. This article is the second of four in a series by a venture capital expert who has both launched and funded new companies.*

by Helge Seetzen

**I**N the first article of this series, we talked about the fundamental building blocks of a new technology venture: inventions and teams. It is a fact that this talent generally wants to be paid. Almost all technology ventures need significant capital to grow their operations.<sup>1</sup> Unless the founders can contribute significant personal cash, something I would not recommend even if possible, that money needs to come from external investors.

<sup>1</sup>Exceptions are usually limited to service businesses that can generate immediate revenue. This is rare for genuine technology ventures where the product, the technology, still requires significant development before it can be commercialized. In this context, it is also important to remember that venture implies growth. Businesses that essentially outsource the work of the principals as consulting or contract work might be able to self-finance from the start, but are best described as self-employment and not ventures. Venture capital investors will certainly not be interested in such opportunities, even if they provide very nice lifestyle returns for the principals.

*Helge Seetzen is CEO of TandemLaunch Technologies, a Quebec-based company that commercializes early-stage technologies from universities for its partners at major consumer electronic brands. He also co-founded Sunnybrook Technologies and later BrightSide Technologies to commercialize display technologies developed at the University of British Columbia. He has published over 20 articles and holds 30 patents with an additional 30 pending U.S. applications. He has a Ph.D. in interdisciplinary imaging technology (physics and computer science) from the University of British Columbia.*

In this article, we will talk about the different sources of investment, their requirements, and typical valuations and terms.

## Capital Needs

The first step is to identify the capital needs of your venture. Few technology businesses achieve profitability after a single round of financing, so it is worth planning multiple investment rounds. The time horizon between rounds thus becomes the determinant of the capital needs of the business. Each round will ideally be raised at a higher valuation than the last one – failure to do so will make your earlier investors very unhappy, with often painful consequences for your ownership of the business. Thus, the goal is to raise enough money to achieve a material increase in valuation and then have sufficient time left to raise the new round.

For convenience, investment rounds are often given names such as Seed Round, Series A, Series B, Series C, etc. The labels have no firm meaning and are sequential (e.g., Series B is the second round raised after a Series A). That said, common understanding in the industry defines typical rounds as follows:

**Seed Round (usually below \$500K):** The initial team is in place with a business plan, but things are usually still a bit rough around the edges. The capital will likely be used to complete the core of the business and build the first product prototypes. Revenue is generally not expected.

**Series A (\$1 million - \$3 million):** Usually this is the first major and/or institutional round. The business is fully operational with

possible initial revenue. Certainly, some form of market validation should be in place, as well as all the core team roles filled with high-quality people.

**Series B (\$3 million +):** At this stage, the engine of the business is humming and the new capital just adds more fuel. The focus will be on scaling and growth management. Of course, there are plenty of companies that raise a Series B, i.e., their second institutional round, while still looking like the Series A company described above, but that's generally a sign of something having gone wrong or both rounds being smaller than usual<sup>2</sup> (see Fig. 1).

Most early-stage companies will consider either a Seed Round or maybe an early Series A if they are able to bootstrap through the Seed stage without raising significant external capital (possibly with the help of the three "Fs" – Friends, Family, and Fools).

When determining capital requirements, consider how much money the business needs to go from one stage to the next. So, if you are raising a Seed Round, consider how long it will take to achieve product revenue and full team build-out (the general criteria for Series

<sup>2</sup>BrightSide Technologies, Inc., my second venture, was an example of the latter. For business reasons, we raised the first five rounds of angel financing below \$1 million each. At that point, we were technically raising a Series F, but in practical terms we had raised less than \$4 million total and were thus functionally similar to a Series A company. Valuation rose with each of our rounds, and the final outcome was a success for all investors, so the above guidelines are not definitive by any means.

## venture capital series

A). Then, add at least 30% as a buffer since nothing ever works as planned in a startup. Finally, add 6 months of additional operating time to account for the fact that fundraising itself takes time. The total amount needed over this period defines the capital requirement for your new round. With that number in hand, you can consider the different funding sources available to early stage technology ventures.

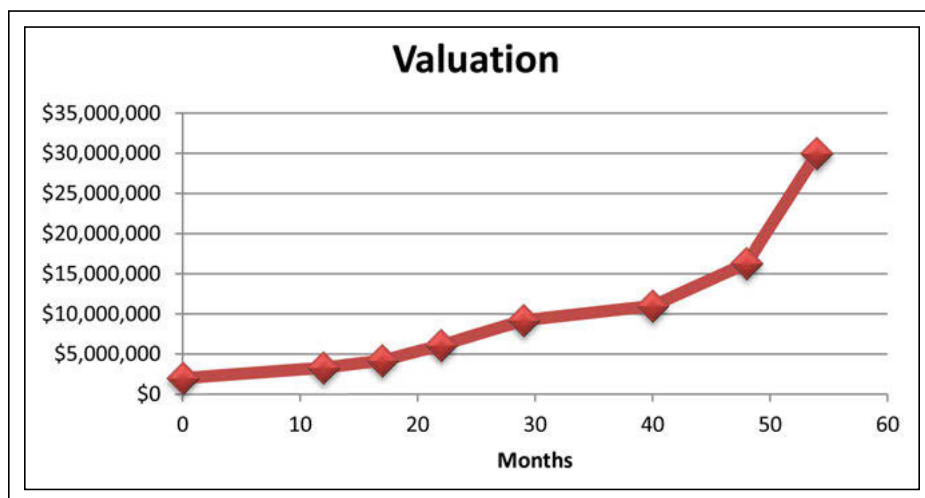
### Sources of Funding

We currently live in a fortunate time for entrepreneurs – investment capital is readily available. However, times do change, apparently fairly cyclically, so enjoy these years while they last.<sup>3</sup> But money comes from many different sources. In practice, however, the wide variety of investor types can be grouped into three principal sources of funding:

**Accelerators:** These entities tend to provide much of their value in kind, through mentorship, support, and services, but often also invest relatively small amounts of money into the business (usually tens of thousands of dollars but rarely more). With a few exceptions, accelerators are designed for ventures that require assistance to get off the ground with the money being usually a secondary benefit – so evaluate them based on the value of the offered support in relation to your venture's weaknesses.

**Angel Investors:** Angel investors are high net-worth individuals willing to invest in early-stage companies. Many of them are former entrepreneurs who are keen on experiencing the start-up rollercoaster but, ideally, without putting their nose all the way to the grindstone again. They tend to invest relatively modest amounts, with \$25K–250K being a common range per investor. Fortunately, angels tend to work in groups, often in formally organized networks, so it is usually possible to raise combined rounds of angel capital up to about \$1.5 million.

**Venture Capital:** Professional investors, called Venture Capitalists (VCs), manage significant funds on behalf of their limited partner (e.g., pension funds, government



*Fig. 1: The valuation history of BrightSide Technologies (one of the author's ventures) is shown over a period of 5 years.*

funding, large corporations, etc.). Such funds come in different sizes and shapes, but commonly invest upward of \$500K during initial rounds. Unlike angels, venture capitalists also have the ability to follow their initial investment with major secondary and tertiary investment rounds, reaching often into the tens of millions of dollars.

These are the three most common types of investors for early-stage technology ventures.<sup>4</sup> Of course, the world is full of variance, including the more recently emerged concept of super angels – effectively venture capitalists who manage smaller funds and behave more like angel investors. Nevertheless, it is easiest to think of investors in these three broad categories: those that assist, those that invest their own money, and those that invest other people's money. These distinctions make a major difference in terms of the amount of available capital and the goals of the investors.

Angel investors are generally more comfortable with modest returns but usually also want to see some cash coming back to them in a shorter time frame than VCs. A common rule of thumb is that a 2–3× return in 3–4 years will make most angels happy. Venture capital funds can deploy much more capital

over longer fund cycles of 10–12 years, but also have much more aggressive 5–10× return goals due to their non-linear compensation structure (more on this next month). Individual investment goals of course vary greatly, so I would strongly recommend an open discussion before you seal your new relationship. In general, it is a good idea to build a positive relationship with future investors long before you need their money – date first, then marry.

Often the match-up between capital needs and sources of funding is fairly obvious at this point. Service business or other opportunities with limited capital requirements are often better served by angel investors. On the other hand, if your business plan requires \$10 million+ to build a viable product or advanced demo, then venture capital is likely the only way to go.

Maybe you can find an accelerator with good access to deep-pocket VC funds or some well-connected angels, but your road will eventually lead you through the doors of a VC. Once on this road, make sure to optimize your business strategy around the goals and timelines of venture capital. Display hardware projects are commonly on this trajectory, with all the positive and negative implications.

Of course, reality is rarely this conveniently defined, so all kinds of mixed deals are possible. Some ventures are able to combine angels and seed VC investors; some use a strong group of angel investors to drum up support for a high-valuation VC round, and so forth. But such schemes are usually best left

<sup>3</sup>Those who feel that fundraising today is too difficult should talk to veterans of earlier times. For example, Sunnybrook Technologies, Inc., my first venture, started fundraising in 2001 – hardly a time when IT technology start-ups were popular, given the recent demise of nearly the entire sector in the dot-com bubble.

<sup>4</sup>Non-investment sources of funding of course also exist: grants, loans, subsidies, etc. Most of those are often inaccessible for early-stage ventures, though I would encourage all entrepreneurs to at least canvass the available economic development grants in their jurisdiction – free money is always a blessing for any new venture.

## venture capital series

to seasoned entrepreneurs – managing different interests is a difficult game with generous amounts of pain waiting on the sidelines if you get off track.

### Valuation and Terms

Once you have defined your investment sources and have built a good relationship with them, there comes the magic moment when you receive a term sheet. As the name implies, this is a short document listing the principal terms of the investment deal. That document will have two important numbers: the size of the investment and the valuation of your company. Let's ignore the more complex terms for now and focus on the most basic scenario to explain the terminology: if you are raising \$1 million and your company is deemed to be worth \$3 million, then your "pre-money valuation" is said to be \$3 million and your "post-money valuation" will be \$4 million. Post-money, you will of course only own 75% of your company (\$3 million out of \$4 million) so you will have experienced a 25% "dilution."

Post-money valuation is just pre-money plus cash raised, but how is the pre-money valuation determined? At this point the technical reader will likely expect a complex formula but reality is much less fancy (at least until you reach the earnings-based valuation models of late-stage ventures). Counter-intuitively, your early-stage valuation is less about the value elements of your business and more about the type of investor you can attract. Most investors will take 20–40% of your company for each round of financing regardless of the amount invested. Thus, a VC Series A round of \$2 million tends to have pre-money valuations of \$3 million – \$5 million, while an angel seed round of \$500K will have pre-money valuations of about \$1 million – \$2 million. There are, of course, plenty of exceptions, but as a rule of thumb this tends to hold fairly well for early stage rounds.

So, why use an approach that is so unscien-

tific? It's about time and mind-share. The stake for investors needs to be small enough to leave incentive for the management team and large enough to make their mind-share investment worthwhile. For example, most VC funds are expected to have one of their partners sit on the Board of Directors of each of their investments. Since a partner can only reasonably sit on about five boards, they need to make large enough investments to make each deal worth their time. Thus, what changes during early stage rounds is the amount of money you get for a given funding round of 20–40% dilution – hot companies getting more while weaker ones get less.

The goal then is to rapidly advance your venture to the point where it can raise money from investors with deeper pockets, watching your effectively pre-money valuation rise as a side effect.<sup>5</sup> Do not spend on infrastructure, support hires, or anything else that does not contribute to the advance to the next investor class. Of course, the value elements of your venture – team, product, revenue – are the means by which you advance to a new investor class. So, ultimately it is all still about building team and traction.

So far, in this series, we have covered building a great founding team and, with this article, the basics of capitalizing that team. In the next piece, we will dig a bit deeper into the structure of a venture capital (or angel) financing scenario, including common deal terms, pitfalls, and some tips for valuation optimization. ■

<sup>5</sup>One of the most common business failures comes from a lack of understanding of advancement criteria. A growing company might be capped to an ~\$4 million valuation range simply because its local angel group cannot find more than \$1 million in capital and cannot close the deal if its members get less than 20% of the company per round. If the CEO cannot advance to the next investor group, the company is likely doomed no matter its business success.

