OLED TECHNOLOGY ISSUE

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SID
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The Next Wave of TV: OLED TV on the Horizon

COMMERCIALIZATION OF AMOLED TV

PROMISES AND MYTHS OF OLED TV

DISRUPTIVE FACTORS IN THE OLED BUSINESS ECOSYSTEM

Sony's 21-in. Prototype OLED TV

Samsung's 31-in. Prototype OLED TV

LG Display's 15-in. Prototype OLED TV

Also

BRAZIL'S DIGITAL DESKS FOR EDUCATION

Plus

Journal of the SID September and October Contents


COVER: *OLED TV on the horizon. Shown is (top) Sony's 21-in. OLED TV prototype featuring a peak luminance of 600 nits, WXGA resolution (1366 × RGB × 768), and a color gamut of over 100% NTSC; (middle) Samsung's 31-in OLED TV featuring a peak luminance of 600 nits, full HD resolution, and a color gamut 107% NTSC; and (bottom) LG Display's 15-in. OLED TV prototype featuring a peak luminance of 450 nits, HD resolution (1366 × RGB × 768), and a color gamut greater than 92% NTSC.*

CREDIT: Cover images provided by Sony Electronics, Inc.; Samsung Mobile Display Co., Ltd., and LG Display.Co., Ltd. Cover design by Acapella Studies, Inc.

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Mobile Display Technology Issue

- Evalution of Mobile Displays
- Polarizer-Free Ultra-Low-Power Reflective LCDs
- The Emergence of MEMS-Based Displays
- Challenges of Incorporating Haptic Interfaces
- *Journal of the SID* November Contents

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The Potential for Change

by Stephen Atwood

We have all been watching the turbulent developments in organic light-emitting-diode (OLED) technology for a long time now. If you scan the *Information Display* archives, you will find numerous articles covering the evolution of OLED materials, the designs for manufacturing, the problems that existed such as packaging and sealing, and the many examples of work on substrates and active-matrix components, including poly-Si TFTs. Each small evolution has fueled more innovation and investment, but the road has had its challenges as well, both from a business and a technical perspective.

Most of us remember the flurry of discoveries and innovations achieved by scientists at Pioneer and Kodak, as well as at Universal Display Corp. (UDC) and Cambridge Display Technology (CDT) over the last decade. Kodak soon partnered with Sanyo, but the effort was unfortunately cut short by economics. CDT and UDC continued on to be joined by Samsung, Sony, LG, Dupont, and many others to form the backbone of the enabling technology we have today.

Unfortunately, as Barry Young points out in his article "OLEDs – Promises, Myths, and TVs," most of the early startups focusing on passive-matrix technology floundered for several technical and business reasons, but in the end it usually came down to the problem every new technology faces: will consumers pay a reasonable premium for the benefits of a new technology long enough for the infrastructure to become mature and the economies of scale to properly develop? If an emerging technology truly addresses an unfulfilled need or it can realize real economic advantages over existing technology, then it has at least a chance to become mainstream.

I think the prospects are a lot brighter for active-matrix OLED technology, and as you can read in our feature article, "Emerging Technologies for the Commercialization of AMOLED TVs," by Hye Dong Kim, *et. al.* from Samsung, the advantages of AMOLED technology for TV applications are numerous and highly promising. Promising enough, in fact, that I think this will be a much more disruptive technology than plasma, at least in comparison to the TV marketplace. While liquid-crystal technology is unlikely to be totally unseated in TV products, I do think there is the real possibility that cell phones and other mobile devices could be using exclusively AMOLED displays within the next 10 years. This prediction is supported by author Antti Lääperi in his article, "Disruptive Factors in the OLED Business Ecosystem," although Antti is more cautious than I am. He predicts a limited or partial disruption in certain key applications such as hand-held devices. I think the disruption will be broader, but with the timing somewhat uncertain. Product manufacturers such as Nokia and device manufacturers such as Samsung do not enter into these endeavors without a great deal of analysis and investigation. If they choose to make a strategic decision to develop AMOLED products with their considerable resources at hand, they probably understand the end-game potential pretty well.

Our Guest Editor this month is Julie Brown, CTO of Universal Display Corp. Julie has lived the path of innovation in OLED materials for many years now and has been a key force in developing a very successful IP portfolio at UDC. As pioneers, Julie and UDC can bear witness to the real challenges of developing new technologies and the problems caused when the hype gets ahead of the substance. As such, there are

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Executive Editor: Stephen P. Atwood
617/306-9729, satwood@azonix.com
Editor-in-Chief: Jay Morreale
212/460-9700, jmorreale@pcm411.com
Managing Editor: Jenny Donelan
603/924-9628, jdonelan@pcm411.com
Administrative Assistant: Ralph Nadell
Sales Manager: Danielle Rocco
Sales Director: Michele Klein

Greener Manufacturing

by Jenny Donelan

Whether a company manufactures toothpicks or twin-engine aircraft, that company is almost certainly "greening up" its operations these days – or at least thinking about it. These efforts run the gamut from simple changes such as using long-life light bulbs to major transformations such as overhauling production lines. For the display industry, green efforts that go beyond general operations include making products more energy efficient, utilizing better packaging, replacing environmentally hazardous materials with more benign ones, and using less wasteful manufacturing methods.

Top of list for these companies is probably making products more energy efficient. This initiative is driven as much by customer demand as by other factors, according to Kimberly Allen, principal of the San Jose based Paññа Consulting. Allen recently completed an environmental issues survey of display manufacturers for market-research company iSuppli Corp. Seventy-three percent of the 520 survey respondents reported that energy efficiency of products was a priority. "This tends to be aligned with a company's goals anyway," says Allen, "because consumers expect that every year, battery life will increase." In order to meet these goals, companies are continually optimizing the backlighting, glass, and other components of displays so that they will drain batteries less. Just one example across much of the industry has been the gradual replacement of CCFL backlighting with more energy-efficient LEDs.

Packaging is another major focus for environmental initiative. Although displays are fragile, thoughtful packaging design can protect equipment while also minimizing environment impact – and helping the bottom line: "If you can pack 500 TVs into a shipping crate instead of 300, you've saved quite a bit," notes Allen. Last year, Hewlett-Packard took this pretty far, shipping its HP Pavilion dv6929 Entertainment Notebook to Wal-Mart and Sam's Club stores in padded messenger bags instead of conventional boxes. According to Allen, this represented an approximate 97% reduction in the amount of packaging. HP also won Wal-Mart's Home Entertainment Design Challenge as a result.

Removing hazardous materials from displays is also an ongoing effort at many companies. Allen's survey revealed that 80% of respondents are working on replacing these materials with less harmful ones. Here again, the replacement of CCFLs, which contain mercury, with LEDs is a step in the environmentally friendly direction. In terms of display glass, Corning has been one of the companies at the forefront of removing heavy metals. Materials such as arsenic and antinomy are fining agents used to remove air bubbles from molten glass, explains Peter Bocko, Chief Technology Officer, East Asia Corning Display Technologies. Barium helps with melting. And halides are sometimes substituted by manufacturers as fining agents when the heavy metals are eliminated. These materials are not only less-than-ideal substances to have around during the glass-making process; they can end up in landfills when the displays get thrown out, and also make it difficult to recycle the glass. The goal, says Bocko, is to be green "before, during, and after use." Corning introduced the first LCD glass with no added heavy metals or halides (such as chlorine or fluorine) in 2006.

Other efforts at reducing the environmental impact of display-making include solution-based processing techniques that can be performed at lower temperatures than conventional deposition methods – "without all those heaters and pumps going," says Allen. This process can be wasteful as well, she says, noting that the trick is to collect and reuse the solutions. If that can be worked out, then companies reap the benefits of dramatically lower energy bills.

In fact, while companies tend to be motivated to go green for multiple reasons, among them the urge to do the right thing and gain the appreciative eye of the consumer, the chance to cut costs may be the most powerful. "Saving money is key," says David Hsieh, DisplaySearch's Vice President of Greater China. "If you can save some cost and also take away some hazardous substances from your products and manufacturing processes, why not?" However, Allen notes that green manufacturing only really saves money when it is carefully and proactively implemented. "The smarter companies have figured out to go upstream and use Design for Environment (DFE) practices," she says. "It does require a bit of strategic investment." Companies that implement "end of pipeline" changes may find those very expensive indeed, she adds.

There is yet another factor behind the greening of display manufacturing: legislation both current and pending. Companies must be careful to comply with increasingly stringent environmental regulations both in the U.S. and abroad. The next installation in this series of news articles will focus on legislation such as the EU's RoHS (Reduction of Hazardous Substances) and WEEE (Waste Electrical and Electronic Equipment) that are affecting the way display companies do business now and in the future. ■

guest editorial

The Value Proposition of OLEDs

by Julie J. Brown

As I set out this year to seek articles for the 2009 OLED issue of *Information Display*, I was compelled to take a step back and view the OLED industry as one not so intimately involved in it. I focused my thinking on the value proposition for small-to-large active-matrix OLED flat-panel displays (FPDs) and quickly realized the key was sitting right in front of me in everyday life. We are living in an energy-conscious or "green"-focused world at the same time that we have an ever-increasing desire for information to be displayed to us on our hand-held, laptop, or wall-mounted devices. This information is predominantly brought to all of us through FPDs. And AMOLED technology fits right into this picture, being a low-power or green technology, with excellent image quality and a low-cost roadmap. From this starting point, I decided to reach out to industry experts to write about these opportunities for AMOLED FPDs past, present, and future. The responses I received were really intriguing as is evident from the cover-page collage of images of OLED-TV prototypes received from Sony (21 in.), Samsung (31 in.), and, the most recent player to join, LG Display (15 in.), along with the articles described below. It is going to be a real exciting and pivotal year for our industry.

The first article comes from Antti Lääperi of Nokia, who has taken it upon himself to study the OLED ecosystem. He shares with us a thought-provoking perspective on how this ecosystem is developing and ties his thinking into a discussion of disruptive technology. Lääperi identifies key potentially disruptive elements for OLED technology (as compared to TFT-LCD technology) to include the use of active materials, the ability to achieve lower power consumption in 2009 (by addition of green phosphorescence), and application to white lighting. His thinking is summarized by a keen focus on green aspects of the technology that will drive the OLED ecosystem.

The next article is from Barry Young, Managing Director of the OLED Association, who takes a hard look at the path of OLED FPD commercialization to date and lays out a set of challenges for the future. Young has an interesting perspective, having analyzed the display industry for a number of years now and having most recently created the OLED Association to help establish a common marketing platform and standards for the growth of the OLED FPD industry. He takes us through what he calls the "hype" and then the reality check for passive-matrix OLED displays. He then focuses on the AMOLED industry, which he believes will put the industry "on the right track." He lays out the challenges for AMOLED industry growth with a focus on TV applications. This focus on OLED TVs is explained by the entrancing image quality that AMOLEDs provide for this application. Young discusses the key areas for continued technology improvement to include energy efficiency, operational lifetime, yield, and manufacturing process scaling. He then touches on using OLEDs in flexible displays and lighting. The article ends with a great perspective: OLED FPDs should not be viewed as a threat to TFT-LCDs but more as "an extension" of FPDs into a new front place technology, namely OLEDs.

Finally, the third article was contributed by Hye-Dong Kim and colleagues from Samsung Mobile Display (SMD). Today, SMD has taken on the leading position in the area of mobile AMOLED displays with great intensity. There are now new products announced on almost a weekly basis that advertise the use of OLED as the display. This is very exciting. The next potential product on the horizon for SMD is the OLED TV. In this article, Kim shares with us a perspective on technology choices and manufacturing vision for SMD's OLED-TV business. He touches on key attributes driving the industry, including excellent image quality and low power consumption for green TV products. He then focuses much of the article on manufacturing process

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Society for Information Display
1475 S. Bascom Ave., Ste. 114
Campbell, CA 95008
408/879-3901, fax -3833
e-mail: office@sid.org
http://www.sid.org

Korea on My Mind

Paul Drzaic
President, Society for Information Display

I had the opportunity to spend a week in Korea a couple of months ago, and as usual came back from my visit to this country energized regarding the future of electronic displays. A large portion of my trip focused on visiting faculty members and students at Korean universities. In this column, I'll note some impressions around Korea's university infrastructure.