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# OLEDs for Professional Lighting Applications

*Organic light-emitting diodes (OLEDs) already represent a strong market segment in display applications such as mobile devices. In the lighting market, they are still in the beginning phase. To achieve a relevant market segment, OLED technology has to compete in terms of performance, cost, and other unique features against established light-source technologies.*

by Jörg Amelung, Christian Kirchhof, Tino Göhler, and Michael Erritt

**O**LED-BASED DISPLAYS are well-established for use in smartphones and tablets. OLED TVs are still in the early stages but will enter higher volume markets soon. In the lighting field, however, OLEDs are still exotic.

To reach a larger lighting market segment, OLEDs have to compete against traditional lighting solutions and, additionally, fulfill lighting requirements for dedicated applications. To achieve this, synergies between displays and lighting architectures must be accomplished.

In 2011, the world residential lighting market was around €21 billion, which represents approximately 40% of the general lighting market.<sup>1</sup> This number covers new fixture installations, including the full value chain, lighting-system control components, and light-source replacements. The professional market segment is €34 billion in total, which is the other 60% of the market. Additionally, the value per application in the professional market is higher than in the residential market; these factors make the professional market rather attractive for OLED applications (Fig. 1).

## Application Requirements

To date, OLED lighting solutions exist mainly

in art installations and decorative lighting. These niche applications are tolerant of high costs and low performance. Actual OLED applications in high-end decorative luminaires or art installations are possible because the requirements for luminous flux or lighting performance are low. To enter a wider range of professional lighting applications, OLEDs must improve in technical parameters and in cost. Additionally, innovative integration concepts for large lighting areas are necessary.

Professional lighting describes the market segment for B2B (business-to-business) solutions, covering office, shop, hospitality, industrial, architectural, and outdoor lighting

solutions. These application fields have many individual application requirements, but, in general, the applications can be summarized as shown in Table 1.

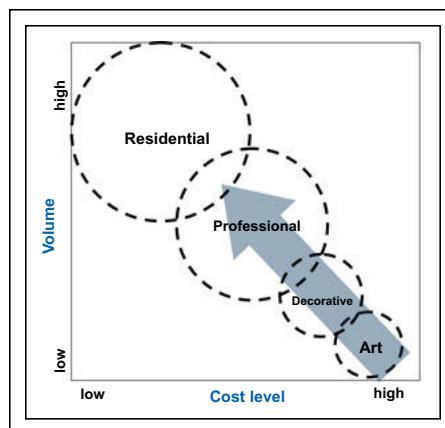
OLEDs could in a near-to-middle time frame cover only a part of these applications, based on their parameter field, which can be summarized as follows:

- Medium-to-low luminous flux due to limited brightness level.
- Medium areas due to actual fabrication limitation.
- High lighting quality based on a good lighting mixture (CRI > 80–90).
- Medium-to-high cost aspect.
- Very good design aspect based on slim format and homogenous lighting area.

Based on these criteria, the application fields of hospitality, shop, and office are the best candidates for OLED applications in the near future.

Office-related solutions are the largest market segment in general lighting; in 2011, they represented €8 billion worldwide.<sup>1</sup> This market segment is very suitable for OLED-related lighting solutions because the applications are indoor, higher-cost related (especially in Europe), and require high-quality lighting generation.

Unfortunately, the largest applications inside the office market are downlights and recessed luminaires. Both applications are not really suitable for OLED integration. Downlights require very high brightness levels and luminous flux; recessed luminaires are mainly



**Fig. 1:** The cost/volume ratio for different lighting applications shows that costs are high and volumes are low in the niche areas of art installations and decorative lighting.

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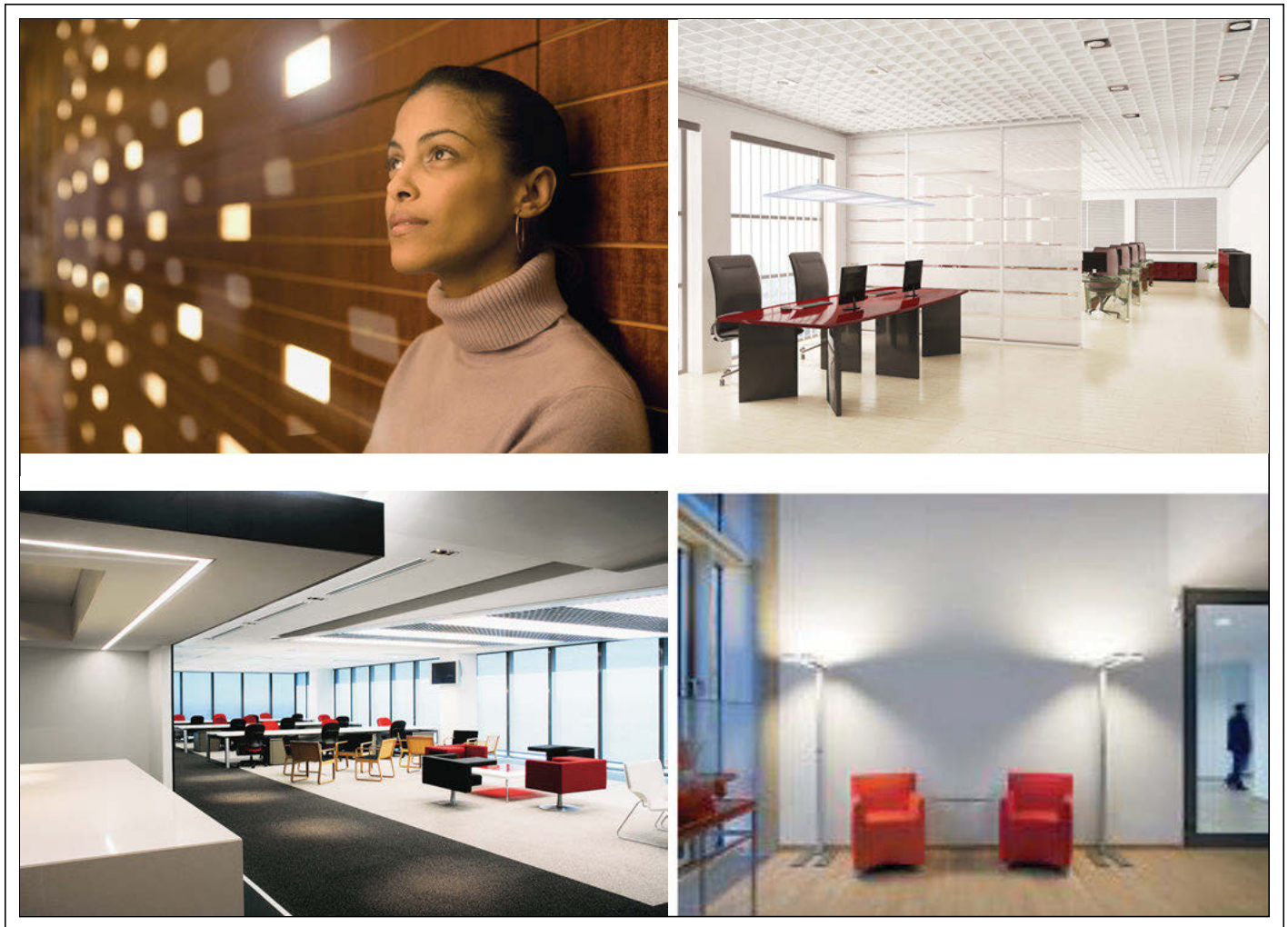
**Table 1:** Requirements are compared for various professional applications.

	Office	Shop	Hospitality	Industrial	Architectural	Outdoor
Main type of light	Area, Slot, Spot, Downlight	Slot, Spot, Downlight	Area, Slot Spot, Downlight	Area, Slot, Downlight	Area, Spot	Spot, Downlight
Luminous flux, Brightness	Medium	High	Medium	High	Low	High
Area	Medium	Medium	Medium	High	High	High
Lighting quality	High	High	High	Low	Medium	Low
Cost segment [\$ /lm]	Medium	Low	Medium	Low	Low	Very low
Design aspect	High	Medium	Medium	Low	Medium	Low

cost driven and do not need a slim form factor because in ceilings additional installations such as air conditioning are required.

Based on the limited luminous flux of OLEDs, potential applications for OLED lighting currently involve those that are in close proximity to the user. The most interesting applications are desk, wall-integrated, pendant, and free-standing luminaires (Fig. 2).

There are two ways of implementing new lighting technology for such applications: by retrofitting elements or by designing new luminaires. Retrofit solutions would require OLED elements that replace in size and luminous flux traditional fluorescent tubes such as T5, T8, or T-CL. Such retrofit solutions with LEDs have already entered the marketplace.



**Fig. 2:** The following office-lighting applications are the most likely to be commercially viable for OLED at this time: wall luminaires (top left), pendant luminaires (top right), light lines or slot lighting (bottom left), and free-standing luminaires (bottom right).

They are ideal because there is no need to redesign the luminaire, which saves cost and time.

For OLEDs, these kinds of retrofit solutions will not work because of the form factors and brightness levels of traditional fluorescent solutions. New flat luminaire designs are the best way to integrate OLEDs into applications. In Table 2, the relationship between volume, price, and type of luminaire is shown. OLED applications will be implemented first into design-oriented luminaires and will follow the route to mass volume by reducing cost and improving performance.

The requirements in price and performance for OLEDs rise dramatically for functional and mass-volume luminaires because there OLEDs will be in direct competition with LED solutions.

Even for this first stage of application, the design-oriented luminaires, OLEDs will have to fulfill some requirements that are commonly restricted by the applications.

These requirements are:

- Luminous flux > 9000 lm/m<sup>2</sup> (> 3000 cd/m<sup>2</sup> if assuming lambertian emission).
- Color-temperature standards; 3000 and 4000K.
- Area sizes: 0.3 × 0.3 m or 0.6 × 0.6 m.
- Simple integration.

None of the OLEDs now in the marketplace fulfil these requirements; in most cases, the luminous emittance is too low or the color temperature is lower than 3000K and/or the sizes are too small.

One additional important target is the cost aspect. Actual OLED solutions are about 100 times more expensive than LED-based ones, so OLED process costs have to be dramatically reduced. OLED display fabrication is well-positioned in the market, so there is the question of which synergies could be used between the display and lighting segment to improve performance and reduce fabrication costs.

With regard to OLED TVs, some of the main parameters are close to those of OLED lighting, so both industries use similar approaches. Normally, the display architecture for the two is completely different based on the required RGB pixel arrangement. Nevertheless, there is an alternative color arrangement in some displays that use white with color filters, which offers certain advantages, especially for large-area displays.<sup>2</sup> In principle, this arrangement consists of a large OLED lighting area integrated into an active-

Table 2: The relationship between application and price/volume is proportional.

↑ Price	Design oriented luminaires
↓ Volume	Functional luminaires
	Mass volume luminaires

matrix backplane. The fabrication synergies are maximal in that arrangement, so similar machine concepts could be used. The OLED stacks in such color-by-white arrangements are also similar; nevertheless, the white color point and brightness level are different. Thus, OLED displays and lighting fabrication technologies could enjoy synergies in the case of fabrication technologies and OLED stack architecture. This could make the market entrance for OLED lighting easier, especially in the professional sector.



Fig. 3: This OLED module system measures 99 × 99 mm per panel.

Highly Efficient OLED Modules

OLED modules represent an important step toward achieving large-area lighting solutions with accepted and required lumen packages. OLED glass panels are not very easy to integrate. The thin-film electrodes on glass have to be contacted in a good manner to avoid voltage drops to the module. Additionally, the glass itself cannot be handled easily, and an additional optical out-coupling system has to

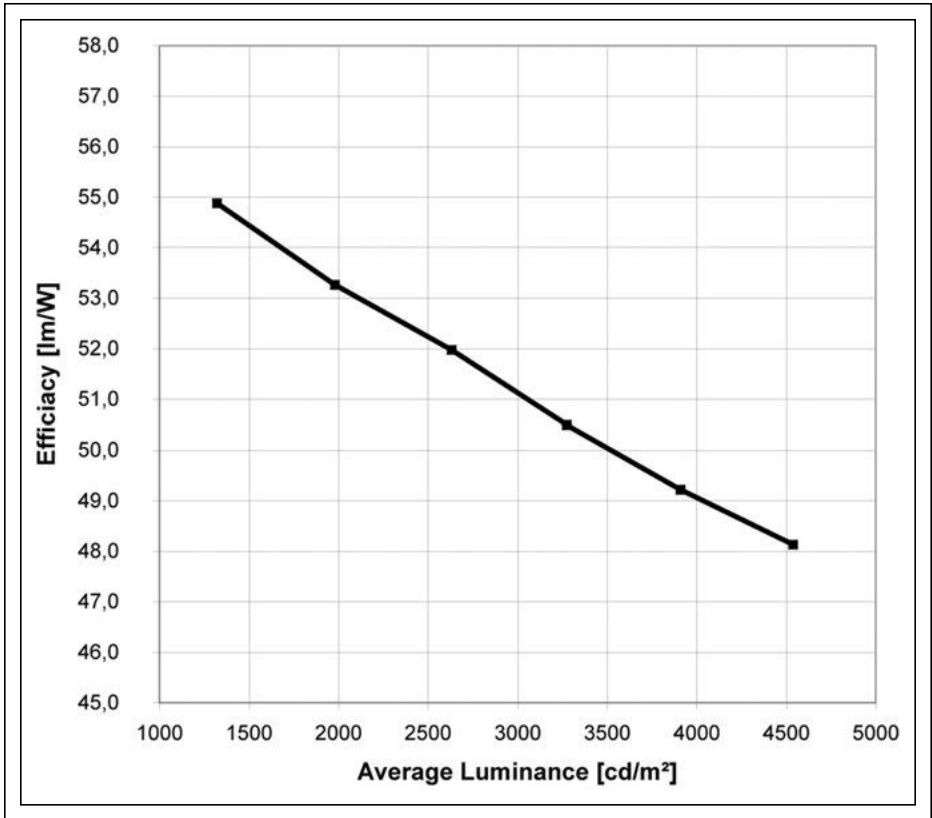


Fig. 4: Module efficacy is plotted vs. average luminance of the module.

be integrated. Based on the limited sizes of OLEDs (up to  $15 \times 15 \text{ cm}^2$ ), large areas of OLED lighting have to be subdivided in several OLED lighting plates.

OLED lighting modules represent an import intermediate level for integration. Such modules could be easily mounted to cover large lighting areas *via* a mechanical support system. Important aspects of these OLED modules could be subdivided as follows:

- Small contact areas to maximize the OLED lighting area.
- High-luminous-intensity homogeneity.
- Minimal thickness.
- Robust contact system.

To achieve a robust contact system, the OLED electrode contacts are bound by a flexible contact spring to a PCB connection plate, which results in a total contact resistance of  $< 1 \Omega$  for a  $99 \times 99\text{-mm}$  OLED module.

A potential OLED module system is shown in Fig. 3. The module combines a large active area ( $> 80\%$  lighting area) with a slim form factor ( $< 3 \text{ mm}$  thickness) and a robust contact system for use in large-area applications.

Based on very efficient OLED panels (fabricated by LG Chem), the OLED module system allows very efficient OLED lighting. The modules achieve a luminous efficacy of over  $50 \text{ lm/W}$  at  $3000 \text{ cd/m}^2$  (averaged luminance at  $230 \text{ mA}$ ) and a total luminous flux of over  $100 \text{ lm}$  for a  $350\text{-mA}$  current, which results in a luminous emittance of over  $12,000 \text{ lm/m}^2$  (Fig. 4).

### Mirror OLED Module Solutions

Besides performance, it is important to provide new features or form factors to users to earn new application scenarios. One interesting implementation for OLED modules inside professional applications is the off-state mirror surface. There are two solutions to achieve an off-state mirror. In the first, the out-coupling foil on top of the OLED is not applied; in the other, an additional mirror is used as secondary optics on top of the light-emitting surface.

An optical system with an additional mirror plate achieves a highly efficient mirror-like OLED in the off-state. In the on-state, the optimized mirror allows a stable color coordinate at different angles, with only a low shift of color compared to an OLED with no out-coupling or secondary optic system. The appearance is uniform even at the edges of the OLED module.

This solution also allows for a more efficient OLED module; the OLED efficacy is still  $34 \text{ lm/W}$  at a luminous flux of  $59 \text{ lm}$  ( $99 \text{ mm} \times 99 \text{ mm}$ ) based on an OLED panel with initially  $40 \text{ lm/W}$  and a milky diffuse surface (Fig. 5).

An innovative luminaire solution based on such modules has been demonstrated by the companies Selux and Art+Com. The luminaire Manta Rhei is a pendant type with individual dimming of 140 mirror-type OLED modules and kinetic movement of the OLED panels that is enabled by the bending of the mounting metal sheet. Based on individual dimming, the illuminance level remains constant during movement (Fig. 6).

### The Future of OLED Lighting

To achieve a larger market segment, OLED's best near-time possibility is in fulfilling product requirements for professional lighting solutions. High brightness and efficient OLED solutions could be achieved by optimized module solutions. Novel surface finishings such as a high-quality off-state mirror surface allow for new luminaire appearances, which may accelerate the OLED market penetration, although initially toward the high end. Last, synergies between OLED solutions in displays and lighting could generate advantages in terms of fabrication costs and OLED stacks. Such advantages could boost both industries.

### Acknowledgment

Some of these OLED results were achieved inside the BMBF-funded OLED project SO-LIGHT (FKZ 13N10536).

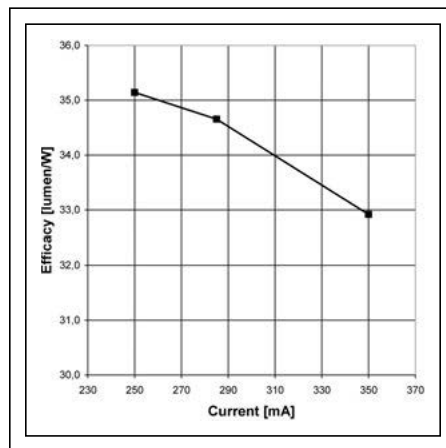


Fig. 5: Module efficacy is shown vs. driving current of the mirror-type OLED module.



Fig. 6: The Manta Rhei luminaire by Selux and ART+COM consists of 140 mirror-type modules. (Source: Selux.)

### References

- <sup>1</sup>Lighting the way: Perspectives on the global lighting market, 2nd ed. (McKinsey & Company, Inc., August 2012).
- <sup>2</sup>C-W. Han *et al.*, "55-inch FHD OLED TV Employing New Tandem WOLEDs," *SID Symposium Digest of Tech Papers* **43**, Issue 1, 279–281 (June 2012). ■

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# High-Performance White-OLED Devices for Next-Generation Solid-State Lighting

*The efficacy of white OLEDs has reached 100 lm/W with RGB-phosphorescent emitters and light-extraction technologies. OLEDs have therefore already exceeded the efficacy of typical lighting equipment with fluorescent lamps.*

by Kazuyuki Yamae, Hiroya Tsuji, Varutt Kittichungchit, Nobuhiro Ide, and Takuya Komoda

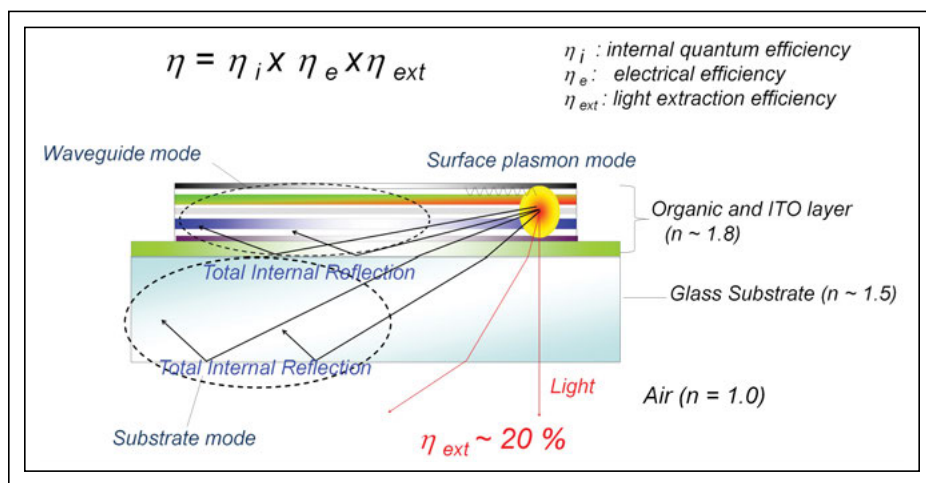
**L**IGHTING represents almost 20% of global electricity consumption. A savings potential of more than 1000 TWh (terawatt hours) per year by 2030 is possible if conventional inefficient lamps are replaced by highly efficient solid-state lighting (SSL).<sup>1,2</sup> The total electricity consumption of the world was approximately 18,000 TWh in 2010, according to Japan's Agency of Natural Resources and Energy ([www.enecho.meti.go.jp/english/](http://www.enecho.meti.go.jp/english/)). Light-emitting diodes (LEDs) are a well-known source of highly efficient solid-state lighting (SSL), and LED equipment has gradually been replacing conventional lighting such as that based on incandescent bulbs. Organic light-emitting diodes (OLEDs) are another candidate for next-generation SSL because they are compact, lightweight, highly responsive, and highly flexible in terms of design. Commercialized OLEDs have already exceeded the efficiency of incandescent bulbs. However, they have not yet surpassed LEDs.

The efficiency of OLEDs is mainly determined by three factors: internal quantum efficiency (IQE), electrical efficiency (EE), and light-extraction efficiency (LEE). First,

optimization of the carrier balance with energy levels and the mobility of stacked layers for emission, transportation, injection, or blockage is required to maximize IQE, especially for effective radiative hole-electron recombination. According to spin statistics, the hole-electron recombination yields singlet and triplet excitons by a ratio of 1:3, respectively. It is well known that phosphorescent OLEDs enable radiation from triplets and that its IQE has already reached nearly 100%.<sup>3,4</sup>

EE is inversely proportional to the driving voltage, which is controlled by charge injection and carrier transfer. High-mobility materials or electrical doping techniques have enabled an extremely low driving voltage of OLED devices that has come close to theoretical limits.<sup>5</sup> However, restrictions are required to achieve both low driving voltage and a long lifetime because of the fundamental issue of durability in organic materials. These architectures can also suffer from resistive losses

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**Fig. 1:** A standard light-extraction model for OLED shows total internal reflection (TIR) at two interfaces.

induced by the relatively large currents required by low driving voltages.

The largest potential of the aforementioned three factors is in LEE. Only about 20% of the total generated light can escape to the air from conventional OLED devices, due to total internal reflection (TIR) at the interfaces as shown in Fig. 1 and explained by Snell's law as one of the limiting factors in LEE. Since organic layers and glass substrates have higher refractive indices than air, light that reaches the outer boundaries of the device at wide incident angles encounters total internal reflection (TIR) and is trapped inside the device instead of being able to escape. The reflected light is then absorbed back into the organic layers or electrodes.

Various optical structures with micro-sized texture or nano-sized gratings fabricated on the surface of the substrate are simple methods that can be used to improve LEE.<sup>6</sup> How-

ever, these technologies are not able to extract the remaining light confined in the transparent electrode and organic layers – this trapped light is called the waveguide mode.

Some internal light out-coupling structures such as scattering layers or diffraction gratings fabricated in the organic layers have been useful in reducing the waveguide mode and have achieved better LEE.<sup>7-9</sup> However, those scattering layers or gratings usually have rough surfaces, which reduce reliability through current leakage or short circuits. A special high refractive index ( $n \sim 1.8$ ) substrate with micro-patterned texture has achieved excellent LEE because of the improved transmission from thin layers to the substrate.<sup>10</sup> However, reliable high-refractive-index glass ( $n \sim 1.8$ ) at low cost is not commercially available for large-area substrates applicable to OLEDs.

In this article, we focus on the progress of light-extraction technology using a Built-up

Light Extraction Substrate (BLES)<sup>11,12</sup> – a technology developed by Panasonic engineering. Using this BLES, an efficacy of over 100 lm/W was achieved in combination with developed white-phosphorescent OLED devices. This measure of 100 lm/W is widely recognized as the first destination for next-generation lighting because the efficacy exceeds current typical lighting applications using fluorescent lamps.