The primary purpose of my trip was to help Hanyang University celebrate the 70th anniversary of its founding. Known locally as the "Engine of Korea," Hanyang University was commemorating this anniversary by holding a series of lectures and panel sessions on each of its seven different areas of focus. Electronic displays represented one of those areas, due to this technology's importance to the Korean economy. Professor Oh-Kyong Kwon organized the program on displays, and I was fortunate to be one of those invited to speak.

During my talk, I tried to stress the importance of connecting technical achievement to the very human needs that drive the demand for electronic displays. I managed to work in a reference to the Korean near-obsession with the video game *Starcraft*, which drew appreciative laughs from the student audience. A large number of students showed up to listen to a panel discussion held in English, and this group posed several insightful questions to me and the other speakers. These are smart young people, well-informed and eager to learn more.

I also had the good fortune to be able to visit Professor Jin Jang at Kyunghee University and see the superb infrastructure of students, equipment, and projects that he has set up there. At Kyunghee, I also gave an extended lecture on electronic-paper technologies to a group of faculty and students. The engagement by the students was strong, and once more, thoughtful questions came from that group. These are clearly people who are thinking hard about engineering new display technologies.

During the week, I also had great visits with leadership from Samsung and LG Display, which were both gracious hosts. There are amazing projects going on within these companies, spanning the gamut of hard-core product engineering to highly advanced research programs. I got a sense that these are enterprises that are not only taking care of near-term business, but also laying the groundwork for future advances.

Finally, I'll note the discussions I had with the leadership of KIDS (Korean Information Display Society), which is an organization focused on promoting display technology within Korea. SID and KIDS have been cooperating for several years now, primarily through the co-sponsorship of the yearly IMID (International Meeting on Information Display) conference. I had great conversations with Professors Y-S. Kim, K-W. Whang, and H-J. Kim, in which we discussed several ideas for expanding the relationship between SID and KIDS, using SID's international scope to connect more strongly with the Korean-based engineers that form KIDS' base. I look forward to another chapter in the ability of SID to provide value to our members worldwide and to continue to strengthen our presence in Korea. ■

The Future Is Here...

Standard Active Matrix OLED Products

Panel Size (diagonal)	Resolution	Color Depth	Active Area (mm)	Outline Dimension (mm)	Brightness (cd/m^2)
2.0"	176 x RGB x 220	262k	31.68 x 39.60	37.30 x 50.25 x 1.60	190
2.4"	240 x RGB x 320	262k / 16.7M	36.72 x 48.96	42.00 x 58.60 x 1.65	200
2.8"	240 x RGB x 320	262k / 16.7M	43.20 x 57.60	49.10 x 67.30 x 1.75	200
3.4"	480 x RGB x 272	16.7M	74.88 x 42.43	82.80 x 54.30 x 1.60	200
4.3"	480 x RGB x 272	16.7M	95.00 x 53.80	103.50 x 67.00 x 2.05	200
7.6"	800 x RGB x 600	16.7M	165.60 x 99.36	177.30 x 118.32 x 5.40	200

Active Matrix OLED Advantages

Supreme Image Quality

Wide Color Gamut (>70% NTSC)

High Contrast Ratio (>10,000 : 1)

Ultra Thin (typical module thickness 1.3mm)

Virtually Unlimited Viewing Angles

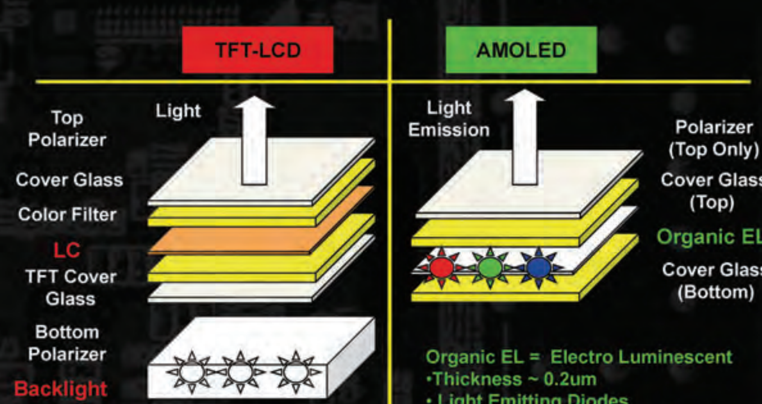
Fast Response Time (<50us)

Wide Operating Temperature Range (-40C to 70C)

Low Power Consumption (30% less than TFT-LCD)

Resistive and Capacitive Touch Screens Available

TFT-LCD vs AMOLED



LC = Liquid Crystal
•Thickness ~ 4um
•Filtering Backlight
•Not 100% Black
•Limited Viewing Angles

Organic EL = Electro Luminescent
•Thickness ~ 0.2um
• Light Emitting Diodes
• No Backlights / Only One Polarizer
•True Black Pixels
•Virtually Unlimited View Angles
• Very Effective Display

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Disruptive Factors in the OLED Business Ecosystem

AMOLEDs have several key, potentially disruptive elements in both display and lighting technology.

by Antti Lääperi

CLAYTON M. CHRISTENSEN is known for his discussion of disruptive technology in books such as *The Innovators Dilemma*,[1] *The Innovators Solution*,[2] and *Seeing What´s Next*.[3] In these works, he defines two cases of disruptions: "low-end disruptions" and "new-market disruptions." The first reshapes existing markets by delivering relatively simple, convenient, low-cost innovations to a set of customers who have previously been ignored by industry leaders; the second creates new markets with new customers. Christensen also points out that disruptive innovations, at least in the near-term, have poorer product performance and underperform established products in mainstream markets, but also offer other features that new and existing customers value.

Disruptive innovations that have taken place in the display industry include an historical example that happened in two different countries in the 1970s. Researchers at Westinghouse in the U.S. and at Dundee University in Scotland separately were able to demonstrate the operation of liquid-crystal cells on glass-based TFTs. This enabled a major breakthrough.

For some time, it seemed as though OLEDs were poised to become a disruptive technology. But, in fact, now it seems that OLEDs have only some aspects of disruptive innovation as defined by Christensen. This article will examine this potential for at least partial disruption in detail.

To evaluate the innovations that are continuing to take place in the display industry, we will use the term "ecosystem thinking." Ecosystem thinking, as discussed in recent literature, such as Judy Estrin's *Closing the Innovation Gap* and Marco Iansiti and Roy Levien's *The Keystone Advantage*,[4,5] enables one to see the importance of single innovations as building blocks of a bigger systemic innovation framework. Using this concept, we will show that new OLED technology has many disruptive features, which are moving from the high-end side of the application spectrum to the mainstream flat-panel business. It is still too early to say whether or not these new disruptive elements will be able to truly disrupt the current flat-panel ecosystem. OLED technology has not found a killer application in the last 10 years, although it is directly competing with TFT-LCD technology today in some areas.

***Antti Lääperi** is with Nokia Corp. located in Helsinki, Finland. He can be reached at antti.laaperi@nokia.com or antti.laaperi@gmail.com.*

TFT-LCD Flat-Panel Ecosystem Case

The first target market for AMOLED disruption involves small- and medium-sized LCDs and TFT-LCDs. These have been used in mobile phones and hand-held devices. The overall market-size estimation for these displays for 2009, according to several sources, is about 1090 million units. The share of TFT-LCDs has increased rapidly since their introduction in the early 2000s and exceeded 50% and 600 million display volumes during 2007.[6] TFT-LCDs can compete with AMOLEDs in optical properties; therefore, the market size of TFT-LCDs indicates the market potential for AMOLEDs. Samsung Mobile Display estimated in August 2009 that AMOLEDs could take a 40% market share in the mobile-phone display market by 2015. The AMOLED share is now 2.3%.[7] Due to the increased need to save on battery life in power-hungry smart phones, AMOLEDs have the best chance of capturing the smart-phone market first, then moving to laptops and then to thin, low-power TV screens.

OLED Ecosystem Case

In the year 2000, strong hype began over potential opportunities for OLED technology. With its excellent image quality, thinness, and response times, it was seen as a rapidly approaching challenger to existing TFT-LCD technology in small- and medium-sized displays. However, during the past 9 years, TFT-LCD technology has been able to improve performance in image quality while at the same time reducing costs dramatically due to big investments in large-sized TFT-LCD fabs. This somewhat decreased the potential for OLEDs to become a disruptive influence during that time.

Partly for the above reason, OLED technology has been without doubt less disruptive than TFT-LCD technology thus far. However, OLED technology does have some dis-

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ruptive elements. The OLED stack structure is much simpler than the structure of a TFT-LCD and that offers cost-saving potential in the long run. The amount of emissive organic material that is needed in an AMOLED display is roughly 1% of the liquid-crystal material needed for the same-sized TFT-LCD. There is no need for color filters and backlight units, and color filters are a significant cost contributor for TFT-LCDs. Currently, costs for equivalent AMOLED displays are higher due to the price of emissive OLED material and the capital costs of new production lines. However, the high OLED material costs compared to that of liquid-crystal material costs are mainly due to the huge volume advantage currently held by liquid-crystal materials. Also, the current method of depositing emissive OLED material uses evaporation technology, which unfortunately wastes a lot of expensive emissive material (see Table 1).

AMOLEDs in Small- and Medium-Sized Displays

AMOLEDs have been used in mobile-phone displays for 2 years now, and feedback from consumers has been relatively neutral. The marketing message has been difficult to create for companies that are otherwise mainly using TFT-LCD screens in their products. At this point, AMOLEDs have not been able to offer consumers any big improvement in image quality or battery life. In fact, power consumption for AMOLED screens in web applications has been higher than that in corresponding TFT-LCD screens. Outdoor readability has also been worse than for transflective TFT-LCD screens. In order to market AMOLEDs as a green technology for smart phones, the power consumption, including web applications, needs to be lower than that for TFT-LCD technology. This is, in fact, forecasted to happen by 2011.

Figure 1 shows the forecast for power consumption development by both TFT-LCDs and OLEDs in the years to come. The TFT-LCD power-consumpion reduction is mainly due to improvement in the efficiency of LEDs used in backlight units, and it is estimated to improve 10% per year. For AMOLED displays, the power consumption is dependent on content. Movie content typically uses only 10% during maximum power consumption, while web applications typically use 80% at maximum power consumption. In TFT-LCDs, power consumption has not been content dependent. However, it is possible to reduce the backlight while watching movies without creating noticeable artifacts in the image, using algorithms to reduce the power consumption by tens of percentages. In web applications, however, these algorithms do not provide significant reductions in power consumption.

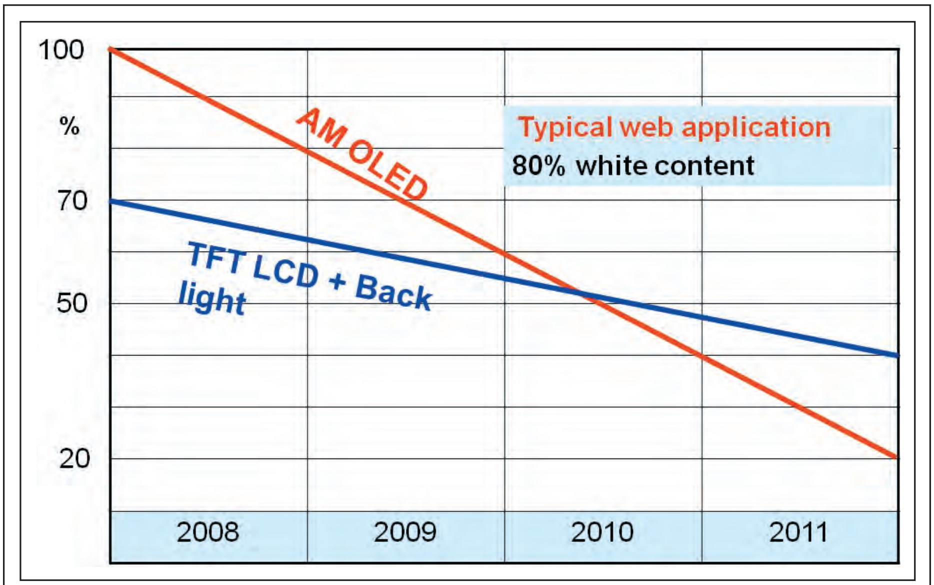

Fig. 1: Projected power consumption through 2011 shows AMOLEDs gradually using less power than TFT-LCDs.[9]

In Fig. 1, the algorithm for web content for TFT-LCDs has been used. The large power consumption reduction in AMOLEDs is mainly due to the introduction of green phos-

Table 1: Major Features of OLEDs. Source: DisplaySearch[8]

Feature	Nature of feature
Material usage	Amount of emissive OLED material equals 1% of the liquid-crystal material used in TFT-LCDs. No color filters needed in OLED displays.
Material costs	Emissive material expensive compared to that of liquid-crystal material, but no need for color filters and enhancement films.
Viewing angle	Wide viewing angle with no degradation of contrast ratio. No color change due to changing viewing angle.
Self-emitting	No backlight unit needed. Additional cost-saving advantage.
Response time	Microseconds vs. milliseconds in LCD technology. Response time remains fast under sub-zero temperature conditions.
Transparency	OLED panel can be bright and transparent. Potential new markets
Flexibility	Easier to make flexible than LCDs. This may be the killer application for OLEDs.
Power consumption	OLED power consumption has been too high for web applications, but is reaching competitive levels.
Lifetime	OLED lifetime was too short 4 years ago for potential mobile-phone customers, but is now much improved to competitive levels.[10]

phorescent emissive material. The lifetime of phosphorescent blue is not yet at commercial levels. The absolute power consumption is dependent upon selected luminance levels, and therefore only relative figures are indicated. TFT-LCDs and AMOLED displays are adjusted to provide the same perceived luminance. The pixel density in both displays is about 250 ppi.

As shown in Fig. 1, the point at which the lines are estimated to cross each other corresponds to the point in time that the power efficiency of AMOLEDs should be made better than equivalent TFT-LCD efficiency. We estimate that this can happen during 2010.

The power consumption of displays in smart phones is becoming more important becaue of two reasons. The first is that consumers prefer to look at the web from a bigger screen (while still keeping it pocket-sized), and the other is the increased time that displays need to be in active mode. This may mean hours per day. If no radical new innovations take place in TFT-LCD technology, it seems obvious that AMOLEDs will begin to achieve more and more market share in smart-phone categories. And increased volumes typically will decrease costs and prices.

AMOLEDs for TV Applications

Normal TV applications are from a lifetime point of view different from mobile-phone applications. The TV screen primarily features moving and changing imagery, and for that reason is not as susceptible to image sticking or the so-called "burn-in" phenomenon that happens over time. Therefore, concerns about lifetime and burn-in do not seem to be show-stoppers for TV applications.

Lifetime is defined to be the time when luminance has dropped to half of the original value. In the case of OLEDs, different colors have naturally different lifetime figures. Blue has clearly lower figures than red and green. This can cause white-point movement over the long run, and images become more greenish. Panel makers can compensate for the lower lifetime by increasing the size of the blue cells. This reduces current density and therefore increases pixel lifetime. However, the lifetime figures are already at such a level that this phenomenon is barely visible after 10 years of usage time. More problematic is the handling of the burn-in effect. The human eye is very sensitive when it comes to observing differences in luminance levels of adjacent pixels. A 10% difference can be easily seen, while a 50% luminance reduction over the years of a screen's lifetime is hardly noticeable.

Subtitled movies and broadcasts, however, present a different challenge. In some countries, the white text is surrounded by a black box. This provides maximum contrast, but is most problematic from a burn-in standpoint and will require further studies and simulations. An initial attempt to understand the sensitivity of the text box and broadcaster's logo for OLED applications was performed using an OLED simulator developed for mobile-phone applications. This simulator is described in detail in the 2007 SID paper "OLED Lifetime Issues in the Mobile-Phone Industry."[11] For the TV simulation, the "camera" image was used to represent subtitled movies and broadcast logos and the center part of the same image simulates the moving content. Input and results are shown in Fig. 2.

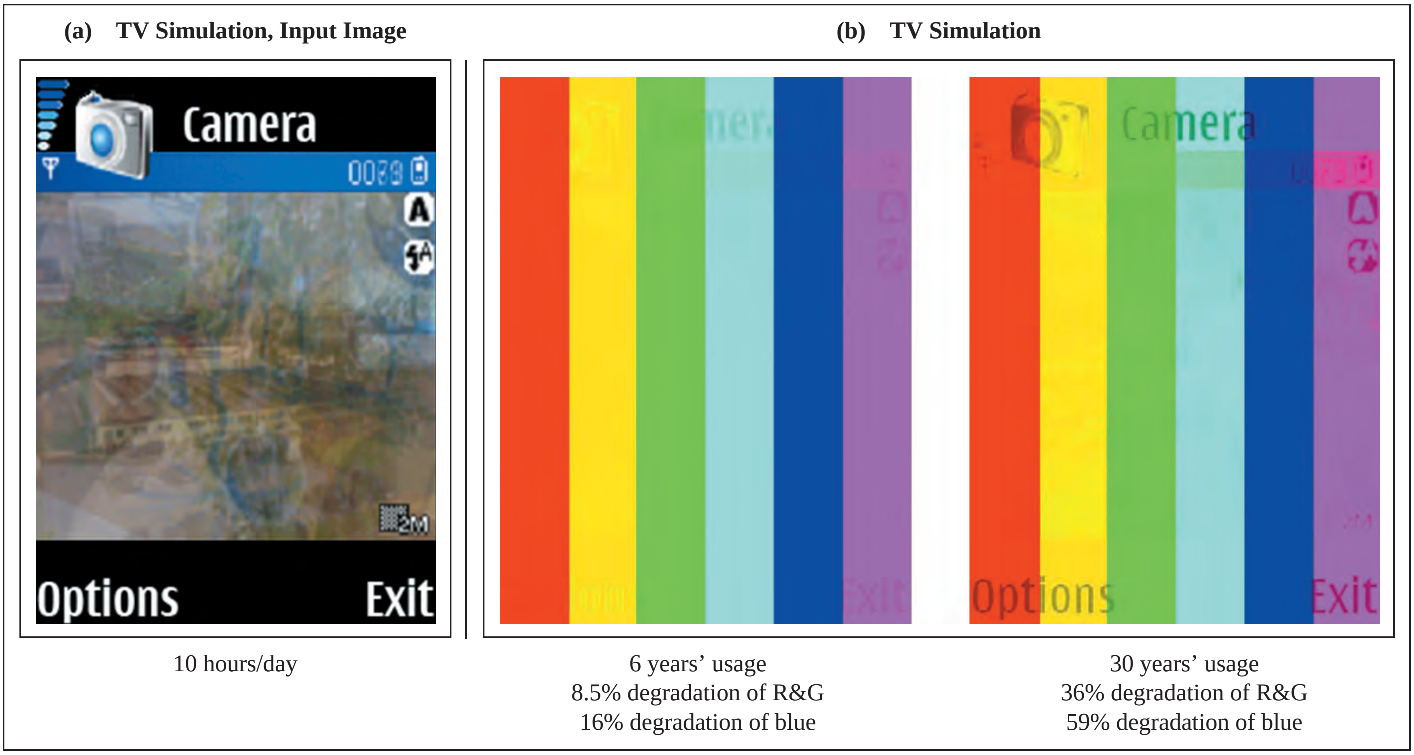

***Fig. 2:** This TV-application simulation shows (a) a test image and (b) two color-bar result images after 6 and 30 years of usage at 10 hours/day. The degradation values show how much luminance the worst pixels lost from the original.*

All the following simulations use the lifetime figures of 100,000 hours for red and green and 50,000 hours for blue. These figures are already obtainable today in panels with an output luminance of about 250 nits. It should be noted that much higher lifetime figures have already been reported, and material development companies are investing a great deal of research into increasing the lifetime figures of blue.

In both cases in Fig. 2 the TV has been "on" for 10 hours a day with subtitled movies playing all the time. The first result was obtained after 6 years of usage. A SID 2007 paper[11] demonstrated that degradation levels under 5% are hardly noticeable. However, as shown above, the degradation value of 8.5% in red and green and 16% in blue cause an annoying burn-in effect. The "Camera," "Options," and "Exit" texts can be clearly seen in the color bars. In order to limit the degradation to 5% with subtitled movies, the lifetime should be 175,000 hours for all colors or the size of the blue subpixels should be greatly increased.

The second color-bar image represents 30 years of usage. This example is mainly to show how the burn-in effect can be seen over a very long run. The tiny "2M" symbol at the lower corner of the "Camera" image and the field-strength indicator at the upper left corner are simulating the broadcaster logo. Those start to be visible in color-bar images after a usage of 30 years with today's OLED materials.

The conclusion is that subtitled movies and images, in which white text is presented in a black box, seem to be too demanding for today's OLED materials. To limit the burn-in effect to less than 5% degradation, lifetimes of 175,000 hours are needed for a usage time of 6 years. It should be noted that black-text boxes are not used in all TV networks, but this study was made from a worst-case perspective. The broadcaster logo does not seem to be problematic.

AMOLEDs in Laptops

The killer application for TFT-LCDs was the laptop computer. For AMOLEDs, the situation is clearly different. Thus far, the power consumption of AMOLEDs in web applications, which are very commonly used in laptops, has been higher than that for TFT-LCDs, and due to scalability limitations, the prices for AMOLED-based laptops have been far too high. The power-consumption obstacle looks to be solved in the near future, as shown in Fig. 1, but cost and price will remain issues for some time.

However, a preliminary simulation analysis was performed to review the laptop application from both a lifetime and burn-in sensitivity perspective. The simulator developed for mobile-phone applications was used[8] by selecting three input images and a color-bar image to show the results of a burn-in analysis. The test images and result images are shown in Fig. 3. The lifetime of emissive materials were 100,000 hours for red and green and 50,000 hours for blue.

The resulting image suffers a maximum of 4% degradation for red and green pixels and a maximum of 7% degradation for blue pixels. Burn-in effect in the resulting image (color bar) is almost invisible. The corresponding figures after 8 years of usage are 6% for red and green and 11% for blue. The burn-in effect is slightly seen after 8 years of usage. The first and second test images represent menu screen and stationary text pages, respectively, and the third one represents moving content. This needs to be further analyzed in the future, but this preliminary result already shows that laptop applications are very valid

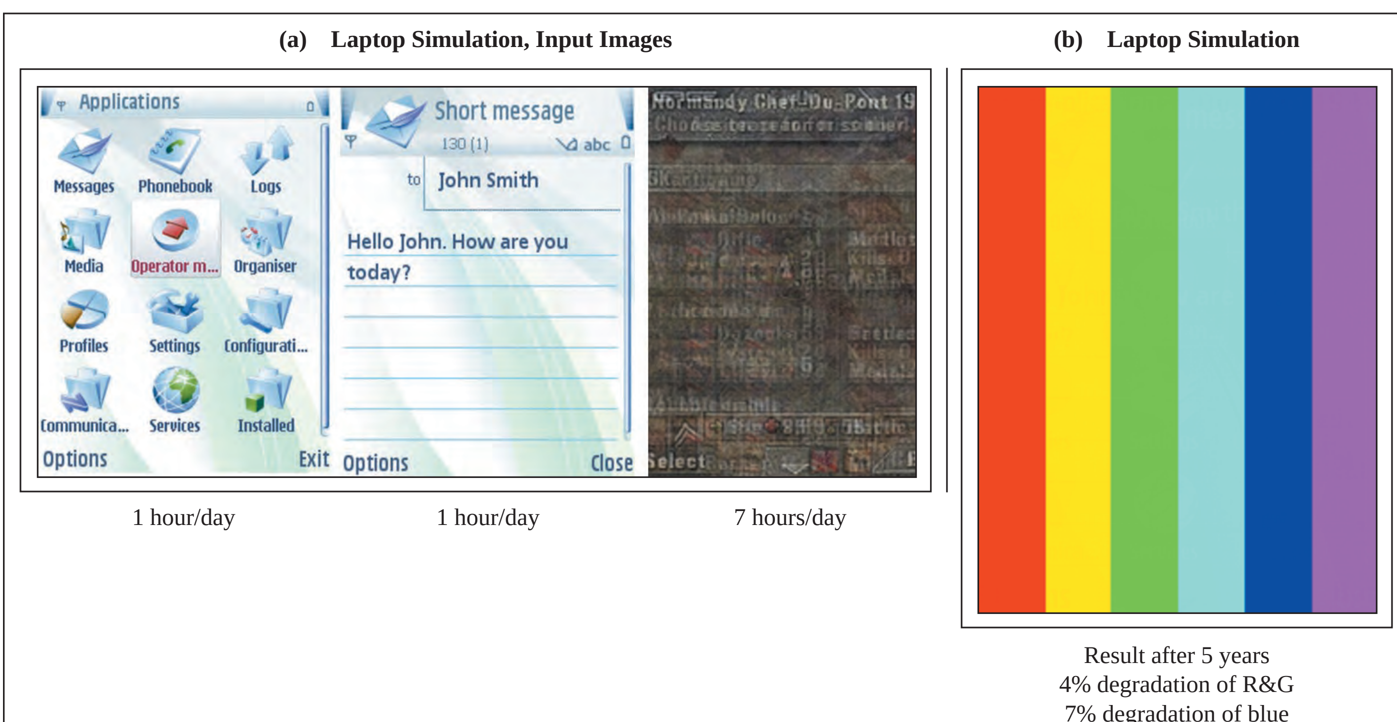

Fig. 3: These laptop test images show results after 5 years of simulated usage.

for AMOLEDs, provided that scalability issues enabling price reductions are solved.