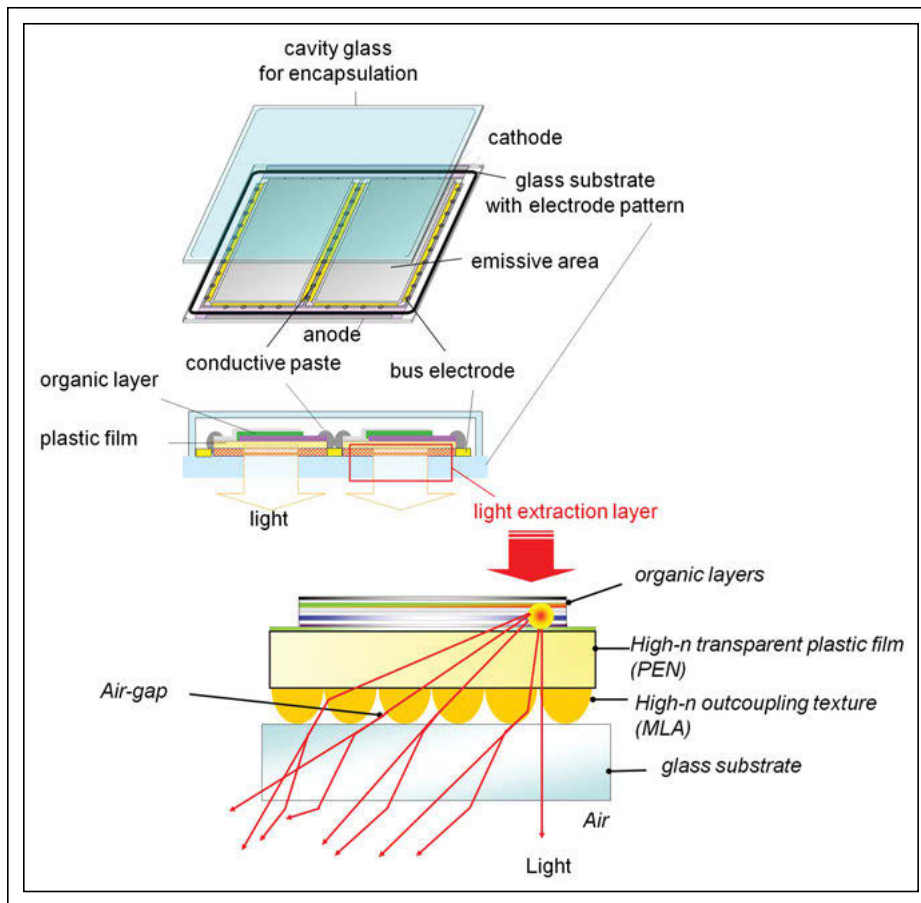
### Built-Up Light-extraction Substrate (BLES)

A cross section of a BLES structure with a bottom-emitting OLED is shown in Fig. 2. BLES comprises a transparent electrode, a high-refractive-index ( $n = 1.77$  at 550 nm) micro-lens-array (MLA) structure made from polyethylene naphthalate (PEN) film, and a glass substrate for encapsulation. An air gap exists between the MLA and the glass substrate.

The BLES was fabricated as follows: A transparent electrode was previously deposited on one surface of PEN film. MLA was fabricated onto the opposite side of the film. This film was then laminated to a glass substrate with the MLA side facing the glass. The micro-patterned texture of the MLA was attached to the glass substrate, and the air gap naturally occurred between the textures and the glass. This assembly was then vacuum-dried at 80°C for at least 15 minutes in order to remove the residual water and gases before use. After the deposition of the OLED device onto the film on the top side, electrodes on the film were connected to the bus electrodes on the glass substrate with a conductive paste. The film and deposited organic device were completely encapsulated by a cavity glass.

Due to the high-refractive-index structure, light emitted from the organic layers propagates into the PEN and MLA layers without TIR. Owing to the existence of the air gap between the out-coupling texture and glass substrate, extracted light from the MLA was able to transmit into the glass substrate without TIR, and an excellent LEE was expected.

BLES has other merits in addition to the enhancement of light-extraction efficiency. First, the smooth surface of the film is applicable to a large-area OLED device. Second, the rigid protection from water vapor, reactive gases, or other physical damages by the glass substrate enables better durability of the OLED device on the film and micro-textures. Plus, the substrate is appropriate for commercial use



**Fig. 2:** This cross section of an OLED shows the structure of the built-up light-extraction substrate (BLES).

because each component is relatively inexpensive compared to high-refractive-index glass.

### Optical Design for BLES

The propagating light in BLES is divided into transmitted diffraction and reflected diffraction at the interface of the MLA and the air gap. Transmitted diffraction is extracted from the air without TIR at the glass surfaces as described previously. Reflected diffraction is extracted through the multiple reflections in OLED and BLES, or absorbed. Thus, BLES has the potential to realize excellent LEE while suppressing internal absorption since TIR is almost eliminated. In a conventional structure, the waveguide, substrate, and air modes are 50%, 30%, and 20%, respectively.

If we use a high-refractive-index substrate such as PEN, the waveguide mode is transferred to the substrate mode and the substrate and air modes are 80% and 20%, respectively. BLES enables substrate mode to air mode. If we can achieve a no-absorption device, 100% of light is extracted. On the other hand, a conventional structure can achieve only 50%, since the waveguide mode is retained in organic layers and cannot be extracted whether absorption is high or low.

The influence of internal absorption to LEE in BLES was fully investigated to obtain higher LEE. To begin with, the transparency of BLES was examined. The measurement results of reflectance and transmittance of BLES are shown in Fig. 3. To avoid the noise

caused by scattering, the MLA was replaced by a flat layer with an equivalent thickness of its height (about 5  $\mu\text{m}$ ) as shown in Fig. 3. No absorption was observed in BLES since the summation of reflectance and transmittance was almost 100% in the region of a visible wavelength. Spectral ripples by optical interference were not observed as refractive indices of PEN film and high- $n$  material for MLA was similar.

On the premise that no-absorption channel is in the BLES, the diffraction at MLA and internal absorption in the OLED became the primary focus of investigation. In this study, the LEE of the OLED with a high-refractive-index extraction layer was simulated by a calculation model combined with rigorous coupled wave analysis (RCWA) and ray-tracing.<sup>13</sup> The calculated model is shown in Fig. 4. Model A was almost equivalent to BLES, which was composed of a high-refractive-index substrate ( $n = 1.78$ ) and MLA ( $n = 1.78$ ). The glass substrate under the MLA was removed to simplify the calculation because its absorption and influence on LEE did not need to be taken into consideration in this case. Model B was a conventional light-extraction structure composed of typical external out-coupling MLA film ( $n = 1.52$ ) that had the same texture as Model A with a glass substrate ( $n = 1.52$ ).

The simulation algorithm is described as follows. First, the incident light  $I_i(\theta_i, \phi_i)$  can be calculated by using a Fresnel coefficient in the OLED multilayers.  $\theta_i$  and  $\phi_i$  are the incident and azimuthal angles, respectively. The average value of  $p$  and  $s$  polarizations is applied to simplify the calculation. The total radiation for the first incidence is expressed by

$$\eta_h = \frac{1}{2\pi} \sum_m \sum_n \int_0^{2\pi} \int_0^{\pi/2} T_{m,n}(\theta_i, \phi_i) I_i(\theta_i, \phi_i) \sin\theta_i d\theta_i d\phi_i \quad (1)$$

The integral numbers of  $m, n$  are diffraction orders of the  $x$  and  $y$  directions.  $T_{m,n}(\theta_i, \phi_i)$  is the transmittance for  $(m, n)$  calculated by using RCWA. On the other hand, the reflection for each direction at the first incidence can be given by a function of the reflection angles  $(\theta_r, \phi_r)$  as

$$\xi_1(\theta_r, \phi_r) = \frac{1}{2\pi} \sum_m \sum_n R_{m,n}(\theta_r, \phi_r) I_i(\theta_r, \phi_r) V_{m,n}(\theta_r, \phi_r) \times |J_{r,m,n}| / \sin\theta_r \quad (2)$$

$R_{m,n}(\theta_r, \phi_r)$  is the reflectance for  $(m, n)$  calculated by using RCWA.  $V_{m,n}$  is a rewrite of  $\sin\theta_i$  as a function of  $\theta_r, \phi_r$ , and  $|J_{r,m,n}|$  is the

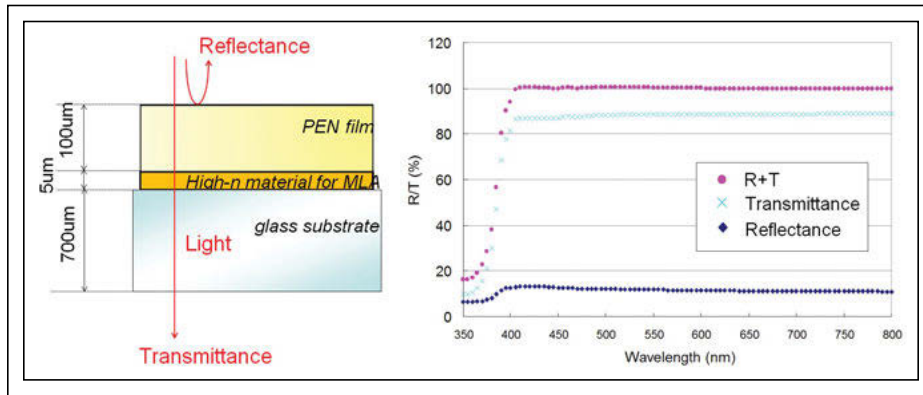


Fig. 3: Reflectance and transmittance measurements for BLES.

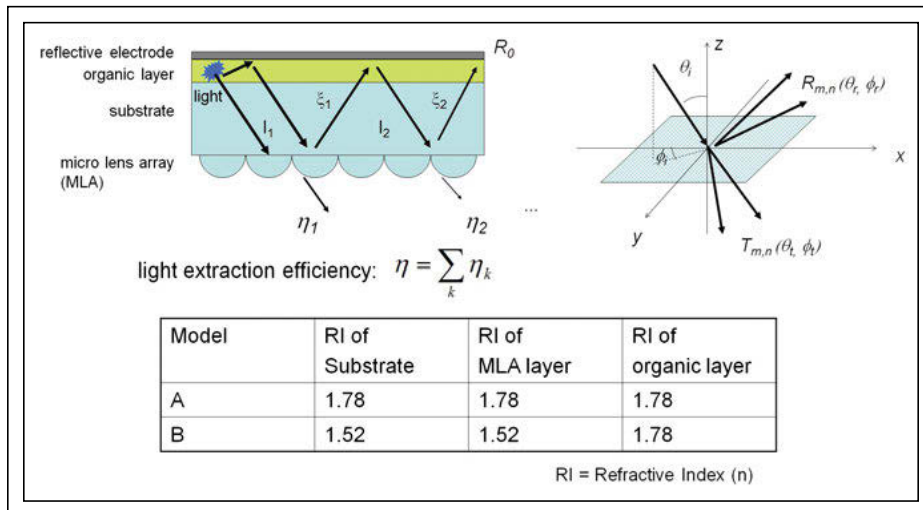


Fig. 4: Two different optical simulation models (A and B) were used for BLES.

Jacobian determinant  $\zeta(\theta_r, \varphi_r)/\zeta(\theta_i, \varphi_i)$ . The second incidence is obtained from the reflectance  $R_o(\theta_r, \varphi_r)$ , which is calculated by using the Fresnel coefficient matrix for the OLED multi-layers and  $\xi_i(\theta_r, \varphi_r)$ , which is calculated by using Eq. (2).  $\theta_r, \varphi_r$  are regarded as the second incident angles because the incident angle of light is not converted at the reflective electrode:

$$I_2(\theta_r, \varphi_r) = R_o(\theta_r, \varphi_r) \xi_i(\theta_r, \varphi_r) \quad (3)$$

Therefore, the radiation for the second incidence  $\eta_2$  is determined by substituting Eq. (3) into Eq. (1). The radiation of each incidence for the multiple reflection of light can be determined in the same manner because its angle is not converted in the OLED and electrodes. Consequently, the extraction efficiency  $\eta$  is described as the sum of all radiation from the micro-structure:

$$\eta = \sum_k \eta_k \quad (4)$$

The calculated result is shown in Fig. 5. It is indicated that the influence of internal absorption was more dominant in Model A with its high-refractive-index substrate than in Model B with its low-refractive-index substrate. The high-refractive-index substrate removed the waveguide mode, which was confined within the organic layers. Thus, all light from the emitting layer could pass through the optical pass with multiple reflections as described. Therefore, the LEE was more strongly influenced by the internal absorption in the OLED with a higher-refractive-index substrate.

Then, the high-absorption layers were carefully specified and replaced by lower-absorption materials. A comparison of light-extraction structures (BLES and conventional outcoupling film) with different absorption devices is shown in Fig. 6. The optical enhancement of the external quantum efficiency (EQE), which is in proportion to LEE, was obviously improved with lower absorption. The trend was more dominant in the BLES than with the conventional structure with external out-coupling film.