AMOLEDs in PC Monitors

PC-monitor applications are in many ways close to laptop applications, except that power consumption is not so critical, and the PC monitor business is more price-sensitive than the laptop business. Usage-time expectations of PC monitors are longer than in laptops. In PC monitors, the screen typically goes to screen-saver mode if there is no activity. This is a good practice from an AMOLED point of view, as long as the screen saver is not using a stationary image. The same tool[8] was used to simulate PC monitor usage from an AMOLED burn-in perspective.

Degradation values have increased to 9% for red and green and to 16% for blue pixels. The runtime in Fig. 4 was 10 years. The burn-in effect caused by text input is now visible. The degradation results after 6 years of usage are 5% for red and green and 10% for blue. The burn-in effect is not easily noticeable.

OLEDs in Lighting

Recent developments in the efficiency of emissive materials have opened totally new applications to OLEDs. The linkage between AMOLEDs and emerging OLED-lighting ecosystems is the development of highly efficient emissive materials and the optimal solution to outcoupling efficiency issues. OLED lighting will be in many ways a very disruptive technology, much more than OLEDs in the display industry. It will afford architects and interior designers totally new ways to design lighting. Instead of point light sources, distributed light panels can be used, including color variations. Also, this disruptive technology is coming from the high-end side, meaning that it does not involve the creation of new markets, but will disrupt the way in which lighting is designed in homes and in public places in the future. It can be assumed that lifetimes over 100,000 hours will be obtained, resulting in 23 years of operational lifetime, if the lighting is used an average of 12 hours per day throughout the entire year. Maintenance and repair issues need to be taken into account, but those most probably will not be any kind of showstoppers. The reduction of illumination to half its value might be observable, reducing the operational lifetime to 10 years or requiring 200,000-hour half-lifetimes. We may even see OLED lighting used in the backlight units of TFT-LCD TV screens before AMOLED scalability issues are solved. LED lighting will be used to replace light bulbs and halogen lamps in the near future for power-saving reasons, but OLED lighting will bring about a new way to design lighting.

Conclusions

TFT-LCD and OLED case studies have shown that many elements of the industry follow or are forecasted to follow Christensen's disruptive theory.[9] To make the theory comply with case studies for the display industry, an extension – high-end disruptions – is proposed to be added as the third element of the set of definitions concerning disruptive innovations. Examples from the display industry show that disruptive technology can come to the business ecosystem also from the high-end side, *i.e.*, more expensive in the beginning, but offering something customers appreciate and are ready to pay more for. For example, a wall-mounted flat TV was a dream of people for a long time, and TFT-LCD TVs were able to come close to living that dream. Now, LED-based TFT-LCD TVs are flater, and OLED-based TV will bring even thinner structures, brilliant colors, and contrast with

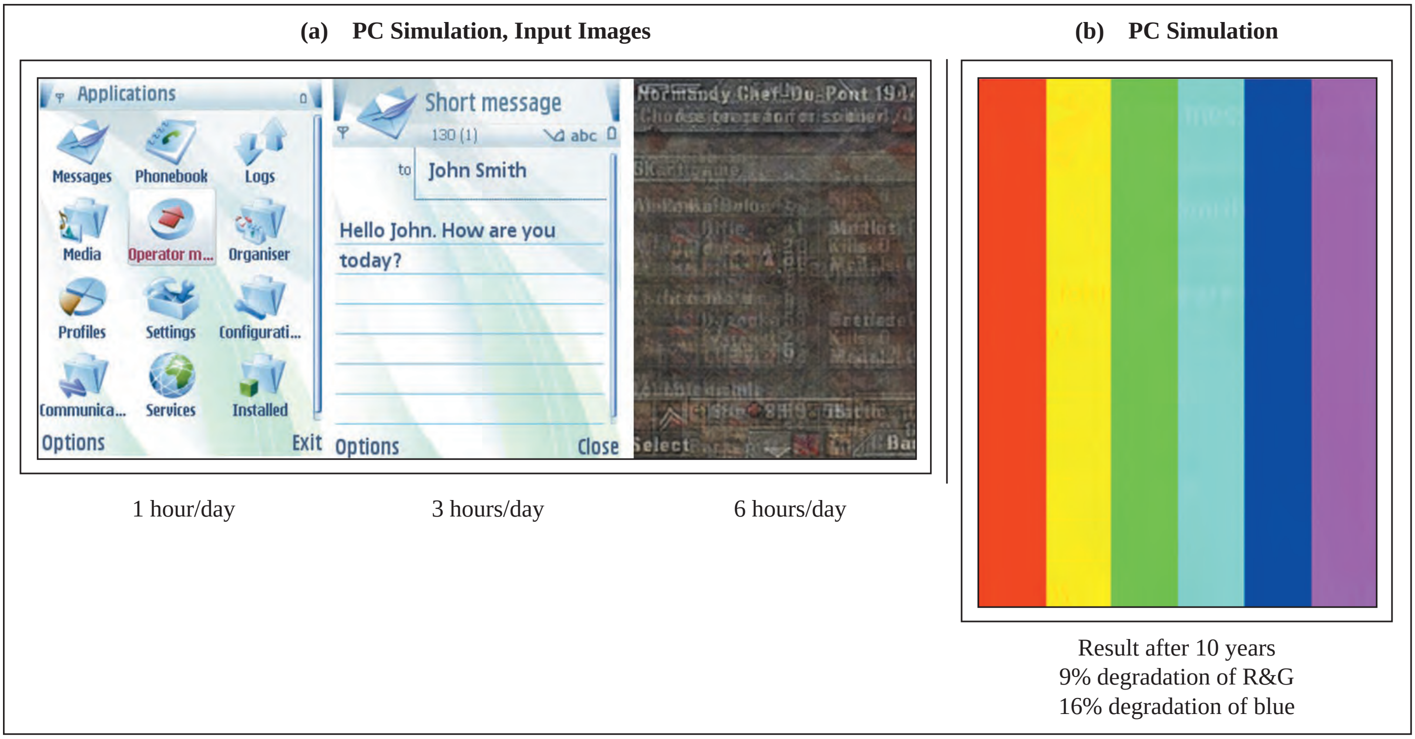

Fig. 4: Test images demonstrate PC monitor results after 10 years of usage.

a wide viewing angle and low power consumption.

The inventions that produced TFT on glass and combined that with liquid-crystal cells formed a disruptive innovation in the late 1970s. These innovations took place in the U.S. and in Europe, but Japanese companies were still able to take the lead in TFT-LCD technology and disrupted the entire display industry in the U.S. and in Europe. The killer application for this disruptive technology was notebook computers. Costs at the time were much higher, but the flatness of the screen was something consumers would pay more for. TFT-LCDs disrupted the CRT business with lower quality, but with a higher cost structure.

AMOLEDs have disruptive elements and are challenging the TFT-LCD ecosystem from the high end with lower power consumption, brilliant colors, a wide viewing angle that does not cause a loss in contrast ratio, and a thin and simpler structure. Displays will be for some time more expensive, but in the long run OLEDs seem as if they will be less costly to produce than TFT-LCDs. The competitive advantages seem to support AMOLEDs in taking a substantial market share, first in small- and medium-sized displays for hand-held devices. AMOLED power consumption is, however, dropping below the corresponding TFT-LCD power-consumption figures in demanding web-page applications. This will enable manufacturers to create a green marketing message and will enable smart-phone manufacturers to design AMOLEDs into their products in larger volumes than that to date.

A further observation is that AMOLEDs are ready to be used in laptops and in PC monitors as soon as scaling can enable cost reductions. Lifetime and burn-in sensitivity are close to acceptable levels based on the preliminary analysis reviewed here. However, more studies and simulations with laptop-oriented content are required. The same observation is valid in the case of the PC monitors. Lifetime and burn-in sensitivity do not seem to be obstacles in taking AMOLEDs to this market.

A preliminary study was also performed for TV applications. Moving content and the logo of the broadcaster do not seem to be problematic from a lifetime and burn-in sensitivity perspective, but black text boxes with white letters will make the worst possible contrast for the screen and will require a further increase in the lifetime of the emissive material or a reduction in the contrast by some other means in the smart receiver itself.

In short, the key OLED technology elements with the potential for disruption (as compared to TFT-LCD technology) are the use of active materials and the ability to achieve lower power consumption by 2010. Another possible disruption may occur in the area of lighting. All of this, of course, relates to the green aspects of the technology, which will almost certainly drive the OLED ecosystem of the future.

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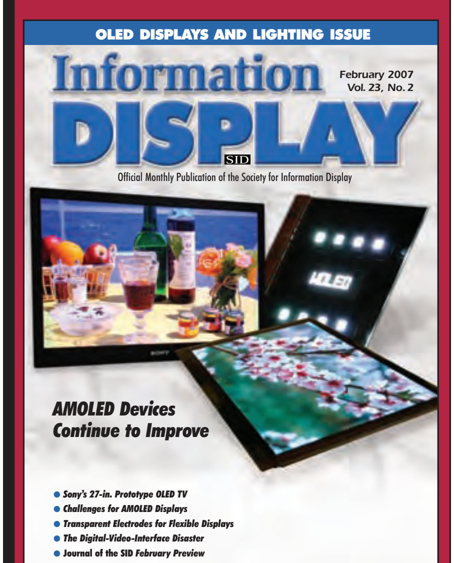

OLEDs – Promises, Myths, and TVs

Much work remains before OLEDs can be considered a player in the display and lighting markets. Among the necessary success factors are mass manufacturing that delivers high yields at competitive costs and a willingness on the part of companies to pursue the technology. But the trends are positive. OLED performance for TVs is outstanding and power consumption is low. Moreover, OLED lighting offers new opportunities in high efficiency, unique form factors, and "relaxing" color temperatures. If the companies practicing the technology follow through with their plans, we should begin to see new competition for TFT-LCDs and LED lighting in the next 3 years.

by Barry Young

IN THE EARLY 1950s, A. Bernanose and co-workers first produced electroluminescence in organic materials. Ching Tang and Steve Van Slyke of Kodak discovered how to produce this light efficiently in the 1980s. But organic light-emitting-diode (OLED) technology came to prominence in the late 1990s when Pioneer delivered its initial product – an area-color display for a car radio – and Nobel Prize winner Dr. Alan Heeger, founder of Uniax, declared OLEDs to be the next great disruptive technology. The availability of a real product and the claims of high contrast ratio, microsecond response time, low power consumption, fully saturated colors, low cost, and thin form factors set up enormous expectations for a technology that appeared to have the potential to displace thin-film-transistor liquid-crystal displays (TFT-LCDs) in virtually every market segment, including small-to-medium and large-area displays and microdisplays. The early delivery of commercial displays set the stage for rapid growth as entrepreneurs in Taiwan and South Korea rapidly joined the field.

***Barry Young** is Managing Director of the OLED Association (http://www.oled-a.org/). He can be reached at barry@oled-a.org.*

The Hype Phase: PMOLED Displays

Between 1999 and 2005, more than 20 companies in the U.S., Europe, and Asia invested a total of over $2 billion to build and staff passive-matrix organic light-emitting-diode (PMOLED) fabs in the hopes of replacing LCDs with PMOLEDs. These companies opened and closed faster than a swinging door in their search for the elusive killer application and manufacturing process. Among the areas of focus were mobile phones, MP3s, MP4s, and automobile consoles, as well as the idea of printing on flexible backplanes. In the end, only five companies remained in the OLED business – Pioneer, RiTdisplay, TDK, Univision, and Nihon Seiki, all using vacuum thermal evaporation (VTE) on glass and making primarily monochrome and area-color displays 2 in. or less on the diagonal.

The PMOLED manufacturers were undone by several factors, including a market limited to 2-in. and smaller displays (due to the constraints of passive-matrix multiplexing), rapid price reductions for passive-matrix LCDs (PMLCDs) and active-matrix LCDs (AMLCDs) as competition peaked in 2005, and high voltages caused by the driving method, which restricted battery life in mobile applications. These passive-matrix displays also brought about a long-term negative marketing effect because the high voltages (>10 V) and high current density (J) of low-efficiency early-stage materials led to short lifetimes of ~5000 hours. These lifetimes were not an issue for the types of products that were being fabricated, but created ongoing concerns about OLED lifetimes in general. In fact, such concerns remain to this day, even though lifetimes now exceed 50,000 hours. Revenue for PMOLEDs peaked in Q1 '04 (see Fig. 1) and has been on a downward trend ever since. Manufacturers are selling more displays for less revenue, vitiating the Y/Y positive unit growth.

Display makers soon determined that the market opportunity lay in high-end active-matrix displays, but for these, LTPS backplanes were necessary in order to meet the mobility needs of OLEDs as well as their high-current-density requirements. Early attempts to use a-Si failed. None of the LTPS manufacturers were willing to sell backplanes at a "reasonable" price, so the passive-matrix manufacturers were unable to change their business plans. (For additional discussion of backplane technologies, see "Emerging Technologies for the Commercialization of AMOLED TVs" in this issue.)

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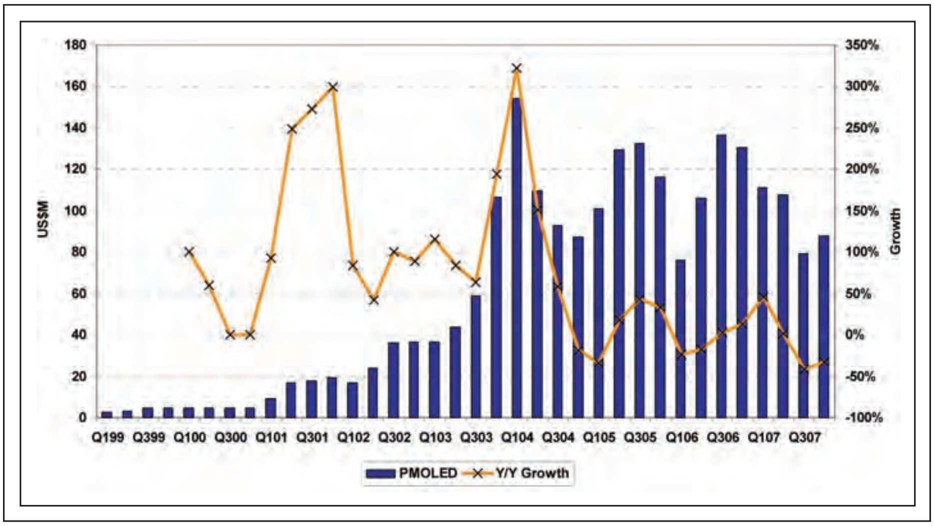

Fig. 1: *PMOLED US$ revenues peaked early in 2004 and have not caught up since. Source: DisplaySearch.*

Only TFT-LCD manufacturers had the capital and/or the facilities to make low-temperature polysilicon. But their road was not without constraints. To begin with, the start-up volumes were low due to the use of second-generation fabs. Next, the appeal of higher performance and thin form factors came at a price premium, and new OLED fabs had to compete with fully depreciated TFT-LCD fabs, which increased the cost premium of OLED displays by ~20% compared to that of LCDs.

Kodak recognized this situation early on and developed a multi-phase strategy that included entering into an alliance with Sanyo, one of the leading LTPS suppliers; developing new materials that included device architectures, new deposition tools, and solutions to LTPS yield problems; and creating barriers to entry from other parties by setting the licensing and royalties at unsustainable levels. Sanyo/Kodak gave up in 2005 after failing to achieve its goal of US$500 million in sales. Sanyo elected to minimize the damage and sell its fabs to Epson, while Kodak retrenched into selling material and licenses.

Making Headway

These days, AMOLED display makers are on the right track, having resolved the yield issues for LTPS and also having achieved production know-how for full-color displays. Samsung established a new venture to concentrate on AMOLEDs and staffed the new company with senior managers from its LCD and other groups. Samsung Mobile Display (SMD) is now the industry leader with the only fourth-generation LTPS facility for AMOLEDs and a half-fourth-generation (730 × 460) OLED fab. SMD produces small-to-medium displays for mobile phones, digital cameras, personal media devices, and netbooks up to 5 in. on the diagonal. The production capacity is 1.5 million 2-in. displays per month and that will be extended to 3 million 2-in. displays per month in 2009, and possibly 5 million displays per month in 2010.

Sony, LG Display, and Chi Mei EL (CMEL) also produce AMOLED displays but have a limited capacity of fewer than 100,000 2-in. displays per month. These companies are expected to expand their capacity in 2009 and 2010. TMDisplay, AUO, TPO, and Panasonic will also likely initiate production of AMOLEDs over the next 1–3 years as they sharpen the practice of making high-yield high-performing OLED displays.

Reality and TVs

The long-term opportunity for AMOLED technology is TVs, where OLEDs shine. Sony, Panasonic, LG Display, and SMD have demonstrated TV prototypes of 25 in. and larger. What has particularly intrigued industry watchers is the potential created with Sony's late 2007 release of the XEL-1, an 11-in. OLED TV that titillates the visual taste buds of both photonics experts and consumers. Virtually without exception, anyone seeing this TV compared to a TFT-LCD or plasma-display-panel (PDP) TV found that it outperformed these technologies by a wide margin in terms of both image quality and form factor. It has by far the thinnest of form factors in the industry. In addition, OLED TVs appear to have the deepest blacks, the highest contrast ratio, the fastest response time, the widest viewing angles, and the lowest power consumption.

In short, the killer application for OLEDs is the "old" TV. But to compete in the TV market, OLEDs have to continue to progress in the following areas of both technology and manufacturing:

1. ***Scaling the backplane.*** Building a cost-competitive TV in the sweet spot of the market (32–42-in.) requires a seventh-generation or larger substrate size and starts of 50K units per month to meet the economic size constraints of display manufacturing. LTPS, which currently maxes out at fourth generation, will likely top out at fifth or sixth generation. What is needed is a-Si or a comparable substitute (see "Emerging Technologies for the Commercialization of AMOLED TVs" in this issue.)
2. ***Scaling the OLED deposition and patterning process.*** The only commercial process available today is VTE through a fine metal mask (FMM). These systems are currently no larger than 730 × 460 (half-fourth-generation) and are also expected to max out at fifth or sixth generation. But new approaches in terms of printing and vertical substrate handling promise to overcome these limitations.
3. ***Improving the efficacy and lifetime of the blue material.*** The lifetime for material has been ~50K hours to T50 (time to reach 50% of initial luminance). Material makers are demonstrating lifetimes in excess of 100K hours for red and green and greater than 50K hours for blue with an initial luminance of 1000 cd/m^2. TVs typically operate at 500 cd/m^2, so there is significant head room. Techniques such as outcoupling and triplet emitters (phosphorescence) are being used to dramatically increase energy efficiency. White-OLED devices and luminaires have already been demonstrated that deliver >100 lm/W, which is competitive with inorganic

LEDs that have efficacies of >100 lm/W for devices but only approximately half that for luminaires. Unlike inorganic LEDs, the OLED luminaire delivers the same efficacy as the device because for OLEDs the device effectively is the luminaire.

4. ***Developing more-efficient material deposition and patterning tools.*** The current VTE process with a FMM yields only 3–4% of the material. Most of it remains on the mask because the typical process uses one mask each for red, green, and blue, putting the maximum utilization efficiency at 33%. Today's single-point source also wastes much material because of the distance from the mask. While the low material utilization efficiency is not an issue for small displays, it is a significant cost issue for large ones. Costs for components such as color filters, electronics, and backlights do not scale with size, but organic material does. Several solutions are being developed, including replacing the single source with multiple sources to reduce waste, printing only the exact amount of material required for each subpixel, and eliminating the FMM and using white with a color filter.
5. ***Gathering the capital.*** Perhaps the most challenging issue for the industry is convincing management that an investment of US$1–3 billion or more will have a payoff, especially in the current environment of excess capacity and falling prices.
6. ***Expanding into other large-area applications.*** One of the advantages TFT-LCDs have over PDPs is the wide product range. Although TFT-LCDs enjoy a higher price per square inch for notebooks, monitors, and small-to-medium displays, the price per square meter is significantly less for TV panels in order to compete with PDP displays that operate in only one high-volume market – TVs. The specifications for notebooks and monitors offer significant challenges to OLEDs due to the use of applications such as Word, Excel, the Internet, and e-mail, where 60–70% of the image is white space. This puts the power consumption for OLEDs at a significant disadvantage. TV applications use very little white space and average less than 30% of white across the image.

The forecast for OLED-display revenues is dependant on the number of suppliers that will produce large-area displays and invest in generation six and larger fabs. The small-to-medium market is expected to grow from approximately US$800 million in 2008 to over US$4 billion by 2015. But the large-area market is dependent on the actions of SMD, CMEL, Sony, LG Display, Panasonic, and AUO. The following forecast shows the revenue based on up to five of these six companies entering the market. If five do enter the market, the revenue could reach almost US$14 billion by 2015 (see Fig. 2).

Reaching Maturity

OLEDs are now reaching maturity and should begin to achieve their early market promise. The keys to growth in OLED market capture are continuous improvement in the following:

- ***Efficiency*****:** This is currently at 20–30 cd/A and growing to 50–60 cd/A, which will reduce the switching voltage and therefore the power consumption. A typical 3-in. OLED display for a mobile phone uses ~250 mW, but by increasing the efficacy to 50–60 cd/A, the power consumption will decrease to <150 mW, which should compete favorably with the 300–400 mW of TFT-LCDs.
- ***Lifetime*****:** Lifetimes for saturated colors are 250,000 hours for red, 150,000 hours for green, and 50,000 hours for blue. These lifetimes are forecast to grow over the next 3 years, putting lifetimes at >100,000 hours at 1000 cd/m^2; significantly exceeding the performance of either LC or PDP displays.
- ***Printing*****:** New approaches to making small-molecule material soluble are expected to lead to slot-printing techniques, which have been demonstrated to be over 70% effective in material utilization, and ink-jet printing may yet prove productive for polymer materials in this new environment.
- ***Backplanes*****:** a-Si is beginning to look more feasible as demonstrated by IGNIS Innovation, which has developed proprietary compensation techniques that adjust for both TFT and OLED performance reductions in real time, and Samsung Mobile Display, which has developed inorganic devices that have sufficient mobility, reliability, and uniformity to support OLEDs.