### Performance of the Two-Unit Phosphorescent White OLED

The improvement of EE was also studied due to the different driving voltages among devices and because the theoretical energy gap was still large. Typically, the blue-phosphorescent host that enables high quan-

tum efficiency has poor injection and transport properties.<sup>14,15</sup> Thus, we assumed that the blue-phosphorescent emitting layer was the main component of high voltage. In this study, the interfacial injection barrier between the electron-transport layer and the blue-phosphorescent emissive layer was examined. Various electron-transport materials with

different energy levels were investigated, and the driving voltage was reduced without being a crucial issue to the quantum efficiency and lifetime. Meanwhile, the injection of holes into the blue-phosphorescent emissive layer was also investigated. The use of the carrier-balancing design resulted in a successful decrease in driving voltage.

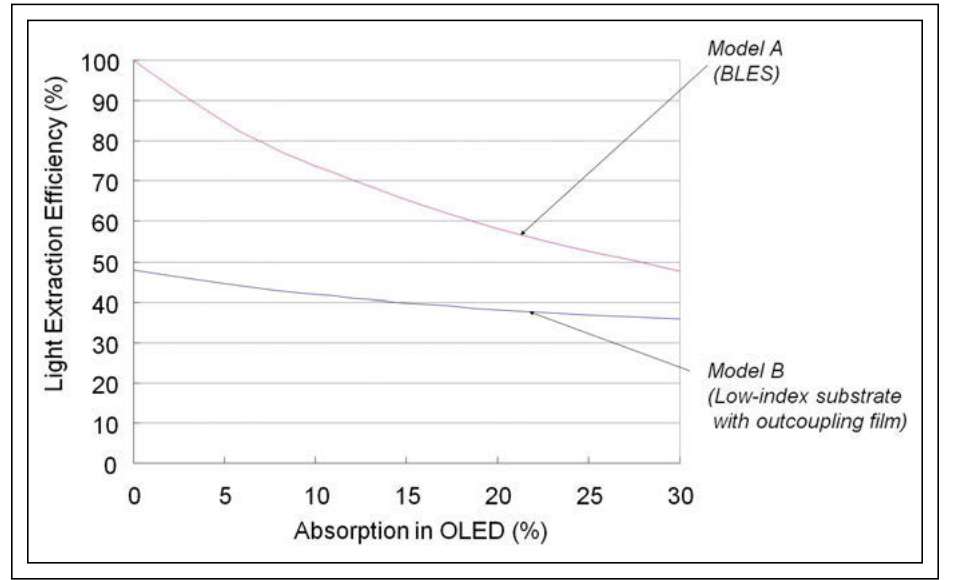


Fig. 5: The optical simulation result of LEE for both Models A and B.

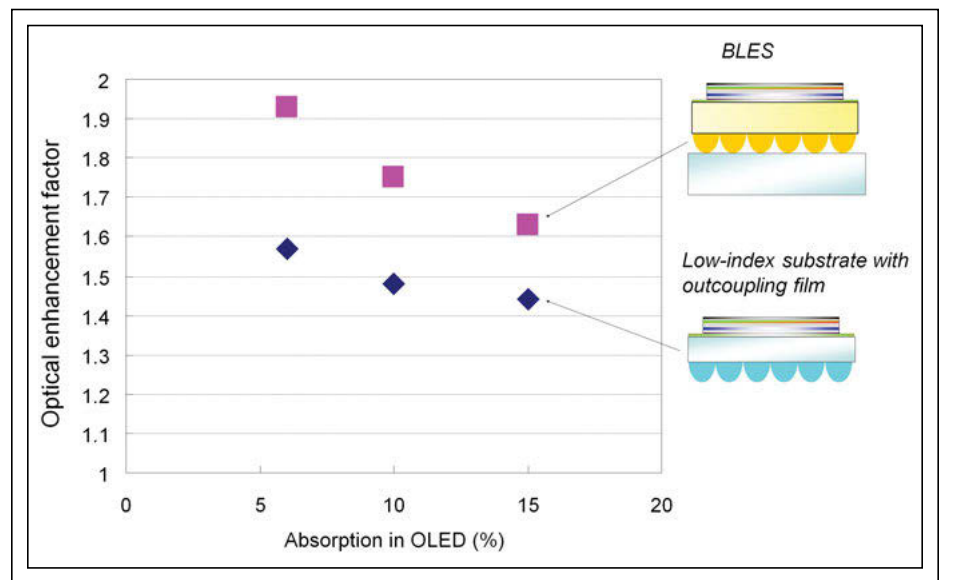


Fig. 6: Optical enhancement with lower absorption was better for BLES than for conventional out-coupling film.

The authors developed two-unit all-phosphorescent white-OLED devices that were optimized for maximized IQE and life-time, minimized driving voltage, and proper color coordinates. The low-absorption materials, specific light-distribution design, and voltage-reduction technologies as previously mentioned were also applied. The performance of fabricated devices with 1-cm<sup>2</sup> pixels is shown in Table 1. The luminance dependence on efficacy at Device A is shown in Fig. 7. Device A showed an extremely high efficacy of 114 lm/W and a quite long half-decay life-time of over 100,000 hours. It also showed 125 lm/W at 100 cd/m<sup>2</sup> and 102 lm/W at 3000 cd/m<sup>2</sup>. Over 100 lm/W was maintained up to a high luminance of about 4000 cd/m<sup>2</sup>. LEE was dramatically improved due to the low-absorption materials and specific distribution pattern with BLES. This indicated that almost half of the light was extracted from the emitting layer because an EQE of about 100% was achieved in the two-unit device. The EE was also improved, and the voltage was reduced by about 0.6 V compared to that of Device C.

Next, a large-area OLED device based on Device A was fabricated. The emission area was 25 cm<sup>2</sup>. The uniform emission without dark spots and visible defects was realized, as shown in Fig. 8. The properties of this panel are shown in Fig. 9. A quite high efficacy of 110 lm/W and a long lifetime of 100,000 hours at 1000 cd/m<sup>2</sup> were also obtained for this OLED panel. The efficacy of the panel decreased by about 3% from the pixel (1 cm<sup>2</sup>)

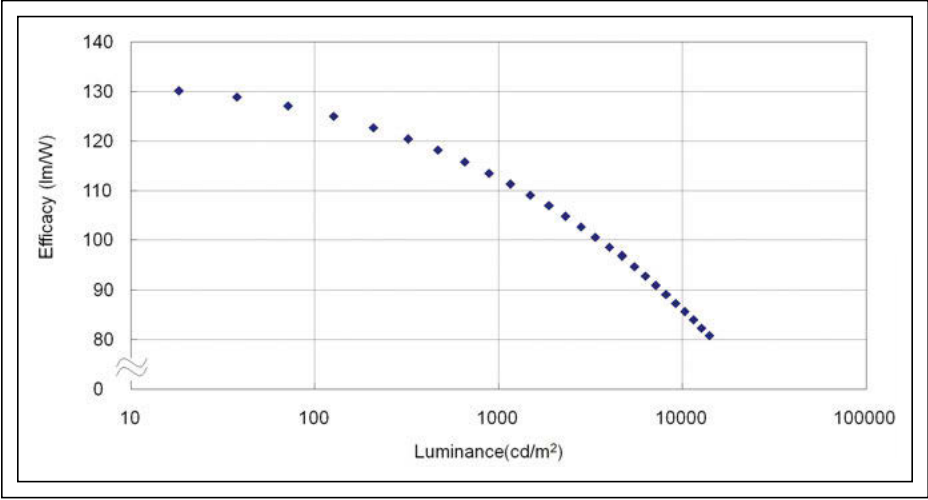


Fig. 7: Luminance depends on efficacy (shown for Device A from Table 1).

Table 1: The performance of fabricated all-phosphorescent OLED devices A, B, and C (1-cm<sup>2</sup> pixel) is compared.

All phosphorescent white OLED	Device A	Device B	Device C
Low absorption materials	optimized	installed	installed
Specific distribution pattern	optimized	installed	—
Lower voltage technologies	optimized	installed	—
Luminance	1,000 cd/m <sup>2</sup>	1,000 cd/m <sup>2</sup>	1,000 cd/m <sup>2</sup>
Efficacy	114 lm/W	101 lm/W	87 lm/W
External quantum efficiency (estimated LEE)	99% (>49%)	84% (>42%)	81% (>41%)
Driving voltage	5.5 V	5.9 V	6.1 V
Estimated lifetime (LT50)	>100,000 h	>30,000 h	>100,000 h
CRI	80	86	82
Color coordinates	(0.48, 0.43)	(0.44, 0.44)	(0.46, 0.42)
Color temperatures	2,550 K	3,200 K	2,800 K

because the voltage of the panel slightly increased with a voltage drop in the circuit or thermal influence. Color coordinates were in the region of the white color.

Future Prospects for OLED Lighting

Figure 10 shows the current-efficiency prospects for OLED lighting. The authors’ immediate target in terms of efficacy is 130 lm/W by the end of this year (2013), a target set by the New Energy and Industrial

Development Organization (NEDO) at [www.nedo.go.jp/english/](http://www.nedo.go.jp/english/). The arrival of an over 100-lm/W OLED lighting device would be a turning point for entering the general lighting market. It is necessary to develop a light-extraction technology for the waveguide mode such as BLES for the realization of an over 100-lm/W OLED lighting panel. Particular effort should be focused on issues such as reliability, productivity, and cost competitiveness in order for OLED lighting to reach the marketplace for signage, decorative illumination, office and industrial use, and indoor and outdoor lighting. Those development activities are also now ongoing in parallel.

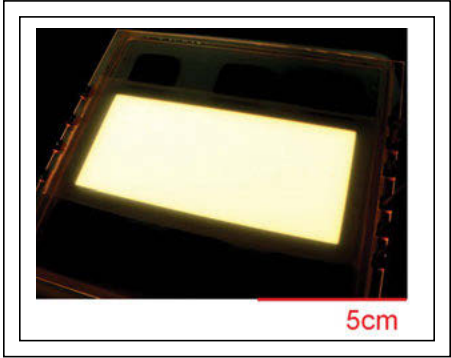


Fig. 8: A large OLED panel (25 cm<sup>2</sup>) was fabricated based on Device A.

## Acknowledgments

This work was supported by NEDO as “Fundamental Technology Development of Next Generation Lighting of High-efficiency and High-Quality” project started in March 2010. We also thank Idemitsu Kosan Co., Ltd., as a member of the project, and also Universal Display Corp. and Nippon Steel & Sumikin Chemical Co., Ltd., for their kind provisions of high-performance materials.

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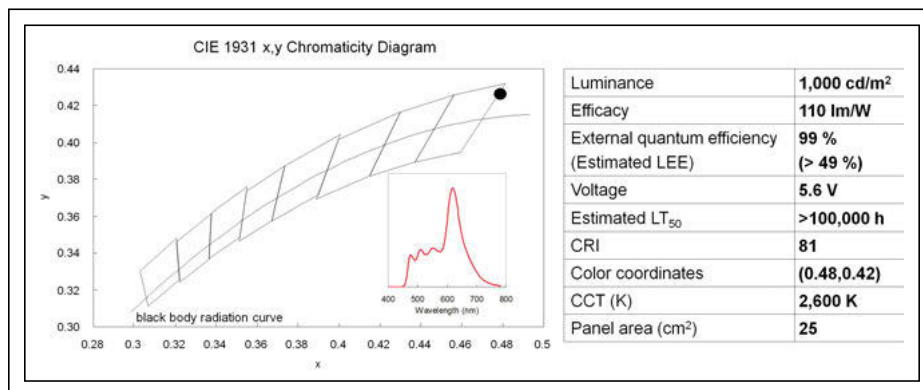


Fig. 9: The performance of the fabricated OLED panel (25 cm²).

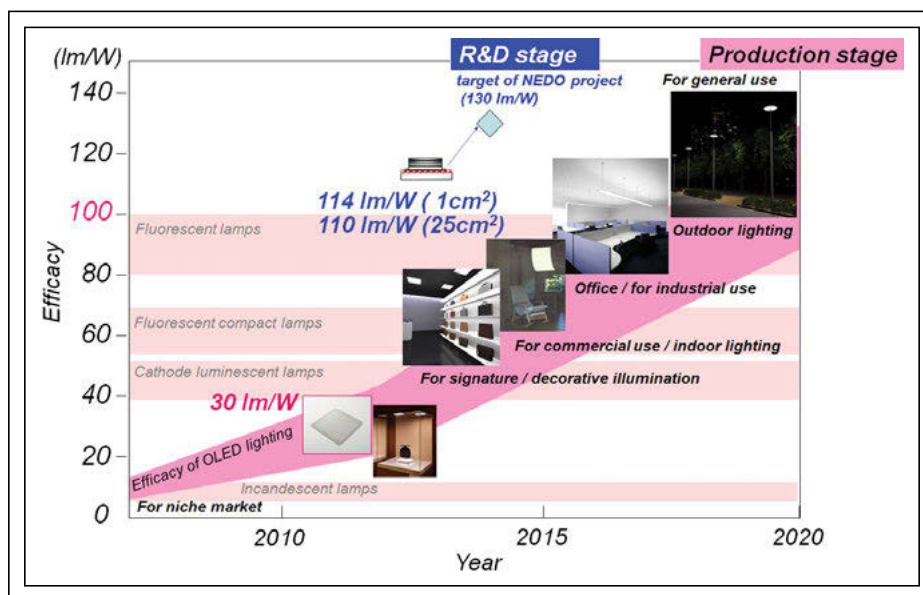


Fig. 10: Current-efficacy prospects for OLED lighting based on the outlook of luminaire efficacy from Ref. 16.

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# New Milestones for LED Lighting

*Thin-film technology has enabled a new generation of high-brightness LEDs.*

by Martin Behringer

**M**OST people think about solid-state lighting in terms of white light – for street lights, vehicle headlights, or subway-station lighting. Of course, we do not live in a black and white world, and our colorful world could benefit from illumination by longer wavelength light-emitting diodes (LEDs). In fact, scientists have pursued this line of research for five decades, as depicted in Fig. 1. While the first LEDs were fairly simple *pn*-junction devices, they were quite complicated for their time. Today's chips are more sophisticated, as a result of several difficulties scientists had to overcome during development.

First, the conversion efficiency was fairly poor due to the low quality of the crystals themselves. Impurities and lattice defects made the conversion of electrical energy in light (photons) inefficient. Then, most of the light got absorbed again before it left the LED die. Absorption took place most of the time in the layers themselves, more severely in the substrate and also at the metal contacts. And while the first LEDs were made from InGaAlP (indium gallium aluminum phosphide) and AlGaAs (aluminum gallium arsenide) in the range between orange and infrared, today's LEDs use additional materials and reach into the UV range of the light spectrum. Packaging concepts and designs also matured dramatically, in parallel with the LED dies. While the first LED devices were only slightly brighter than a glowing candle, LED systems now are bright enough for headlamps in cars and even trains.

Today, many applications require yellow, red, or hyper-red illumination. Such applica-

tions include projectors, color mixing for warm white illumination, hyper-red illumination coupled with blue light for greenhouses (as shown in Fig. 2), and also infrared illumination with high brightness for closed-circuit TV, adaptive cruise control for cars, or light curtains (door detectors) in elevators.

After more than 12 years of efforts in thin-film technology, Osram Opto Semiconductors recently achieved a significant technological breakthrough: a red LED at 200 lm/W at a dominant wavelength of about 615 nm. For red light, 200 lm/W is quite challenging, as the theoretical limit for 615 nm with 100% efficiency is about 300 lm/W. So, 200 lm/W is coming fairly close.

Currently, two companies claim to have surpassed 200 lm/W – both in a laboratory setting at specific current densities. To place these developments in context, the balance of this article briefly recounts the history of colored-LED development.

## How LED Lighting Works

In solid-state lighting devices, the light is generated in the semiconductor crystal. Here, the electrical energy is converted into photons, and, in this crystal, Osram introduced improvements to make the entire system more efficient. To get the light out of a light package, the barrier of total internal reflection (TIR) at the crystal–die boundaries has to be

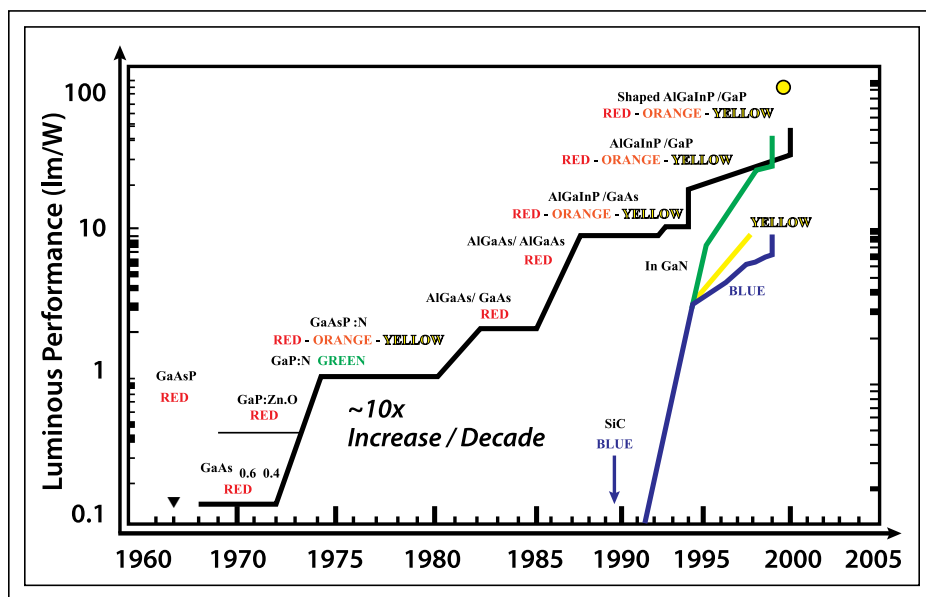


Fig. 1: Brightness development for red, yellow, green, and blue LEDs is shown for the last 50 years.<sup>1</sup>

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overcome. As the light is reflected back into the die, it is incident to the surface of the die with an angle larger than a specific value. There are two ways to help emit the light. The first is to continuously change the angle of the light so if it is reflected once; the direction will be changed and it can escape in the next run. Changing the direction of the light can be done by surface roughening or by internal absorption and re-emission. The other way is to reduce the loss mechanism (equal to absorption without re-emission of light with the same wavelength) as far as possible. This gives the light more opportunities to leave the die before it is lost.

Colored light can be generated either directly (by generating the desired color through direct emission) or by conversion from one emission spectrum to another. In the first case, typically, a medium is excited electrically and emits photons in a specific wavelength. In the second scenario, a photon is emitted, then that photon is absorbed in a medium, and then another photon of a second, longer wavelength is emitted.

LEDs made from InGaAlP can directly and efficiently generate light for the wavelength range from 560 nm to about 660 nm.

The internal efficiency of a metal organic vapor-phase epitaxy (MOVPE) LED makes it the most commonly used crystal growth technology in the LED industry today. Efficiency



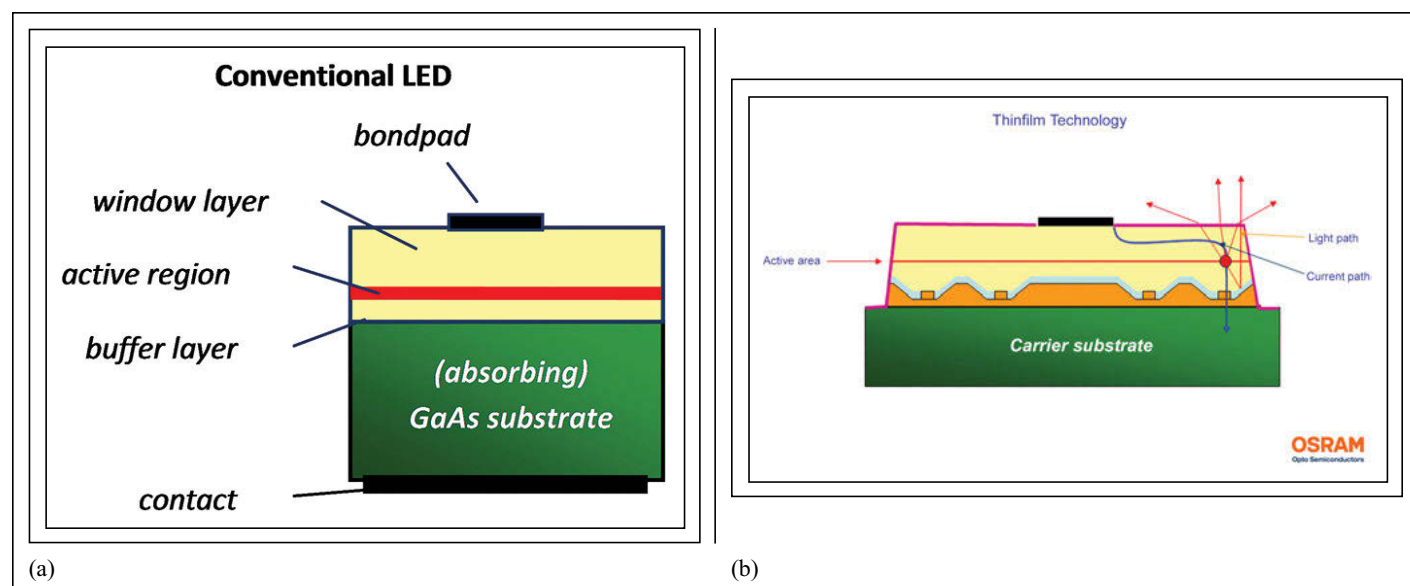
*Fig. 2: LEDs are now employed for a wide variety of applications, from solid-state lighting to projectors to industrial applications. Here, multiple monochromatic LEDs are combined in a horticultural lighting system.*

has increased to more than 90% in the longer wavelength range. But due to the high index

of refraction of InGaAlP LEDs, only 4% of the generated light can leave the chip directly to be used for illumination; the remaining 96% is either reabsorbed by the material or reflected at the chip/air interface and eventually absorbed into the chip. Encapsulation in silicon or resin reduces the disadvantage of internal reflection. But, as in InGaAlP, it has a very high index of refraction of about 3.4 and because there is no encapsulant that comes close to this value, light out-coupling remains a problem.

### The Development of Thin-film Technology

Thin-film technology was invented by the lighting industry to increase efficiency and reduce light loss. (Many companies worked on this technology, and many now offer thin-film devices, but Osram was one of the first to commercialize it, winning a German Future Prize for its technological efforts.) In thin-film LEDs, the light is also generated in a quantum-well structure. In contrast to conventional LEDs, the growth substrate is removed and the active epilayers are bonded onto a carrier, which can be germanium, silicon, or another material that matches the requirements for this carrier. A highly reflecting mirror can be deposited in between the epilayer and the carrier, which prevents the light from being absorbed in the substrate. In



*Fig. 3: A schematic sketch of a conventional LED is shown on an absorbing substrate (a) next to a thin-film LED with a metal mirror between the active epilayer and carrier (b).*

addition, the active epilayers can be so thin that the light is absorbed differently from before, when thick layers were required to extract light efficiently. Normally, the surface is roughened to enhance light extraction or micropisms are included to increase efficiency (see Fig. 3).