Other Uses for OLEDs

Perhaps the kicker in the future will be the use of flexible substrates, which will allow new display formats that can be curved or even rolled, creating new uses for displays. It is likely that lighting, not displays, will be the first application for flexible OLEDs because the backplane requirements are significantly less stringent. OLEDs may soon enter the fast-growing solid-state-lighting market, with complementary tools and device architectures

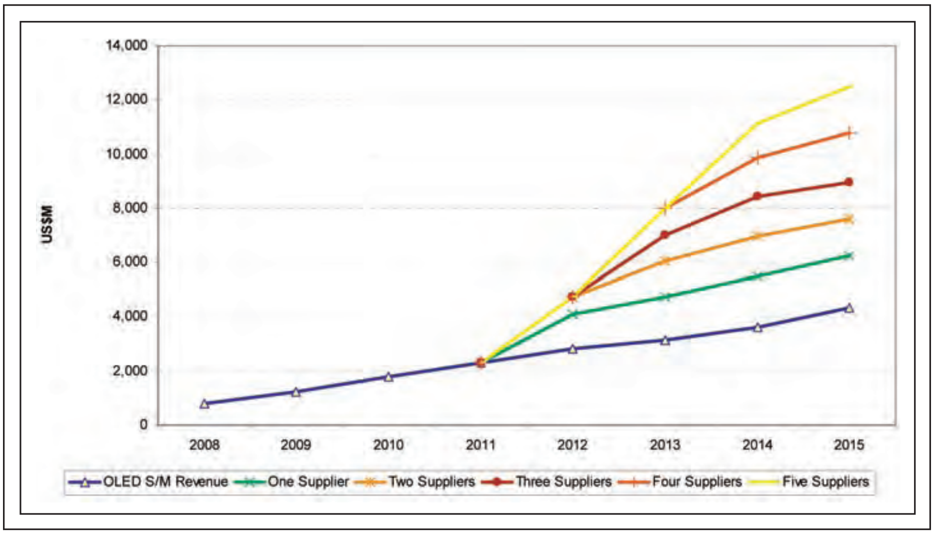

Fig. 2: *OLED revenue forecasts increase steeply as additional companies enter the market. Source: OLED Association.*

such as roll-to-roll manufacturing with flexible substrates as demonstrated by GE, low-temperature white panels from Philips and OSRAM, and new outcoupling techniques that double the useable light.

OLEDs are expected to join inorganic LEDs as replacements for incandescent, fluorescent, and high-brightness lighting applications. LEDs have a significant lead in terms of maturity and are strong producers of spot lighting, but can be configured for area lighting. OLEDs are excellent area-lighting replacements for fluorescent lighting because they are more efficient than fluorescent bulbs, last longer, and contain no toxic material, *i.e.*, mercury.

There have been some announcements of organic solar-energy usage to compete with silicon and thin-film photovoltaics, but the efficiency is well below existing silicon or thin-film approaches. It appears to be too early to judge whether OLEDs can be competitive in this application.

Summary: Learning the Manufacturing Game

Much work remains before OLEDs can be considered a player in the display and lighting markets, but demonstrated performance in terms of black level, contrast ratio, efficacy, and lifetime is competitive in today's environment and should improve by 2–4 times over the next 10 years. What remains is for mass manufacturing to deliver high yields at competitive costs and for companies to be willing to pursue the technology.

In reality, OLED displays are not a threat to TFT manufacturers; they are just an extension of thin-film technology. OLEDs replace the liquid crystal in a display but keep the expensive thin-film technology and the electronics. OLEDs are just another level of device architecture growth, the way VA and IPS improved upon TN-LCDs. TFT manufacturers should thus reap the benefits of a range of new technology created by chemists and chemical engineers. ■

Emerging Technologies for the Commercialization of AMOLED TVs

Advances in AMOLED materials, device structures, and manufacturing are paving the way for a new generation of TVs that will be interactive, ultra-light and slim, eco-friendly, and more.

by Hye Dong Kim, Hyun-Joong Chung, Brian H. Berkeley, and Sang Soo Kim

SINCE THE FIRST market emergence of black-and-white CRT TV in 1937, the evolution of TV technology has accelerated with increasing demands for better picture quality and realistic image reproduction. It took more than 30 years for color TV to replace black-and-white CRT TV. Then 20 years later, demands for larger and flatter screens resulted in flat CRT and projection TV being introduced to the market. About 15 years later, the high-end market was revolutionized with the launch of flat-panel displays based on plasma and liquid crystals. In particular, LCD technology, which dominates the TV market these days, is further evolving with the adoption of high-speed driving and LED backlights that enable slim TVs with low power consumption.

Active-matrix organic light-emitting diodes (AMOLEDs) are ideally suited for future TV applications because of their superb image quality, digital addressing, and self-emissive nature. AMOLEDs are rapidly expanding their market share for small-sized mobile applications since their mass production launch in 2007. In addition, exhibitions of Sony's 27-in.[1] and Samsung's 31-in.[2] and 40-in.[3] AMOLED TV prototypes have resulted in massive "wow factor" recognition from experts and the public.

In this article, we will review the technological challenges with regard to mass commercialization of AMOLED TVs, as well as the emerging technologies that will overcome these challenges.

The authors are with the OLED R&D Center, Samsung Mobile Display Co., Ltd., San #24 Nongseo-Dong, Kiheung-gu, Yongin-si, Gyeonggi-do 446-711, Korea.

AMOLED: The Ultimate Solution for Future TV

The basic and most important feature of TV is the ability to faithfully reproduce real images. With the launch of high-definition digital broadcasting, viewers can now enjoy a vivid presence from large flat-panel-TV screens. As a result, perceptual image quality, which is the reproduction of real color and motion features, has become more important than measures such as contrast, luminance, and color gamut. Because AMOLEDs are self-emitting, light emission can be controlled for each pixel at extremely high speed. Therefore, AMOLEDs are intrinsically capable of expressing high contrast, blur-free motion features, vivid colors, and wide viewing angle. Old color-gamut models cannot express these perceptual image qualities; thus, new standards, such as CIECAM02, the most recent color appearance model ratified by the C.I.E. (http://www.cie.co.at/index_ie.html), have been suggested. Figure 1 compares the perceptual image qualities of OLEDs and LCDs. AMOLEDs can produce more vivid images at low brightness due to their high contrast ratio and peak luminance. These advantages result from the deep-black background and self-emitting nature of OLEDs.

The global environmental crisis has gained attention recently, and for geopolitical and economic reasons, many countries are legislating green policies. Naturally, TVs are also required to be eco-friendly. The environmental compatibility of flat-panel displays can be categorized into each of the areas of components, manufacturing processes, and power consumption. AMOLEDs offer advantages in each of these areas.

From a component point of view, AMOLEDs are intrinsically eco-friendly because they do not contain backlights or color filters and do not require many other optical components. Removal of the backlight provides the additional advantage of a slimmer and more lightweight panel, creating a more eco-friendly product as a result of reduced energy consumption for transportation. In addition, AMOLED panel components are free from toxic materials, such as Hg and Cd, whose application is prohibited by RoHS regulations.

For the manufacturing process, the key to eco-friendliness lies in minimal production of waste by-products. For example, wet-etch and spin-coating processes waste large

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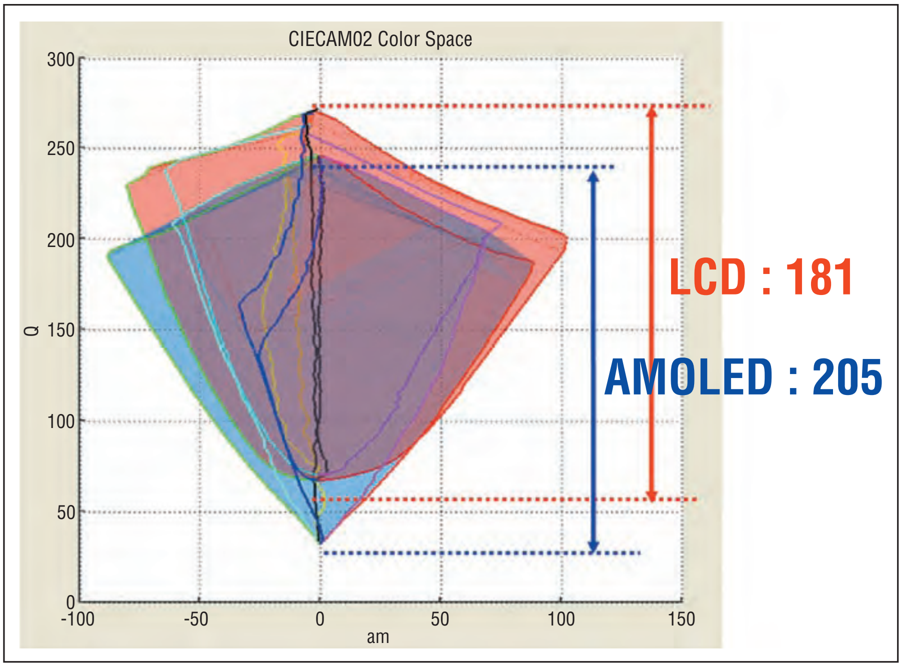


Fig. 1: Perceptual contrast-length comparison of LCDs and AMOLEDs expressed on CIECAM02 color space. The luminance values of LCDs and AMOLEDs are 256.3 and 189.9 cd/m², respectively. It is notable that only 110.9 cd/m² is required for AMOLEDs to achieve the same perceptual contrast length as LCDs. Source: Samsung.

amounts of chemicals, whereas ink-jet printing results in good material usage efficiency. OLEDs are advantageous from an environmental point of view because their manufacture makes use of direct-patterning processes such as shadow masks and printing.

In terms of power consumption, AMOLEDs have a great advantage over LCDs built with "always-on" CCFL or edge-lit-LED backlights. In an AMOLED, each pixel is individually controlled, and light is only generated if it is actually needed for the display. Furthermore, there is still significant opportunity for further reduction in AMOLED power consumption. For example, phosphorescent light-emitting materials represent an exciting recent development in OLED technology. If phosphorescent emitters can replace current fluorescent emitters, an extremely power efficient (<15 W) 40-in. TV could be possible by 2012, according to Universal Display Corp. (Fig. 2).

Technological Challenges for AMOLED TV

In recent exhibitions, Sony and Samsung displayed the potential of AMOLED TV by making the largest size possible on their pilot lines (27-in. for 3G and 40-in. for 4G, respectively). For mass production, however, AMOLED TVs must be manufactured at a cost that competes with LCD TVs. Current AMOLED mass-production lines employ an excimer-laser-annealing (ELA) based poly-Si TFT backplane, a shadow mask for color patterning, and edge sealing for encapsulation on a 3.5G-sized (460 mm × 730 mm) motherglass.

The biggest hurdle for commercially viable large-sized AMOLED TV is the need to increase the motherglass size. In order to compete with the cost of LCD TVs, multiple panels must be fabricated on a single motherglass, and 8G (2200 mm × 2500 mm) or larger glass is desired. Existing mass-production technologies, however, face limitations in scaling up to this size; therefore, new methods are required.

Emerging Backplane Technologies

OLEDs are current-driven devices, which places additional requirements on the backplane, including precise control of current and high-threshold-voltage stability. Low-temperature poly-Si (LTPS) TFT backplanes fabricated by ELA are currently employed in

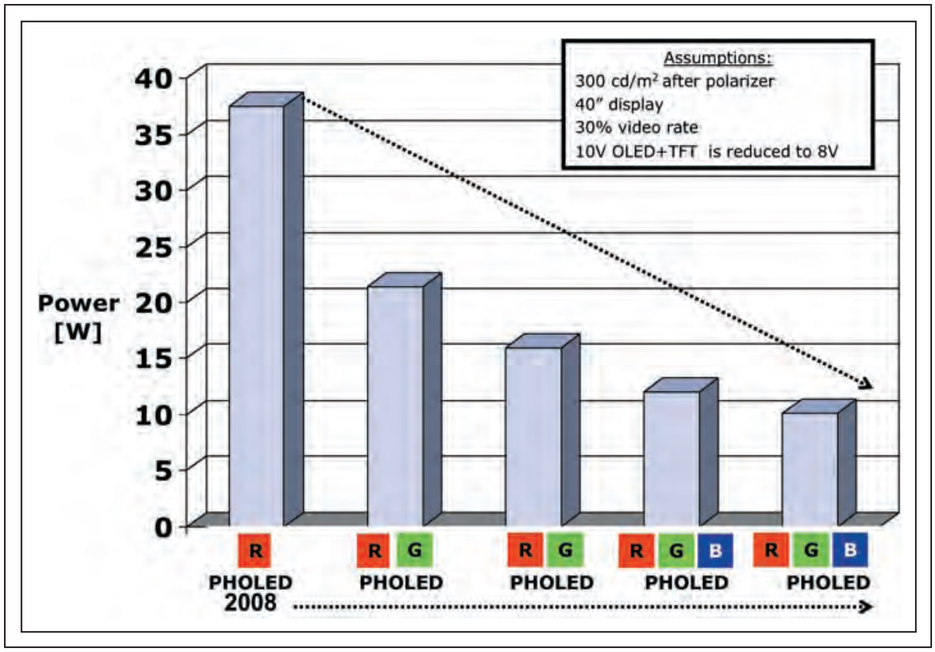


Fig. 2: Above is a power-consumption roadmap for a 40-in. AMOLED panel based on expanded incorporation of phosphorescent OLED (PHOLED) technology over approximately 5 years. Source: Universal Display Corp.

the mass production of AMOLEDs, owing to their excellent TFT performance and device stability. However, uniformity and scalability issues create challenges for the use of ELA in large-area applications. For example, laser-power fluctuation can cause image non-uniformity, and a finite laser-beam length restricts process scalability. Moreover, ELA-based LTPS TFTs require many (8–11) masks compared to the number of masks required for LCDs (4); thus, ELA-based LTPS is less cost-effective and less eco-friendly.

Because laser equipment is expensive and can present maintenance problems, generally, non-laser crystallization techniques are believed to have greater potential for large-sized AMOLEDs. One of the simplest non-laser methods to increase mobility of amorphous-Si (a-Si) film is conventional solid-phase crystallization (SPC). But SPC usually requires high-temperature (>650°C) annealing for a relatively long time, and thus can be harmful for large-area glass substrates. One way to reduce the crystallization temperature is to apply metal atoms as crystallizing seeds on the a-Si surface. However, these metal seeds can contaminate the channel area and thus may result in large current leakage. Moreover, the grain size from this method is usually small and irregular, resulting in lower mobility and high grain-boundary-induced leakage current. In order to circumvent these drawbacks, the super grain silicon (SGS) method has been suggested.[4] SGS employs a sacrificial capping layer on the a-Si layer before seeding metal deposition, followed by annealing to diffuse metal atoms to the a-Si surface through the capping layer. However, the application of SGS is challenged by its complicated process and production yield.

Amorphous-oxide TFTs have great potential to scale up size. Basically, oxide TFTs combine the merits of a-Si and LTPS TFTs.[5] For example, oxide TFTs are free from the non-uniformity problem that comes from the polycrystalline nature of LTPS, while their device performance is reasonably good with large carrier mobility (~10 cm^2/V-sec) and excellent sub-threshold gate swing (down to 0.20 V/dec). Moreover, the channel layer can be formed by a simple sputtering process without further crystallization steps; thus, the fabrication process can basically be identical to that of a-Si TFTs for LCDs. For this reason, existing a-Si production lines can easily be converted without significant change. In addition, oxide TFTs can be deposited at room temperature; thus, cheap soda-lime glass or flexible plastic substrates can be used in principle. However, device instability issues need to be addressed in order for oxide TFTs to be used for AMOLEDs. As is well known, oxide semiconductors are sensitive to oxygen and moisture, and for this reason they have long been used as sensor materials. Therefore, environmental control during the production process and proper passivation techniques are required for oxide TFT fabrication.

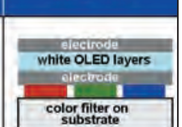
	Evaporation (precision shadow mask)	Solution Printing	Laser Printing	White + CF
				
Materials	Small molecule	Soluble materials	Soluble material Small molecule	Small molecule
Printing accuracy	±15um	±10um	±2.5um	±2.5um
Maximum resolution	~250ppi	~200ppi	300~400ppi	300~400ppi
Material usage efficiency	10-20%	80-90%	20-30%	60-80%
Glass size	Production: 460mm x 730mm Development: 730mm x 920mm	Development: 730mm x 920mm	Development: 730mm x 920mm	Development: 730mm x 920mm
Equipment price	Very expensive	Cheapest	Medium	Medium
Status	In production	In development	In development	In development
Issues	Large size Tact time	Materials Life time Yield	Materials Life time Yield	White materials Life time Yield

Fig. 3: AMOLED color patterning technologies include evaporation, solution printing, laser printing, and white and color filters.

Emerging OLED Patterning Technologies

Shadow-mask technology, also known as fine metal mask (FMM), is currently being employed in the mass production of AMOLEDs. However, FMMs are prone to sagging problems when applied to large-sized motherglass because the masks are made by metal films that are too thin (50 µm) to be used over a large area. In addition, FMMs have other issues such as pixel-size variation by ±10 µm, shadow effects due to non-zero metal thickness, and alignment accuracy between the mask and substrate. Frequent mask cleaning is also required to maintain pattern quality. An alternative solution could be to use white OLEDs with color filters. However, the white-OLED approach sacrifices some of the advantages that come from the self-emissive nature of OLEDs; thus, this approach is not an optimized solution for large AMOLEDs. For this reason, emerging OLED patterning technologies, including ink-jet printing, nozzle printing, and laser-induced printing, are receiving a great deal of attention for potential application to large AMOLEDs (Fig. 3).

Among the laser-induced printing techniques, laser-induced thermal imaging (LITI),[6] radiation-induced sublimation transfer (RIST),[7] and laser-induced pattern-wise sublimation (LIPS)[8] are currently under development for mass production. These technologies are in principle very similar in the sense that the patterns are transferred from a donor substrate to the active-matrix backplane by local heating using laser beams. The major difference is that LITI transfers the OLED layer from a conformable donor film by local melting, whereas RIST and LIPS use a glass donor substrate and the transfer occurs by sublimation of materials while the gap between the donor and the active-matrix backplane is in vacuum. Current issues from these laser technologies are thermal damage, process stability, and process yield.

Direct-printing methods, such as ink-jet and nozzle printing, use solution-based OLED materials. These approaches have the potential to be the most cost-effective and eco-friendly because they exploit complete use of the OLED materials. However, solution-based OLED materials are often very expensive. Compared to evaporation-based materials, solution-based materials face a serious disadvantage, which is that OLED lifetime is extremely sensitive to impurities, film quality, and environmental conditions. The development of high-performance soluble OLED materials is the biggest challenge for the use of printing for OLED patterning.

Encapsulation Issues

For reliable operation and long-term performance, OLEDs must be encapsulated. For small-sized AMOLED devices, edge-sealing encapsulation is adequate for the fabrication of reliable panels. However, for large devices, edge sealing has some serious problems, including delamination, sagging, and breaking of the encapsulation glass by external stress. In order to prevent breakage and to improve mechanical reliability, new techniques are currently under development, including filling the gap between the AMOLED and encapsulation glass and the use of non-etched glass. Challenges for these techniques include the development of liquid filler material and film-lamination technology.

Thin-film encapsulation (TFE) can provide another interesting solution for large-area encapsulation.[9] Instead of using encapsulation glass, TFE employs layer-by-layer deposition of thick films with compensating diffusion barrier properties. The biggest merit of TFE is that it enables a single glass display, in turn enabling extremely slim and flexible panels. Challenges for TFE include material optimization, minimization of stacking layers, and applicability to large-sized motherglass.

Circuit Issues

In AMOLEDs, the active-matrix circuit lies beneath each pixel, and the circuit is comprised of power-supply lines and power-control TFTs. For each AMOLED pixel, at least two transistors (switching and driving) and one capacitor are required. However, because the OLED pixel luminance is directly changed by the current, subtle variations in the TFT current result in brightness differences from pixel to pixel. As a result, even a slight non-uniformity in TFT performance can create serious image-quality problems. For this reason, most AMOLED panels incorporate compensation circuits to correct this problem.

■ 40-inch FHD-TV – World's largest LTPS-based AMOLED

Items	Specification	Unit
Diagonal Size	40	Inch
Resolution	Full HD	-
	56	ppi
Number of Pixels	1920 x RGB x 1080	
Pixel Pitch	151 x 453	um
Panel Size	897.8(H) x 517.2(V)	mm

■ 12.1-inch NPC Monitor – World's largest oxide TFT-based AMOLED

Items	Specification	Unit
Diagonal Size	12.1	Inch
Resolution	WXGA	-
	123	ppi
Number of Pixels	1280 x RGB x 768	
Pixel Pitch	69 x 207	um
Panel Size	283(H) x 181(V)	mm

Fig. 4: *40-in. full HD and 12.1-in. WXGA AMOLED displays have been displayed by Samsung.*

Two types of compensation circuits, current programming and voltage programming, have been suggested. The-current programming method compensates TFT threshold-voltage and mobility differences, whereas voltage programming compensates only for the threshold-voltage differences.[10, 11] However, for large-area applications such as TV, the voltage-programming method is more useful because of its ability to work over large areas and for compatibility with LCD driver ICs.

AMOLED Prototypes Utilizing Emerging Backplane Technologies

Samsung has demonstrated a 40-in. AMOLED TV prototype by combining an SGS-based LTPS TFT backplane and FMM OLED technologies.[3] A 12-in. AMOLED notebook panel has also been prototyped and exhibited by the use of amorphous-oxide TFT backplanes and FMM OLED technologies.[12] Figure 4 shows images and specifications of these demonstration panels.

Conclusion

Due to fundamental advantages in display quality, underlying cost, and eco-friendliness, we believe a new era of AMOLED TV is inevitable. In this article, technological challenges have been discussed from the point of view of the active-matrix backplane, OLED patterning, and encapsulation processes. In order to effectively compete with LCDs, AMOLEDs need to realize their full potential both in terms of eco-friendliness and price competitiveness. The best future AMOLED-TV solution may incorporate a combination of a-Si TFT-like backplane, printing-based OLED patterning, and thin-film encapsulation technologies.

AMOLEDs are ideally suited to become the TV of the future – not only due to their superb image quality and eco-friendliness, but also based on their potential to expand the scope of displays. Indeed, the use of AMOLEDs has already resulted in real displays, including transparent, bendable, foldable, and flexible displays that were previously only conceived of in science-fiction movies. As convergence technology and interactive interfaces become increasingly important, the need for vivid and intuitive displays will certainly grow, and these changes will transform the concept and expectation of future TVs. AMOLEDs provide special capabilities and will inspire completely new applications that are not yet conceived, thus revolutionizing the future TV industry.

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Back to School with Tablets Embedded in Digital Desks

A digital-desk pilot program in Brazil uses a unique display design to provide an interactive interface developed to enhance education and minimize ergonomic concerns.

by Victor Pellegrini Mammana, Cynthia Yukiko Hiraga, Ana Maria Pellegrini, Daniel den Engelsen, Luiz Alberto Castro de Almeida, Alexandre Cândido de Paulo, Gustavo Junior Alves, Miguel Joao Neto, Carlos Ignacio Zamitti Mammana, and Antonio Carlos Camargo do Amaral

PROVIDING high-quality education is important everywhere, but in Brazil, in particular, education has become a top priority because of its importance in the fight against social and economic inequality. For this reason, the Brazilian Federal Government has been encouraging R&D with regard to information technology for education and digital inclusion. One of the approaches currently being pursued is the intensive use of computers inside classrooms. While computer labs and laptops – the latter especially as provided by the One Laptop Per Child program – go far toward providing an enriching technology experience in the classroom, digital desktops are an additional and intriguing educational option.

***Victor Pellegrini Mammana, Daniel den Engelsen, Luiz Alberto Castro de Almeida, Alexandre Cândido de Paulo**, and **Antonio Carlos Camargo do Amaral** are with the Renato Archer Information Technology Center (CTI). **Cynthia Yukiko Hiraga** is with the Escola de Artes, Ciências e Humanidades, Universidade de São Paulo (USP). **Ana Maria Pellegrini** is with the Instituto de Biociências, Universidade Estadual Paulista (UNESP). **Gustavo Junior Alves, Miguel João Neto, and Carlos Ignacio Zamitti Mammana** are with Associação Brasileira de Informática (ABINFO).*

One of the foremost researchers in the field of education and technology is Seymour Papert from MIT, who has explored opportunities related to the use of computers with a focus on math teaching.[1] He later extended this exploration to other disciplines. In 2005, the MIT program "One Laptop Per Child" (OLPC) proposed by Nicholas Negroponte was presented to the Brazilian Government as a way of transferring the ideas of Dr. Papert and other educational gurus from the academic scene to reality. The proposal by Negroponte[2] was based on the idea that all school children should experience so-called "one-to-one technology," *i.e.*, each child would have his own laptop, provided by the federal government. In practical terms, approximately 45 million laptops would be required to supply the Brazilian public schools. Although the ideas included in Negroponte's proposal have evolved from 2005 to the present, the main concepts of the OLPC program – free distribution of laptops to kids and teenagers with full access to the Internet – still remain vivid in the heads of policy makers all over the world.