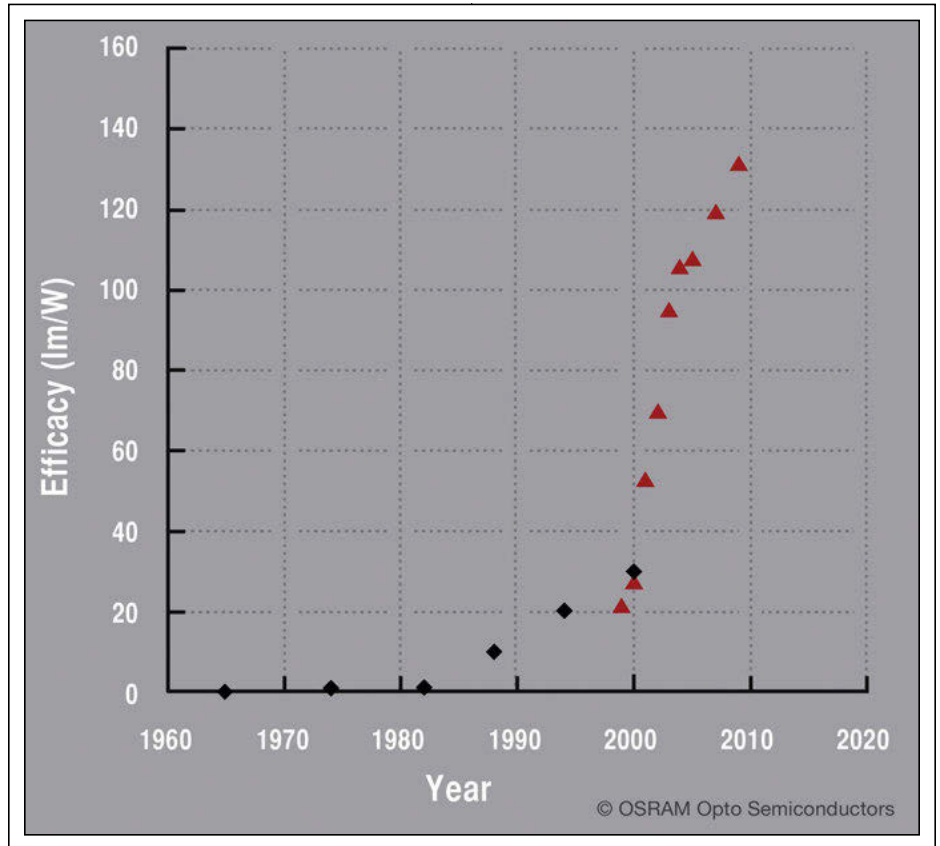
In Figs. 3(a) and 3(b), the blue line shows that the current is directed away from the bond pad to avoid shadowing. The red arrows depict the light path. The light, which is initially emitted toward the substrate, is reflected by the underlying mirror and redirected toward the chip surface where it can then leave the semiconductor die.

Figure 4 highlights the historic efficiency of red LEDs (dominant wavelength, 615 nm). As the triangles and diamonds demonstrate, conventional LEDs reached a peak efficiency of approximately 30 lm/W.

Beginning in 1998, Siemens/Osram began research to develop thin-film LEDs for high-brightness emission. Initially, a number of difficulties arose. Perhaps the biggest problem was transferring the thin semiconductor layer ( $\sim 5 \mu\text{m}$ , which is about 1/10 of the thickness of a human hair) to a carrier in a large area ( $5 \mu\text{m} / 100 \text{ mm} = \text{an aspect ratio of } 20,000$ ). Because this layer is very fragile and requires a high yield for an economically meaningful concept, about 10 years transpired between the first publication of the idea in 1993 and Osram's first commercial ThinFilm LED in 2003. Regardless of this and other thin film problems, it quickly became obvious that by using thin-film technology, higher brightness can be obtained (see the triangles in Fig. 4). By 2010, levels of approximately 140 lm/W were reached.

Some advantages of thin-film LEDs include:

- Scalability: In theory, all chip sizes can be made similarly, and, in turn, possess similar characteristics and performance, according to their size.
- Surface emitters have Lambertian beam patterns, and thus make it possible to combine many chips side by side without changing the beam pattern. Also, a Lambertian beam pattern means that the LED seems to have the same brightness from all viewing angles, and a chip with this profile is suitable for both reflector and focusing optics.



**Fig. 4:** The historic efficiency of red LED brightness is shown by black diamonds indicating volume emitters on an absorbing GaAs (gallium arsenide) substrate. Red points indicate thin-film LEDs since 1999.

- High efficiency.
- Cost-efficient design and manufacturing processes (based on lm/\$).

During the last few years, further investigations into loss mechanisms within the devices have not only improved efficiency, but also reduced cost and increased reliability. An analysis of different materials and semiconductor compositions used within the diode for electrical conductivity and optical transmission helped in the replacement of absorbing layers with non-absorbing layers of similar or even better functionality.

Figure 5 depicts the current curve and efficiency for a 1-mm<sup>2</sup> die mounted into a laboratory package, optimized for efficient out-coupling of its generated light.

In Fig. 5(a), the light output for currents up to 350 mA is shown. A linear curve indicates efficient light generation over a wide current range. In Fig. 5(b), the efficiencies are given.

The orange curve depicts the efficacy in lm/W, while the black curve provides wall-plug efficiency.

Both curves show a distinct maximum at about 50 mA, with approximately 201 lm/W and 61%, respectively. At 350 mA, the values reduce to 168 lm/W and 52%. The explanation for this decline can be found in the red curve, which shows the external quantum efficiency. It shows a very broad maximum, and the value is almost unchanged between 50 and 350 mA and between 58% and 59%. The decline in efficacy and wall-plug efficiency must therefore be attributed to an increase in operating voltage due to still-existing ohmic resistances within the die. The high lm/W values were reached with a red die, which emits at a dominant wavelength of about 609 nm at room temperature. For longer wavelengths, eye sensitivity lessens and, therefore, similarly high lm/W values are harder to realize. On the other hand, high

wall-plug efficiency values are easier to realize with longer wavelengths. Therefore, the high value of 61% is quite remarkable.

These improvements were made possible in the following ways:

- By reducing the absorption of the layers as much as feasible, it is possible to extract more light, even if it travels 10 times through the die before escaping the semiconductor.
- This was accomplished, in part, by increasing the bandgap and, in part, by adjusting the doping. To avoid high-ohmic resistances at these high operating voltages, increasing thickness improved the conductivity of the layers. The contact design was optimized to keep the operating voltage low. Figure 6 shows a 1-mm<sup>2</sup> die. The dense arrangement of these metals' current paths enables strong electrical performance despite adjusted doping levels.

Finally, these improvements resulted in a very-broad process window, which allows for high yield and, therefore, lower overall cost.

This new technology was applied to chip sizes of varying lengths: 250  $\mu\text{m}$ , 300  $\mu\text{m}$ , 500  $\mu\text{m}$ , 750  $\mu\text{m}$ , and 1 mm. A 150  $\mu\text{m}$  and a 2-mm<sup>2</sup> die followed in 2012. The dominant wavelength range is from 590 to 645 nm; 560 nm and infrared range followed in 2012 and 2013, respectively.

As mentioned above, maximum efficacy is reached at about 610 nm, while wall-plug efficiency is highest at a wavelength of 645 nm.

Figure 7 depicts the characteristics for a 1-mm<sup>2</sup> die at a dominant wavelength of 645 nm ( $\lambda = 660$  nm peak) in the same laboratory package as used for the 615-nm emitting chip. The output power over current and the wall-plug efficiency are shown.

The output power rises linearly with current and reaches about 437 mW at 350 mA (at about 2.1 V). The wall-plug efficiency reaches about 59% at 350 mA and is above 70% between 5 and 60 mA. Due to reduced eye sensitivity (photopic curve), the maximum output at 350 mA is only 21 lm. Lifetime depends on operating conditions such as current and temperature. The entire LED community is continuously working to improve the reliability of these devices.

With the new generation of thin-film dies, however, output power could be increased by 30–50% for a bare die compared to the previ-

ous generation and about 10–30% for a packaged die in an LED. This is quite significant. With this kind of increase, new and more numerous applications can be addressed. An already widespread application is the combi-

nation of highly efficient – but aesthetically unpleasant – cold white with amber or red, which changes the color temperature to a more visually pleasant and high-quality white. As a result, both higher overall efficiency

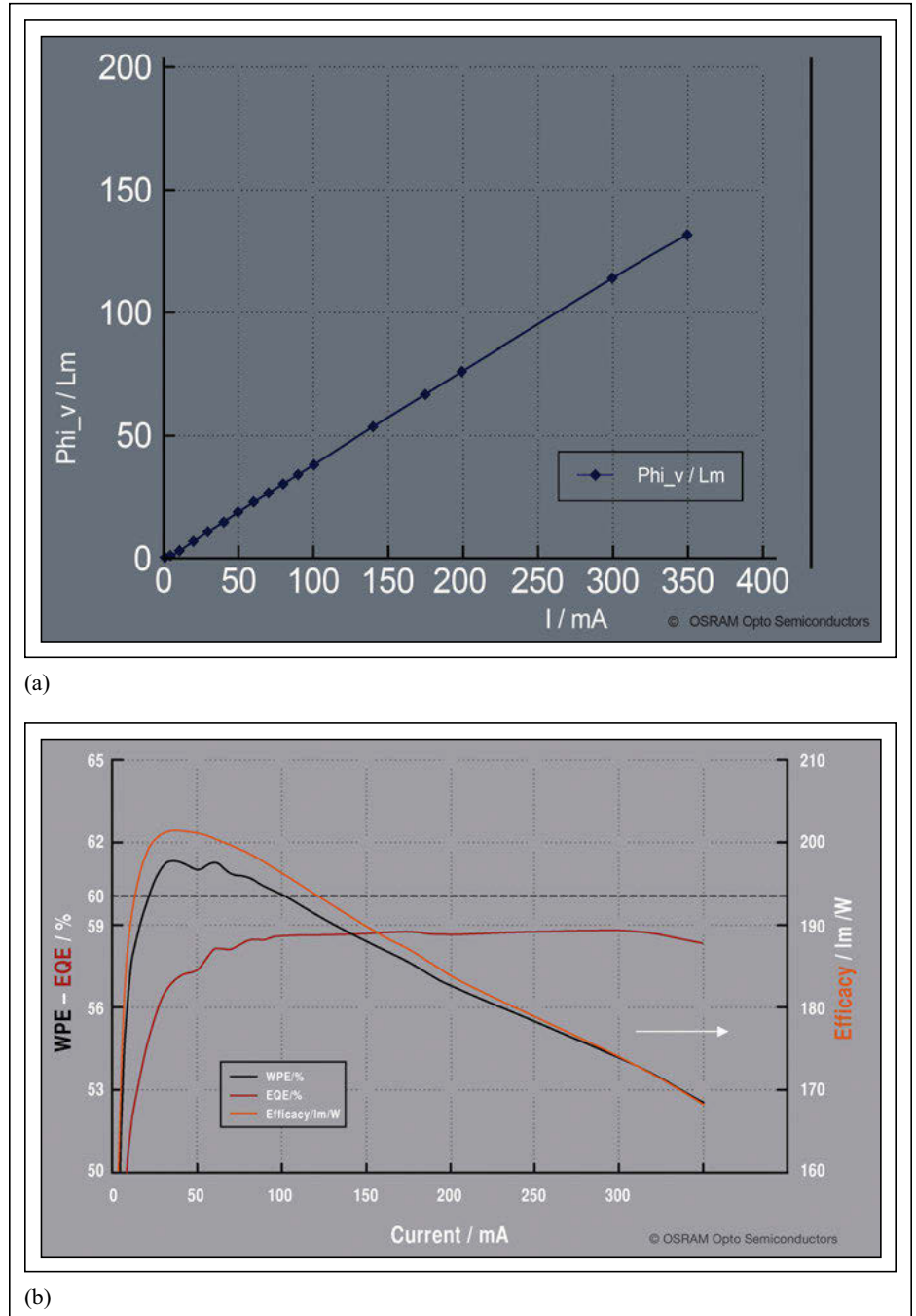
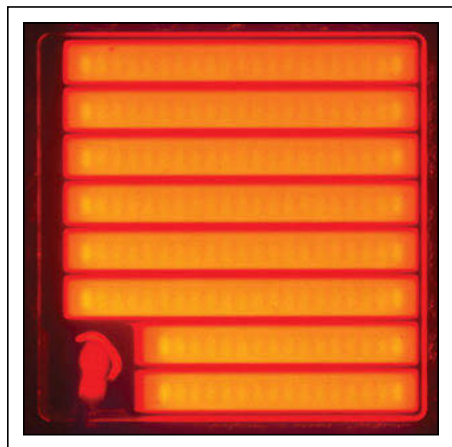


Fig. 5: (a) The light-current curve and (b) the efficiency/efficacy over the current of a 1-mm<sup>2</sup> LED in a laboratory package .



**Fig. 6:** Shown is the illumination pattern of a 1-mm<sup>2</sup> die from the latest thin-film generation.

and good color rendering can be achieved simultaneously.

Meanwhile, projection and signaling applications absolutely require high-efficiency red light and will doubtlessly profit from these breakthroughs. As far as mobile applications are concerned, either more power or longer battery life will provide tremendous customer benefits. For industrial applications, lower energy consumption will reduce operating costs and brighter devices will minimize initial installation expenses.

In this context, it is clear that improvement in 660-nm LEDs will also have a positive impact

on LED-illuminated greenhouses. With such high efficiency, energy costs can be reduced by almost half compared with conventional lighting; furthermore, LED cooling is made easier. For example, when comparing a light with 40% efficiency to the above-mentioned record values, it is realistically possible to generate 75% more light with the same amount of electrical energy and up to 250% more light at the same amount of waste heat.