Many programs based on the intensive use of computers in the classroom have shown excellent results – in the appropriate environment. However, when the environment includes individuals with a variety of educational, social, economical, and political backgrounds, results are more mixed. We will not go further into this here; however, the main focus of this article is to discuss some of the aspects of different types of computer systems inside classrooms. The issues presented here are in part based on the results of a study of the OLPC program that was conducted by the authors on behalf of the Brazilian government.

Computer Labs

The most common approach to introducing computers into schools in Brazil is with a separate room called the "computer lab" that contains about a dozen systems. Such a room is shared among all students of a given school. In many cases, a group of students shares a mouse and keyboard and each student may actually use the computer for only a few minutes. On several occasions, we heard educational experts state that computer labs remain locked most of the time. Although we did not quantitatively examine such statements, it appears that the locked computer lab is not a myth. Through visits and interviews with administrative staff and teachers in Brazilian primary schools, we collected statements such as "children break computers" and "I don't want trouble if the computer lab breaks." If intensively used, the "computer lab" poses a further concern: the existence of a display

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between the student and other individuals inside the classroom (including the teacher) can provide an undesirable element of segregation.

Laptops

The one-to-one computer strategy as proposed by Negroponte is a way of circumventing the tragedy of the locked computer lab because it gives children full access to computers anytime. This strategy obviously has the potential for mobility if sufficient battery time is provided; otherwise, dependence on multiple outlets in the classroom is unavoidable. The OLPC program has focused on a solution that minimizes power consumption, which also limits the display's maximum size and processor performance because the LCD backlights are responsible for a significant part of the power consumption in laptops. The bill-of-material of a laptop indicates another limitation to display size: it is one of the most expensive parts of the computer. For a project such as OLPC, weight, cost, and power expenditure needed to be minimized, leading to laptops that originally had display sizes of about 7 in.[2]

Finding a sufficient number of outlets to power the laptops, and using the outlets without creating a tangle of confusion during the school day, can be a challenge in the typical Brazilian public school. In more organized pilots, such as the one sponsored by Bradesco Schools in the city of Campinas, the laptop batteries are charged during break time, thus providing a mobile experience for two periods of 2 hours each day.

Another potential drawback for laptops is that of ergonomics. Recently, we have studied the use of laptops by children and we agree, in general, with Hedge's statement[3] that "laptops are intrinsically non-ergonomic because the display and the keyboard are integrated into a single piece." In other words, when the display is adjusted to fit the position of the user's eyes, the keyboard is in an unnatural position. When the keyboard is adjusted to fit the user's hands, the display is in an unnatural position. However, all statements related to ergonomics are subject to investigation and debate. For instance, it is reasonable to accept that many activities of children are non-ergonomic, such as "watching TV in a wrong posture, intensive sporting, intensive music practicing, video gaming, and even hand writing".[4] This is not, of course, to dismiss consideration of ergonomics as a mere trifle.

In the evaluation of the OLPC program, we also analyzed the cognitive consequences of small displays by comparing quantitatively the user performance among displays of 15, 10, 8, and 7 in. In this study, tasks demanding interaction with displays were performed by two groups: 18 children from 6 to 12 years old and 20 adults from 19 to 29 years old. The time required to perform the same task in each display size was used as an indication of the user's effort to achieve the interaction goals. We believe longer times needed to perform the same tasks indicated higher levels of difficulty that resulted from a less-comfortable interface. For the adult group, there was a consistent trend of longer times for smaller displays; for the children's group this trend was not statistically significant. We attribute this difference to the fact that the group of children in the test had very little experience with computers in general and mice, in particular, leading to longer times to perform the tasks regardless of display size. We believe that if the two groups had possessed similar computer experience they would have both performed more quickly on the systems with larger displays.

Conventional Input Devices

The discussion of whether intensive keyboard and mouse use can cause occupational hazard, pain, or other physical complaint is an evergreen in the literature. Keir *et al.*[5] reported that "the carpal-tunnel pressures measured during mouse use were greater than pressures known to alter nerve function" in 14 healthy individuals evaluated in their work. However, a study conducted by Andersen *et al*.[6] involving thousands of individuals indicated an unlikely connection between keyboard use and risk for developing carpal-tunnel syndrome. Again, controversy is present. Our decision to use a tablet in a digital desk instead of a conventional input device stemmed from a different motivation: we believe that with a keyboard, touch pad, or mouse the information surface (display) is separated from the points of motor interaction, leading to a less attractive and intuitive experience than the one offered by touch screens and transparent tablets.

Tablets

We define a tablet as a device constituted by a flat surface that is capable of identifying the position of one or more styli that touch its surface or "hover" over it. We have developed a new type of low-cost tablet that is based on a resistive principle (one of our authors has a U.S. patent for it). As opposed to conventional resistive touch screens, ours does not require two layers separated by spacers. We do not use ITO conductive layers, but SnO_2 instead, which costs much less and can be deposited at atmospheric pressure. High transparencies can be obtained in the 90% range in our tablet, while robustness is guaranteed by the outstanding tribological characteristics of SnO_2 on glass.

Figure 1 shows the working principle of a resistive tablet, in which the position is determined by measuring the voltage drop using a conductive stylus along a uniform resistive and transparent film. It is assumed that the voltage is approximately linear with the position (actually linearization algorithms are

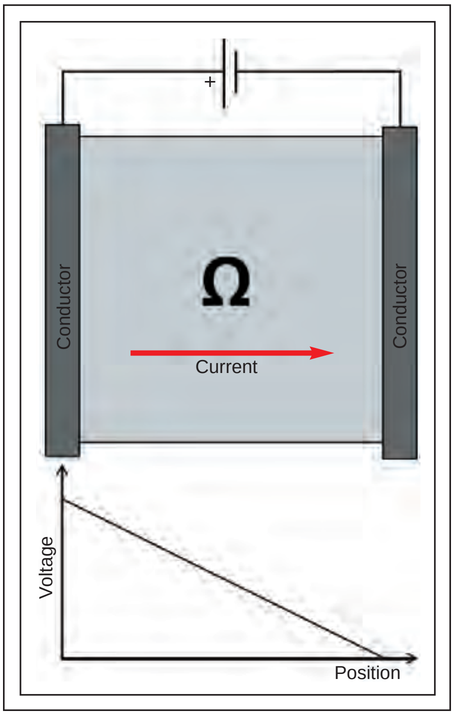

Fig. 1: *The tablet has a general working principle similar to many other resistive solutions: the measured voltage is linear with position. Instead of having conductive layers in parallel, we use a single film for X and Y by changing the direction of the current from cycle to cycle. This solution reduces cost substantially.*

Fig. 2: One of the first versions of the "Digital Desk" was demonstrated at Latin Display 2007. The child is using the stylus to interact with the display image.

required to make the tablet work appropriately). In our tablet, we manage to obtain "X" and "Y" by switching the current in perpendicular directions in the SnO_2 film, and that is why only one layer is required. The current design allows control of the cursor when the stylus is not in contact with the surface.

Digital Desks

During the last two SID-sponsored LatinDisplay conferences in Campinas (November 2007 and 2008), the small Brazilian city of Serrana participated in exhibitions showing a new technology that provided one-to-one experiences within classrooms; *i.e.*, each student using a computer integrated into a school desk (Fig. 2).

The technology is basically a low-cost metallic school desk with a display integrated into the table top, which consists of a robust and transparent plate, such as thick glass. This plate has a stylus-based tablet technology, or alternatively a touch-screen technology, applied to it, allowing the direct interaction with the desk display image. The table top can be used in the horizontal position, as indicated in Fig. 2, or vertically, or in any intermediate position. Two models are now available: a PC board integrated into the tablet top and a multi-terminal version, in which five desks are connected to a single computer, allowing independent operation by each user.

We believe that this Digital School Desk is a way to overcome the challenges of conventional computer labs and laptops as mentioned earlier in this article. First, if the Digital School Desk is made available in the regular classroom, there is no need to lock it in a computer lab. Next, the table top of the Digital School Desk can be positioned horizontally, enabling an open line of sight between students and teachers, and it has a transparent tablet or touch-screen integrated on the table top, allowing direct interaction with the display image. The Digital School Desk can also substantially increase the number of hours spent by children with computers that offer less health risk (although an educational program based on digital desks will also require measures to guarantee their rational use in order to further reduce risks). This type of desk has more options to circumvent health hazards through ergonomic optimization than laptops. Because there is no limitation on power, large displays can be used, offering better options of visual interaction for students. Last, making the desk furniture adjustable is easier than making laptops adjustable, so multiple-sized devices can be avoided.

On the downside, the Digital School Desk cannot offer the mobility of laptops, which implies that it can only be used in the classroom. Digital School Desks are also designed to be connected to power outlets on a permanent basis, which will require the rewiring of the classroom. (This, however, is also the case for intensive laptop usage at school, since battery life constantly reduces as the recharging cycles increase). Making laptops really mobile in Brazilian schools may require frequent battery substitution, a challenge for

Fig. 3: This Serrana public classroom is fully equipped with Digital Desks, air-conditioning, and a digital board at the front of the room. Students in this picture are using the multi-terminal version: one computer is a server for five desks. The digital board at the front of the classroom is based on a projector (courtesy of the city of Serrana). The table tops can also be put in horizontal position during operation, to ensure a clear line of sight between teacher and student.

which our cities are not prepared with regard to supply and environmentally responsible disposal.

Figure 3 shows the first classroom fully equipped with the multi-terminal version of the desks. The full concept in the city of Serrana includes a digital white board and air-conditioning, which is rarely present in Brazilian public schools. The use of air-conditioning itself may be a key factor in improving education because it can provide thermal comfort for kids in very hot areas, although we do not have quantitative data on which to base this statement yet.

It is too early to evaluate the impact of the desks on the learning performance of the students at Serrana, but according to the comments of the teachers involved with the pilot study there, the new technology certainly has already changed their attitude toward the school environment, increasing attendance and motivation. We believe that digital desks can serve as key components not only toward a more satisfying technology interface, but toward a better educational outcome overall.

Acknowledgments

The development and evaluation of the Brazilian Digital School Desk is the work of many individuals. We would like to thank all of them for their contributions. Daniel den Engelsen acknowledges the financial support from FAPESP. We would like to acknowledge the support from SECIS/MCT and thank Prof. Afira Ripper from UNICAMP for his helpful discussions.

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editorial

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few people in the industry with as much perspective and experience, which is why we welcome Julie back for another year as our Guest Editor for our OLED issue.

Now that September is in full swing, and many children around the world are back in school, it seems like a good time to look at display technology that may not be at the cutting-edge corporate-funded level like OLEDs, but that also has potential to bring about important changes. Some of the people in our Brazil SID chapter have been focusing on the methodologies of effectively integrating technology into the classroom, recognizing that computer literacy and technology education are key elements for the success of the next generation's young people. In order to integrate computers into schools, the cost must be low, and in the case of the typical laptop and tablet PC, the display is still one of the most expensive components. As you can read this month in their article "Back to School with Tablets Embedded in Digital Desks," there are many challenges to achieving a fully electronic educational setting, but the authors have been exploring some very interesting ideas with regard to digital desktops. This type of focus in integrating education with computers and displays will surely bring about needed changes, not only in Brazil but in the rest of the world. Those of us at *Information Display* look forward to these and countless other developments that display technology continues to make possible. ■

guest editorial

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selection for both backplane and frontplane technologies that are required to realize a successful OLED-TV business. The article is rounded out by a stunning image of SMD's most recent 40-in. FHD-TV prototype, which has been drawing crowds at exhibitions.

I hope you enjoy reading these three articles and that the information is helpful in developing your own image of AMOLED displays today and into the future. It is truly an exciting time for this industry and an opportunity to join forces to build the OLED ecosystem by driving technologies forward and participating together in entities such as the OLED Association. On a personal note, I cannot wait for my 40-in. OLED TV! ■

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

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