Due to the improved performance of the chips themselves, package and luminaire designers are emboldened to design bigger and higher-powered packages and lamps that are driven at higher operating currents. While the first LEDs were for the mA range, today often several amperes are run through the die. Even though efficiency has been greatly improved, these higher operating conditions still require good thermal management, due to higher total load. Thus, modern LEDs and luminaires must provide low-ohmic resistance in terms of electrical supply; they must efficiently remove the heat with low-temperature increase, and they must also guarantee efficient light out-coupling and beam shaping to fulfil needs for modern light sources.

### What Comes Next?

Considering 60% efficiency, it is clear that incremental brightness improvements will be harder to realize as we approach the ideal of 100%. With that said, other parameters con-

tinue to require improvement. In particular, companies will want to see better production and process values.

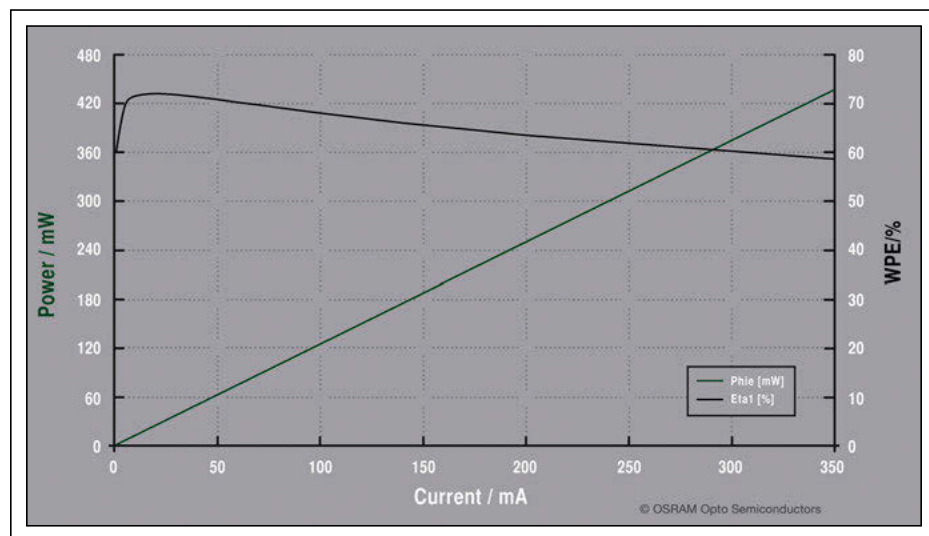
Also important will be improvements in high-current and high-temperature operation. Certain devices are commonly characterized at room temperature, while approximately 80–100°C is a more realistic operating condition. Therefore, work is being done to optimize output power at these temperatures, as well as reducing the shift in operating parameters when changing the temperature.

Last but not least, light out-coupling remains a constantly evolving challenge. On the package level as well as on the bare die, there is ongoing research dedicated to obtaining every photon that is generated out of the die. Certainly, out-coupling in bare die configurations offers a wide range of possible improvements.

To summarize, since 1998, thin film has become a preferred solution for generating high-brightness LEDs. It was recently determined how to reduce optical and electrical loss mechanisms to realize a maximum efficacy output of 200 lm/W. This enables far-broader LED use in many applications, which will increase lighting quality considerably.

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<sup>1</sup>Source: Elsevier/Academic Press. This image was published in M. George Craford, "High Brightness Light Emitting Diodes, Semiconductors and Semimetals," *Overview of Device Issues in High Brightness Light Emitting Diodes* (Elsevier/Academic Press, 1997), p. 48. ■



**Fig. 7:** Light output and wall-plug efficiency are demonstrated over the operating current for a 1-mm<sup>2</sup> die emitting at 660-nm peak.

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## Display Week 2014 Symposium to Feature OLED TV, Wearable Displays, 3D, and Lighting

The Society for Information Display has issued a call for papers to be presented at the 2014 Display Week Symposium. SID's annual Display Week is the premier event for the global display industry. This year's symposium will feature presentations on every aspect of display technology, but submissions on the following special topics are particularly encouraged: OLED TV, Wearable Displays, 3D, and Lighting. This year's event takes place June 1–6, 2014, in San Diego.

For the OLED-TV special topic, submissions on all advanced OLED-TV technologies are encouraged, including novel device structures, backplane technologies, manufacturing processes, deposition techniques, mask fabri-

cation, encapsulation, driving methods, and next-generation applications.

The special topic on Wearable Displays will cover the emerging development of wearable display products, applications, and technologies. This is one of the fastest growing areas in both consumer products and technological development. Paper topics include wearable applications, near-to-eye systems, textile displays, and more.

The 3D symposium sessions will encompass display technologies for enabling depth perception in viewers, applications for 3D displays, 3D content generation, measurement and characterization of 3D systems, and human factors.

Last but not least, the special topic on Lighting will focus on advances in the LED and OLED industries. Submissions on all aspects of solid-state lighting are encouraged, including novel lighting systems, lighting measurement, backlighting, optical systems, and more.

Work in the new fields listed above may also relate to the following general symposium topics: Active-Matrix Displays, Applied Vision/Human Factors, Display Applications, Display Electronics, Display Manufacturing, Display Measurements, Display Systems, Emissive Displays, e-Paper and Flexible Displays, Liquid-Crystal and Other Non-Emissive Displays, OLEDs, Projection, and Touch and Interactivity.

The Society for Information Display encourages the submission of original papers on all aspects of the research, engineering, application, evaluation, and utilization of displays. Paper submissions are welcomed for any of the general symposium or specific topical sessions.

For information about submitting an abstract (due Dec 2, 2013), see "First Call for Papers" on [www.sid.org](http://www.sid.org).

— Jenny Donelan

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The biggest piece missing in the puzzle so far is the commitment to larger investments in manufacturing volume. This is similar to the situation that AMOLED display makers were in some years ago before Samsung led the way.

In contrast to AMOLED displays, however, production lines for lighting modules are far less complex and cost intensive. So we will not have a limited amount of companies dominating the market, but rather a multitude of companies as active producers. With a 40% annual reduction expectation, OLED lighting prices should reach a level where functional rather than decorative uses will become viable – probably in the next 2–3 years. Now might be the right time to invest in those missing additional manufacturing lines.... ■

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## industry news

continued from page 3

### Shanghai AVIC and NLT Form New Company

If you've been wondering when the folks involved in Renesas/NEC/NLT/Tianma would change company names again, wonder no longer: Shanghai AVIC Optoelectronics Co., Ltd., and NLT Technologies, Ltd., have announced the official launch (currently scheduled for November 1, 2013) of a new joint venture, Tianma NLT America, Inc. The new company has been created to provide AMLCD solutions specifically for the Americas industrial market. It will have responsibility for sales, marketing, and engineering support of the NLT/Tianma product line as well as management responsibility of the distribution channel for Tianma AMLCD products in the Americas. (These are the responsibilities currently managed by Renesas Electronics America's Display Business Unit. ■



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*continued from page 2*

industry expert Ken Werner set about to chronicle it all for us in his review article on 3-D displays.

I sometimes wonder whether those in the media create hype or simply report it. We can probably agree that the right answer is a mixture of both. In the case of OLED TVs, the promise of the technology certainly created enough buzz and interest to keep everyone excited in Vancouver. The reality did not disappoint, with another year of great demonstrations from Samsung and LG showing the future of OLED technology. Samsung had OLED displays at Display Week but no big OLED TVs this year. Only LG had them. But TV was just a small part of the story, as you will realize when you read the review from our reporters Sven Murano and Anke Lemke. You may also note that since the exhibitions in May, both Samsung and LG have released 55-in. curved OLED TVs to the consumer marketplace, as reported this month in our Industry News section.

Although not as headline grabbing as OLED and 3-D displays, flexible displays continue to evolve as well and in many cases hold promise for new and highly innovative products to emerge. E Ink is the name everyone knows, and for good reason, but if you look beyond this iconic brand, as author Jason Heikenfeld did, you will find a rich landscape of innovations and recent industry developments. Fortunately, Jason did his homework and scoured the show to bring us all the highlights in his review article on flexible displays and e-paper technologies.

In addition to looking back, we're looking forward this month to the future of solid-state lighting with a pair of feature articles brought to us by guest editor Sven Murano from Novald AG. Sven worked very hard on this part of the issue and rightly deserves our thanks. Highly complementary to each other, these Frontline Technology articles provide a strong overview of the market needs and opportunities for OLEDs as well as some concrete results in achieving record-setting light-output efficiencies. I encourage you to read Sven's guest editorial first. "OLED Lighting Edges Closer to Commercial Reality" offers a more complete introduction to both features.

One observation Sven makes in his column is how competition from inorganic LEDs in the lighting market is strong, with this technology demonstrating increasing performance

levels and decreasing costs. Providing perspective from that camp this month is our third Frontline Technology feature, "New Milestones for LED Lighting" by author Martin Behringer from Osram. He discusses both the historical evolution of LED technology and the latest advances of his team in achieving industry-leading performance in color and light-extraction efficiency with thin-film devices.

Last but not least, we welcome back author and SID EC member Helge Seetzen, who contributed the second of his series of articles focused on successful strategies for creating, funding, and growing new technology ventures. This month, in "Raising Capital for Technology Ventures," Helge explains the next steps to raising capital after you have built the necessary foundation in your startup venture. It's not as easy as it may look from the sidelines and I think you can avoid a number of setbacks by learning from Helge and the experiences of his team. This series will continue for several more months and I'm already excited about next month's offering, in which Helge will talk in some detail about the potential pitfalls of venture capital funding.

As the leaves on the trees start to turn color, and the summer holidays are now memories for most of us, I wish you all a very prosperous and healthy fall season. We'll be back in a couple of months with another issue focused on very-high-resolution displays and digital signage. As always, we welcome your comments and suggestions for future articles in *Information Display*. ■

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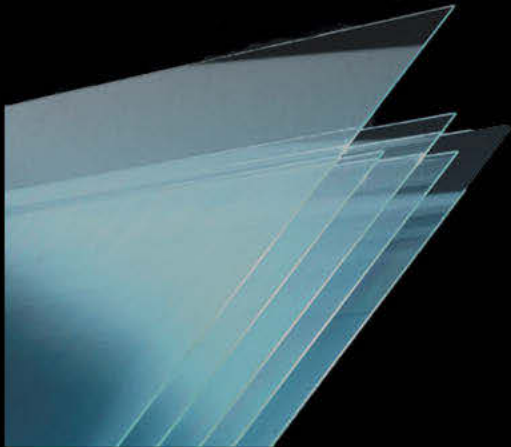
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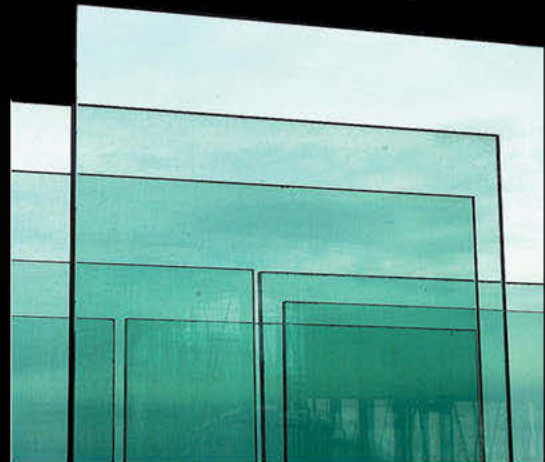
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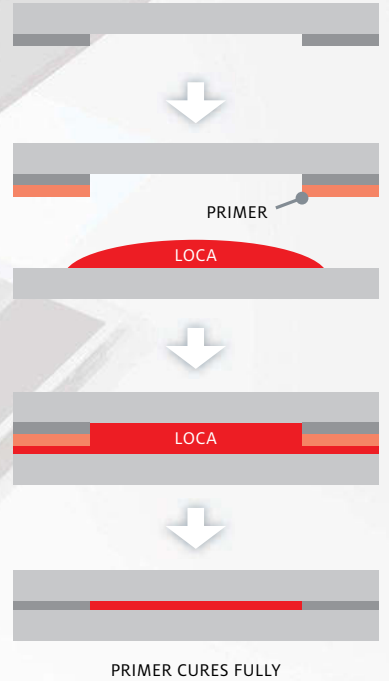
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